Research Project co-funded by the
European Commission
Research Directorate-General
7th Framework Programme
Project No. 312642

E-AIMS

Euro-Argo Improvements for the GMES Marine Service

Arctic float final evaluation

Del 2.5.2

Date: September /2015

Authors: Waldemar Walczowski and Ilona Goszczko (IOPAN)

Lead:

Institute of Oceanology Polish Academy of Sciences – Poland

Co-ordinator:

Institut Français de Recherche pour l'Exploitation de la Mer - France

Table of contents

1. INTRODUCTION

The dramatic changes in the Arctic climate observed in recent years have generated an urgent need to intensify the oceanographic investigation of this region. The Arctic Ocean is the most undersampled region of the global ocean. Intensive investigations in the 2000s, in particular during the IPY period, have improved our knowledge about the Arctic Ocean circulation, currents structure and transports, yet it still remains unsatisfactory.

The oceanographic investigations of the northern areas are much more expensive than in other regions. A part of the Arctic Ocean is covered by multiyear ice. The seasonal ice covers most of the Arctic Mediterranean. Although in recent years the sea ice cover in summer has decreased, in winter ice covers the Arctic Ocean again. It necessitates the use of icebreakers – the most costly vessels. Strong seasonality is the reason why most of the data is collected in relatively mild summer and autumn, while winter data would be even more valuable.

Until recently it seemed that modern technologies would resolve these problems. Rapid development of autonomic devices – Argo floats, gliders, AUV-s, led to much better coverage of oceans by measurements. Wide stream of synoptic data from Argo floats is transferred to datacenters. This concerns all regions except the Arctic. Coverage by measurements taken by autonomic instruments in this region is still poor. After some spectacular observations made by gliders in the Fram Strait, institutes withdraw their equipment from that region. Losses of the expensive gear were too frequent, which also concerns the Argo floats. The survival rate of the floats in ice-covered region is much lower than in open waters. Consequently the cost of a single CTD profile is much higher than in other regions. Institutes do not want to invest money in such an activity; usually the money comes from grants and all expenses must be accounted for.

Therefore, there is a coherent strategy needed to solve these specific problems. Deployment of a stable amount of floats along the Fram Strait, the Barents Sea Opening (BSO) and in the Nansen Basin (in the areas free of ice, along the Atlantic water pathways) would be advisable. Together with increasing number of ice tethered systems deployed in the Arctic Ocean it can make a valuable network for studies of climatic and ecological importance. To build a sustained array of Argo floats covering the whole Arctic Ocean also better coordination of floats deployment is necessary.

The severe Artic conditions make it necessary to develop special floats for the Arctic Ocean. The most unfavorable feature is presence of sea ice. The solid ice cover prevents surfacing of the float and transmitting data, surfacing in a floating ice may result in damage of the device. Sea ice cover creates also other problems – difficult contact with the sea surface hampers navigation based on the GPS signal and telemetry, thus preventing data transmission.

Under Task 2.5 of the E-AIMS project, the Institute of Oceanology Polish Academy of Sciences (IOPAN) tested the Arctic floats. The available resources and time range of the project did not allow to construct a new float. And it was not an objective of the task. IOPAN had deployed floats in the Nordic Seas earlier, and on the basis of our experience the experiment with the Arctic float was designed (Del n°2.5.1) and conducted. During that work the authors collected some interesting contacts, collaborations, experiences and came to some conclusions. New Inertial Navigation System was developed and applied in one float. One of the two deployed Arctic floats is still working and transmitting data.

2. THE ARCTIC OCEAN SEA ICE LOSS

The sea ice in the Arctic Ocean continues to decline. In September, when it reaches its minimal value it diminished as much as twice – from more than 7.5 million km^2 in 1980 to less than 3.4 million km^2 in 2012 (Fig. 1, 2, 3). The change in the ice maximal extent in March, even though not so dramatic, follows the fall decline. The sea ice cover area losses equals more than 2 million km^2 - from 16.6 million in 1979 to 14.3 million km^2 in 2015. The sea ice thickness is also changing with thinner first year ice and decreasing thick multiyear ice (Fig. 4).

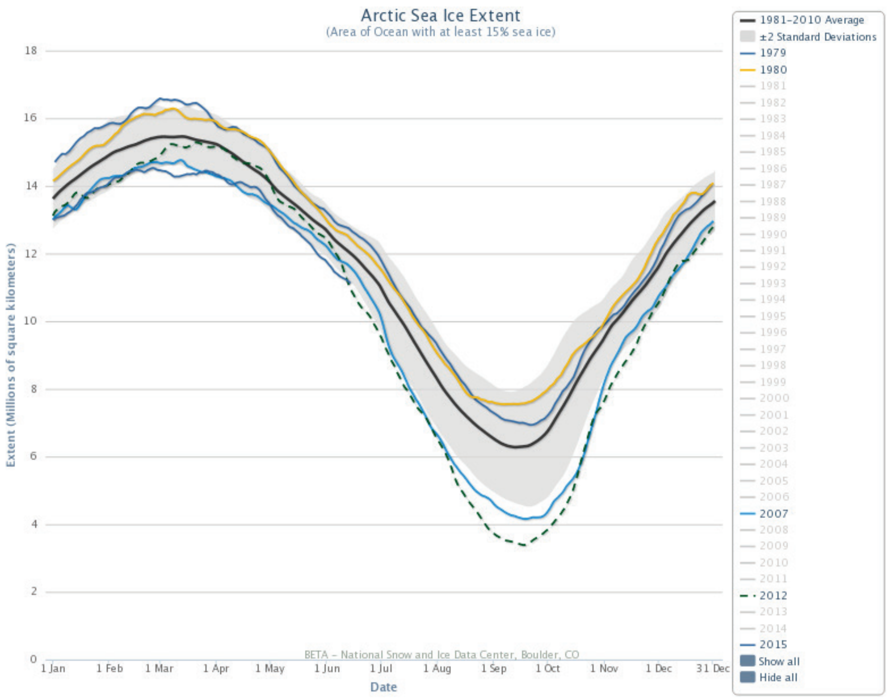


Figure 1. Seasonal cycle of sea ice area. Extremal years are distinguished as well as mean and standard deviation values. Credit: National Snow & Ice Data Center.

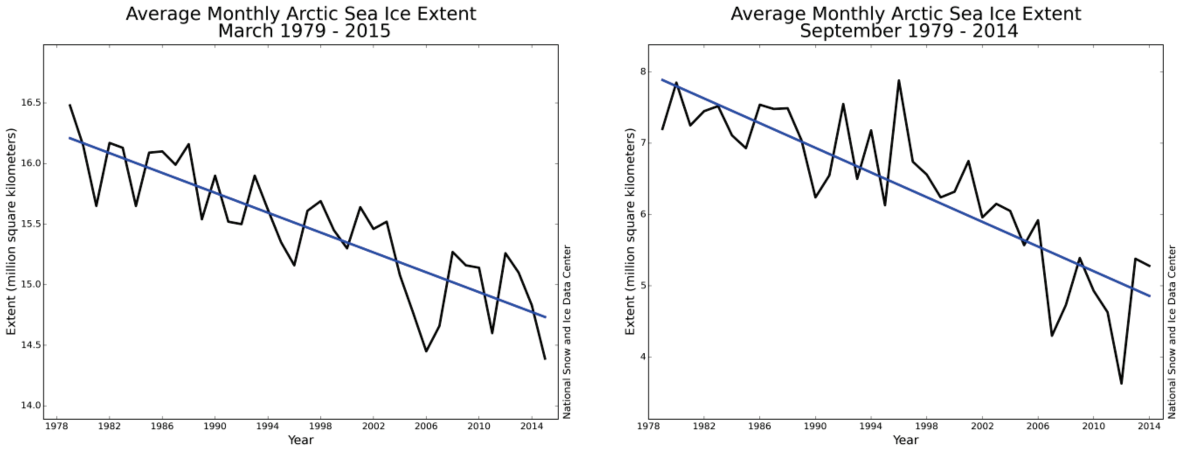


Figure 2. Comparison of sea ice loss observed in freeze season and melt season. The minimal value in March was noted in 2015, while the absolute minimum was reached in September 2012. Note different scales. Credit: National Snow and Ice Data Center.

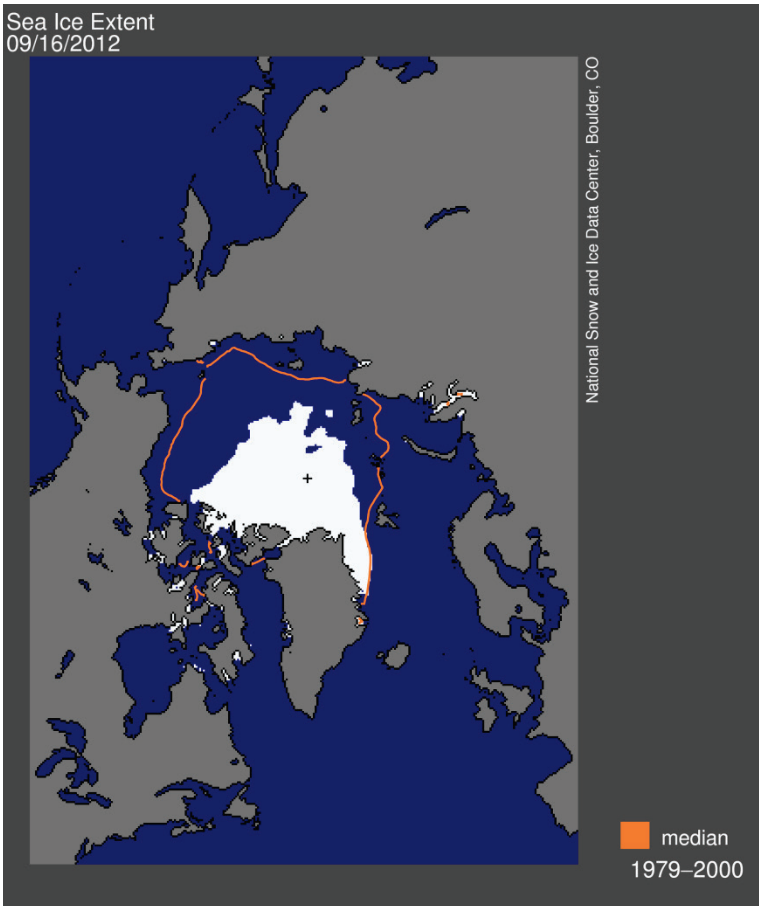


Figure 3. The absolute minimum of the Arctic sea ice extent reached in September 16, 2012 equals 3.41 million square kilometers. The orange line shows the 1979 to 2000 median extent for that day. The black cross indicates the geographic North Pole. Both transit ways: the Northwest Passage through the Canadian Arctic Archipelago as well as the Northeast Passage along the Siberia were ice free. Credit: National Snow & Ice Data Center.

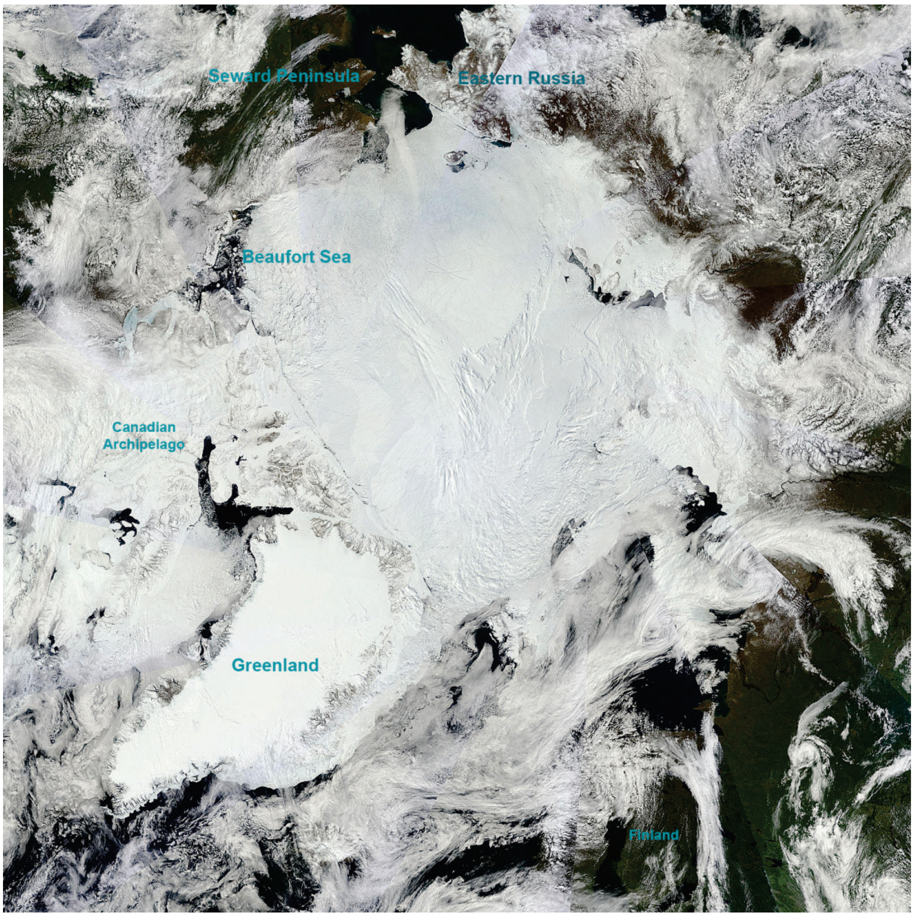


Figure 4. The Arctic Ocean in June 2, 2015. Ice, snow and clouds are all depicted as white patches. Nevertheless, the satellite image shows broken ice over the eastern Beaufort Sea. Eastern Russia is snow covered, while the Seward Peninsula is relatively snow free. Credit: Land Atmosphere Near-Real Time Capability for EOS (LANCE) System, NASA/GSFC.

Correct assessment of the sea ice loss and climate changes occurring in the high latitudes and their impact on the ecosystem requires better estimation of heat, salt and freshwater exchange between the Nordic Seas and the Arctic Ocean through the Fram Strait on one hand and the Barents Sea on the other. Likewise, a circulation scheme of the Arctic Ocean, especially in the Eurasian Basin is still under debate. Furthermore, seasonal and long-term evolution of the mixed layer during the changing sea ice regime is also crucial for better understanding and prediction of changes which occur in the Arctic Ocean heat transfer and freshwater budget (Peralta-Ferriz & Woodgate, 2015). Studies concerning the variability of the dissolved oxygen rates in the warming environment and its impact on the biological life (the primary production of phytoplankton and ice algae) were also carried out based on the profilers data (Laney et al., 2015). Among others these problems constantly remain hot topics of the present-day oceanographic studies (Rudels et al. 2015, Sirevaag et al., 2011, Toole et al., 2010, Toole et al., 2011, Timmermans et al, 2010, Walczowski, 2014).

Nevertheless, the low number of Argo floats profiling in the Nordic Seas and Arctic Ocean is not sufficient yet to bring a meaningful help – only two floats reached the Barents Sea (one flowed near the western side of the Novaya Zemlya). Moreover, all the floats deployed in the Greenland Sea recirculated south of the Fram Strait or are stuck in the Greenland Sea Gyre.

At present, a comparison between the Argo data and the calculations coming from mooring measurements and ship-based observations is difficult.

3. DEPLOYING ARGO FLOATS IN THE ARCTIC OCEAN

According to the AIC all in all 96 Argo floats have been deployed in the whole Arctic Ocean basin since the 2003 (Fig. 5). Most of them (63) are APEX floats, additionally, there have been also: 14 NEMO, 2 PROVOR and 4 SOLO-W floats. A few ice tethered instruments (but not all of them, see Tool et al, 2011 for the comparison) have been notified in the AIC as well: 7 ITP and 6 POPS devices. Only two communication systems have been used thanks to their coverage in Polar Regions: Argos and Iridium broadcasting. Data collected by all platforms have been supplied the DACs and then GDACs as well.

Data flow depends on the transmission system. When Argos was chosen, the data are sent to CLS and from there directly to the real time data center (RDAC) which creates NetCDF files published online. If there is no national DAC, data are transferred to the GDAC (Coriolis) which should act as a RDAC.

When Iridium transceiver is used, then information is disseminated via email to: data operator, float owner and RDAC. The attached data files are in a binary format.

The data format is explained in technical manuals attached to every device. For example, NEMO floats receive binary data output in files of hexadecimal format. Then, a dataset needs to be decoded into physical units using tips included in the manuals. Otherwise, the dataset may be decoded by a data operator, saved as ASCII files and shared via an FTP server.

Real-time and delayed mode quality control (DMQC) is usually done by a RDAC (or GDAC if there is no DAC). The .nc files are created from the incoming data and real-time QC procedures are applied. The following files are created: meta-file, trajectory-file, technical-file and prof-file. Usually this procedure is implemented within 24 hours. The DMQC is usually performed by the home institution of the float owner. The agreed DMCQ is applied and agreed Matlab routines are used. All data procedures and validation procedures are explained in the user manual and DMQC manual which can be found at the Coriolis website. The procedures concerning Argo data from the Arctic Ocean are more or less the same as for the rest of the world ocean.

If too many data is flagged as bad during the QC, then changes have to be made in the validation procedures to avoid this. To check whether global procedures work in the Arctic (as a result only bad data are flagged as bad) input from experts (special vertical and horizontal settings to choose the climatological background data or more recent CTD data) is needed.

According to AIC, ice detection software has been implemented in 17 floats in the whole Arctic Ocean basin (perhaps there were more, if information concerning ISA was not notified to AIC). There were 12 APEX and 5 NEMO-float. 9 floats with included ISA are currently active (May 2015).

The DO sensors have been also tested in the Arctic Ocean – all in all 10 floats have been deployed until now, 7 of them are still active (based on AIC).

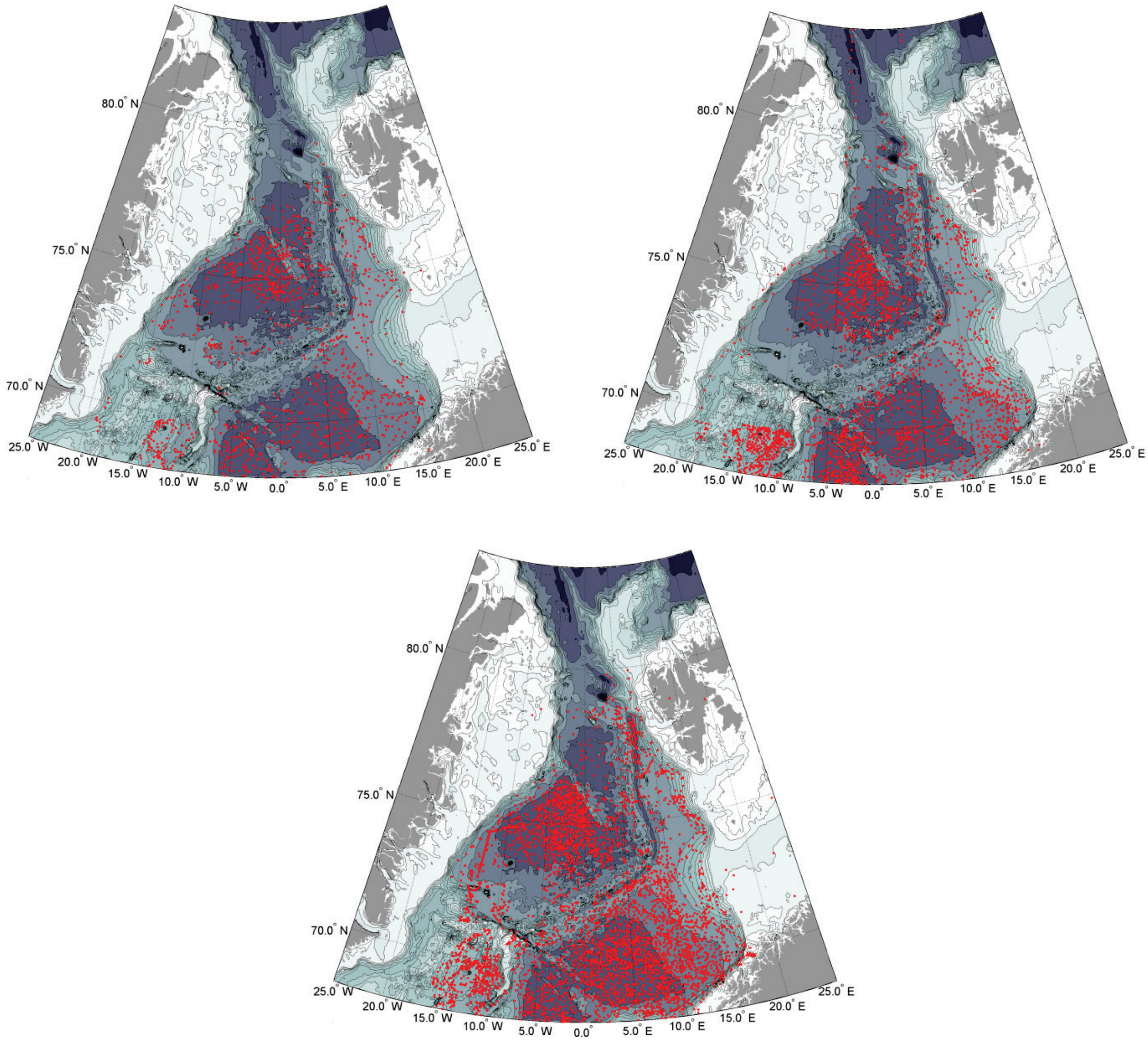


Figure 5. Maps showing the progress in coverage of Argo profiling in the polar Atlantic Ocean: in years 2003-2005, 2006-2010 and 2011-2015, respectively. A great number of Argo floats were deployed during the IPY. Several dots north of 80°N indicate the ITP measurements.

4. ICE-TETHERED PROFILERS

Even though the Ice ITPs and POPSs seem to be the best practice of measuring the frozen Arctic Ocean continuously during the whole year, it is still uncertain how the situation will evolve in future, perhaps summer ice-free, Eurasian Arctic. Also, to deploy several instruments in the source region of the Arctic Ocean Transpolar Drift (and thereby to get the longest pathway of the instrument use) it is necessary to involve a powerful ship or a helicopter to reach the ice float thick and big enough (Fig. 6).

By 16 June 2015 there have been 22 active ITPs in the whole Arctic Ocean (Fig. 7). All in all, 83 ITPs have been launched since the program started in 2004. It shows a relatively sparse coverage (compared to the Argo program). Also, the mean velocity of moving platforms is relatively high due to fast ice drifting (compared to standard 1000 dbar drift level of floats).

Figure 6. Deploying the ITP # 74 in summer 2013 by WHOI personnel (S. Lambert, J. Kemp and C. Rauschenberg from Bigelow Laboratory for Ocean Sciences) during the NABOS cruise in the Eurasian Arctic. In the background AARI research vessel Akademik Fedorov (photos I. Goszczko, IOPAN).

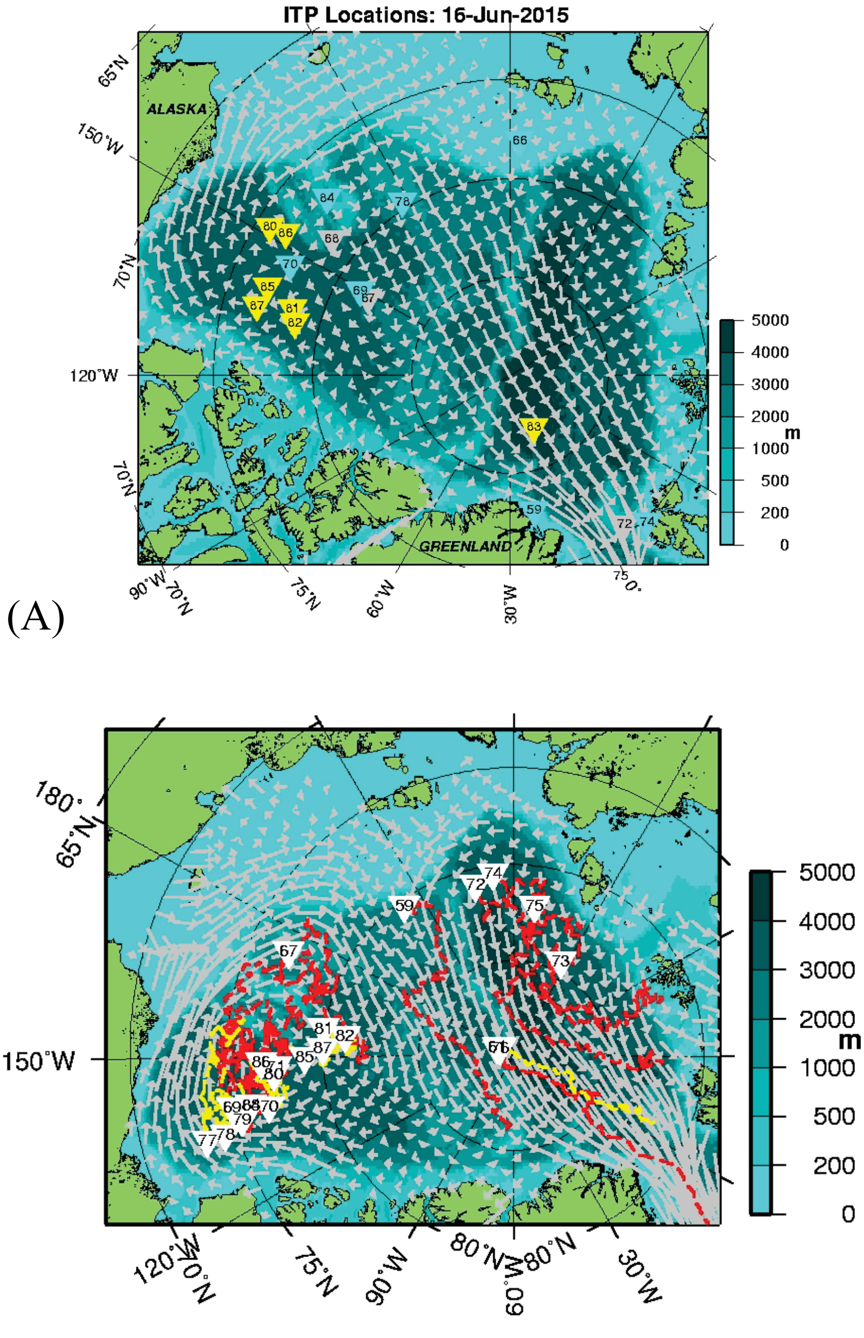


Figure 7. The map shows that the Nansen, Amundsen and Makarov Basins are hardly measured by ITPs, while in the Canada Basin profilers mostly circulate in the Beaufort Gyre. (A) location of all 22 active ITPs by 16 June 2015, (B) deployment locations (triangles), last profiles (crosses), and drift tracks of all ITPs deployed in 2013 (red) and 2014 (yellow). The Ice-Tethered Profiler data were collected and made available by the Ice-Tethered Profiler Program (Toole et al., 2011; Krishfield et al., 2008) based at the Woods Hole Oceanographic Institution (http://www.whoi.edu/itp).

5. THE ARCTIC FLOAT

There is no definition of the “Arctic float”. The “Arctic float” is commonly understood as an Argo float which has been adapted to ice-covered ocean conditions. The main aim of the adaptation is to increase the float’s life. It is also done to enable under-ice profiling, navigation, data storage and transmission in delayed mode. As in other newly constructed floats, the new sensors and deeper measurements are also important.

There are various reasons why floats get damaged, stop transmission or even get destroyed. A lot of floats deployed in the Arctic were equipped with a standard, long antenna (Fig. 8).

Figure 8. The Argo float with long antenna.

This kind of antenna usually brakes out during the first contact with solid ice, when the float ascends - a technically efficient float stops transmitting data and becomes useless. Therefore, the first and a very simple modification made in floats deployed in the Antarctic and Arctic region was equipping it with a shorter antenna and protection for both the antenna and the CTD sensors (Fig. 9 and 10).

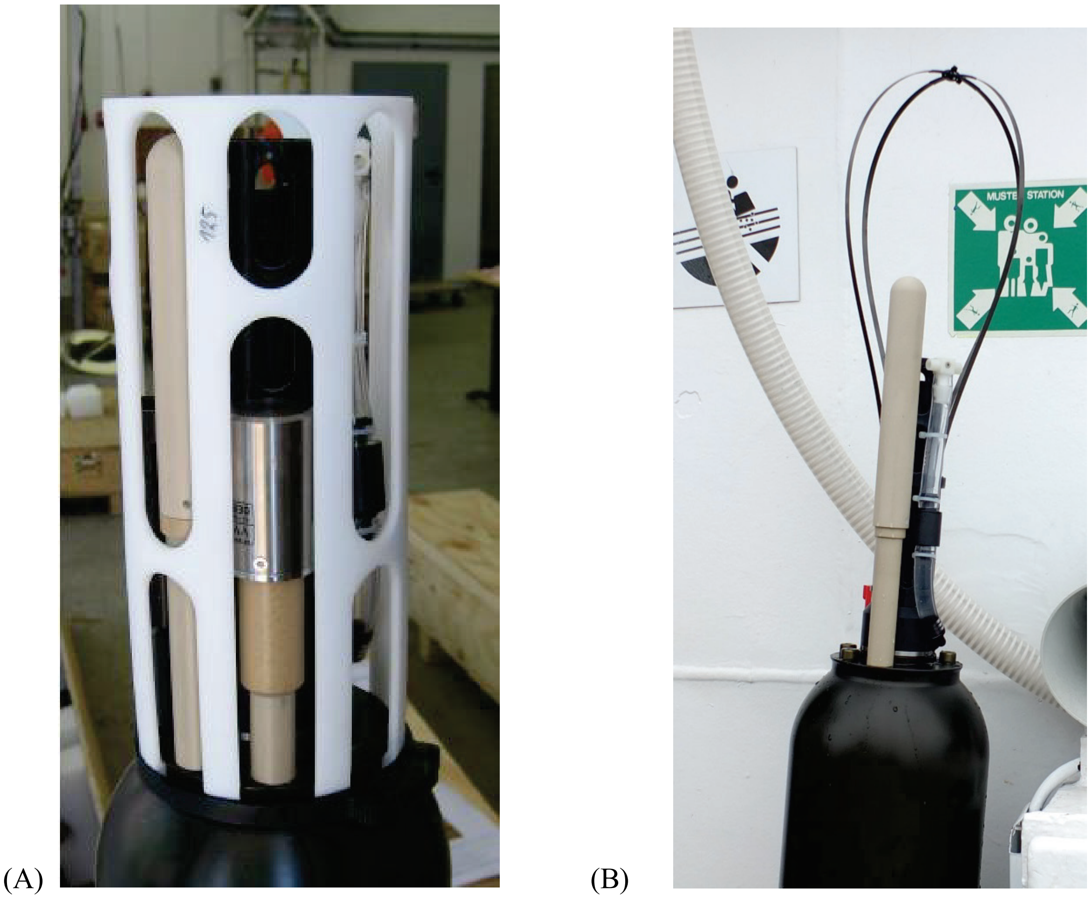


Figure 9. Ice-protection of sensors and Iridium antenna applied by OPTIMARE in the older (A) and newer (B) models of NEMO floats.

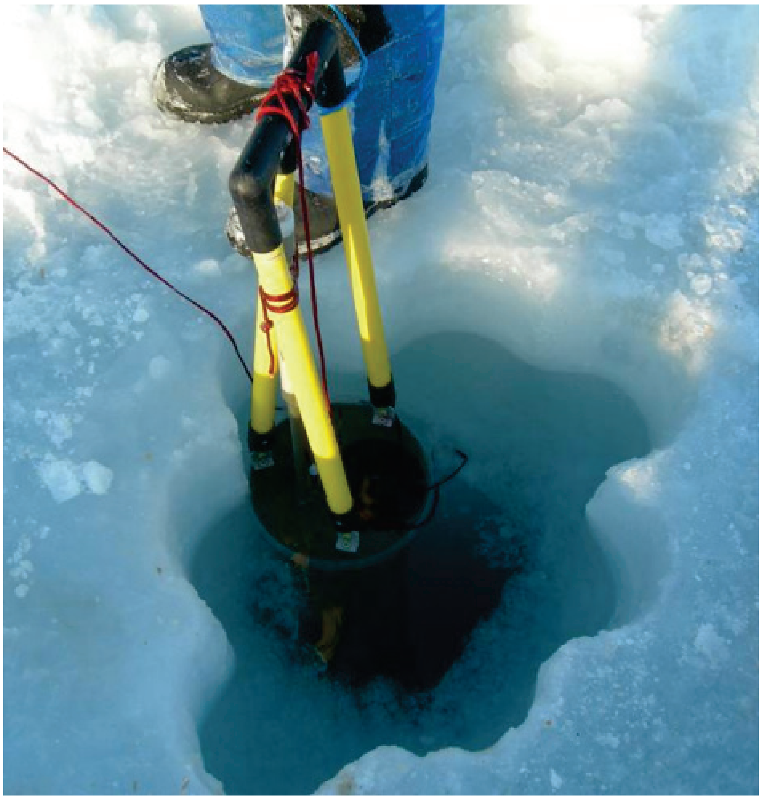


Figure 10. The firm ice bumper applied by the NKE in a modified PROVOR float. Credit: NKE

Generally, avoiding contact with ice, especially when a float ascends is the most popular method for adapting floats to conditions prevailing at ice-covered oceans. The so-called “Ice Sensing Algorithm” (ISA) is a relatively cheap method of float protection. ISA analyses water temperature at pre-defined levels while going up and compares it with the predefined temperature characteristics for ice cover. If the measured water temperature indicates that there may be of ice cover on the surface, the ascending may be aborted and the data are stored in internal memory. The float may continue its prescribed cycle or “look” for open water. The ISA has proven its usefulness in the Southern Ocean conditions (Klatt, 2007, Wong and Riser, 2011). The mortality rates of floats with ISA are now equivalent to those deployed in less demanding conditions. In the Arctic the structure of the upper water column is more complicated and variable than in the Antarctic, therefore, the ice-sensing algorithm is not so efficient.

Thus, various methods of ice detecting are developed and planned. Some of them include:

- Mechanical
- Passive acoustic
- Active acoustic
- Optical

The simplest mechanical technique was used by WHOI (Fig. 11). Other techniques are tested under various projects.

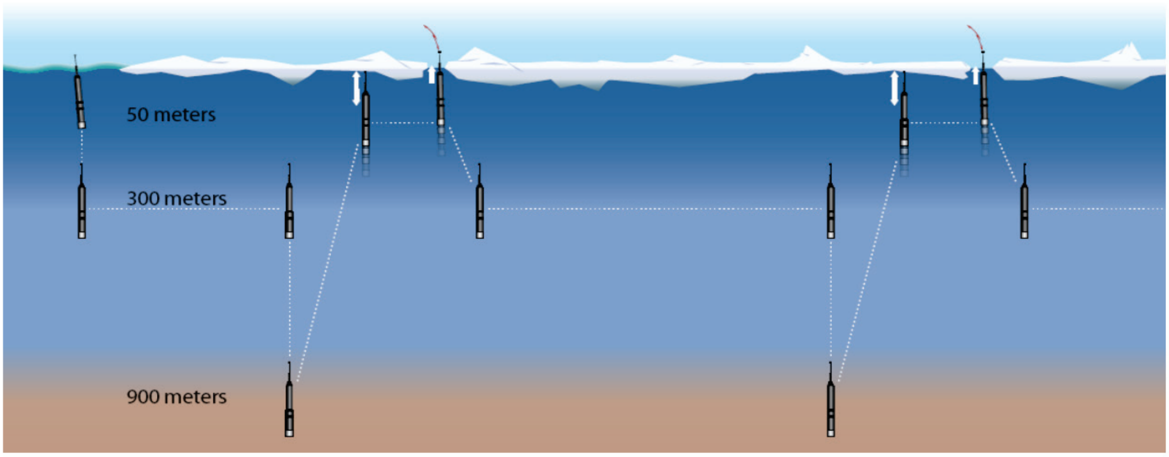


Figure 11. Scheme of work of a Polar Profiling Float. Credit: B. Owens and P. Winsor, WHOI (http://www.whoi.edu/ppf/index.html).

The second very important problem connected with the Arctic float is under ice navigation. The ice cover prevents the float from surfacing and fixing the geographical position. The data collected in the internal memory during the cycles without surfacing are not so valuable because the geographical position of profiles is inaccurate. This problem may be resolved by installing signal receivers in the RAFOS floats. The float position is obtained by tracking sound sources on moored stations.

This technique was used by IOPAN in previous years (see Section 7, Fig. 20). Unfortunately, there is no RAFOS sound sources installed in the European Arctic at present. The sources and moorings are very expensive and need maintenance (battery change).

Another method used in some oceanographic projects is installing temporary sound sources on ice. The sources work during the project time and are removed afterwards (Lee, 2012).

Another possibility for underwater navigation is using the Inertial Navigation System. Nowadays, the accuracy of these systems is too low for float positioning, but development of the inertial sensors and data processing methods is very fast (Section 6). Therefore, under the framework of the WP 2.5, IOPAN, in collaboration with other partners, developed and integrated such devices into a float and then tested it (see Section 7).

Fewer lost floats and better efficiency may be achieved also in other ways. Active management of floats, including changing the parking depth, profile depth, cycle time and surface time, are possible underway thanks to using the 2-way Iridium (and Argos-2) communication. This is also convenient over sloping topography to avoid float grounding. Faster data transfer provided by modern systems shortens the time required for the float to stay on the surface and reduces the risk that the float will get damaged.

Another solution to avoid the contact with ice is allowing floats to intelligently analyze the collected data in the field. These floats, currently developed by NKE in cooperation with researchers from several institutions (Marec et al, 2012), and tested recently under the NAOS project (http://en.naos-equipex.fr/The-project/) have enhanced electronic boards: one dedicated to navigation, and one for collecting data from several sensors and processing them. The current environmental conditions are analyzed and used for better prediction and navigation. For instance, the intelligent float may process data from ice-detection sensors, satellite images of the sea-ice cover, output from models (ice, currents) or climatology.

This kind of instantaneous feedback given by float itself is obligatory in the dynamically changing situation on the sea surface covered with ice (with many ice floats, leads and changing local wind). Data collected by the ice detection sensor should have impact on the navigation plan or the plan should be changed remotely by the mission pilot. However, the latter raises the question of autonomous character of the float.

6. E-AIMS DEPLOYMENTS IN 2014 – THE WEST SPITSBERGEN CURRENT

Two Arctic floats were executed by IOPAN in summer 2014. Both floats were deployed from the IOPAN research vessel "Oceania" (Fig. 12). The first float was launched on the 1st July, 17:20 GMT at the position 75°0.025'N, 012°29.650'E, and got WMO# 6902041. The second float with the Inertial Navigation System (INS, see Section 7) was deployed at the position 76°29.864'N, 007°32.284'E on the 10th July, 20:00 GMT and got WMO# 6902042 (Fig. 1).

Some technical problems were encountered with the first float. The first data package was sent 59 days after deployment, however, the data were incomplete. Eventually, the float sent 10 incomplete sets of data and stopped to transmit on the 9th October. All in all, the float did 33 profiles (part of them was not sent).

Deployment of the second INS float was successful. By the 27th June 2015 the full set of hydrographic data was transmitted. The INS data were transmitted as planned for the first 17 days (16 profiles with INS data were received). Two way communication via IRIDIUM was tested and changes in the float working mode were successful (INS was stopped). So far, the float has done 83 profiles and it is still working (Fig. 13).

Figure 12. The NEMO float with INS mounted internally deployed in the West Spitsbergen Current in summer 2014 (photo I. Goszczko, IOPAN)

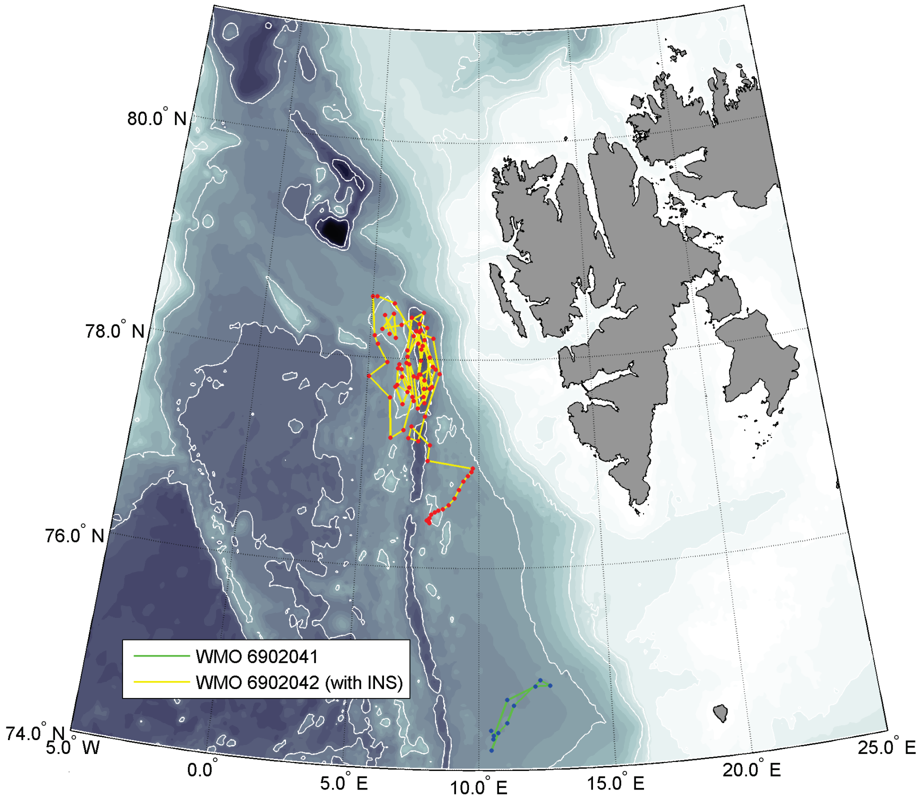


Figure 13. Surfacing position of two Argo floats deployed south and west of Spitsbergen in July 2014. The first (green line) sent incomplete data from 10 profiles while the second (yellow line) sent data from 83 profiles by 27 June 2015 and 16 datasets from INS and it is still working. The latter float circulates at 1000 dbar (since the profile # 17th) not far from the Arctic Ocean drifting sea ice, providing crucial information about interactions between the ocean and the atmosphere.

7. INERTIAL NAVIGATION

Inertial navigation is a self-contained navigation technique in which measurements provided by accelerometers and gyroscopes are used to track the position and orientation of an object relative to a known starting point, orientation and velocity (Fig. 14). An inertial measurement unit (IMU) typically contains three orthogonal rate-gyroscopes and three orthogonal accelerometers, measuring angular velocity and linear acceleration, respectively. By processing signals from these devices it is possible to track the position and orientation of a device. Inertial navigation is used in a wide range of applications including navigation of aircraft, tactical and strategic missiles, spacecraft, submarines and ships. Recent advances in the construction of MEMS devices have made it possible to manufacture small and light inertial navigation systems. These advances have widened the range of possible applications to include areas such as human and animal motion (Woodman, 2007).

Until recently the weight and size of inertial measurements units precluded their use in underwater instruments as Remote Operated Vehicles (ROV) or Argo floats. Recent improvements in the performance of small and lightweight electronic inertial sensors have made the application of inertial techniques to such problems possible. The modern Inertial Measurement Units (IMU) sensors are manufactured at the basis of the Micro-Electro-Mechanical Systems (MEMS). The technology allows manufacturing of small and relatively cheap IMUs. The performance of the MEMS inertial devices is also improving rapidly.

IMU is an integrated sensor package which includes several accelerometers and gyros to obtain a three dimensional measurement of both specific force and angular rate, with respect to an inertial reference frame, as for example the Earth-Centered Inertial reference frame. Specific force is a measure of acceleration relative to free-fall. Subtracting the gravitational acceleration results in a measurement of actual acceleration. Angular rate is a measure of rate of rotation. A typical IMU is a combination of 3-axis accelerometer combined with a 3-axis gyro. An IMU by itself does not provide any kind of navigation solution (position, velocity, attitude). It only gives the information for the Inertial Navigation System (INS), which integrates the measurements of its internal IMU and then the navigation solution. An Inertial Navigation System uses an IMU to form a self-contained navigation system which uses measurements provided by the IMU to track the position, velocity, and orientation of an object relative to a starting point, orientation, and velocity (Vectornav). INS is a combination of IMU sensors, computer running navigation equations, internal memories, power supply and other components.

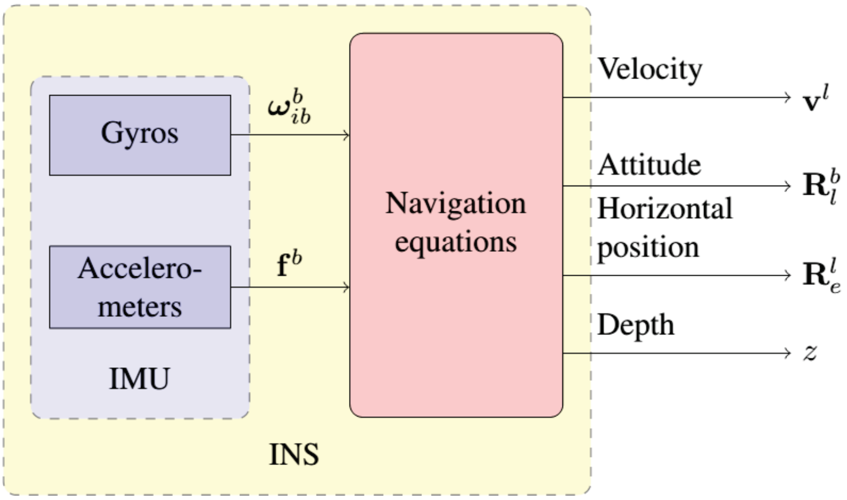


Figure 14. The Inertial Navigation System scheme. Credit: K. M. Fauske

The inertial sensor market spans an enormous range in terms of product price and performance. There are six orders of magnitude difference in price and performance between the highest end inertial systems and the lowest.

In general, inertial sensors can be grouped into one of the following four performance categories:

- Marine & Navigation Grade
- Tactical Grade
- Industrial Grade
- Automotive & Consumer Grade

Aside from the custom inertial navigation systems used on Intercontinental ballistic missiles, the marine grade inertial systems are the highest grade sensors that are commercially available. They provide the best overall performance in terms of both determining position and orientation. These systems are typically used on ships, submarines, and some spacecraft. A high-end marine-grade INS can cost over 1 million dollars. These systems will typically provide un-aided navigation solution drifts that are less than 1.8 km per day. This represents the best that is possible with commercially available inertial sensing technology.

Navigation grade systems have slightly lower performance than the marine systems and are typically used on commercial airliners and military aircraft worldwide. A navigation grade system will typically have less than 1.5 km drift per hour. These systems cost around $100,000 and have a size of about 6in x 6in x 6in. A navigation grade system can be combined with GPS to create positioning systems that are accurate to within centimeters in real-time.

The lowest grade of inertial sensors is often referred to as automotive grade. They are typically sold as individual accelerometers or gyros, however, many companies have begun to combine multiple accelerometers and gyros from different manufactures to create self-contained IMU units. This grade of IMU's is not accurate enough to be used for inertial navigation.

Errors in the position estimate will actually be caused by many factors including the gyro bias stability, accelerometer scale factor uncertainty, and many other parameters; however, the largest contribution will be due to un-corrected errors in the accelerometer bias. The error in position due to a bias in the accelerometer will have quadratic growth with time (Vectornav).

There are two ways of mounting the INS on the platform: stable platform (Stable Platform Systems) and Strapdown Systems. In Stable Platform Systems the IMU sensors are mounted on a platform which is isolated from the external rotational motion. In strapdown systems the inertial sensors are mounted rigidly onto the device.

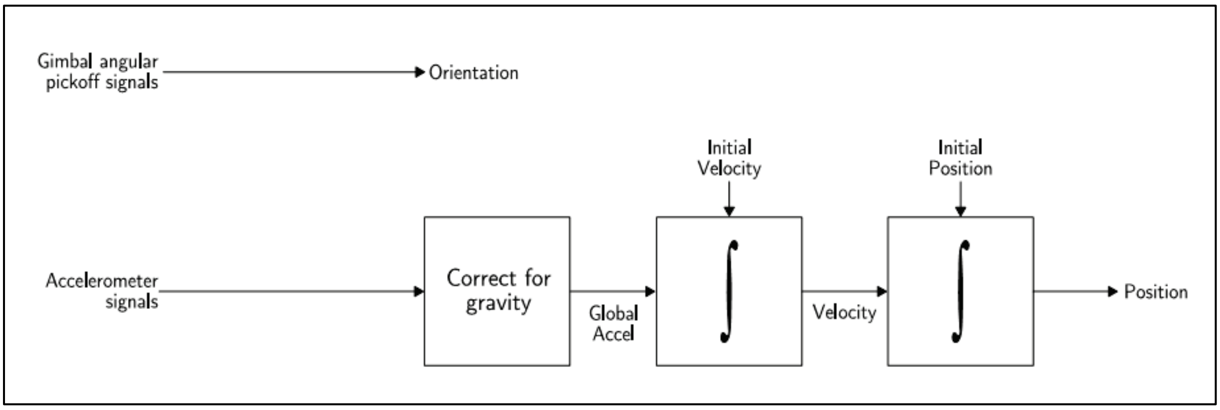


Figure 15. Stable platform inertial navigation algorithm (from Woodman, 2007).

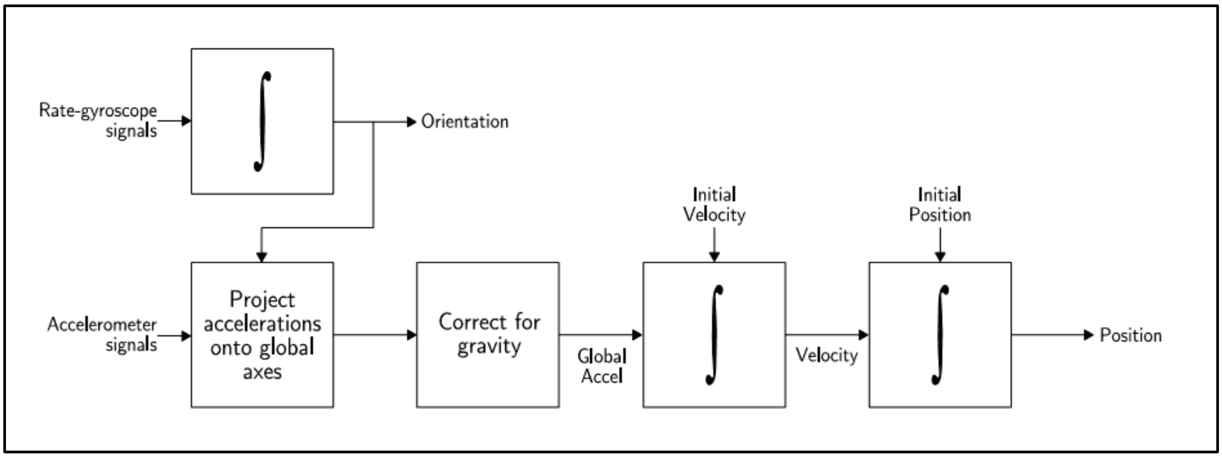


Figure 16. Strapdown inertial navigation algorithm (from Woodman, 2007).

8. INERTIAL NAVIGATION SYSTEM INSTALLED IN THE ARGO FLOAT

The idea of integrating an IMU sensor and processor into an Argo float was realized by the IOPAN, FORKOS and OPTIMARE.

Negotiations with various floats manufacturers on integrating an IMU sensor into a float were conducted from the beginning of the E-AIMS project. The most advanced negotiations were reached with the French NKE and German OPTIMARE. NKE offered PROVOR float or a newly constructed float, but without a possibility of experiments with the INS. Finally, the OPTIMARE GmbH from Bremerhaven as the float producer was chosen. OPTIMARE offered the NEMO float with the Ice Sensing Algorithm (ISA). The Polish Research and Production Enterprise FORKOS Ltd. as the Inertial Navigation System (IMU sensor, processor, software and data storage module) provider were selected. OPTIMARE agreed to apply the necessary changes in their float and install the experimental Inertial Navigation System.

Before the final implementation, various IMU devices had been tested by IOPAN:

1) **Razor IMU**, **SparkFun**, 9 Degrees of Freedom on a single, flat board: ITG-3200 - triple-axis digital-output gyroscope, ADXL345 - 13-bit resolution, ±16g, triple-axis accelerometer, HMC5883L - triple-axis, digital magnetometer. Outputs of all sensors processed by on-board ATmega328 and sent out via a serial stream.
2) **LPMS-CU IMU/AHRS unit** with 3 axis accelerometers range +/- 2/4/8/16 g, 3 axis gyros range +/- 250/500/200 deg/sec and three axis magnetometer, +/- 130-810 uT. Unit outputs data in CAN BUS format - X,Y,Z acceleration, pitch, roll, yay rate of turn, X,Y,Z magnetometer data, and 3D orientation - pitch, roll and yaw angle as Quaternion and Euler angles. Power supply 2.5-18vDC 165mW. Sample rate 5-500Hz. Dimensions 37x28x17mm.
3) **STM32F3 - DISCOVERY** - Cortex-M4F STM32, Microcontroller STM32F303VCT6: Core: Cortex-M4F, Frequency: 72MHz, 256 KB Flash, 48 KB RAM. L3GD20 3-axis digital gyroscope, LSM303DLHC 3-axis, digital accelerometer and magnetometer, 10 LED, communication USB
4) **MEMS Accelerometer and magnetometer LSM303DLHC, MEMS Gyro L3GD20, microcontroller Atmel ATMEGA2560**
   LSM303DLHC - specification

- Ultra compact high performance e-compass: 3D accelerometer and 3D magnetometer module
- The LSM303DLHC is a system-in-package featuring a 3D digital linear acceleration sensor and a 3D digital magnetic sensor.
- The LSM303DLHC has linear acceleration full scales of ±2g / ±4g / ±8g / ±16g and a magnetic field full scale of ±1.3 / ±1.9 / ±2.5 / ±4.0 / ±4.7 / ±5.6 / ±8.1 gauss.

L3GD20 - specification

- a low-power three-axis angular rate sensor.
- Three selectable full scales (250/500/2000 dps)
- I2C/SPI digital output interface
- 16 bit-rate value data output
- 8-bit temperature data output
- Two digital output lines (interrupt and data ready)
- Integrated low- and high-pass filters with user-selectable bandwidth

Finally, in the INS mounted in the Argo float the strapdown configuration was applied (Fig. 17). It is much lighter and consumes less energy than the stable platform. Increased (in comparison to the stable platform systems) complexity of computations is solved with modern processors.

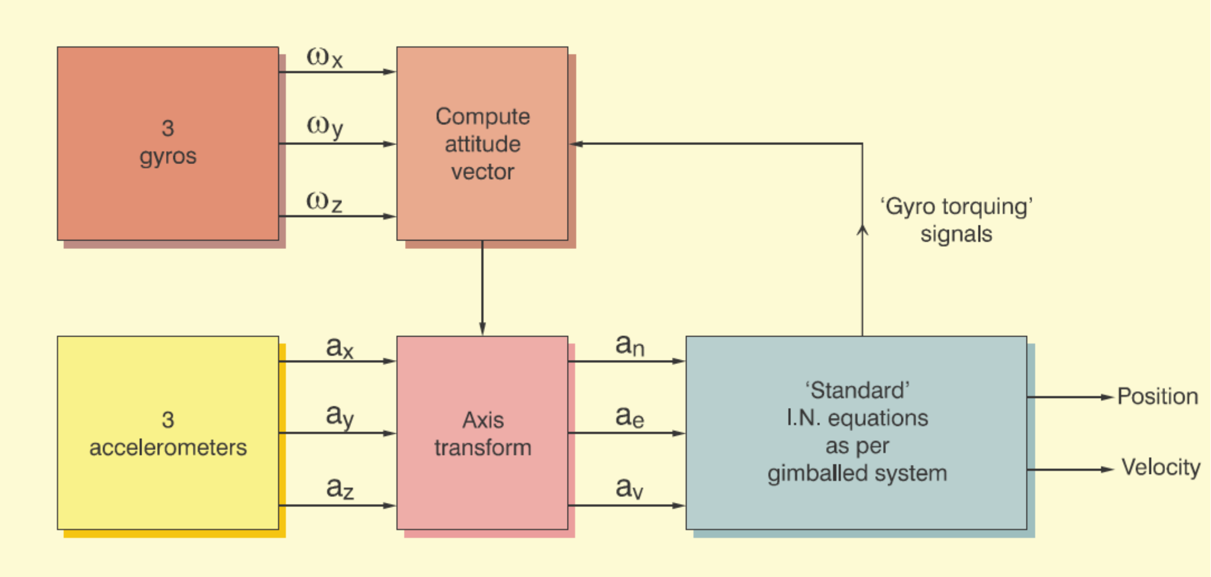


Figure 17. Strapdown inertial navigation unit block diagram (from King, 1998)

Finally, the INS was developed by FORKOS Ltd. on the basis of the microcontroller Atmel ATMEGA2560**,** MEMS Accelerometer and magnetometer LSM303DLHC, MEMS Gyro L3GD20 (Fig. 18).

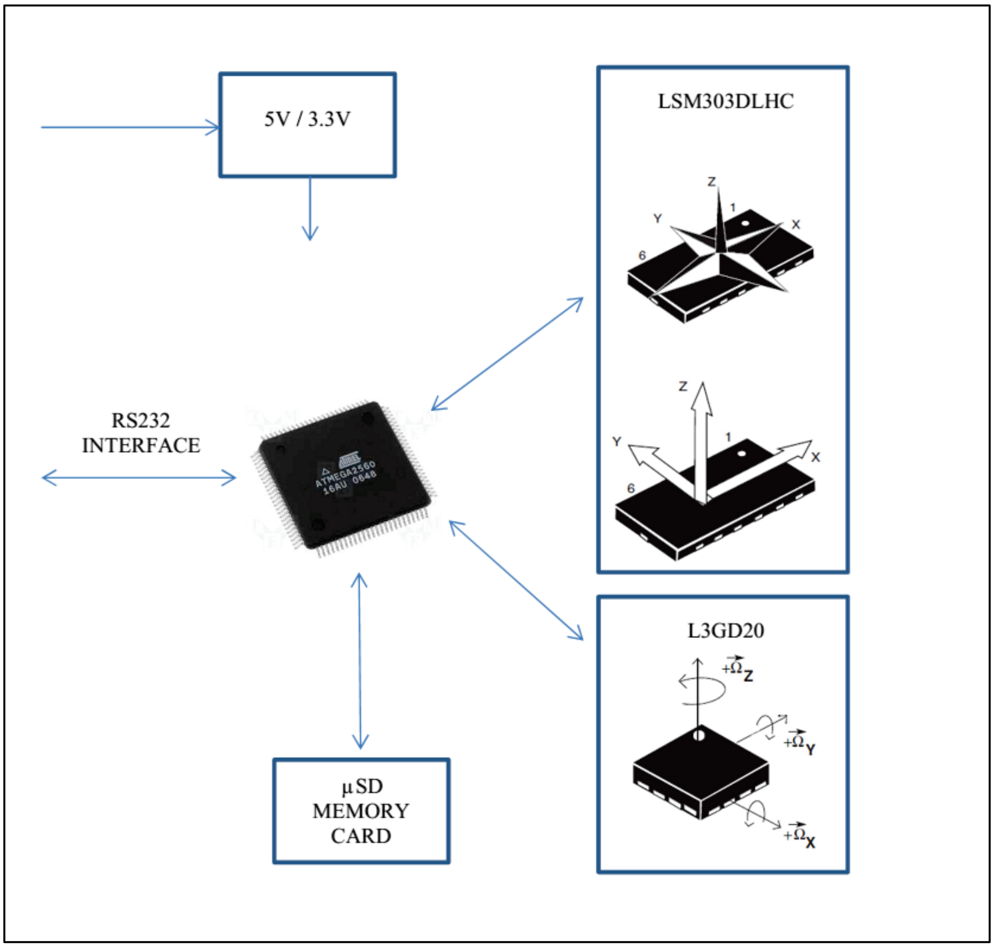


Figure 18. The Inertial Navigation System installed internally in the NEMO float built-up from accelerometer and magnetometer MEMS type LSM303DLHC, gyro MEMS type L3GD20 and microcontroller Atmel ATMEGA2560.

The processing software was also developed by FORKOS Ltd. Euler angles are determined based on the algorithm of Direction Cosine Matrix. Acceleration and rotation is measured at a frequency of 100 Hz, magnetometers operated at 10 Hz. The obtained data are calibrated and averaged. After determining the orientation angles, accelerations in the X, Y, Z directions are calculated. Then, through the trapezoidal numerical integration method the velocity and distance are calculated. The calculations are made 100 times per second for accelerators and 10 times per second for the magnetometers. The data were stored in the internal memory of the developed INS once per hour. The position was updated after float surfacing using the GPS signal.

The update of the NEMO float by installing the INS was longer and more expensive than planned, but finally successful. A lot of problems had to be resolved by engineers from both companies, such as communication of the INS with the main board of the NEMO float, power supply, data storage and data transmission. . Two INS were developed and transferred to OPTIMARE, to fulfil all the needs of the system.

The biggest problem of the INS is drift of the position. To minimalize the drift, high frequency of sampling and computing is necessary. This consumes energy. The energy consumption of the developed INS (mostly data processor) was higher than expected.

Therefore, to save batteries for standard float functions, we decided to switch off the navigation system several weeks after deployment. The two-way data transfer via the IRIDIUM communication allowed this operation.

The Argo float with the INS was deployed in summer 2014 from the IOPAN research vessel "Oceania" (Section 5). The deployment of the float was successful. By 27 June 2015 transmission of full set of hydrographic data continued. The navigational data from INS were transmitted as planned for the first 17 days. Two-way communication via IRIDIUM was tested and changes of the float working mode were successful. During the experiment the float has changed its position by more than 80 km (Table 1). Yet, the device has returned mostly zeros or incorrect numbers (Fig. 20). Most likely the current sensors accuracy is still not sufficient to provide good information about device displacement. Moreover, the internal noise could also provide additional errors.

Before the experiment authors had realized that the accuracy of the commercial IMU sensors based on the MEMS technology is still too low to keep accurate navigation of the float during the underwater part of the float drift. As a result of this experience the idea, hardware and software for the IMU data processing, storage and transmit were developed. Data were transmitted and received during the first field test. The accuracy of the available IMU devices is still low, but development of this technology is very fast. Even now there are IMU devices (based on the laser technology) with accuracy sufficient for application in floats, but they are still too big, too expensive and consume too much electric energy. In future IOPAN in cooperation with other interested institutions, is going to continue development of the Arctic float with IMU sensor as an alternative way of under ice navigation.

At present MEMS sensors cannot match the accuracy of optical devices, however, they are expected to do so in the future. The advantageous properties of MEMS sensors include (D. Titterton and J. Weston):

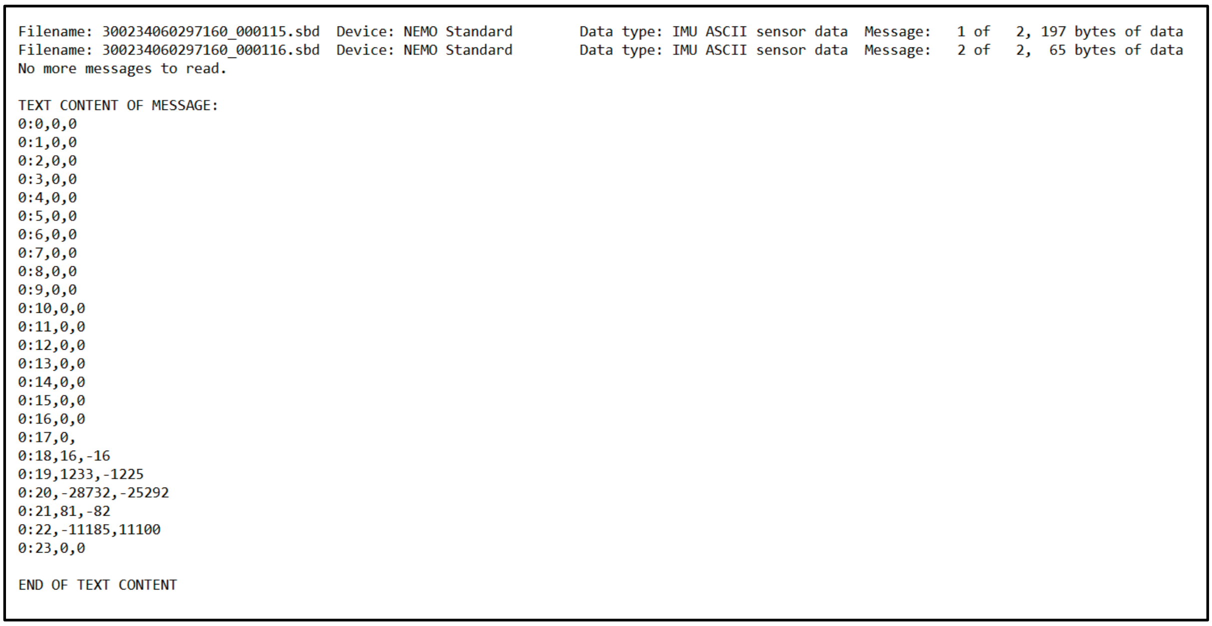
- small size
- low weight
- rugged construction
- low power consumtion
- short start-up time
- inexpensive to produce
- high reliability
- low maintenance
- ability to operate in hostile environments.

In the authors' opinion it is one of potential ways to solve the problems of underwater / under ice navigation of the ARGO floats and may be implemented in future.

Table 1. Drifting positions and distance between them. After every profile INS data were sent

Profile number	Latitude	Longitude	Distance from the last	Cumulative distance [km]

			measured position [km]	
1	76.464	7.834	0.00	0.00
2	76.444	7.918	3.14	3.14
3	76.436	7.945	1.18	4.33
4	76.449	7.924	1.59	5.91
5	76.485	7.938	3.99	9.90
6	76.521	8.006	4.36	14.26
7	76.541	8.151	4.41	18.67
8	76.561	8.300	4.45	23.12
9	76.573	8.492	5.14	28.26
10	76.613	8.738	7.71	35.97
11	76.679	8.969	9.44	45.41
12	76.763	9.147	10.44	55.85
13	76.847	9.340	10.50	66.35
14	76.899	9.531	7.51	73.86
15	76.936	9.677	5.58	79.44
16	76.969	9.740	3.97	83.41

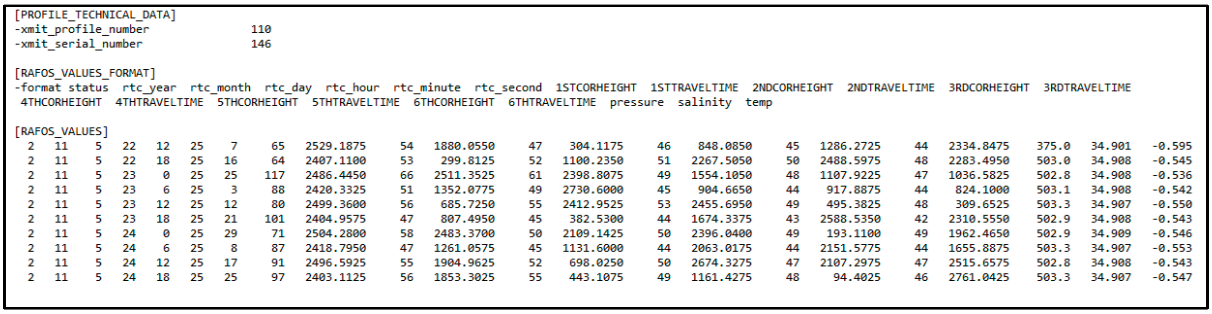


```
Filename: 300234060297160_000115.sbd  Device: NEMO Standard       Data type: IMU ASCII sensor data  Message:   1 of   2, 197 bytes of data
Filename: 300234060297160_000116.sbd  Device: NEMO Standard       Data type: IMU ASCII sensor data  Message:   2 of   2,  65 bytes of data
No more messages to read.

TEXT CONTENT OF MESSAGE:
0:0,0,0
0:1,0,0
0:2,0,0
0:3,0,0
0:4,0,0
0:5,0,0
0:6,0,0
0:7,0,0
0:8,0,0
0:9,0,0
0:10,0,0
0:11,0,0
0:12,0,0
0:13,0,0
0:14,0,0
0:15,0,0
0:16,0,0
0:17,0,
0:18,16,-16
0:19,1233,-1225
0:20,-28732,-25292
0:21,81,-82
0:22,-11185,11100
0:23,0,0

END OF TEXT CONTENT
```

Figure 19. Text message received after binary-ASCII conversion of two data packets (sbd files) transmitted by NEMO float equipped with INS – profile number 14. The format of incoming data is d:h, dN, dE (time – day:hour, northward displacement, eastward displacement in hundreds of meters). Unfortunately, processed raw data gave incorrect results – northward and eastward displacements should be mainly positive – as we see on the map of surfacing positions.



```
[PROFILE_TECHNICAL_DATA]
-xmit_profile_number              110
-xmit_serial_number               146

[RAFOS_VALUES_FORMAT]
-format status  rtc_year  rtc_month  rtc_day  rtc_hour  rtc_minute  rtc_second  1STCORHEIGHT  1STTRAVELTIME  2NDCORHEIGHT  2NDTRAVELTIME  3RDCORHEIGHT  3RDTRAVELTIME
 4THCORHEIGHT  4THTRAVELTIME  5THCORHEIGHT  5THTRAVELTIME  6THCORHEIGHT  6THTRAVELTIME  pressure  salinity  temp

[RAFOS_VALUES]
  2   11    5   22   12   25    7    65   2529.1875    54   1880.0550    47    304.1175    46    848.0850    45   1286.2725    44   2334.8475   375.0   34.901   -0.595
  2   11    5   22   18   25   16    64   2407.1100    53    299.8125    52   1100.2350    51   2267.5050    50   2488.5975    48   2283.4950   503.0   34.908   -0.545
  2   11    5   23    0   25   25   117   2486.4450    66   2511.3525    61   2398.8075    49   1554.1050    48   1107.9225    47   1036.5825   502.8   34.908   -0.536
  2   11    5   23    6   25    3    88   2420.3325    51   1352.0775    49   2730.6000    45    904.6650    44    917.8875    44    824.1000   503.1   34.908   -0.542
  2   11    5   23   12   25   12    80   2499.3600    56    685.7250    55   2412.9525    53   2455.6950    49    495.3825    48    309.6525   503.3   34.907   -0.550
  2   11    5   23   18   25   21   101   2404.9575    47    807.4950    45    382.5300    44   1674.3375    43   2588.5350    42   2310.5550   502.9   34.908   -0.543
  2   11    5   24    0   25   29    71   2504.2800    58   2483.3700    50   2109.1425    50   2396.0400    49    193.1100    49   1962.4650   502.9   34.909   -0.546
  2   11    5   24    6   25    8    87   2418.7950    47   1261.0575    45   1131.6000    44   2063.0175    44   2151.5775    44   1655.8875   503.3   34.907   -0.553
  2   11    5   24   12   25   17    91   2496.5925    55   1904.9625    52    698.0250    50   2674.3275    47   2107.2975    47   2515.6575   502.8   34.908   -0.543
  2   11    5   24   18   25   25    97   2403.1125    56   1853.3025    55    443.1075    49   1161.4275    48     94.4025    46   2761.0425   503.3   34.907   -0.547
```

Figure 20. Fragment of the message received after binary-ASCII conversion of several packets (sbd files) transmitted by NEMO float equipped with RAFOS (profile number 110) deployed by IOPAN in 2010 in the same area, yet when the RAFOS source in the Fram Strait was available.

9. ICE SENSING ALGORITHM USED IN NEMO FLOAT

The ISA implemented in the used NEMO floats contains several steps:

- during the ascent phase the float reaches a "certain depth" where a decision needs to be taken. At that depth temperature value from the last n data sets is used for the median calculation and compared with the pre-defined ice detection temperature
- if the calculated median is smaller (which means that water is colder) than the pre-assumed ice detection value, the float assess the situation as potentially dangerous and instead of surfacing it begins a new cycle by going deep to the parking depth.
- the "certain depth" pressure value is selected from the pressure values of the depth table.
- the above mentioned number "n" from the last temperature measurements, refers to the "n" entries of the depth chart . The number is limited to 13.
- at each even number of data sets, the arithmetic mean value is formed from 2 middle values.
- all used measurements for ice detection and median value are stored in the profile data, which are further transmitted by telemetry.
- after table is completed, the NEMO initiates the surfacing phase. For safety reasons, the surfacing phase can be stopped, even if ice was not detected after one or more ice-detections in previous profile cycles.
- This parameter is called "successful ascents":
  - if it is set to zero, the NEMO will begin surfacing immediately after no ice is detected for the first time
  - if the parameter is set to 1, the NEMO stops the ascent, if no ice is detected for the first time after one or more ice-detected profiles
  - when it is set to 2, the NEMO will abort the ascent if no ice has been detected during 2 profiles after one or more ice-detected profiles.

The following is the mission scenario, illustrating the above function:

Mission configuration:

- depth table with 17 entries [dbar] in the following sequence: 2000, 1000, 500, 100, 50, 45, 40, 35, 30, 25, 20, 15, 12, 10, 8, 6, 4.
- ice_dtentry = 14 (equates 10 dbar)
  ice_dtmedian = 5

Using this information, the temperature values of the depth 25, 20, 15, 12 and 10 dbar are used for the median calculation. The case decision (ice yes/no) will be made immediately after a CTD measurement at 10 dbar.

10. CONCLUSIONS

Concluding, the future Arctic float becomes a more sophisticated and more expensive device. It is more resistant and more intelligent. The amount of information entered, collected and processed by the float increases. Almost all technologies necessary to produce this kind of float exist. Yet, it costs energy consumption. The biggest problem is the energy source. These new devices needs better batteries of higher capacity and operation time. Even lithium batteries are insufficient. Moreover, lithium batteries are expensive and difficult to transport by planes. It is particularly troublesome in the Arctic. Furthermore, the costs of the Arctic float exploitation rises, because, similarly to gliders, it needs piloting - permanent supervision by staff in a data acquisition center. That is why there are still so few Argo floats in the Arctic. Potential users do not want to pay for operation costs and suffer the risk of losing such expensive equipment.

Another idea is to construct new, less sophisticated and cheaper floats, assigned for short missions. This kind of float should be designed for missions shorter than one year, for operation in shallow waters (big part of the Arctic Ocean and subarctic seas are shelves). Compact construction (spherical shape?) should prevent from getting damaged by floating ice or getting stuck on bottom. A simple cheap electronic module should contain the bathymetry map, which would also help in preventing contact with the bottom. Floats for shallow seas must meet very similar conditions, and efforts towards constructing a cheap float for the Arctic and shallow seas should be joined. Such floats may be much more attractive for potential users.

By using both kinds of floats – sophisticated ones for long missions under sea ice and cheaper ones for short missions in ice free regions – may improve coverage of the Arctic by the Argo floats.

But only a revolution in the development of efficient, stable and cheap sources of energy will enable using all the technological advances, such as the active ice and bottom detection, inertial navigation, wide spectrum of sensors, big amount of data processed by intelligent floats.

11. REFERENCES

King, A.D. Inertial Navigation – Forty Years of Evolution, GEC REVIEW, VOL. 13, NO. 3, 1998.

Klatt, O., O. Boebel, and E. Fahrbach. 2007. A profiling floats's sense of ice. *Journal of Atmospheric and Oceanic Technology*, 24, 1301-1308.

Laney, S.R., Krishfield, R.A., Toole, J.M., Hammar, T.R., Ashjian, C.J., Timmermans, M.-L. Assessing algal biomass and bio-optical distributions in perennially ice-covered polar ocean ecosystems (2014) Polar Science, 8 (2), pp. 73-85.

Lee, C.M., S. Cole, M. Doble, L. Freitag, P. Hwang, S. Jayne, M. Jeffries, R. Krishfield, T. Maksym, W. Maslowski, B. Owens, P. Posey, L. Rainville, A. Roberts, B. Shaw, T. Stanton, J. Thomson, M.-L. Timmermans, J. Toole, P. Wadhams, J. Wilkinson, and Z. Zhang, 2012. Marginal Ice Zone (MIZ) Program: Science and Experiment Plan, Technical Report APL-UW 1201. Applied Physics Laboratory, University of Washington, Seattle, September 2012, 48 pp.

Marec C., Babin M., Becu G., Nobert P., Bourliaguet ., Cantin D., Chateauneuf F., Forand L., Fournier G., Jouan A., Matthieu P., Roy G., Claustre H., Ortenzio F., Leymarie E., Penkerc'h C., Poteau A., 2012, Deployment of biogeochemical profiling floats in the ice edge zone of the Arctic Ocean: developing a sea-ice optical detection sensor for a safe navigation, White Paper.

Peralta-Ferriz, C., Woodgate, R.A. Seasonal and interannual variability of pan-Arctic surface mixed layer properties from 1979 to 2012 from hydrographic data, and the dominance of stratification for multiyear mixed layer depth shoaling (2015) Progress in Oceanography, 134, pp. 19-53.

Rudels, B., Korhonen, M., Schauer, U., Pisarev, S., Rabe, B., Wisotzki, A. Circulation and transformation of Atlantic water in the Eurasian Basin and the contribution of the Fram Strait inflow branch to the Arctic Ocean heat budget (2015) Progress in Oceanography, 132, pp. 128-152.

Sirevaag, A., de la Rosa, S., Fer, I., Nicolaus, M., Tjernström, M., and McPhee, M. G.: Mixing, heat fluxes and heat content evolution of the Arctic Ocean mixed layer, Ocean Sci., 7, 335-349, doi:10.5194/os-7-335-2011.

Titterton, D. and J. Weston. Strapdown Inertial Navigation Technology. The American Institute of Aeronautics and Astronautics, second edition, 2004.

Timmermans, M.-L., R. Krishfield, S. Laney, J. Toole, 2010. Ice-Tethered Profiler Measurements of Dissolved Oxygen under Permanent Ice Cover in the Arctic Ocean, Journal of Atmospheric and Oceanic Technology, 27, 1936-1949, doi: 10.1175/2010JTECH0772.1.

Toole, J.M., R.A. Krishfield, M.-L. Timmermans, and A. Proshutinsky. 2011. The Ice-Tethered Profiler: Argo of the Arctic. Oceanography 24(3):126-135.

Toole, J.M., M.-L. Timmermans, D.K. Perovich, R.A. Krishfield, A. Proshutinsky, and J.A. Richter-Menge, 2010. Influences of the Ocean Surface Mixed Layer and Thermohaline Stratification on Arctic Sea Ice in the Central Canada Basin, Journal of Geophysical Research, 115, C10018, doi: 1029/2009JC005660.

Walczowski, W.: Atlantic Water in the Nordic Seas, Springer International Publishing, 300 pp, 2014.

Wong, A. P. S. and S. C. Riser, 2011. Profiling Float Observations of the Upper Ocean Under Sea Ice off the Wilkes Land Coast of Antarctica. Journal of Physical Oceanography, 41, 1102-1115, http://dx.doi.org/10.1175/2011JPO4516.1

Woodman, O. J. An introduction to inertial navigation. University of Cambridge Computer Laboratory, 2007.

Vectornav http://www.vectornav.com/support/library.