# The use of AUVs (autonomous underwater vehicles) under sea ice – achievements so far

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**Abstract**

One of the first uses of AUVs under sea ice was an experiment in the Greenland Sea in 2002 conducted by Wadhams and Krogh, in which the Maridan M150 vehicle was used with a sidescan sonar to map the ice underside. Next came a long range AUV study (2004) involving the UK Autosub with multi-beam sonar and transects of up to 175 km in length. This produced a large number of 3-D images of first-year and multi-year pressure ridges. Following this operation, emphasis switched to the use of small AUVs deployed by hand and used for mapping relatively small areas of ice. Both the use of the Gavia (2007, 2008, 2014, 2017) and the WHOI twin-hulled AUV (2012) proved not to be optimal due to the limited range or slow control systems. Both large and small AUVs have been used successfully to map the 3D structure of the ice underside, but always in an experimental context. The challenge now is to determine the best way forward to improve the quantity and quality of data gathering, and to turn the under-ice AUV into a reliable vehicle for routine use. This will be covered in an accompanying ISAR-5 paper.

**Keywords**

AUV, UAV, ice thickness, multibeam sonar, sidescan sonar, ice surveys.

## 1. Introduction - ice thickness profiling

The need to know the distribution of sea ice thickness in the Arctic was recognised very early. The mass balance of sea ice - the seasonal growth and decay - is an important quantity for understanding the role of ice in climate, while the heat flow from the ocean to the atmosphere depends on how thick the intervening sea ice is. The first figure quoted for mean Arctic ice thickness was 5 m by Fridtjof Nansen but it is important to recognise that this was based on only a few drill holes done during the drift of the "Fram" (1893-6). Later experiments, such as the Russian "North Pole" series of stations starting in 1937, resulted in larger numbers of drill holes, but the results were still statistically weak and said nothing about the shape of the ice bottom, the distribution of pressure ridge depths or the difference between the roughness levels of ridged and level ice, or between first-year and multi-year ice.

The first successful ice underside profile was during the transect of USS "Nautilus" under the Arctic Ocean in 1958 (Lyon, 1961), and yielded a leap forward in our understanding of under-ice roughness and ridge features. From then on it was submarines, and the upward sonar with which they were equipped, that set the basis for our understanding of sea ice thickness distributions. From single-beam sonar profiles it was determined that the distribution of thick ice is a negative exponential (Wadhams, 2000), that pressure ridge depths also follow a negative exponential distribution, that pressure ridge spacings obey a lognormal and that the deepest ridge observed in the Arctic is approximately 55 m in draft.

The type of sonar employed for under-ice mapping improved in a series of steps. First came single-beam upward sonar, yielding a linear profile. Then came sidescan sonar, with a fan-shaped beam in which the backscattered signal strength from each pulse is plotted against time, being interpreted as slant range. This constructs a map as the vessel proceeds along its track, with strong scatterers showing as bright echoes and shadow zones as dark. The ultimate solution, however, was multibeam sonar which gives a proper 3-D picture of a swath of ice underside. The first use of upward-looking multibeam sonar from a submarine was by the present author in 2007 from HMS *Tireless* (Wadhams, 2008) using a Kongsberg EM2000 system. Multibeam sonar employs an electronically steered beam which gives individual echoes from 100 to 500 angles of beam emerging from a single ping, building up a quantitative map of the topography of the target surface.

Despite these successes of submarines in gaining an understanding of basin-wide ice thickness properties, a need was identified to obtain local ice thickness information in support of field programmes on sea ice dynamics and thermodynamics. Is it possible to map ice thickness around an experimental site without the need for a manned submarine? Some reasons for wishing to do this are:

1. A military submarine is usually on an operational voyage and so data gathering is not entirely under the control of the experimenter.
2. An AUV is capable of carrying out a “lawnmower” pattern of surveys, i.e., a grid with sidelapping, which permits a square area of ice bottom to be mapped rather than a long narrow swath. A submarine can also do this, but it is more difficult to achieve both in terms of vessel guidance and ship-time availability.
3. An AUV can be targeted on a specific small area of icefield
4. An AUV can proceed more slowly and at a more shallow depth than a submarine, allowing higher resolution under-ice imagery to be obtained.
5. An AUV can operate in regimes which are dangerous or impossible for a manned submarine, e.g., in shallow water or under ice shelves.

## 2. The growth of systematic studies

The first attempt to use an unmanned vehicle was very expensive but did work. The University of Washington built the Unmanned Arctic Research Submersible (UARS) in 1973, essentially an early design of autonomous underwater vehicle (AUV, an acronym not yet invented) with three upward sonars. Because of its weight it had to be winched up and lowered by crane down an ice hole, and each deployment cost $500,000. The vehicle was kept for many years on display at the Applied Physics

Laboratory in Seattle after successful experiments in the Beaufort Sea (Francois and Nodland, 1972; Francois, 1977).

The UARS was far ahead of its time, and the next under-ice use of an AUV was during the winter Lead Experiment (LeadEx) in 1992, in the Beaufort Sea (Morison and McPhee, 1998). The 1.6-m-long vehicle carried a CTD but no sonar and was launched and recovered from a lead, homing to an acoustic beacon before recovery in a net. The Canadian Defence Research Establishment (Atlantic) used a large AUV for cable-laying under ice in the Arctic in 1996, but no scientific data were collected (Ferguson et al., 1999). In 2001, single-beam upward sonar data were successfully collected in the Antarctic from the UK Autosub vehicle (Brierley et al., 2002) and in the Arctic from a test cruise of a vehicle developed by Monterey Bay Aquarium Research Institute and intended for transpolar use (Tervalon and Henthorn, 2002*)*.

After these sporadic efforts, a systematic, continuous research and development programme on AUVs under ice has been accomplished by the present Author, his colleague Bo Krogh, and other colleagues following a first EU-sponsored study in 2002 using the Maridan Martin 150 vehicle built in Denmark. The vehicle was equipped with a sidescan sonar, giving the first 2-dimensional AUV imagery from a region of multi year ice off East Greenland (Wadhams et al, 2004.) The Maridan was equipped with a SeaKing 675-kHz sidescan sonar, a CTD and an ADCP.

Next came a long range AUV study (August 2004) over the NE Greenland continental shelf around 79°N involving the UK Autosub II with Kongsberg EM2000 multi-beam sonar (swath width 100 m) and transects of up to 175 km in length. This enabled 3-D imagery of large numbers of first-year and multi-year pressure ridges to be obtained (Wadhams et al., 2006), as well as a systematic measure of the shape of the ice underside which permitted its oil containment factor to be estimated. The accompanying on-board ADCP instrumentation mapped upper ocean currents along the track. This was the first example of divergence in AUV-under-ice development, in this case the search for a long-range capability to mimic a submarine as opposed to a focused effort on a small area. More than 450 track-km were imaged. The same vehicle later collected multibeam sonar data under the Fimbul ice shelf in the Antarctic (Nicholls et al., 2006) before sadly being lost under the same ice shelf.

During the 2004 missions the vehicle obtained data of unprecedented quality. Fig. 1 is an example. The displayed image is a perspective view of the underside of ridged multi-year ice, obtained at 40 m depth, with the deepest point in the ice ridge being 33 m deep. The scenes are shown illuminated as if by a sun of elevation 20°. Alongside the image is a probability density function (pdf) of ice draft for the image region compared with a pdf for the entire mission. The ice was a combination of ridges and thick floes frozen into place by ice formed the previous winter. The sonar itself operated at 200 kHz, producing 111 beams with 1.5° beam spacing, over a 120–150° swath. Its power consumption of 80 W makes it suitable for use only in large AUVs or submarines.

Emphasis for under-ice AUVs now switched to the use of small AUVs deployed by hand through ice holes or from boats alongside a sea ice edge, and used for mapping relatively small areas of ice. A vehicle used frequently in such studies (2007, 2008, 2014, 2017) has been the Icelandic Gavia, with a GeoSwath multi-beam sonar; but difficulties with its navigation system have meant that it has normally been used with a tether, limiting its range. We began using Gavia AUV in April 2007 in the Beaufort Sea at the APLIS-2007 ice camp. The vehicle was 3.1 m long, weighed only 80 kg in air, and was fitted with a GeoSwath 500 kHz interferometric sonar system. We used Gavia again in April 2008, in the Lincoln Sea, on fast ice north of the Canadian Forces base at Alert, Ellesmere Island (82°33′N, 62°34′W), obtaining valuable under-ice sonar images of a specific study area (Wadhams and Doble, 2008; Doble et al., 2009), using a GeoSwath sonar system.

The image shown here (Fig. 2) was obtained beside a recently formed pressure ridge in first-year (FY) ice. Multi-year (MY) ice lay within range of the AUV to the west (top of image) and a thin (48 cm draft) refrozen lead lay to the right of the ridge. The main study ridge, next to the ice hole, was up to 14 m deep and runs from left to right across the lower centre of the image. It is a very young ridge which had been observed to form only about 8 days before the measurements were done. We see the classic shape of an FY ridge, with a continuous crest and a triangular cross-section, composed of small ice blocks piled randomly and loosely. FY ice forms most of the level area (modal draft 1.6 m), then an associated rubble field (modal draft 2.4 m) towards the top right of the plot and a refrozen lead to the lower right (modal draft 0.85 m). Most extraordinary, however, is the region just within range of the vehicle, at the extreme top of the image. Out of an area of MY level ice (modal draft 2.9 m) emerges an 8.8 m draft MY ridge. The contrast between the old, rounded, solid ice blocks of the MY ridge and the small piled-up blocks of the FY ridge is particularly striking, and can be compared with a FY/MY ridge juxtaposition in Fig. 1d. It can be seen that the ageing process, rather than simply solidifying the ridge structure and smoothing its outer shape, has inserted a succession of cracks (opening into refrozen leads) across the crest line of the ridge, breaking it up into a chain of individual large blocks. The ridge is clearly more formidable than the FY ridge, but is also more discontinuous.

Since 2008 we have used Gavia for experiments from the USCGS “Healy” in the Beaufort Sea (August 2014, see fig. 3), “Arctic Sunrise” in the Greenland Sea (2011) and “Polarsyssel” in the Barents Sea (2017). We have experimented with other vehicles such as the WHOI Sea Bed twin-hulled AUV (2012), but the slowness of this vehicle meant that it could not maintain planned positions or tracks when a sub-ice current was present. We did obtain data under a **stamukha**, a very old pressure ridge, in conjunction with laser data on the ice surface.

## 3. The present situation

The current situation is that both large and small AUVs have been used successfully to map the 3-D structure of the ice underside, but always in an experimental context. The problem is now to determine the best way forward to improve the quantity and quality of data gathering, and to turn the under-ice AUV into a reliable vehicle for routine use. This topic is addressed in an accompanying paper (Krogh and Wadhams, 2018, Mapping sea ice from above and below).

As described above, we conclude that in the early stages of summer melt a pressure ridge can retain much of its winter structure, especially if it is a multi-year ridge such as the Stamukha and other ridges seen in Fram Strait in 2012. In fact the

Stamukha represents a class of ridge that has spent many complete summers aground on the continental shelf while the ice around it has disappeared and re-formed.

In the case of first-year ice, and at a more advanced stage of melt such as seen in August 2014 in the Beaufort Sea (fig. 3), ridges appear to break up into individual blocks and lose the coherence of their underwater structure (e.g. linearity disappears). However**,** the ridges still represent a large, and possibly dominant, fraction of the remaining ice volume in the rotting ice cover, and as such can be seen as an ice reservoir.

## 4. Conclusion

Finally, what lessons do our field experiences have for the future of ice bottom mapping by short-range AUV? We can draw the following:

1. (From 2012 experiments) A slow-moving vehicle where depth control is achieved by vertical propeller (WHOI vehicle) is not suitable for use under ice floes in a marginal ice zone situation where shear currents may occur, as they are likely to be driven further under a floe and be incapable of following a programmed course outward.
2. A faster moving vehicle like Gavia is more appropriate as well as being easier to launch and recover.
3. The single short-baseline acoustic tracking system is potentially better than the multiple transducer system used by WHOI, because of quickness of deployment. Installing two or three transducers through the ice in 2012 meant that the floe of interest could break up in the time which it took to set up the system for the profiling operation. We feel that the future lies with single-buoy tracking systems.
4. There is always a trade-off between sophistication and cost. For instance, during earlier surveys we found Autosub to be a superb vehicle for under-ice use. Yet it is very expensive, large and requires a large ship for deployment. There are systems even cheaper and more basic than Gavia, which possibly have the advantage that an under-ice loss would not be a major financial loss. Somewhere between these extremes an optimum solution remains to be found.
5. If an AUV-buoy-sonar system that works reliably at low cost can be identified for routine use, its use in combination with a surface mapping system (laser or photogrammetry) will be very valuable in improving our understanding of the critical processes of ice deformation and summer ice decay, as well as validation of airborne and satellite-borne altimetry.

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## Figures

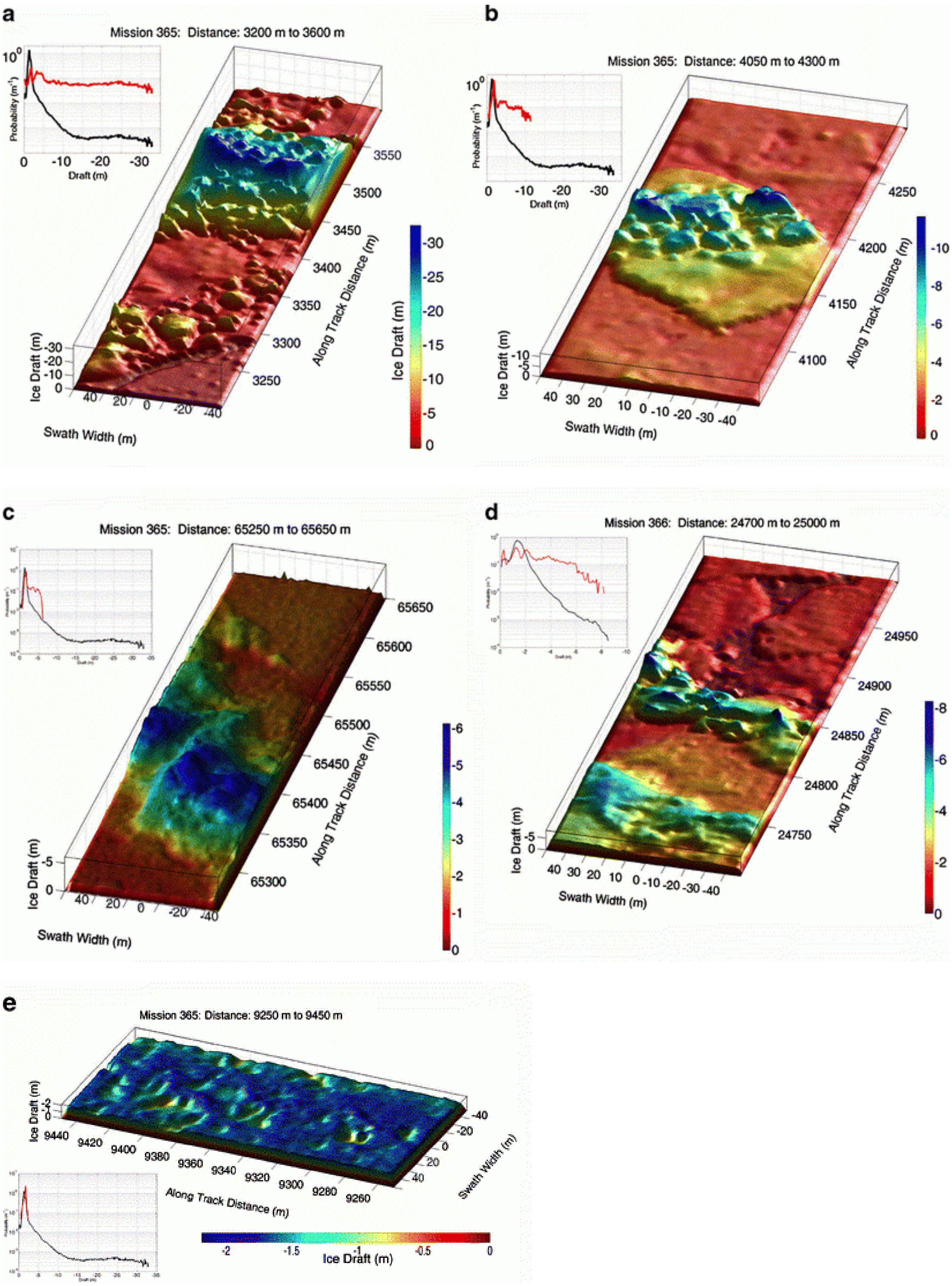


Fig. 1. Autosub II cruise to NE Greenland: five examples of EM-2000 multibeam ice draft data in perspective views, as if illuminated by a sun of elevation 20°, showing the diversity of ice conditions revealed by the AUV. Data points fill 2 × 2 m grid. No vertical exaggeration unless otherwise stated. Each image is accompanied by its

probability density function (*pdf*) of ice draft (*red*) compared to the pdf of the mission as a whole (*black*) (lin-log scale, 5-cm bins). **a** Deep 33 m ridge on Belgica Bank, with shallower ridge in foreground, both surrounded by undeformed ice. **b** Thick multi-year ridged floe of draft 3–5 m, with linear edges suggesting production from fracture of larger ice sheet, embedded in undeformed fast ice of draft 1.8 m. Fast ice shows pattern of depressions due to mirroring of surface melt pools. Thicker ice contains pressure ridge of maximum draft 11 m which has partly disintegrated into individual ice blocks of diameter 5–20 m. Evidence is that thicker floe came from MIZ. **c** Pressure ridge from western side of Norske Trough. Maximum draft 6.0 m. Smooth undeformed ice has peaks at 1.7 and 1.3 m. Vertical exaggeration 1.75:1. **d** Image showing in background first-year floes of 1.2 m draft with rounded edges embedded in young ice of 0.25 m draft. In centre is young linear ridge, possibly shear ridge formed between the first-year ice and thicker floe in foreground. Foreground floe is multi-year ice of 1.85–2.25 m draft and in front a worn-down multi-year hummock. Vertical exaggeration 1.25:1. **e** Multi-year undeformed floe which has developed deep craters in underside to match deep surface meltwater pools. Modal draft is 1.7 m, with maximum of 2.2 m and with some craters as thin as 0.5 m. Vertical exaggeration 4:1. Wadhams, 2012.

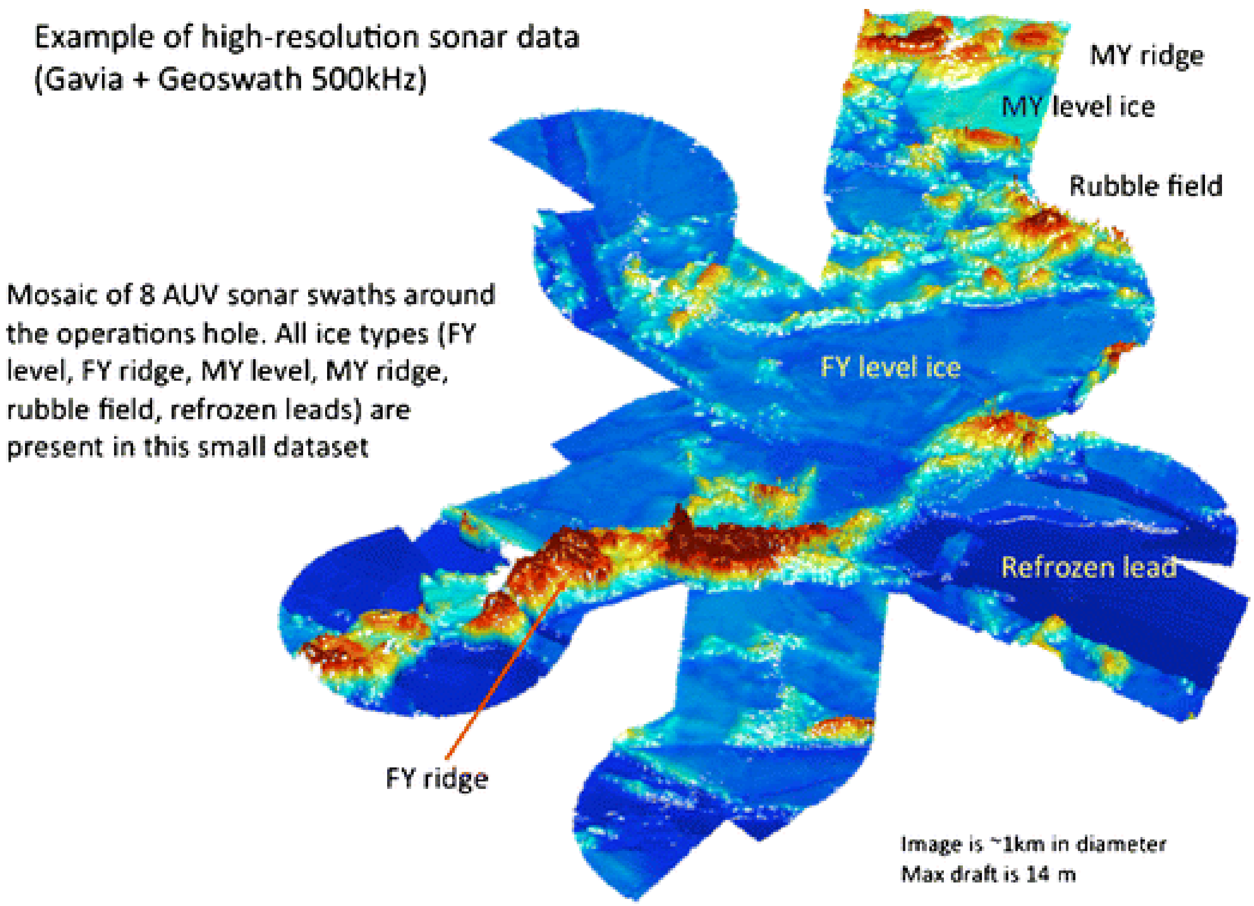

Fig. 2. Gavia AUV study in Beaufort Sea 2007: sonar data gathered around the deployment hole, showing a refrozen lead, a young pressure ridge (8 days old), FY level ice, a rubble field, and a MY pressure ridge at the top of the image. The contrasting roughness and shapes of FY and MY ridging is clearly shown. Running depth of the vehicle was 20 m. Wadhams, 2012.

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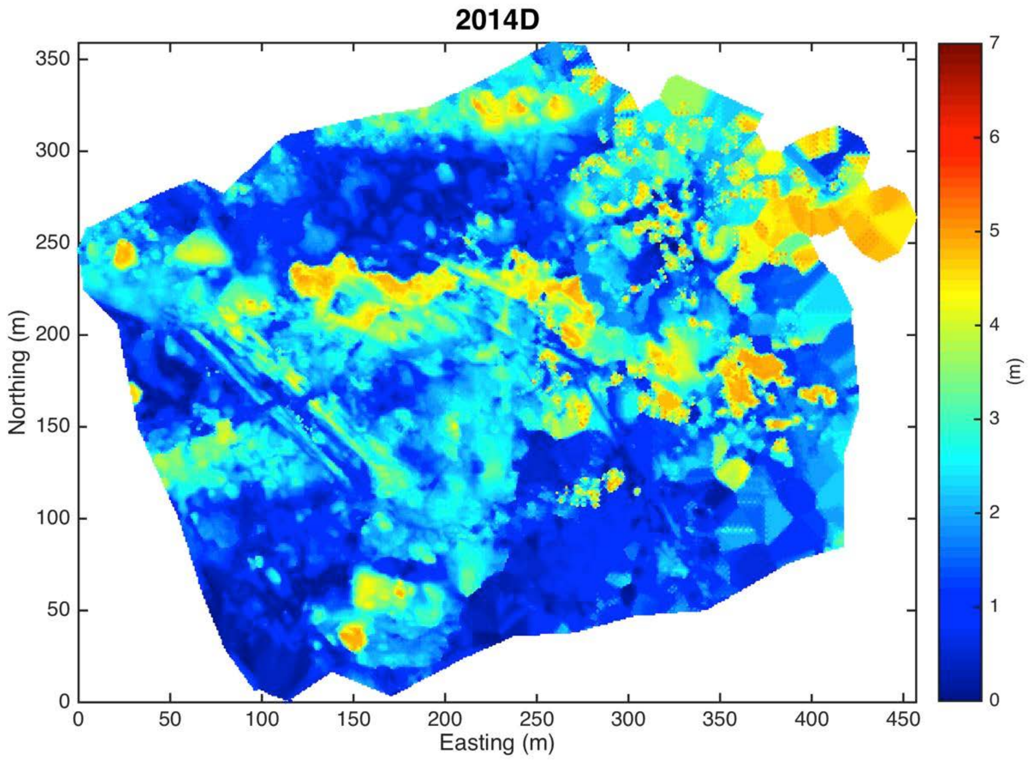


Fig.3. An example from a recent operation from USCGS "Healy" in an icefield in the southern Beaufort Sea that was in an advanced state of melt (August 2014). Here all ridged ice has been worn down or melted to the point where the maximum draft does not exceed 5 m, the deepest ice being the remains of a ridge which ran W-E across the centre of the image. A few days later this entire icefield disintegrated. Rotten as it is, the area of icefield shown would have weighed approximately 300,000 tons.