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# ALIGNING THE NEEDS OF FLOATING DRILLING AND THE CAPABILITIES OF ICE MANAGEMENT

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## ABSTRACT

Floating drilling operations in dynamic Arctic sea ice will require an ice management program to reduce ice loads to levels that are within the capacity of the protected vessel's stationkeeping system (dynamically positioned or moored). Since some conditions cannot be adequately managed by current icebreaker capabilities, the ability to safely suspend operations, secure the well and disconnect the marine drilling riser must be accounted for as a part of normal operations for floating drilling in ice. Ice management operations should be structured in order to deliver, with confidence, alerts consistent with the required warning times for suspension of drilling operations and disconnection.

Planned disconnections under normal operations are typically executed to leave the well in "optimal" condition for quickly resuming drilling activities. Disconnections within shorter timeframes maintain well integrity, but may result in increased time to resume normal operations. Achieving high drilling uptime without compromising safety requires harmonization of the functional requirements and capabilities of both drilling and ice management operations. It is necessary to balance the ability of ice management to deliver alerts consistent with well integrity objectives with the need to minimize the time required to resume operations upon reconnection.

This paper discusses functional requirements to ensure safe well suspension for varying target disconnection frequencies. Based on assumed drilling systems and scenarios, the practical capabilities of ice detection and ice management are also described in this context. Ice drift records from the Canadian Beaufort Sea and realistic icebreaker performance characteristics are used to compare the practical capabilities of ice surveillance methods to the minimum requirements for target drilling disconnection alert times. It is shown that these objectives can be attained, but may require the aid of airborne ice monitoring, advanced ice drift forecasting and one or more scouting icebreaker(s) to test ice breakability sufficiently far ahead of the rig in dynamic ice environments.

## INTRODUCTION

One of the most significant challenges facing development of undiscovered oil and gas resources in the Arctic is the need to drill wells from floating vessels in ice for water depths beyond about 100 meters. Ice loads from thick, multi-year or heavily ridged first-year ice are capable of exceeding the limits of conventional stationkeeping systems. Hence, some degree of ice management will be needed to support stationkeeping of the floating drilling rig if it is to drill during a season when ice is present. Regardless of the extent of the ice management operation, such floating drilling systems must be capable of disconnection from the well and mooring system (if applicable) in the event that critical ice features or unmanageable ice conditions are encountered.

Oil and gas drilling is a complex operation that requires detailed up-front planning to manage the potential risks and consequences. One example of such planning is designing systems and procedures to reduce the time required to secure a well prior to disconnection. While the capability exists to perform emergency disconnects with less than a minute's notice, it is desired that such events be very rare and not be routinely utilized while drilling in ice.

Disconnections are typically associated with open-water dynamically positioned (DP) floating drilling operations because of the occasional need to disconnect in the event of DP loss of stationkeeping (e.g. drift-offs or drive-offs) or in advance of approaching storms. A sketch of an open-water DP drilling system disconnection for an approaching storm is shown in Figure 1. In the storm case, after securing the well, DP vessels typically leave the location, whereas moored vessels typically remain on station. In ice environments, however, moored vessels must also be able to disconnect and leave the location.

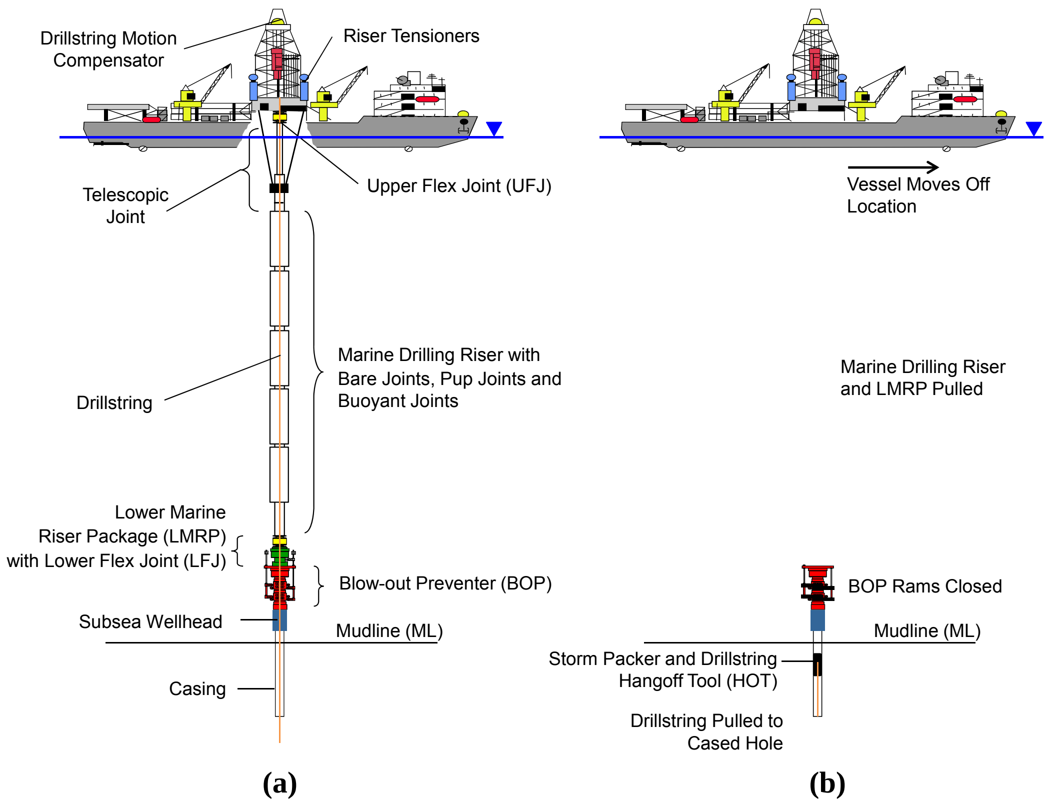



**Figure 1. Schematic of (a) typical open-water DP drilling and (b) its disconnection in advance of an approaching storm.**

Approaching storms can usually be detected days in advance, providing adequate time to secure operations regardless of the drilling activity in progress at the time of alert. Due to limitations in existing ice forecasting models, achieving disconnection alert times of more than a day or two will not always be possible when the approaching hazard is severe ice conditions. Moreover, for some locations in the Arctic, critical ice features and unmanageable ice conditions may occur with greater frequency than severe storms in conventional floating drilling operations. Consequently, Arctic floating drilling operations will need to be set up to disconnect more quickly and more frequently than conventional floating drilling operations.

This paper explores implications of including disconnection as part of routine drilling operations and the resulting functional requirements for ice management. The proposed framework for conducting drilling operations in the Arctic in a safe manner employs a tiered disconnection approach consistent with the ability of ice management and ice forecasting to provide alerts. In previous papers (Hamilton *et al.,* 2011a, Hamilton *et al.,* 2011b), we described the use of decades of IPS/ADCP ice drift records acquired in the Canadian Beaufort Sea by the Canadian DFO to evaluate the efficacy of floe size reduction using systematic, near-field ice management approaches. Here we use the same records to derive ice drift and thickness parameters to estimate the required full suite of ice management capabilities, including far-field ice monitoring, detection of potentially unmanageable features, ice drift forecasting, and mid-field verification of ice breakability prior to near-field systematic floe size reduction.

## DISCONNECTION REQUIREMENTS FOR DRILLING

Orderly suspension of drilling activities and securing of the well for disconnection requires a varying amount of time depending on the current well status and the drilling operation in progress at the time of suspension. API 65–Part 2 (API, 2010) provides guidance on barriers that can be used to secure the well when suspending drilling activities and disconnecting.

Additional steps can be undertaken to leave the well in a condition favoring expedient resumption of drilling operations, e.g., circulating out cuttings, hanging-off or pulling the drill string. In general, the more of these operations that can be accomplished prior to disconnection, the quicker drilling operations can be resumed and the less costly the disconnection. The impact of a disconnection can vary from the lost time while disconnected to total economic loss if the restart requires plugging and abandoning the well and constructing a new one.

For floating drilling operations in ice, there are four potential classes of disconnection listed below and summarized in Table 1. The minimum alert times are the authors' best estimates based on consultation with drilling engineers regarding (a) times to establish reliable well flow barriers, (b) existing and potentially adaptable drilling technology advancements and (c) comparative remediation cost and complexity for various suspension scenarios. In all cases the well is left in a secure state. The desired frequencies are notional values based on the relative impact of the disconnections on overall well cost and are intended to be used to assess preliminary ice management functional requirements. Note that even moored systems will need to have this full range of disconnection capabilities (including emergency disconnection) due to the magnitudes of ice loads in comparison to conventional mooring system capacities.

a) ***Planned disconnection*** – disconnection at the end of the season or upon reaching a target drilling objective (e.g. a casing point) with adequate time to plug and abandon or to leave the well in ideal condition for resuming operations at a later date. A planned disconnection might require advance notice on the order of several days to complete depending on the well condition and status.
b) ***Managed disconnection*** – routine disconnection due to the forecast of potentially unmanageable ice conditions such as pressure or high drift speed or identification of a critically thick ice feature in the far-field coupled with drift forecasts that would bring the feature within a defined zone around the rig. The well is left in good condition for resumption of activities with no or a small amount (< 1 day) of remediation work. Minimum alert time to secure the well and disconnect is on the order of 24 hours. Potential frequency is three to six times per drilling season (or year) or less.

c) ***Rapid disconnection*** – disconnection due to a scouting icebreaker's verification of unbreakable ice that was not detected in the far-field and that is in the forecast path of the near-field ice management operation. The well is left in a condition that allows resumption of drilling with potentially substantial (several days) remediation work. Minimum alert time to secure the well and disconnect is on the order of six hours. (Six hours minimum alert time assumes implementation of some degree of technology advancement that currently exists but may not yet be commercial, such as a means to eliminate the need to pull the entire length of the riser. Retrieval of the entire drilling riser in 500+ meters of water can take in excess of 24 hours.) Potential frequency of rapid disconnections is less than one time per drilling season (or year).

d) ***Emergency disconnection*** – disconnection due to an unanticipated failure of the near-field ice management system or mooring system. The well is left in a safe, secure condition but may ultimately require additional remedial operations to restore it to pre-disconnection status or be plugged and abandoned depending on the actual alert time, well condition and operation at the time of disconnection. In this case, the alert time is >1 minute and <6 hours. The desired frequency is very rare; consistent with unplanned emergency disconnects of open water DP drilling operations.

**Table 1. Types of drilling disconnection for operations in ice.**

| Type of Disconnection | Typical Cause for Disconnection | Minimum Alert Time | Anticipated Frequency in a Single Drilling Season |
|---|---|---|---|
| Planned | Completed well, end of season | Days | As needed |
| Managed | Unmanageable ice, critical ice feature in the far field | >24 hours | <3-6 times |
| Rapid | Unbreakable ice in the mid field | >6 hours | <1 time |
| Emergency | Unmanageable ice in the near field, imminent stationkeeping system overload | <6 hours | Almost never |

## IMPLICATIONS OF DISCONNECTION MINIMUM ALERT TIMES FOR ICE MANAGEMENT

The above minimum requirements for disconnection alert times help to establish the high level functional requirements for a comprehensive ice management operation to support floating drilling. A comprehensive ice management program for a severe ice environment includes ice monitoring and surveillance, ice drift forecasting, verification of ice breakability and systematic floe size reduction. This operation takes place in three distinct operational stages upstream of the stationary drilling vessel. As depicted schematically in Figure 2, we break the operational stages into far-field, mid-field and near-field defined as follows:

a) Far-field surveillance, detection and forecasting of potentially unmanageable ice features (PUIFs) to support managed disconnection must be conducted at distances providing greater than 24 hours alert time ahead of the drilling vessel.

b) Mid-field operations must verify breakability of the ice prior to its reaching the near-field floe size reduction icebreakers. As demonstrated by previous studies of ice management optimization (Hamilton *et al.*, 2011b), the near-field floe size reduction operation will very frequently occur significantly less than six hours upstream of the drilling vessel in order to reliably maintain the vessel within the managed ice channel. Hence, breakability must be verified upstream of the near-field operation at a distance corresponding to at least six hours ahead to avoid the need for emergency disconnection in the event ice is found to be unbreakable. It is the consensus of icebreaker captains consulted by ExxonMobil that the only means to guarantee breakability of thick heavily ridged first year ice or multi-year ice is to actually break it with an icebreaker. Hence, a scouting icebreaker is needed to verify breakability a minimum of six hours in advance of the drilling rig.

c) Near-field icebreakers perform near-field systematic ice floe size reduction as close as safely allowable to the protected drilling vessel to insure the drilling vessel remains well within the managed ice channel as the drift direction changes dynamically.

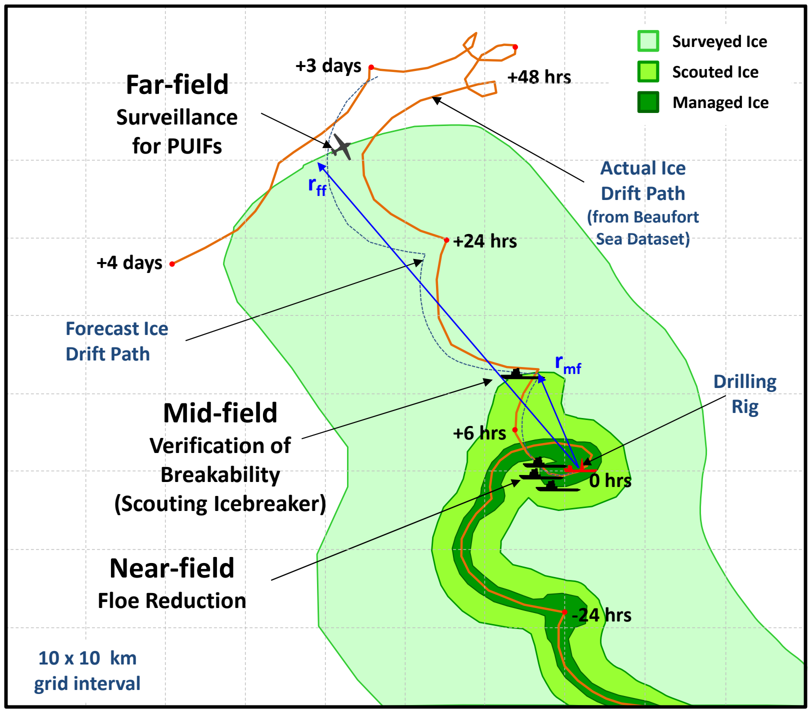



**Figure 2. Three-stage ice management operation in support of floating drilling.**

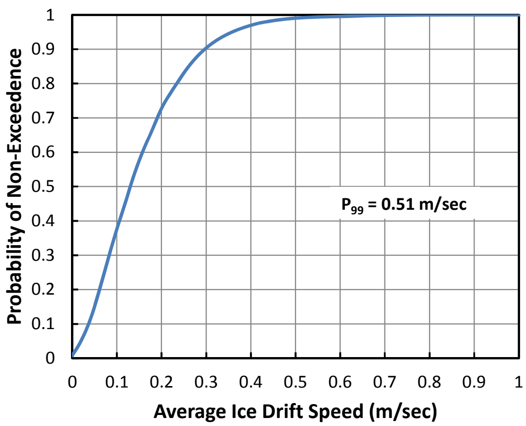
## DIMENSIONAL REQUIREMENTS FOR FAR- AND MID-FIELD OPERATIONS BASED ON HISTORIC ICE DATA RECORDS

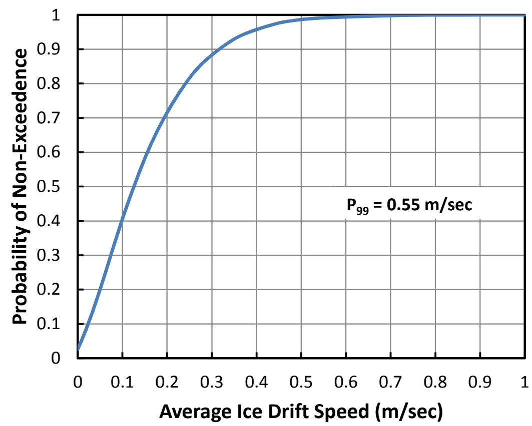
### *Lead Distance*

Given the minimum alert time requirements for drilling operations, historic ice drift records can be used to establish lead distances for far- and mid-field operations ahead of the drilling rig. To develop an example estimate, we performed an analysis of July-November ice drift records for two IPS/ADCP stations in the Canadian Beaufort Sea. The data were collected by the Canadian Department of Fisheries and Oceans for the years 1992-2007 and have been described in Melling and Riedel, 2004. The analysis determined average 24-hour and 6-hour drift speeds using a moving window advanced at 15 minute intervals for all of the available data. Cumulative probabilities of occurrence curves are provided for 24-hour and 6-hour average ice drift speeds in Figures 3a and 3b. The authors have assumed that a 99% non-exceedence value is a reasonable choice for average drift to establish the appropriate lead distance of far- and mid-field operations ahead of the drilling rig. The 99% non-exceedence drift speed for a 24 hour period is 0.51 meters/sec and for a 6 hour period is 0.55 meters/sec. Hence, the required lead distances for far-field and mid-field operations (denoted $r_{ff}$ and $r_{mf}$ respectively) are:

a) $r_{ff}$ = 44 km for far-field ice monitoring and drift forecasting;

b) $r_{mf}$ = 12 km for mid-field verification of ice breakability.




**3a) 24-hr average drift** **3b) 6-hr average drift**

**Figure 3. Non-exceedence probabilities for average ice drift speeds in the Canadian Beaufort Sea during the months July-November; 24-hr and 6-hr periods.**

The challenge that must be addressed is how to provide a sufficient investigation swath width of far- and mid-field surveillance in order to provide these minimum lead distances with confidence that the drilling rig will stay within the investigated area. This is especially true given the widely variable ice drift paths that can occur (see example drift paths in Figure 2 or in Hamilton *et al.,* 2011a). The required investigation swath width will be dependent on the accuracy of the ice drift forecast.

***Investigation Swath Width***

In ice management discussions, we generally refer to a cone-shaped area of investigation ahead of the drilling vessel wherein the width of the area requiring investigation increases at greater lead distances to account for the uncertainty in ability to forecast the future ice drift track. If fixed lead distances are established based on 99$^{th}$ percentile drift rates, as in the preceding discussion, the area of investigation becomes a sector whose width is consistent with a fixed forecast angle. The sector is centered on the forecasted ice drift path as shown in Figure 2. To evaluate the practicality of conducting far-field and mid-field operations, one can either prescribe investigation angles thought to be compatible with anticipated accuracy of 24- and 6-hour drift path forecasts, or examine the limits of the sectors that can be attained using aerial surveillance equipment and a scouting icebreaker. Here we undertake the latter investigation after a consideration of the ice features that need to be identified and tested for breakability.

***Survey Density for Detection of Potentially Unmanageable Ice Features***

Potentially unmanageable ice features include heavily ridged first year ice, ridged second year ice, multi-year ice floes, and fragments of multi-year ice or ice islands embedded within first year ice floes. These features can be detected to some degree in satellite imagery; however in our experience, they cannot be detected with sufficient confidence to rely on satellite reconnaissance alone. In the Canadian Beaufort Sea environment, one often finds relatively small inclusions of multi-year ice fragments within much larger conglomerate floes of mainly first year ice. The fragments typically are on the order of 200-400 meters in size, 3+ meters thick, and are quite capable of stopping the progress of ice management icebreakers. An example of one such 300 meter multi-year ice floe embedded in a 100 km$^2$ first year ice floe is shown in Figure 4. Features of this scale cannot be allowed to impact a floating drilling vessel. Likewise, it is not prudent to assume that the near-field floe size reduction icebreakers could deal with such a floe in the short time window available ahead of the drilling vessel. Consequently, a far-field reconnaissance program must sample with sufficient areal density to detect PUIFs as small as a few hundred meters in size.

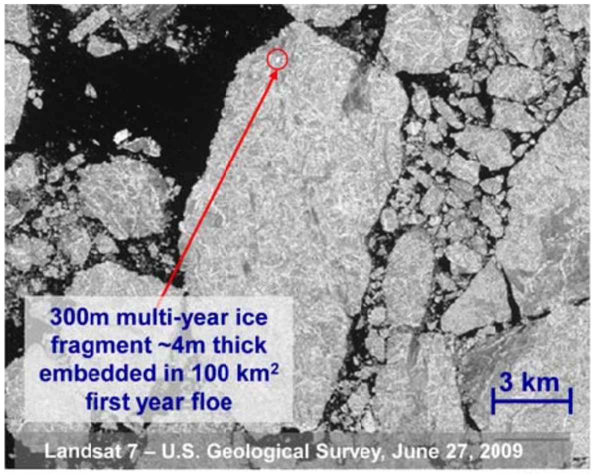



**Figure 4. Multi-year ice fragment embedded in large first-year conglomerate ice floe. Image: Lansdat 7 optical satellite image acquired June 27, 2009, courtesy of the USGS.**

***Far-field PUIF Detection and Monitoring***

The key characteristic of interest for PUIFs is thickness, which is a parameter that to-date cannot be reliably measured using satellite imagery. Hence aerial surveillance is needed in conjunction with satellite imagery to identify PUIFs within the far-field ice zone. A two-tier far-field aerial survey approach is envisioned using a broad-swath method to identify potential thick ice followed by a local investigation technique to confirm thickness of identified zones or features. Currently, there is no proven technology for remote, broad-swath ice thickness surveying. One technology being investigated for this purpose is Multi-band Synthetic Aperture Radar (MSAR) flown on a fixed-wing platform (Holt *et al.*, 2009, Scheuchl, *et al.*, 2002 ). High-power SAR instruments can potentially be flown at high altitude (2500+m) and at air speeds of 250 to 400 kts (450 to 750 km/hr). In such a configuration it would have a very wide single-pass survey swath of approximately 8+ km and could cover the far-field investigation zone quite rapidly.

Tier-two, or local ice thickness confirmation measurements of areas identified in the tier-one survey could then be made using the well-established Electromagnetic Induction (EMI) methodology. EMI sensors have been routinely deployed for ice reconnaissance for several decades (Kovacs *et al.*, 1987, Haas *et al.*, 2006). This method requires that the EMI instrument be flown approximately 20 meters above the ice, either attached to a helicopter or suspended from a cable beneath an airplane (Haas, 2010). Airspeed for a fixed-wing EMI survey is about 80-120 kts (150 to 225 km/hr). One potential limitation for tier two measurements is sensitivity of low altitude flights to weather and visibility.

In the event MSAR is not proven effective, reconnaissance using EMI alone would require considerably more flight time due to the need to fly much more closely spaced survey passes in a systematic pattern-search mode. The effective swath width of surveyed ice using EMI is only 10-20m. Hence successive passes would need to be spaced no more than about 200m apart to insure all relevant PUIFs are detected. The following sections explore the practical widths of investigation achievable by aerial surveillance and scouting icebreaker.

## KINEMATIC ANALYSIS OF FEASIBLE SURVEY AREAS

In a pattern survey mode the airplane is assumed to move along arcing paths, subtended by angle $\phi$, ahead of the stationary drilling vessel. The angle $\phi$ corresponds to the degree of uncertainty inherent in the ice forecast. The survey area is assumed to begin at a radial distance $r_{ff}$ away from the drilling vessel and continue out a radial distance $l$. For example, to survey ice that could potentially contact the drilling vessel within a timeframe of 24 to 48 hours, a survey area subtending angle $\phi$ and spanning from $r_{ff}$ to $2r_{ff}$ should be used ($l = r_{ff}$ in this case).

A relative velocity approach is used to perform kinematic analysis of feasible survey areas – the desired survey area is expressed relative to the moving ice sheet, whereas performance parameters of the aircraft are expressed in terms of motion relative to the earth. A fixed reference frame $r_1$-$\theta_1$, with origin at the drillship, is used to express the motion of the airplane relative to the earth. A moving reference frame, $r_2$-$\theta_2$, translates with the moving ice sheet. The velocity of the ice is assumed to be, in polar coordinates, $\mathbf{v_i} = \mathbf{v_2} = \{\ -v_i\ \ 0\}^T$. Physically, the entire ice sheet cannot have this velocity; however, it is assumed that at any given instant the ice directly below the aircraft has this velocity.

Figure 5 depicts the geometry of a pattern-based aerial reconnaissance program for far-field PUIF detection. It is important to note that the path shown in the figure is the path of the airplane *relative to the surveyed ice*, that is, $\mathbf{s_{1/2}}$. The aircraft is assumed to have a cruising speed of $v_a$ (relative to earth), a swath width of $s^*$ and an endurance (allowable flight duration time) of $E_{provided}$. The tolerance for maximum size of missed feature is $b$.

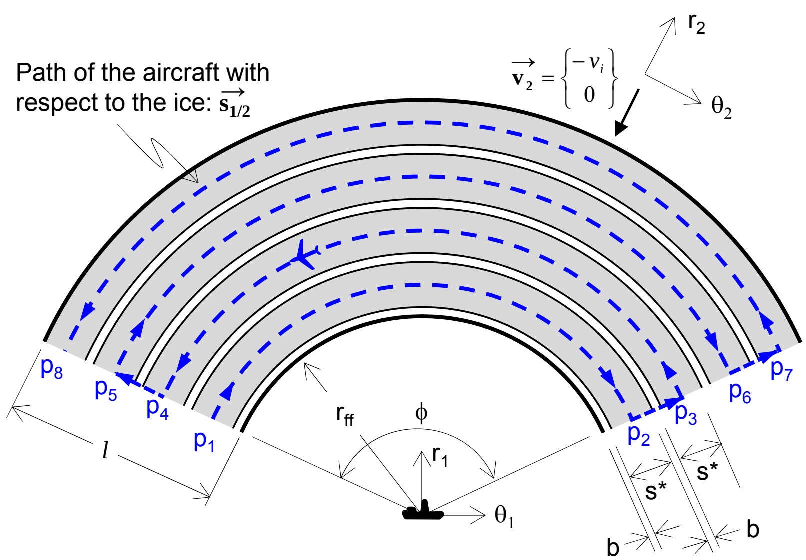



**Figure 5. Illustration of pattern survey mode of aerial reconnaissance.**

One pass is considered to be a lateral sweep (e.g. P1 to P2) and then an updrift turn (e.g. P2 to P3). In a single pass the radial length surveyed is $s^* + b$. Therefore, to complete the survey, the total number of passes required, denoted by $N$, is

$$N = \frac{l}{s^* + b} \tag{1}$$

Note that $N$ is always rounded to the next highest integer so the entire length is surveyed.

To calculate parameters related to endurance and maximum surveyable angle, the average pass radius, $\overline{R}$, must be determined. It is recognized that the radius, $R_n$, increases with each successive pass (and accordingly the distance travelled and time required to complete the pass). The average pass radius is defined as the average of the first and last (or $N^{th}$) pass and is given by

$$\overline{R} = r_{ff} + \frac{N}{2}s^* + \frac{N+1}{2}b \qquad (2)$$

For calculations it is assumed that the survey completes $N$ passes of radius $\overline{R}$. The duration of this average pass is given by

$$\overline{\Delta t} = \frac{\phi \overline{R}}{v_\theta} + \frac{s^* + b}{v_a} \qquad (3)$$

Note in equation (3), $v_\theta$ represents the speed of the plane in the tangential direction relative to the ice. Recognizing that the cruising airspeed relative to the ground is $v_a$, then

$$v_\theta = \sqrt{v_a^2 - v_i^2} \qquad (4)$$

Using equations (1) to (4), the required endurance, $E_{reqd}$, to survey an area of length $l$ subtended by angle $\phi$ is therefore,

$$E_{reqd} = N \times \overline{\Delta t} = \frac{\phi}{\sqrt{v_a^2 - v_i^2}}\left( Nr_{ff} + \frac{N^2}{2}s^* + \frac{N^2+N}{2}b \right) + \frac{l}{v_a} \le E_{provided} \qquad (5)$$

Rearranging equation (5), one can obtain the maximum angle, $\phi_{max}$, that can be surveyed given the aircraft endurance, $E_{provided.}$

$$\phi_{max} = \left( E_{provided} - \frac{l}{v_a} \right) \times \frac{\sqrt{v_a^2 - v_i^2}}{\left( Nr_{ff} + \frac{N^2}{2}s^* + \frac{N^2+N}{2}b \right)} \qquad (6)$$

***Fixed-wing MSAR Survey***

If MSAR is effective, it provides more than enough capability to conduct a far-field survey of the approaching ice. As an illustrative example, consider a situation in which we wish to survey a length corresponding to 24 hours ice drift ($l$ = 44 km assuming $v_i$ = 0.51 m/sec). It is assumed that the aircraft has a flight endurance of 6 hours and can continuously survey for $E_{provided}$ = 4 hours per day (allowing for travel to and from the survey area). Using MSAR with $v_a$ = 450 km/hr, $s^*$ = 8km and $b$ = 200m, a sector having $\phi$=244° can be surveyed. Due to the wide swath width, only 6 passes are needed to survey the desired area. In fact, the full 360° circle around the drilling vessel could be surveyed within 6 hours. This would not eliminate the need for ice drift forecasting because as demonstrated below, other localized PUIF detection methods will require forecasting to narrow the investigation area.

***Fixed-wing EMI Survey***

Fixed-wing EMI measurements must be made with much more closely spaced passes due to the very narrow measurement swath width of 10-20m. If the survey density is assumed to be $b$ = 200 meters, 34 passes of EMI are needed to cover the same investigation area as a single pass of MSAR with 8 km measurement swath. Using EMI with $E_{provided}$ = 4 hours, $v_a$ = 225 km/hr, $s^*$ = 20m and $b$ = 200m, to survey the same length of ice as in the previous example ($r_{ff}$ = $l$ = 44km) a sector of only $\phi$ = 4° can be achieved. The largest $\phi$ that can be surveyed using a continuous operation 44 km ahead of the drilling rig is only 17°. While recent work on ice drift forecasting reported by Blunt *et al.* (2013) has demonstrated promise of the ability to improve ice drift forecasting over longer periods of time, achieving forecast angles on the order of 17° for 24-hr periods seems unlikely. Consequently, while EMI ice thickness measurement will be an important component of ice management surveillance, it should be used in a local verification mode rather than a systematic, pattern survey mode.

***Single Mid-Field Scouting Icebreaker***

In a pattern survey mode the mid-field icebreaker must be capable of systematically searching for features larger than given threshold size, *b*. If operated in a targeted scouting mode the mid-field icebreaker will instead (1) verify that all thick features deemed breakable are indeed breakable and (2) investigate if identified PUIFs are breakable so that the disconnection initiated in the far field can be aborted.

The efficacy of a mid-field scouting icebreaker in a pattern survey mode can be investigated using the kinematic approach described above with the swath width $s^*$ replaced with the icebreaker beam, $l_b$, and the airspeed $v_a$, replaced with the average icebreaker forward progress, $v_{ib}$. The approach is more straightforward in that icebreakers will not advance through the ice field – they instead operate continuously and maintain the same orbit with respect to the earth at a radial distance $r_{mf} + l_b/2$ from the drillship. Therefore, the icebreaker must be able to transit one complete orbit back and forth in less than the time it takes for the ice sheet to travel the distance $l_b+b$. The maximum angle that can be surveyed in a pattern mode is therefore

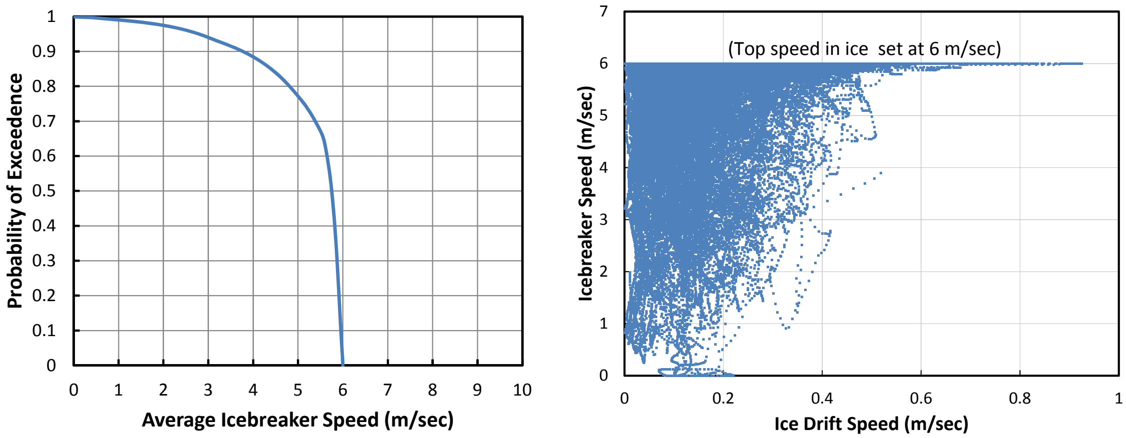
$$\phi_{max} = \frac{v_{ib}}{v_i} \times \frac{l_b + b}{2r_{mf} + l_b} \tag{7}$$

Equation (7) is approximate in that it does not include the time it takes the icebreakers to turn 180 degrees. Moreover, it does not continuously account for the change in the path of the icebreaker to correct for the ice velocity in the same way equations (1) – (6) do.

For this study, the icebreaker speed was estimated based on the previously described Canadian Beaufort Sea station IPS thickness records, coupled with proprietary, calibrated icebreaker performance relationships. We computed frequency histograms and exceedence probability curves for average icebreaker speeds over 6-hour periods. The icebreaker speed is based on parameters derivable from the IPS data such as parent ice thickness and ridge frequency and size. Figure 6 shows the resulting estimated speeds for a capable scouting icebreaker. Based on the analysis, the median icebreaker speed for a 6-hour period is 5.7 m/sec, and the 99th percentile is 1.2 m/sec. The speeds are likely biased towards the higher end due to the prevalence of thinner ice in the October-November time frame.

To illustrate the practical limits of using a scouting icebreaker, assume a systematic pattern survey at a mid-field alert distance of $r_{mf}$ = 12 km with $b$ = 200 m and an icebreaker beam of $l_b$ = 30m. Using equation (7), with an ice drift speed of 0.55 m/sec, a scouting icebreaker moving at the 50th percentile speed of 5.7 m/sec could achieve a survey sector with angle $\phi$ of only 6°. The 50$^{th}$ percentile icebreaker speed is used instead of a lower value because, as can be seen in Figure 6b, the fastest ice drifts generally correspond to thin ice conditions (therefore permitting faster icebreaker speeds).

The foregoing analysis implies that either multiple scouting icebreakers are needed to survey the required area (essentially shifting primary icebreaking to the mid-field which is probably too costly), or the scouting icebreaker must spend its time only verifying breakability of thick or ridged zones identified in the far-field survey that were deemed likely to be manageable. In this mode, the scouting icebreaker would transit between and verify breakability of localized regions of interest and not be required to systematically break all of the ice.




**6a) 6-hr average icebreaker speed** **6b) Icebreaker speed vs. ice drift speed**

**Figure 6. (a) Exceedence probabilities for calculated 6-hr average icebreaker speeds based on ice thickness/ridging data; (b) Computed icebreaker speed vs. ice drift speed. Note fast ice drift speeds correspond to fast icebreaker speeds, i.e., thinner ice.**

## CONCLUSIONS

Floating drilling operations in Arctic ice are unique in that they must plan for regular disconnections as part of the drilling program, particularly if there is a possibility of encountering multi-year ice. A comprehensive ice management program, which includes ice surveillance, drift forecasting, verification of breakability and systematic floe reduction, must be sufficient to provide several levels of disconnection alert times with very high reliability. With envisioned drilling technology extensions, minimum alert times of 24 hours for managed disconnection and 6 hours for rapid disconnection would be aligned with drilling safety and economic criteria.

A three-stage ice management operation is required to achieve the critical minimum disconnect times in severe ice environments. Far- and mid-field surveillance zones can be defined by upper-bound estimates of the average 24 and 6-hour ice drift velocities, which for the Canadian Beaufort Sea are on the order of 0.5 m/sec during the summer-fall season of July-November. Far-field aerial ice surveillance requires a broad-swath measurement technique to identify zones of thicker ice for local thickness measurements. High-altitude multi-band SAR is a potential candidate for such measurements but needs further testing and validation. Local ice thickness verification can be accomplished with low-altitude EMI measurements; however, use of EMI alone appears impractical due to the limited width of area, or sector angle, that can be surveyed in a systematic pattern survey.

Unanimous input from a number of very experienced icebreaker masters points to the need to verify breakability of ice ahead of the floe reduction operation using a scouting icebreaker.

Given the 6-hour minimum alert time for rapid disconnection, and the desired frequency of occurrence of less than one event per season, scouting must take place at least 6 hours ahead of the drilling rig. This is well ahead of the near-field systematic floe reduction operation. Based on expected ice drift speeds and estimated icebreaker speeds, it is not practical to conduct a pattern-based systematic scouting operation in a sector wide enough to meet estimated drift forecasting accuracy. Hence, scouting for breakability must be directed at specific targets identified in the far-field surveillance operation.

The authors conclude that such a comprehensive ice management program is feasible, but that key components need to be field-demonstrated to increase confidence in their performance. Most of this discussion is directed at high-Arctic environments that experience multi-year ice. A less comprehensive approach may be acceptable for a 100% first year ice environment, but only if the ice management fleet consists of appropriately capable icebreakers.

## REFERENCES

American Petroleum Institute, 2010. API Standard 65-Part 2: Isolating Potential Flow Zones During Well Construction, American Petroleum Institute, 83 pp.

Blunt, J.D., Mitchell, D.A., Matskevitch, D.G., Younan, A.H. and Hamilton, J.M., 2013. Tactical Sea Ice Drift Forecasting for Summer Operation Support in the Canadian Beaufort Sea, Proc OTC Arctic Tech Conf, Houston, TX, Paper No OTC 23824.

Haas, C., Goebell, S., Hendricks, S., Martin, T., Pfaffling, A., and von Saldern, C.2007. Airborne electromagnetic measurements of sea ice thickness: methods and applications. Wadhams, P., and G. Amanatidis (Eds.): Arctic Sea Ice Thickness: Past, Present and Future. European Commission, Climate Change and Natural Hazards Series, 136-148.

Haas, C, Hendricks, S., Eicken, H., and Herber, A., 2010. Synoptic airborne thickness surveys reveal state of Arctic sea ice cover. Geophysical Research Letters, Vol. 37, L09501, doi:10.1029/2010GL042652, 2010.

Hamilton, J.M., Holub, C.J., Blunt, J., Mitchell, D.A., and Kokkinis, T., 2011a. Ice Management for Support of Arctic Floating Operations. Proc OTC Arctic Tech Conf, Houston, TX, Paper No OTC 22105.

Hamilton, J.M., Holub, C.J., and Blunt, J., 2011b. Simulation of Ice Management Fleet Operations Using Two Decades of Beaufor Sea Ice Drift and Thickness Time Histories, Proc 21st Int Offshore and Polar Eng Conf, Maui, ISOPE, Vol 1, pp 1100-1107.

Holt, B., Kanagaratnam P., Prasad, S., Gogineni, S.P., Ramasami, V.C., Mahoney, A., and Lytle, V., 2009. Sea ice thickness measurements by ultrawideband penetrating radar: First results. Cold Regions Science and Technology, 55 pp. 33–46. doi:10.1016/j.coldregions. 2008.04.007.

Kovacs, A., Valleau, N.C., and Holladay, J.S., 1987. Airborne electromagnetic sounding of seaice thickness and subice bathymetry. Cold Reg. Sci. Technol., 14, 289–311, doi:10.1016/0165-232X(87)90021-8.

Melling, H. and Riedel, D.A., 2004. Draft and Movement of Pack Ice in the Beaufort Sea: A Time-Series Presentation, April 1990 – August 1999. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 238. v + 24 p.

Scheuchl, B., Hajnsek, I., and Cumming, I., 2002. Sea Ice Classification Using Multi-Frequency Polarimetric SAR Data. Proc IEEE Intl Geoscience and Remote Sensing Symposium, Toronto, Canada, 2002.