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THE POTENTIAL OF SATELLITE EARTH OBSERVATION OF ICE CONDITIONS IN SUPPORTING ISO 19906

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ABSTRACT

An accurate assessment of ice conditions is essential for the safe and reliable planning of operations and the design of offshore structures in ice covered waters, in both Arctic and sub-Arctic locales. This includes mean and median conditions and extremes, as driven by seasonal and inter-annual variability. Parameters of importance to design include ice type, ice concentration by type, extreme ice feature dimensions (e.g., diameter and thickness of multiyear ice floes), ice velocity, ice season length and others, as described in ISO 19906 (Annex B). Historically, data to define these parameters and their probability distribution functions have been derived from field measurements with support from earth observation. Going forward, there is an opportunity for satellite earth observation to play an enhanced role in establishing these design parameters and to ultimately enhance the probabilistic design practice described in the new ISO 19906. Benefits include a more accurate assessment of ice conditions, due to higher spatial and temporal coverage as compared to field measurements, faster data collection due to the ability to draw upon decadal archives of satellite imagery, simplification of the data acquisition process due to reduced reliance on logistical support for field activities, and keeping people out of harm's way. In this paper, we propose how satellite earth observation data may be used within the context of ISO 19906.

BACKGROUND

ISO 19906 provides the basis for how to design Arctic (or sub-Arctic) offshore facilities that meet international standards for safety and performance (ISO/FDIS 19906:2010(E), 2010). In order to get full value from this standard, a probabilistic description of the ice environment is essential. Establishing this description involves carrying out the following tasks, the first two of which contain an important requirement for observations of environmental ice conditions:

1. Identifying ice features of importance for determining 'characteristic' ice action values (e.g., multiyear ice, icebergs, first year ridges);
2. Developing probability distribution functions for ice feature dimensions (random variables) from (1);
3. Computing ice action probability distribution functions based on (2) and ice action equations for ice-structure interaction from ISO 19906 applicable to structure configuration of interest;

4. Determining Extreme level ice event (ELIE) and Abnormal level ice event (ALIE) loads based on 'characteristic' values from (3) and appropriate action factors given in ISO 19906 as a function of exposure level.

ADVANTAGES OF SATELLITE EARTH OBSERVATION

Historically, environmental ice observations have been collected using *in situ* and airborne platforms, in particular involving the following sensors:

- Under-ice topography, keel profiling and ice thickness from ice profiling sonar and acoustic Doppler current profilers;
- Over-ice topography, ridge profiling and ice thickness from LIDAR and electro-magnetic induction sensors;
- Ice thickness from mechanical and thermal drilling;
- Ice mechanical and thermal properties from in situ measurements including thermistor strings and flat jacks;
- Distribution and spatial properties of ice features from aerial photography, airborne synthetic aperture radar and side-looking airborne radar;
- Ice trajectories and other environmental parameters from drifting buoys.

These airborne and *in situ* techniques have several generic limitations which constrain their ability to support the effective implementation of ISO 19906, in particular in the following ways:

- The spatial and/or temporal resolution of these conventional observations may be excellent, but the temporal and/or spatial coverage associated with airborne and *in situ* sensors is always highly constrained, leading to difficulties in establishing the representative nature of the observations.
- Multiyear measurement campaigns to obtain a statistically significant data set and/or observe long term trends are an extremely high cost proposition;
- There are increasingly stringent health and safety constraints to the deployment of personnel and equipment into the offshore environment;
- The deployment of aircraft or equipment into the offshore environment is logistically complex and extremely expensive and there are significant additional costs associated with purchasing or leasing the appropriate sensors;

Satellite earth observation (EO) does not suffer from these limitations[1]. In fact, satellite EO has several particular strengths with regard to implementation of ISO 19906, as follows:

- Archives of data now exist which extend back to years to decades, depending on the type of data required, providing in some cases temporal coverage that may be considered representative of recent climatological conditions, and in some cases sampling extreme ice conditions. This includes a significant body of radar data, which is insensitive to atmospheric or natural lighting conditions.

[1] Although equipment failure in space is final, there are nowadays other space-borne missions that can serve as backup.

- The observation capabilities of satellite EO data are improving constantly, enabling new acquisitions of data to be increasingly well matched to requirements, such as spatial resolution. These capabilities include spatial resolutions of about 1m, multiple daily observing opportunities at high latitudes, multiple spectral and polarimetric options that improve feature discrimination, and multiple platforms that ensure backup capabilities.

CAPABILITIES OF SATELLITE EARTH OBSERVATION

Satellite EO can contribute both to providing an overview of the ice environment in the vicinity of the design location and to providing quantitative information on ice parameters related to ice actions. The capabilities of satellite EO data in supporting ISO 19906 are summarised here and in Table 1.

Overview of Ice Environment

An archive of EO data extends back to the 1970s in some cases, which can be used to establish temporal-spatial patterns of ice conditions which may be linked to distinct probability functions associated with ice actions. Much of the relevant data in this category have already been processed into geophysical parameters of interest, such as ice drift and ice concentrations at regional to hemispheric scales of coverage. In this category we include ice charts, which are in most cases predominantly derived from satellite EO data.

Ice Floes

The ability to characterise ice floes depends on having data with a spatial resolution able to resolve the floes. SAR data at a resolution of about 30m or larger extends back to the early 1990s, so in principle there is information on floe size distributions of the order of 100m or more in dimension. There is also systematic information on ice drift in some areas from 1996, particularly the Arctic basin extending to the Beaufort Sea, Fram Strait and northern Barents Sea, although derived ice drift tends to be limited to areas of pack ice rather than the marginal ice zone. Lagrangian processing of SAR data in these areas of pack ice has resulted in estimated ice thickness distributions (Kwok et al., 1999). Altimeter data extending back to 1991 may, in principle, be re-processed to extract 1D profiles of freeboards in the vicinity of offshore structure design locations, with an along-track resolution of the order of a few km (Connor et al., 2009).

Deformed Ice

Resolving deformed first year ice features, including pressure ridges, stamukhi, rafted ice and rubble fields requires high spatial resolution. In general, the satellite EO archive contains little data that is of sufficient resolution to contribute to defining ice actions from deformed first year ice. However, the exceptions include the possibility of obtaining ice drift trajectories and speeds based on SAR data and surrounding ice thicknesses based on reprocessed altimeter data or Lagrangian SAR products. There is, however, significantly more scope for use of satellite EO data in recently launched SARs which have a spatial resolution capability of 1m, and through new techniques such as single pass bistatic interferometry which may be able to generate sea ice topography and drift at high spatial resolution (Moreira et al., 2004). The spatial configuration of such features (e.g., orientation) will also be enhanced through the use of more useful SAR configurations including high incidence angles and L band operating frequency and specialised image processing (e.g., Fitton and Cox, 1998).

Icebergs and Ice Islands

Icebergs of the order of 30m or so in size (perhaps less, given that icebergs can be detected that are somewhat smaller than the resolution of SARs) may be extracted from the archive of SAR imagery extending back to the early 1990s, although some areas are much better sampled than others. New SAR techniques of value include the use of dual polarisation to detect icebergs in sea ice and higher spatial resolution and incidence angles to improve detection of smaller icebergs (Howell et al., 2008).

Table 1. Summary of potential contributions of satellite earth observation data to ice parameter estimates in support of ISO 19906 (SAR=synthetic aperture radar; ALT=altimeter; PMR=passive microwave radiometry; INSAR=interferometric SAR; VIR=visible/infrared imagers).

	Contributing ice parameters	Archive Data	New acquisition opportunities
Overview of ice environm't	Ice concentrations	Ice charts (global from 1972, based on EO data) PMR from 1979 at 25km resolution	Ongoing ice charts and PMR, some at improving spatial resolution (e.g., AMSR-E at 6.25km resolution)
	Ice type concentrations		
	Ice season start and end		
	Snow thickness	PMR from 2000s at 12.5km resolution	Possibility of X/Ku band SAR
	Melt onset	PMR from 1979 at 25km resolution	SAR sensitive to melt onset
	Ice drift	25km resolution multi-sensor blended data from 1978;	Daily >10km resolution drift vectors available from PMR
Ice floe actions (e.g., multi-year ice)	Fraction cover	SAR from 1990s at >~30m resolution, VIR from 1970s (subject to cloud, etc)	SAR to ~1m resolution available; polarimetry to improve ice vs. water
	Horizontal dimensions		
	Ice freeboard and thickness	Radar ALT from 1990s and laser ALT during 2000s (reprocessing to extract local ice/snow freeboards) Lagrangian SAR in Arctic for ice thickness distributions from 1996	Single-pass bistatic INSAR possibility for 2D topography; repeat pass INSAR for land-fast ice; Cryosat improved ALT along-track resolution
	Snow thickness	Not generally available	Possibility of X/Ku band SAR
	Drift direction	SAR-derived data from 1990s in part processed by ESA/NASA	high spatial resolution vectors require custom data acquisitions; along-track INSAR for ice drift
	Drift speed		
Deformed ice actions (i.e. ridges, rafted ice, refloated stamukha and rubble ice)	Sail height (ridges)	Not generally available	Single or perhaps repeat pass INSAR (latter for land-fast only)
	Keel depth (ridges)	Not generally available	
	Orientation w.r.t structure	Not generally available	Fine resolution >~1m SAR, particularly at high incidence angles and/or L-band
	Length and width (ridges)		
	Spacing or frequency		
	Drift direction	SAR-derived data from early 1990s	Daily coarse resolution drift vectors available; high spatial resolution vectors still require custom data acquisitions
	Drift speed		
	Impact edge geometry	Not generally available	Fine resolution >~1m SAR available
	Surrounding ice thickness	ALT from 1990s, requires reprocessing; Lagrangian SAR in Arctic from 1996	Single-pass bistatic INSAR for 2D topography; Cryosat improved ALT
	Number of ice layers	Not generally available	
	Degree of consolidation	Not generally available	
Iceberg and ice island actions	Mass	Not generally available	
	Drift direction	Scatterometry at >10km for largest icebergs; SAR available at >30m from 1990s in many areas	Short repeat SAR at fine resolution; along-track INSAR
	Drift speed		
	Shape		Fine resolution >~1m SAR Polarimetry for detection in sea ice
	Orientation w.r.t structure		
	Spacing or frequency		
	Waterline length x width		
	Depth of impact	Not generally available	
	Freeboard	Altimetry for sampling of larger icebergs (~500m dimension) from 1990s (reprocessing required)	Single pass bistatic INSAR to metres resolution
	Draught	Not generally available	

METHODOLOGY

The fit of satellite EO data into the probabilistic design methodology promoted by ISO 19906 is illustrated in Figure 1. In the remainder of this paper, we expand on the role of satellite EO in these tasks.

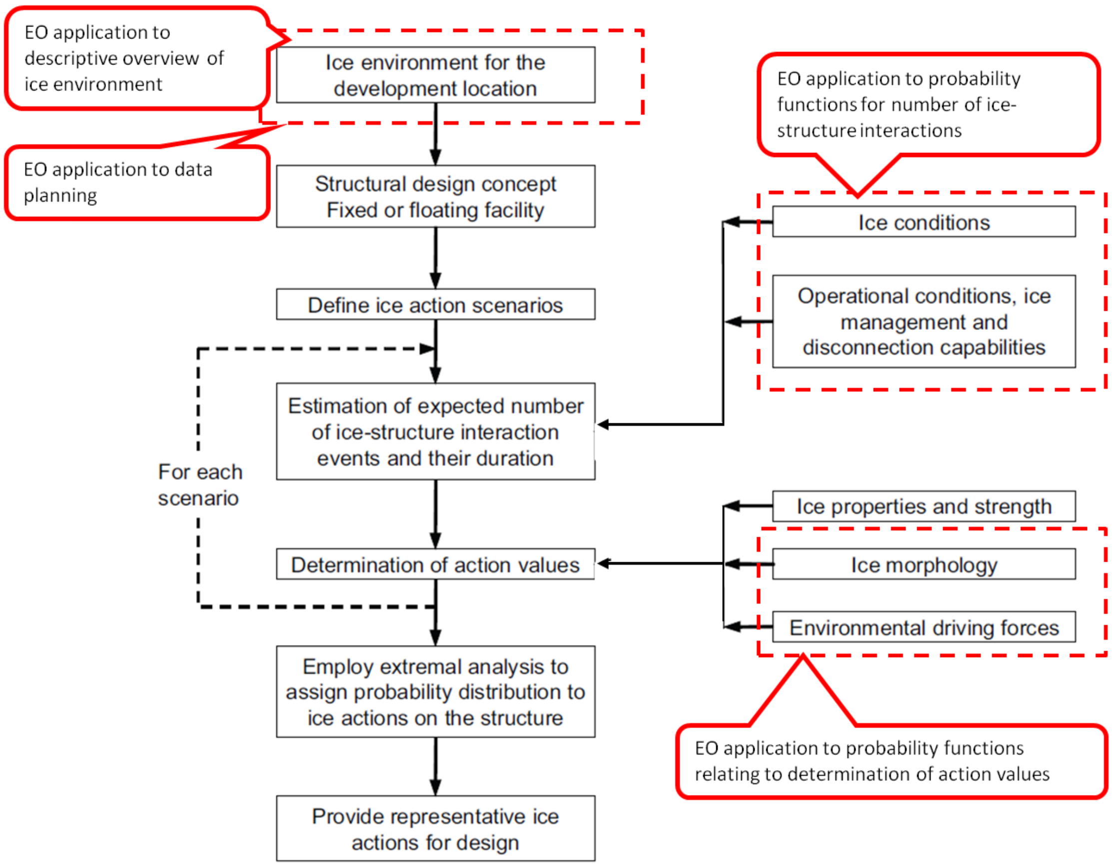

Figure 1. The role of environmental ice observations in offshore design criteria assessment, based on Figure A.8-1 from ISO 19906. Tasks involving satellite earth observation are outlined in red.

EO APPLICATION TO DESCRIPTIVE OVERVIEW OF THE ICE ENVIRONMENT

For safe and reliable design it is necessary to assess ice conditions proximal to a location of interest to ensure local variability is accurately captured. Analysis can focus, at least initially, on coarser resolution satellite EO data and EO-derived derived datasets, which have a continuous and long record of climate and ice-related variability in some cases extending back decades. A key goal is to assess the variability of ice conditions in the region of ice design location and in particular to identify those ice conditions of importance for determining ice action 'characteristic' values. Unless these conditions are understood in terms of their recent historical characteristics and trends, there is a danger that analysis of archive observations (from satellite EO or other sources) may be biased. Satellite EO data provides an excellent record of information on ice regimes and variability, and this may be used not only directly through analysis, but indirectly through published research into climate-related processes that link ice regimes and conditions to atmospheric and oceanographic conditions in different areas. The key task here is to establish "representative sampling periods" in which both benign and extreme (e.g., contributing to 'characteristic' values) ice conditions are sampled.

The data that can be used for these tasks include the following:

- National ice charts (themselves largely derived from earth observation data), from which ice types and total partial ice concentrations and sometimes other parameters may be derived (Partington et al., 2003);
- Passive microwave data, from which ice concentrations, ice drift, snow depth, date of melt onset and season start and end dates may be derived (Comiso et al., 2003; Fowler, 2003 updated 2007);
- Coarse resolution radar imagery (scatterometry and global mode SAR) from which multi-year ice and ice drift and very large icebergs and ice islands may be derived (Long et al., 2001, Walker et al., 2006).

Analysis can be carried out in conjunction with data derived from reanalyses of numerical weather prediction models, observations covering recent decades and other datasets that provide a holistic description of distinct ice and related atmospheric conditions. A number of techniques can be used which are either empirically based (e.g., empirical orthogonal functions, Partington et al., 2003) or partially physically based in order to resolve these patterns.

Although there may be good *a priori* knowledge of potential ice actions in the vicinity of the design location, satellite EO data may be useful in validating this understanding, but may indeed introduce new potential ice actions, if for example the trajectories of multiyear ice floes or small icebergs are extended into previously considered "virgin" areas as a result of improved sampling of particularly extreme ice regimes.

EO APPLICATION TO DATA PLANNING

Assessment of the Satellite EO Archive

Moderate to high resolution satellite EO data is required in order to assess most ice parameters, and useful satellite EO data at resolutions of less than about 1 km are, in many cases, not routinely available, either as a result of sensitivity to atmospheric and natural lighting conditions (in the case of Visible and infrared imagery), power consumption constraints (e.g., synthetic aperture radar) or sampling constraints (e.g., altimetry). Assessment of this archive is therefore an important early stage in the use of satellite EO data and can help to determine the requirements for additional data collection in the form of new satellite, airborne or *in situ* observations. The context for this assessment is provided by the results of the previous task: the recent historical timings associated with the range of ice regimes that can be encountered in the vicinity of the design location.

The archive of higher resolution data includes visible infra-red (VIR) imagery, altimetry (ALT) data and synthetic aperture radar (SAR) data. These instruments are capable, in principle, of meeting some of the measurement requirements for ice parameters in terms of spatial resolution. VIR data can be very useful in terms of measuring ice parameters because there is normally excellent contrast between ice and open water. However, the availability of VIR data is limited by lighting and cloud conditions and the task of identifying all useful VIR data for a location is a major one. Automated detection of clouds has been improved by the multiple spectral channels available with more recent VIR sensors, but even cloud masking with MODIS, with its 36 spectral channels, has some problems in areas of sea ice (Ackerman et al., 2004) and the difficulties are compounded in earlier sensors such as AVHRR, which has many fewer channels (although a much longer sea ice record). However, the LandSAT image archive extends back to 1972 and the US Geological Society has recently provided free access, resulting in a potentially important resource for design studies (along with more recent MODIS and other VIR datasets).

Radar data have the advantage of being insensitive to conditions of natural illumination or the presence of cloud. In general, there is significant moderate resolution SAR data (of the order of 10-100m resolution) in the archives (often with systematic coverage of an area, but with interrupted coverage extending back to the early 1990s). There is a shorter, but more continuous wide coverage archive of ice conditions from SAR data, extending back to around 1996 in many areas (with resolution coarser than 100m), while the high resolution imagery capable of detecting ice deformation features in detail (with resolution better than about 10m), has very little systematic coverage in any polar region. In general, older and coarser resolution SAR is very cost effective with archived ENVISAT wide swath imagery, for example, being priced at a few tens of euros per image, while more recent and new high resolution image acquisitions are more likely to be priced at a few thousand euros per image. In some cases, it may be necessary to prioritise high resolution acquisitions based on sampling of extremal ice regimes.

Unlike SAR sensors, radar altimeters collect data continuously, and so the availability of data is limited only by the orbital repeat cycle and inclination. ALT data is collected along narrow sub-satellite swaths that are, in effect, one-dimensional profiles. The sampling improves towards the latitudinal limit of the satellite, but it is quite likely that any particular design location will not be sampled at all by altimeters, and hence the importance of defining a representative sampling area associated with a design location. In some cases, the orbital repeat cycle is modified at different stages during a satellite mission, in which case the sampling of a particular area may change significantly.

Establishing a Representative Sampling Area

It is important to establish a "representative sampling area" around the ice design location in order to be able to assess the value of the EO data archive and to plan for any additional data acquisitions, whether they be *in situ*, airborne or satellite-based. The representative area needs to be the largest possible area that is characterised by ice conditions that may be considered representative of those at the design location. The representative area may vary depending on the ice features of interest: the representative areas associated with sea ice and icebergs are likely to be different. With sufficient data, the representative area(s) may be defined in terms of statistically homogeneity, or may be defined *a priori* in terms of knowledge of ice drift and other relevant factors (e.g., bathymetry in terms of features of a particular draft), or may be defined semi-empirically using a combination of the two. Satellite EO data can support the definition of representative area(s), through an iteration involving different areas and statistical analysis of ice parameters extracted from the EO data.

Planning New Data Acquisitions

Having assessed the EO data archive within the context of the ice conditions of importance to determining the 'characteristic' ice actions and having defined representative sampling area(s), it is then possible to plan for new data acquisitions that "fill in" observational gaps. The definition of the representative sampling areas can be used to help define locations for *in situ* or airborne observations. However, there is also the opportunity for new satellite EO acquisitions to exploit the enhanced capabilities of new sensors, potentially including the following as examples:

- SAR interferometry, potentially including single pass bistatic interferometry, for 2D mapping of sea ice topographic information.
- Use of polarimetric SAR imagery to detect icebergs in sea ice and to improve detection and characterisation of ice deformation features, such as stamukhi.
- Use of high resolution imagery to detect features such as icebergs that might not reach sufficient size to be observed in archive imagery.
- Use of low frequency (L band) and high incidence angle SAR imaging for effective mapping of sea ice deformation features.

EO APPLICATION TO PROBABILITIES OF ICE-STRUCTURE INTERACTIONS

Earth observation imagery can play a key role in assessing the probabilities of ice structure interaction. Ice drift datasets may be used to assess mean ice trajectories. Floe size information from high resolution satellite imagery may be used to assess mean floe size and its associated probability distribution function. Together, this type of information is critical for assessing the probabilities associated with ice actions taking place within a given time period for an offshore structure of a particular cross-section.

Earth observation imagery may also be used indirectly to help define ice management strategies and thereby reduce the number of ice-structure interactions. Satellite EO data can be used to help assess what ice management and operations strategies are viable. Ice velocities and concentrations (icebergs and sea ice) are one factor, for example, which will influence the time to respond and flexibility of response and hence the viability of particular ice management plans. The dimensions of ice hazards will also determine the viability of particular ice management strategies.

EO APPLICATION TO PROBABILITY FUNCTIONS OF ICE PARAMETER VALUES

Ice actions are a function of the structure configuration and applicable ice parameter probability distribution functions. As discussed, Satellite EO can help to define the ice action loadings by providing probability density functions for the values of ice parameters that contribute to these loadings. More specifically, earth observation data may be used in the following ways:

a) To provide single or joint probability density functions of ice parameter values within the representative sampling area over a representative sampling period;

b) To provide nominal values of ice parameters which are not specifically associated with ice actions but which are required to calculate loadings, e.g., snow cover;

The samples of satellite EO data used in generating ice parameter probability density functions and nominal values should include extreme ice conditions as well as more benign ice conditions, in order to be unbiased. The probability density functions and nominal values can then be used in Monte-Carlo simulations, along with ice action loading equations, to estimate ALIE and ELIE representative values of loadings.

CONCLUDING REMARKS

Earth observation has an important role to play in the establishment of design criteria for offshore structures subject to ice interaction. It has the advantages of being readily available and being safe and frequently cost effective in comparison to data acquisitions from field and airborne campaigns. With the adoption of ISO 19906 and probabilistic approach taken, the requirement for greater quantification of the ice environment has increased. This paper has discussed the potential of earth observation in this respect and has outlined a methodology for its role in meeting this challenge, but at the same time it is expected that this role will be refined through experience. Four recommendations are made as a result of this brief overview, as follows:

- Studies establishing design criteria using ISO 19906 should incorporate earth observation and ideally provide feedback to the rest of the community to help build up best practices.
- Access to earth observation archives is challenging because of the diverse sources. A tool which enabled easy multi-mission assessment, and even access, to archives would be extremely useful.
- The efficient and effective exploitation of earth observation archives will require the use of image analysis tools, some of which will require development.
- Consideration should be given to the integrated use of models and archived observations for generating a more complete picture of decadal-scale ice conditions at a design location. This would have the benefit of being able to generate estimated probability density functions of poorly observed ice parameters in addition to well observed parameters. This may well make the optimum use of earth observation for establishing design criteria but may also have long term benefits in terms of developing local ice forecasting and outlook capabilities. One way to approach this is to employ a sea ice model driven by assimilated ice observations and output from a reanalysis of a regional scale numerical weather prediction model (Hopkins, 2002).

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