AN OPEN SOURCE, VERSATILE, AFFORDABLE WAVES IN ICE INSTRUMENT FOR REMOTE SENSING IN THE POLAR REGIONS

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ABSTRACT

Sea ice is a major feature of the polar environments. Recent changes in the climate and extent of the sea ice, together with increased economic activity and research interest in these regions, are driving factors for new measurements of sea ice dynamics. While satellite data provide valuable inputs for the monitoring of sea ice extent and drift, some phenomena, such as waves in ice, require in-situ monitoring. Waves in ice are important as they participate in the coupling between the open ocean and the ice-covered regions. Measurements are challenging to perform due to remoteness and harsh environmental conditions. In this article, we present an open source instrument that was developed for performing such measurements. The versatile design includes an ultra-low power unit, a microcontroller-based logger, a small microcomputer for on-board data processing, and an Iridium modem for satellite communications. Virtually any sensor can be used with this design. In the present case, we use an Inertial Motion Unit to record wave motion. High quality results were obtained, which opens new possibilities for remote sensing in the polar regions. Our instrument can be easily customized to fit many remote sensing tasks, and we hope that our work will provide a framework for future developments of open source remote sensing instruments.

Keywords  Waves in ice · Open Source instrument · Remote sensing

1 Measurements of waves in ice

The interaction between surface waves and sea ice involves many complex physical phenomena such as viscous damping [Weber (1987); Rabault et al. (2017)], wave diffraction [Squire et al. (1995)], and nonlinear effects in the ice [Liu & Mollo-Christensen (1988)]. Therefore, it is complex and still an area of ongoing research [Rabault (2018); Squire (2018)]. Better understanding and modeling of wave propagation in sea ice can allow for the improvement of ocean models to be used for climate, weather and sea state predictions [Christensen & Broström (2008)], the estimation of ice thickness [Wadhams & Doble (2009)], and the analysis of pollution dispersion in the Arctic environment [Pfirman et al. (1995); Rigor & Colony (1997)]. More generally, all these aspects must be better understood to allow safe, environment-friendly operations in the arctic. Therefore, there is considerable interest in measuring sea ice dynamics.

While satellite and airborne Lidar data are providing valuable inputs for the monitoring of sea ice extent and drift [Shen et al. (2018a); Ardhuin et al. (2017); Shen et al. (2018b); Sutherland & Gascard (2016)], some phenomena, such as wave damping in the ice, require in-situ monitoring [Sutherland & Rabault (2016)]. Such measurements are usually performed using tiltmeters, accelerometers, and more recently Inertial Motion Units (IMUs) [Wadhams & Squire (1980);...
At the core of the instrument lies a GPS and a high-accuracy, thermally calibrated IMU. The IMU chosen is the VN100, produced by Vectornav Co. It includes a 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer, pressure sensor, temperature sensor, and a 32 bits processor for running an on-board extended Kalman filter. This IMU has been tested and used in a series of previous works (Rabault et al. 2016, 2017; Sutherland & Rabault 2016; Marchenko et al. 2017), which allowed to both confirm the quality of the data acquired by the IMU and provide valuable information about wave propagation and attenuation in landfast ice and some grease ice layers. Using the on-board Kalman filter together with low-pass filtering of the signal, wave motion can be accurately measured (Sutherland et al. 2017).

The newer version of the instrument, which was tested on landfast ice in Tempelfjorden, Svalbard in March 2018 and deployed during the Physical Processes cruise of the Nansen legacy research project in September 2018 (Reigstad et al. 2017), has extended capabilities compared with the simple logger presented in Rabault et al. (2017). Namely, it integrates a Raspberry Pi microcomputer which allows to process the data in-situ and to generate compressed spectra from the data recorded, together with an Iridium modem which enables satellite communications. Moreover, a low-power unit is added to allow for efficient energy use which, together with the addition of a solar panel, allows for long term operation. In the following, the older instruments without in-situ processing and satellite communication capabilities. As a consequence, the new instrument has become a powerful solution for performing remote sensing of complex physical processes such as waves in ice. In this article, we provide a detailed technical description of this new instrument, a brief overview of the data collected which confirms its good functioning, and we discuss implications for the communities performing remote sensing. We believe that releasing our design as open source material may help create a scientific community sharing the design of their instruments, therefore making the study of the Arctic much more cost effective and enabling far more data to be collected.

2 Technical solution used

In this section, we present a technical description of the design and functioning of the waves in ice instrument. All the code and the files for the Printed Circuit Board (PCB) are released as Open Source material (see Appendix A), so that our design is fully reproducible. Moreover, the design is highly modular, and therefore it would be easy to add sensors to the logger and to measure and transmit additional information, such as wind speed, temperature, humidity, illumination, or any other relevant physical quantity if they would be required. We chose to design our instrument around affordable, easily available and well documented hardware such as Arduinos and Raspberry Pis, and we prefer solutions that are slightly non optimal but easy to build, rather than more involved designs which would require sophisticated assembly.

2.1 Hardware

The technical solution used in the present work is a further development of what was presented in Rabault et al. (2017). At the core of the instrument lies a GPS and a high-accuracy, thermally calibrated IMU. The IMU chosen is the VN100, produced by Vectornav Co. It includes a 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer, pressure sensor, temperature sensor, and a 32 bits processor for running an on-board extended Kalman filter. This IMU has been tested and used in a series of previous works (Rabault et al. 2016, 2017; Sutherland & Rabault 2016; Marchenko et al. 2017), which allowed to both confirm the quality of the data acquired by the IMU and provide valuable information about wave propagation and attenuation in landfast ice and some grease ice layers. Using the on-board Kalman filter together with low-pass filtering of the signal, wave motion can be accurately measured (Sutherland et al. 2017).

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More specifically, the waves in ice instrument is composed of 4 main modules, as indicated in Fig. 1:

- A power control module, composed of a low power microcontroller, a LiFePO4 battery cell, a solar panel, and a step-up converter, takes care of power management. LiFePO4 battery technology is chosen owing to the robustness of the cells, and their ability to withstand low temperatures. The step-up converter generates the 5V supply needed by the electronics, from the voltage of a single element. The microcontroller takes care of
implementing the logics of the power control. Namely, it controls the charging of the battery by coupling the solar panel, and decides when the logger itself should be waked up. This module is optimized for low energy use, being the only one that is always powered on.

• The logger itself, which records the wave motion, is composed of an Arduino board, the VN100 IMU, a GPS, and a SD card for storing the data. It is very similar to the waves in ice logger which was presented in Rabault \textit{et al.} (2017). The logger is activated by the power controller around each 5 hours, and performs measurements of waves in ice for 25 minutes. The use of an Arduino board means that other sensors could be easily interfaced in both hardware and software, and added to the logics of the instrument.

• The processing module, composed of a Raspberry Pi microcomputer running a stripped-down version of Linux, takes care of analyzing the data generated by the logger, and generating the compressed spectra that are sent through Iridium. It communicates with the Arduino board for both receiving the waves data, and sending the compressed results.

• The communication module, which comprises an Iridium modem and the active antenna, allows transmission of data through satellite. The modem is driven by the Arduino board. The Short Burst Messages (SBM) protocol, allowing messages of 340 bytes to be sent by the modem, and 270 bytes to be received from the satellite, is used for communications as it is both cost effective and sufficient for sending compressed data.

All the components are integrated on a central PCB, which connects all the modules together, see Fig 2. This makes the instrument easy to produce and assemble. The whole instrument is packaged into a single Pelican Case with the solar panel mounted on the top, which makes it rugged, compact and convenient to use in fieldwork (dimensions are $34 \times 30 \times 15$ cm). The complete design weighs about 4.5 kg. In the present version of the instrument, all the antennas are mounted inside the case. This means that the instrument is self-contained, robust and easy to deploy. The PCB is designed in KiCAD, an open source electronics CAD software and can be directly produced at a low cost. Therefore, the typical total cost of the complete instrument is around 2000 $, where the IMU itself represents around 1100 $ (included in the total cost). One instrument can be built in around 4 to 6 hours of work.

### 2.2 Software and in-situ data processing

Following this architecture, the workflow of the software of the instrument is the following. It should be noted that this workflow can be easily customized in software to change the activity pattern or integrate additional measurements:

• At the beginning of each measurement cycle, the low-power unit of the instrument wakes up the logger.
• The logger measures waves in ice using the IMU and records GPS information during 25 minutes.
• When the measurements are finished, a status message is sent through Iridium. This contains information such as the logger GPS position, the battery level, and some technical information about the logger health.
• Following transmission of the status information, the Raspberry Pi (RPi) is awaken. It receives a copy of the data that has just been recorded, processes the data so as to produce compressed spectra, transmits the data back to the logger, and shuts itself down. The RPi is only awake for a few minutes.
• Following shutdown of the RPi, the logger transmits the compressed spectra through Iridium.
• Finally, the logger is shut down and only the low-power unit is kept awaken. The instrument goes into ultra low power mode for a pre-programmed time interval of around 5 hours.

The code for the low power unit and the logger is written in C++, while the signal processing on the RPi is in Python. The Iridium transmission cost is kept low as only compressed spectra and some status information are transmitted. The typical Iridium cost is about 3 $ a day. Moreover, the iridium modem allows for bi-directional communications with the instrument. This means that further developments in the software would allow to control remotely the behavior of the instrument, such as the interval between measurements.

As a consequence of the limited amount of data that can be transmitted through Iridium, the in-situ data processing and compression are important parts of the design. In order to balance these two aims, all of the onboard data processing is performed at 10 Hz. This includes the calculating of auto- and co-spectra and any integrated spectral parameters we wish to send by Iridium. In addition, the first five Fourier coefficients, i.e. the 1-D energy spectrum and the four directional coefficients, are sent via Iridium at a reduced frequency resolution in order to meet our requirements for data transmission. Details of the onboard data processing can be found in the subsequent paragraphs.

The vertical acceleration ($a_z$) and the two orthogonal components of the buoy slope (i.e. pitch and roll) are recorded internally at 10 Hz on the North, East and Down reference frame as calculated by the onboard Kalman filter (running internally at 800Hz together with the raw data acquisition). To calculate the vertical displacement $\eta$ the vertical acceleration is integrated twice with respect to time in the frequency domain using the same method as Kohout et al. (2015). This is done by calculating the Fourier transform and using the frequency response weights of $1/\omega^2$ and a half-cosine taper for the lower frequencies to prevent an abrupt cut-off Tucker & Pitt (2001), i.e.

$$\eta(t) = \text{IFFT} [H(f) \text{FFT}(a_z)],$$

where FFT and IFFT denote the Fourier and Inverse Fourier transforms respectively and $H(f)$ is the half-cosine taper function,

$$H(f) = \begin{cases} 
0, & 0 < f < f_1 \\
\frac{1}{2} \left[1 - \cos \left(\frac{\pi f - f_0}{f_2 - f_1} \right)\right], & f_1 \leq f \leq f_2 \\
\frac{1}{2}, & f_2 < f < f_c,
\end{cases}$$

where $f$ is the frequency, $f_c$ is the Nyquist frequency, and $f_1$ and $f_2$ are the corner frequencies for the half-cosine taper. We use the same corner frequencies as Kohout et al. (2015) of $f_1 = 0.02$Hz and $f_2 = 0.03$Hz, which are suitable for a frequency bandwidth of 4 - 20 s. The time series of the vertical displacement is then the real part of the inverse Fourier transform.
The spectra and co-spectra of these time series can be used to provide the directional distribution, which is usually written as [Kuik et al., 1988]:

\[ E(f, \theta) = S(f)D(f, \theta), \]  

where \( S(f) \) is the 1-D power spectral density (PSD, also referred to as \( PSDF \), in the following), calculated from the heave, and \( D(f, \theta) \) is the normalized directional distribution which has the property

\[ \int_{-\pi}^{\pi} D(f, \theta)d\theta = 1. \]  

While several methods exist to calculate \( D(f, \theta) \) [Kuik et al., 1988; Sutherland et al., 2017] they are predominantly based on the following four Fourier coefficients [Longuet-Higgins, 1961]:

\[
\begin{align*}
a_1(f) &= \int_{-\pi}^{\pi} \cos(\theta) D(f, \theta)d\theta = \frac{Q_{xx}(f)}{k(f)C_{zz}(f)} \\
b_1(f) &= \int_{-\pi}^{\pi} \sin(\theta) D(f, \theta)d\theta = \frac{Q_{yy}(f)}{k(f)C_{zz}(f)} \\
a_2(f) &= \int_{-\pi}^{\pi} \cos(2\theta) D(f, \theta)d\theta = \frac{C_{zz}(f) - C_{yy}(f)}{k^2(f)C_{zz}(f)} \\
b_2(f) &= \int_{-\pi}^{\pi} \sin(2\theta) D(f, \theta)d\theta = \frac{2C_{yy}(f)}{k^2(f)C_{zz}(f)}
\end{align*}
\]

where \( C \) represented the auto- and co-spectra and \( Q \) the quadspectra, with \( x \), \( y \) and \( z \) denoting the pitch, roll and heave respectively. Here \( k(f) \) is the wavenumber, which can be obtained from the known dispersion relation or estimated from the autospectra as:

\[ k(f) = \left( \frac{C_{xx}(f) + C_{yy}(f)}{C_{zz}(f)} \right)^{1/2}. \]  

Equation (9) is sometimes used as a quality control flag [Tucker & Pitt, 2001] when compared with the open water dispersion relation \( k_0 = \omega^2/g \) where \( \omega \) is the angular frequency \((2\pi f)\) and \( g \) is the acceleration due to gravity. When sending data via Iridium we will use this ratio,

\[ R(f) = \left( \frac{C_{xx}(f) + C_{yy}(f)}{C_{zz}(f)} \right)^{1/2} \frac{g}{\omega^2}. \]  

The spectra is calculated using the Welch method [Earle, 1996] and 12000 samples (20 minutes at 10 Hz sampling), using a hanning window on 1024 sample segments and a 50% overlap. The Fourier coefficients are then downsampled into 25 logarithmically equally spaced bins between 0.05 Hz and 0.25 Hz. This type of sampling gives greater resolution at low frequencies (a minimum resolution of 0.0035 Hz near 0.05 Hz) and less at higher frequencies (a maximum resolution of 0.0162 Hz near 0.25 Hz). Therefore this downsampling strategy allows for greater resolution at low frequencies where wave motion in ice is expected to be prevalent.

Each Iridium message containing the spectral parameters consists of 340 bytes. This includes estimates of the significant wave height and zero-upcrossing, calculated both from the time series as well as from the spectral moments, as well as the reduced six spectra: \( S(f), a_1(f), b_1(f), a_2(f), b_2(f) \) and \( R(f) \). In order to reduce the number of bytes sent via Iridium the maximum absolute value (\( \max_i \)) for each array is sent as a 32-bit float, and the array is sent as a signed 16-bit integer between \(-\max_i\) and \( \max_i \).

The significant wave height and zero-upcrossing periods are calculated from both the full time series and the full spectrum. Both temporal and spectral methods are used for redundancy checks to compare with the reduced spectrum also sent via Iridium. The significant wave height can be calculated from the time series as \( H_{S1} = 4\ \text{std}(\eta) \) where \( \eta \) is the elevation time series. The significant wave height can also be calculated from the spectral moment as \( H_{S0} = 4\sqrt{m_0} \) where the \( n_{th} \) spectral moment is defined as

\[ m_n = \int_{-\pi}^{\pi} f^n S(f)df. \]  

The zero-upcrossing period can be calculated from the time series by calculating the mean time between successive times where \( \eta \) goes from positive to negative. The zero-upcrossing period can also be calculated using spectral moments, i.e. \( T_{z0} = \sqrt{m_2/m_0} \). A summary of all the variables sent via Iridium, and the precision of each, can be found in Table [1].
We find experimentally that while some information about spectral noise levels are available in the datasheet of the IMU, this is often difficult to apply to the transmitted spectra on the receiver side. Applying denoising on the receiver side allows to switch it on and off, to perform quality checks if necessary. Namely, the IMU has a stable noise characteristic which translates into a reproducible background noise on the spectra as illustrated in Fig. [9]. In all the following, denoising will only be discussed and applied to the the 1-D PSD (i.e., $S(f)$), but this approach could be generalized to the other Fourier coefficients that are being transmitted.

While some information about spectral noise levels are available in the datasheet of the IMU, this is often difficult to translate into a real-world estimate of the noise background due to the internal Kalman filtering, and processing applied on the signal. Therefore, the noise level as a function of frequency $n(f)$ is obtained by fitting a theoretical shape of the form $n(f) = (9.81 \times 10^{-3}C)^2(2\pi f)^{-4}$ to a record obtained on still ground, where $C$ has unit $1/\sqrt{\text{Hz}}$ and characterizes the noise level. This specific noise shape is chosen as it describes the effect of a uniform spectral noise density on the acceleration measurements on the spectra obtained, taking into account the double integration to obtain vertical acceleration. As visible in Fig. [9] this theoretical noise shape is well verified, and the effective noise level is small (in practice, waves of around 1.5 cm at a frequency of 0.15 Hz can be reliably distinguished from the background noise).

We find experimentally that $C = 0.24/\sqrt{\text{Hz}}$ describes the obtained noise satisfactorily, which compares reasonably well with the product specification of the VN100 (which states that the spectral noise density should be 0.14 mg/$\sqrt{\text{Hz}}$ [Co., 2018]), taking into account that the datasheet value may be an optimistic estimate obtained in the laboratory.

In practice, the effect of noise can be neglected for waves larger than around 15 cm. However, in the case when small waves (i.e. typically under 5 cm) are observed as was the case during the deployment in Tempelfjorden (see next section), correcting for this background noise improves the quality of the measurements especially for the lowest frequency where the noise introduced by the double integration of the vertical acceleration is largest. More specifically, we consider that the wave signal $s(t)$ and the IMU noise $n(t)$ are uncorrelated, and we want to compute the power spectral density of the combined output $w(t) = s(t) + n(t)$. Remembering that the power spectral density is the Fourier transform of the auto-correlation function $\Gamma$, we mean to calculate:

$$\Gamma_{w,w}(\tau) = \mathbb{E}[(s(t) + n(t))(s(t + \tau) + n(t + \tau))]. \tag{12}$$

Applying the distributivity of the expected value operator and using the condition that the signals $s$ and $n$ are uncorrelated, the cross-terms disappear leading to $\Gamma_{w,w}(\tau) = \Gamma_{s,s}(\tau) + \Gamma_{n,n}(\tau)$, therefore $PSD(w) = PSD(s) + PSD(n)$. This means that the stable sensor noise level can be subtracted from the power spectral density of the transmitted spectra to reduce noise. In the following, this processing will be applied to the wave elevation spectra.
Figure 3: Illustration of the stable noise level of the IMU after processing with the Welch algorithm. The IMUs 1 and 2 are two different VN100 IMUs that were used for tests on still ground. The noise level is consistent across both IMUs, which can be used to denoise afterhand the transmitted spectra. The noise theory is obtained by fitting a theoretical noise shape to the data on the high frequency part of the spectra, where the effect of noise is most important due to the double integration performed to compute the wave elevation.

3 Deployment on the ice

3.1 Deployment on landfast ice in Tempelfjorden, Svalbard

In this section, we present a validation of the algorithms and methodology used for the on-board processing and data compression by comparing results obtained from the raw data recorded by a waves in ice logger Rabault et al. (2017), with the results obtained from a waves in ice instrument, which were transmitted over Iridium. The methodology used for analyzing the raw data from the logger is similar to what has been presented in previous articles Rabault et al. (2017); Sutherland & Rabault (2016).

The data were obtained during a deployment in landfast ice in Tempelfjord, Svalbard performed in March 2018. The ice conditions were similar to what was encountered in an earlier deployment in 2015 Sutherland & Rabault (2016), see Fig 4. A waves in ice logger and a waves in ice instrument were deployed side-by-side on the frozen fjord, around 500 meters from the ice edge. Both performed measurements from March 21st to March 27th. A wave event was detected between the evening on March 22nd and early afternoon on March 23rd. As the deployment took place on landfast ice in the inner part of a fjord, the waves were small (the peak significant wave height was about 2.5 cm), but nonetheless could be reliably measured by our instruments.

Figure 4: Illustration of the deployment of a waves in ice instrument on landfast ice in Tempelfjorden, Svalbard (left), and waves in ice logger deployed on its side (right). The shovel gives an idea of the size of the instrument boxes.

The spectrograms obtained by both instruments are presented in Fig. 5. Obviously, the resolution in time is much higher in the case of the logger (which records data continuously) than with the iridium-enabled instrument which
transmits data only around each 3 hours (as this was a test run over a shorter amount of time, the wakeup frequency was increased compared to the standard value of 5 hours). The resolution in frequency is also reduced, due to the integration and down-sampling of the spectra, which has for effect to slightly smear out the individual spectra. However, both the distribution and typical value of the power spectral density are satisfactorily reproduced by the under-sampled spectrogram. This validates the methodology and implementation of the data compression and transmission.

Figure 5: Comparison between the spectrogram produced from analyzing the data logged continuously by a waves in ice logger (left), and the spectra produced in-situ and transmitted using Iridium by a waves in ice instrument (right). The data were generated during a deployment on landfast ice in Tempelfjorden, Svalbard in March 2018. While the frequency and time resolutions are, obviously, lesser in the second case, both the energy level and frequency distribution of the wave signal are very similar in both cases.

3.2 Deployment in the Marginal Ice Zone in the Northeast Barents sea

In this section, we present early results obtained in the course of the Nansen legacy cruise which took place in September 2018. The aim of this section is not to present a detailed analysis of the results, which will be performed in future work, but to check and validate the good functioning of the waves in ice instruments. A total of 4 instruments (named 1 to 4 in the following) were deployed from the research vessel RV Kronprins Haakon on September 19th. The deployment took place in the Marginal Ice Zone (MIZ), Northwest of Svalbard. During the deployment, the vessel was steaming inside the MIZ and the pack ice. As a consequence, the 4 instruments were deployed as an array with the first sensor being located on an ice floe in the outer MIZ (ice concentration 1/10th), the second on an ice floe further in the MIZ (ice concentration 3/10th), the third at the beginning of the closed pack ice (ice concentration 9/10th), and the fourth inside the closed pack ice (ice concentration 10/10th), as illustrated in Fig. 6. During deployment, the instruments were equipped with a floating device and buried half-way inside the snow, with only the top of the case (hosting the solar panel and the antennas) directly pointing to the sky.

The evolution in time of the battery level of the second instrument, which was the one which transmitted for the longest time, is presented in Fig. 7. As previously stated the battery technology used inside the instruments is LiFePO4, and according to the datasheet the voltage of a fully charged battery is around 3.3V, and a fully discharged battery has a voltage of around 2.7V. As visible in Fig. 7, the battery barely got drained over the period of 12 days for which it was deployed. This is due to both the high power efficiency of the instrument, and the presence of the solar panel.

Figure 6: Deployment of the instruments 1 to 4 (left to right) in the Marginal Ice Zone, Northeast Barents sea. The concentration of ice increases from instrument 1 to 4, as visible in the pictures (1/10th, 3/10th, 9/10th, 10/10th). The instruments, equipped with buoys, are visible on the ice. Photos: credit Malte Müller and Lars R. Hole, Norwegian Meteorological Institute.
Figure 7: Time evolution of the battery level of instrument 2. The background color indicates time of the day: yellow is for 06:00 to 18:00, gray is for 18:00 to 06:00 on the next day. The full and empty battery levels correspond to 3.3V and 2.7V, respectively. The battery level remains very high thanks to efficient power management and the presence of a solar panel.

Figure 8: The drift of the instruments, as obtained from the GPS strings transmitted through Iridium. The symbols indicate the position of each instrument for the first transmission received on the corresponding day. A general drift pattern is clearly visible.

that provides energy at least for the first days of deployment, until the start of the polar night. It should be noted that temperature can also influence the battery voltage, which explains for apparent increases in battery level during some night periods. As visible in Fig. 7, the battery level was not the cause for the end of transmission. This confirms the quality of the power management solution and overall design, and is further discussed later in this section.

The GPS information transmitted by all 4 instruments is presented in Fig. 8. As visible in Fig. 8, the trajectories of the instruments are well resolved until transmissions are lost. While some dropouts are present, a pattern of drift first to the West, then South and South East is clearly visible. During this period of 12 days, the instrument 2 (which survived the longest) drifted by around 340 km. This corresponds to the effect of the transpolar current, together with the forcing created by a storm present in the region September 24th and 25th. The data will be used for validating satellite tracking of ice drift and models, and these results also indicate that the instruments are valuable to use as drifters.

The core mission of the instruments is to provide in-situ measurements of waves in ice. The spectrograms presenting the wave information transmitted by the instruments are visible in Fig. 9. Each spectrum is obtained from a Welch analysis of the data recorded by the instrument which is binned and compressed before being sent through Iridium, as described in the previous section. As visible in Fig. 9, the patterns for the waves in ice activity are coherent among sensors. In particular, there is an episode of high wave intensity between September 24th and September 25th, which corresponds
to a storm in the region. Clear damping is visible as the waves propagate deeper into the ice, and the damping is higher for high frequency waves in agreement to what is expected from theoretical considerations. These data further validate the approach and algorithms used for the measurements of waves in ice.

Another cross-checking of the good quality of the on-board processing and data compression can be performed by comparing the scalar results transmitted, such as the significant wave height SWH and wave period Hs, with values calculated from the reduced spectra sent through Iridium. This is illustrated for both quantities measuring wave height and period by the results presented in Fig. 10. In this figure, the quantities obtained from the scalar values transmitted through Iridium are presented alongside those calculated from the reduced spectra (indicated by the 'proc' suffix), following the methodology presented in the previous section. As visible on Fig. 10, we observe very good agreement between quantities transmitted and calculated from the reduced spectra, which is an additional validation of both the methodology used and an indication that the resolution of the reduced spectra is enough to capture the dynamics of interest. This figure also further validates the ability of the instrument to clearly detect changes in wave characteristics arising as a consequence of their propagation through the MIZ. Namely, both the wave damping and the preferential propagation of low frequency waves are clearly visible from comparing the results obtained by the different sensors.

Regarding end of transmission, the battery level is clearly not to blame. Most likely, environmental conditions were at the origin of both transmission dropouts and finally loss of contact. The main possible causes for loss of contact are snowfalls covering the antenna and shielding radio transmissions, polar bears damaging the instruments (3 polar bears were encountered during the deployment of the last two sensors), and ice breakup. This last factor is especially likely for the sensor most outside of the MIZ, which lost contact when the storm was at its strongest. While little can be done about polar bears and ice breakup, we will consider mounting the antennas on a pole on the side of the main instrument in future iterations, in the hope that this may help getting contact with the satellite. However, this constitutes a tradeoff. Indeed, we believe that the reason why the instruments could survive for such a long duration despite polar bear activity lies in the low profile of the instruments, and probably a design featuring a case of larger vertical dimension or a pole may be more attractive and get damaged withing short time.

4 Conclusion and future work

Instruments performing remote measurements of waves in ice were successfully designed in-house at the University of Oslo, tested during a controlled experiment on landfast ice in Svalbard, and deployed in the MIZ in the Arctic, North of Svalbard during the Nansen legacy cruise in collaboration with the Norwegian Meteorological Institute. High quality data about ice drift and wave propagation in sea ice were obtained, which confirms the engineering choices made in designing the instrument. These data will be used for further development and calibration of waves in ice models.
Figure 10: Comparison between the scalar quantities transmitted by Iridium, and the equivalent integral quantities calculated from the reduced spectra following the methodology presented in the previous section (quantities with suffix 'proc'). The quality of the agreement confirms both the methodology and under sampled spectra resolution chosen. In addition, the evolution of the wave statistics as they travel through the MIZ are clearly visible. Namely, waves get attenuated (visible in the significant wave height), and the attenuation is larger for higher frequency waves (visible from the shift in the peak frequency of the waves). The quantities obtained from the reduced spectra are only presented for the first sensor to not overload the figure, but similar agreement is found for all instruments.

As both the hardware and software of the instrument are made available as an open source design (see Appendix A), this opens new possibilities for remote sensing in the Arctic. Indeed flexible, more affordable instruments may allow to perform far more and higher quality measurements in regions like the Arctic. Using open source code and PCBs allows to cut the price of the electronics to the point where the sensor performing the measurement represents over 50% of the total cost. In addition, flexibility means that scientists with specific needs will be able to quickly design the instruments they need by adapting the baseline design to their own needs, rather than going through long and costly contracting with private companies. This means that production of a small series of instruments adapted to the needs of a specific measurements campaign can take place within a few weeks, therefore greatly reducing risks and costs.

We will continue to work on this design to provide simplified assembly processes for the end user and to further reduce costs and enhance functionality in the years to come, adopting the same kind of incremental refinements approach that was used for evolving from the first waves in ice loggers presented in 2016 to the present remote sensing instruments. We hope that sharing our design may participate in creating an ecosystem for open source remote sensing instruments and benefit the community at large. Developing cost-effective instruments for remote sensing in the Arctic is a promising avenue for collecting the data that several communities need, and may help towards better studies of these challenging, remote environments.

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Appendix A: open source code and designs

All the designs and files used for the building of the instruments, including the PCB files ready for production, the code used on all processors (low power unit, logger, Raspberry Pi), and general instructions for assembling the instruments, are made available on the Github of the author under a MIT license that allows full re-use and further development (link: 11
[to be released upon publication]). All software and designs are based entirely on open source tools, so that the designs can be easily modified and built upon. The code used for generating the figures presented in this article, including the parsers and algorithms used for unpacking and analyzing the Iridium messages, are also released together with the design of the logger.

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