Review of Remote-Sensing Autonomous Platforms in The Polar Region

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Date: 14 September 2020

The following document provides a literature review of the current state of polar technology. A review of In-Situ Measurement devices is provided as well as hardware choices, processing capabilities, remote communication strategy and data strategy.

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2 INTRODUCTION

The new SHARC Buoy system aims to provide an IoT solution to remote sensing in Antarctica. The goal of the project is to develop in house, expandable, affordable technology that can be expended into a large-scale network for true coverage of the Southern Ocean. While the project is novel, the state of autonomous sensing has been developing since 2010 with more systems being deployed around the year. While these systems are different, they provide insight into the techniques used in Polar engineering as well as insight into existing infrastructure and how it is being utilized. Also, each buoy has a unique purpose and is defined in terms of its objectives, sensors, measurands and processes. This document aims to explore the current state of the art by turning to both institutional and private sector solutions currently being employed and how they overcome the challenges created by the Harsh Southern Ocean Environment

3 METHODOLOGY

For this report data on 8 Autonomous Platforms was collected and sorted into 3 main categories

1. Power Supply and Management
2. System Hardware Overview
3. Remote Communication
4. Wave Data Strategy

The platform is evaluated against the following criteria. Where possible, certain specifications have been converted into standardized formats. The original data can be found in the publications list found at the end of this document. To ensure a fair evaluation, data were collected from the latest technical publication of each platform where possible. These publications may not contain all relevant data. In this case, the data has been left out or interpolated from another source.

4 STRUCTURE OF THIS REPORT

The report is divided into sections based on the categories used to evaluate the system. Each section contains a brief discussion highlighting any significant feature/ commonality amongst the systems. The comparison is provided in a Table form with references available at the end of the report. The order of these sections is as follows:

1. Remote Communication – This chapter explores the infrastructure used to communicate data. Most systems require wireless communication strategies due to their free-floating nature. The discussion will include: Network used, Hardware/Modem, Packet Size and structure, network bandwidth and cost

2. Power Supply Management – This chapter will briefly explore the power source used by each system, Auxiliary power sources and power management strategies

3. System Hardware Overview – This Chapter will explore the overall system. Each buoy will be quantified in terms of sensors, sensor types and measurands, Then, the processors will be listed with their purpose. Finally, an overall data cost (where given) will be provided

4. Wave Data Strategy – This Chapter will identify systems used for wave data measurements in the Polar Region. In this chapter, the measurands are given along with the Sensors used for detection of these variables. A sampling strategy is provided as well as the processing strategy

5 Device List

The Table Below shows a list of devices selected for comparison. The list is made up of 8 platforms each designed by a Company/ Institution. The key collaborators as well as the name of the institution are provided. Where a Buoy name is not given, the device will be named after the key Contributor to the project. These systems have been selected due to their prevalence in global polar/ oceanographic science as well as notability in publications. The devices are as follows:

Device Name	Developed By	Institution
Waves in Ice (WII) buoy	Jean Rabault	University of Oslo
Waves in Ice Observ System (WIIOS)	Alison Kohout	National Institute of Water and Atmospheric Research
DOBLE Buoy	Martin Doble	Polar Scientific Ltd, Appin, UK
Surface Kinematic Buoy (SKIB)	Pedro Veras Guimarães1	Université de Bretagne Occidentale
SWIFT Buoy	Jim Thomspon	University of Washington
Seasonal Ice Mass Balance Buoy (SIMB)	Donald K. Perovich	Dartmouth College
UptempO	MetOcean	MetOcean
Trident	Trident Sensors	Trident Sensors

6 Remote Communication

All systems that have been deployed in both the Arctic and Antarctic Marginal Ice Zones use Iridium for remote Telemetry Data. Other systems such as Zigbee are alluded to however these systems are only used when the device is close by. Notably, The SIMB buoy details consideration for Remote communication using the ARGOS satellite network however, the unreliability of the network resulted in irregular timestamped data. Iridium is a Satellite Network with global coverage and a variety of modems for various IoT uses. The company offers 4 main data services which put constraints on Data transmission rates, bandwidth and modem selection. This is shown in the table below:

Service Name	Purpose	Bandwidth	Modems	Payment Plan
Short Burst Data (SBD)	Sending Short Messages in bursts	• 340 bytes (upload)/270 bytes (download) • 1960 bytes (upload)/1890 bytes (download)	9602/9603 Iridium Edge 9522A 9523B	Billing per quantity of data
Router-based Unrestricted Digital Interworking Connectivity Solution (RUDICS)	Transferring large Real-Time Data from a large array of devices to a host	• 6 – 10 Kbytes/min	9522A/B 9523	Billing per duration of transmission
Circuit Switch Data (CSD)	Transmitting large volumes of Data over Dial-Up Network using a SIM Card	• 6 – 10 Kbytes/min	9522A/B 9523	Billing per duration of transmission
Pilot	For mission-critical communication requirements	• 134 KBPS	Iridium Pilot Kit	Billing per duration of transmission

Table 1: List of data services provided by Iridium, their function, bandwidth as well as supporting devices

These options allow for various data transmission strategies amongst the platforms. Also, the various processing strategies from each platform have taken into account the aforementioned data serviced and have processed their data packets according to the capabilities of their modem and data service providers. Short Burst Messages may be ideal for this project however, Complex processing strategies are required. Modems with large buffers may increase the overall project cost significantly and consume more power. The modem, Network and data management strategy of each system is shown in the table below.

Device Name	**Communication Technology**	**Modem**	**Bandwidth (bytes)**
WII Buoy	Iridium	*Information unavailable	340
WIIOS	Iridium	9602	340
Doble	Iridium	Motorola 9522B	6 - 10 Kbytes/min
SKIB	Iridium/Zigbee	9602 (IR), Xbee Pro	340 bytes
SWIFT	Iridium /Ethernet	Geoforce SmartOne (Tracking)/ SBD Modem (Telemetry), Digi XPress Ethernet Bridge	1960
SIMB Buoy	Argos/ Iridium	9603	340
Uptempo	Iridium	9602	340
Trident	Iridium	9603	340

Table 2: List of devices and the network/s used for remote communication with the user as well as the hardware modem and maximum bandwidth associated

The Transmission information including packet sizes and data rates are shown in the table below

Device Name	Transmission Strategy	Packet Size (bytes)/rate
WII Buoy	Short Burst Data Message	340
WIIOS	Short Burst Data Message	(N/A)
Doble	RUDICS transmission every minute	54Kb/hour
SKIB	Short Burst Data Message	N/A
SWIFT	Short Burst Data Message	4 - 1228
SIMB Buoy	Short Burst Data Message	275
Uptempo	Short Burst Data Message	*User Configured
Trident	Short Burst Data Message	16

Table 3: Table Showing the Transmission strategy of each system as well as the date sizes transmitted during regular intervals. Note: Some systems such as the SWIFT buoy have variable-sized packets depending on the sensor being sampled

Unanimously, all devices use the Iridium Satellite Network for remote communication with the most common system being the Iridium 9602/3 SBD modem. This choice is justified for its small form factor, low power and easy interfacing however it suffers greatly from limited bandwidth having a maximum transmission size of 340 bytes. Systems that use these modems for transmission of wave data rely on complex data processing algorithms and therefore do not transmit the raw Time Series. The only notable exception to this is the Wave Buoy Developed by M. Doble et. al. which continuously transmitted AHRS and IMU Time Series data once every minute. For this purpose, they used the 9522B modem which allowed for continuous transmission using the RUDICS data service. This modem, along with the SBD modem used for the SWIFT Buoy also has a much larger SBD data buffer (1.92KB) However this comes at the cost of much higher power consumption and significant price increase.

7 System Overview

This section provides an overview of each system. Power systems and sources are given as well as component choices. Also, the data storage strategies, measurands and deployment locations of the system are provided.

7.1 Power Systems

The power system for each buoy is shown in the table below

Device Name	Power Source	Voltage
WII Buoy	LiFePo4 Solar Recharging +Step up converter	5V
WIIOS	Panasonic LR20 Alkaline 1.5 V in Series	12V

Doble Buoy	Alkaline Battery Array D-cells, Lead Acid Battery E-Cell Array + Solar Panel Chagrin	12V
SKIB	LiSOCL2 Batteries	3.6V (from batteries)
SWIFT	Lithium/ Alkaline Battery Array	14V
SIMB	Custom 60 Cell Alkaline D-cell Battery Pack, LMZ12003 Step Down Converter for 3.3V & 5V, MIC29201-12W LDO for 12V power	18V
UpTempo	LiSOCL2 Batteries	12V
Trident	4 x Alkaline AA Batteries	3.3V

Table 4: Comparison of Power systems for each buoy and the nominal supply voltage of each system

As shown in the table above, all systems use batteries as a source of power. Most systems opt for off-the-shelf Alkaline or Lithium-based batteries except for the Buoy by M. Doble et. al. which uses a Lead Acid battery. Systems deployed in the Arctic Marginal Ice Zone have been designed with a recharging system such as a solar Panel in the case of WII Buoy and Doble Buoy, however, most long-range deployment buoys have opted for non-rechargeable systems composed of Lithium Thionyl Chloride (LISOCL2) or Alkaline batteries that have allowed for survivability up to 6 years. In the case of the high-power buoys (SIMB, WIIOS, DOBLE, UPTEMPO) a battery of 3.3-3.7V cells is connected to provide a nominal voltage in series with a regulator to provide a stable output. The strategy for each system is to pack as many batteries in as possible to satisfy the long-term energy requirements. No power optimization calculations or methodologies are provided

7.2 Electronic Selection

Component selection for each system is based on the original mission for each buoy. These objectives are shown in the table below along with significant deployment locations:

Device Name	Measurands	Deployment Location
WII Buoy	Ice Drift, Waves in Ice, Temperature, Pressure	Marginal Ice Zone, Northeast Barents Sea, Antarctica
WIIOS	Wave Energy Attenuation, Significant Wave Height, Data Quality	East Antarctic Packed Sea Ice Zone
Doble Buoy	Ice Drift, Wave induced ice breaking, Temperature, Pressure	Beaufort Sea, Arctic

SKIB	Ice Drift, Surface Waves	North Atlantic Ocean, France
SWIFT	Surface Images, Waves, Turbulence Profiles, Current Profiles, Conductivity, wind sensor	Antarctic Marginal Ice Zone, Arctic Marginal Ice Zone
SIMB	Surface and bottom ice position and snow depth, air pressure and temperature, vertical temperature profile, and GPS location data	Hanover New Hampshire (prototype), Beaufort Sea MIZ (Deployment)
UpTempo	Sea Ice Drift, Environmental Monitoring	Antarctic Marginal Ice Zone, Arctic Marginal Ice Zone
Trident	Sea Ice Drift, Battery Voltage, Ambient Temperature	Antarctic Marginal Ice Zone, Arctic Marginal Ice Zone

Table 5: Each Device is designed to collect data on specific variables. This table outlines the measurands of each system as well as the region these systems have been designed for/deployed in.

The table above shows that most wave buoys have been built for and deployed in the Arctic Marginal Ice Zone i.e. The Beaufort Sea. Technology developed for the Antarctic Ocean typically revolves around Ice drift and Environmental Sensing. WII Buoy and WIIOS buoy have been developed as open-source, low-cost solutions for Wave in Ice measurements, however, lack the robustness of Arctic-focused systems. SWIFT Buoy and SKIB buoy provide advanced solutions to wave surface monitoring however these systems are not intended for long term use

Systems designed specifically for drift will have scaled-down processors, cheaper IMUs with more accurate, more expensive Temperature Sensors and GPSs where systems designed specifically for wave measurements have more powerful, sometimes multiple, processors and advanced IMUs with cheaper tracking and Environmental sensing technology. The components for each system are shown in the table below.

Device Name	Sensors	Storage strategy	Onboard Processing
WII Buoy	GPS, Temp, Pressure, IMU	SD Card	32-bit Extended Kalman Filter, Low Power Unit, Arduino (Data Logging), Raspberry Pi (Data Compression + Measurement)
WIIOS	GPS (MTK3339), Accelerometer, IMU, DS18B20 Temp Sensor	32 GB SD Card	Dual-Core Edison Processor (Wave processing), Atmega328 (Power Controller)
Doble Buoy	AHRS sensor, GPS, Barometric Pressure MXP-5100-APAHRS, CPU Load Cycle sensor, Battery Voltage, Internal Temperature, Humidity	None	ACME Systems Fox G20 for Power and control
SKIB	GPS (MTK3339), Accelerometer LIS3DK	SD Card	EFM32-M3: Spectral Processing + Controller
SWIFT	uCam, Inertial Navigation System (SBG Elipse N), Doppler Profiler (Nortek Signature 1000), Conductivity & Temp Sensor (Aanderaa 4319), Airmar WX200	SD Card	Sutron Expert for Data processing
SIMB	Acoustic Rage Finder for Snow (Maxbrook MB7374)and Underwater (Airmax Echo Ranger), Air Temp Sensor (DS18B20), Temperature Chain Sensor (Bruncin DTC), GPS (MTK3339), Barometer (BME280)	SD Card	ATSAMD21G18 for Data Processing and system control
UpTempo	GPS (Navman Jupiter 32), Barometer (Vaisala PTB100) Air Temperature (YSI 44032)	N/A	MetOcean's Global Platform Transceiver Controller (GPTII) TM
Trident	GPS, Temperature Sensor, Battery Monitor (ADC)	128KB Flash Chips	Microprocessor + Intelligent Smart Unit

Table 6: Overview of subsystems and component used for each buoy including sensor type and hardware, processor and data management Strategy

From the table above, we see the methodology for each buoy come into action. The Doble buoy for instance builds its system around the dominant sensor i.e. the AHRS IMU with a single processor controlling all the peripherals as well as allowing for data processing. Drift Loggers such as Trident, and UpTempO feature sparser sets of electronics with smaller, lower-powered processors for Power control and peripheral control, In contrast, WIOS and WII Buoy compartmentalise subsystems with a cluster of processors handling different aspects from the buoy. This shows a focus on computation rather than sensing as multiple controllers are used to allowing the main processor to implement advanced Digital Signal processing. SWIFT Buoy appears as the outlier as the system is built around a dedicated data logger i.e. The Sutron Xpert with an integrated processor and Satellite communication link abstracting data processing strategies on the buoy side. The SIMB buoy has the most advanced and largest number of sensors of all the buoys. A commonality amongst the buoys is the use of off the shelf components and processors. A predominant feature, the GPS is an Adafruit MTK339 device that is low cost as well as SAMD Chips, Raspberry Pis and Arduino boards whereas, for Trident and MetOCean, more expensive solutions are used. This shows that developers have opted for readymade that components that are auxiliary to the main measurements. This should explain why some components on a system are more advanced than others.

7.3 MOTION DETECTION STRATEGY

As mentioned previously, most systems focus on measuring Sea States and ocean processes. Common measurements of interests are Significant Wave Height and Dominant Wave Frequency. Also, Wave data can be analysed in terms of its power spectral density. the basis for Wave Data analysis from Ocean buoys comes from A method developed by A. J. Kuik et al where the pitch and roll of an ocean buoy are measured. By using an Accelerometer, Gyroscope or any Inertial measurement system to measure these parameters, it is possible to reconstruct the sea state given a set of data provided the data is of a specific length sampled above the Nyquist frequency of dominant ocean swells.

Another method was developed by M.D. Earle in 1996 for Non-Directional Wave Analysis. In this method, a digital time series representation of the Vertical Acceleration along with 2 orthogonal Gyroscope measurements and Magnetometer readings relative to the earth's magnetic field is obtained. The data is analysed in terms of Spectra and co-spectra. Data is segmented into a set of N-bins and averaged to produce a statistical result. This approach brings into account the possibility of spectral leakage however, this can be greatly minimised by sampling above the Nyquist frequency of the upper Wave frequency band (generally taken to be 0.5Hz) for a minimum of 1000 seconds (about 16 – 17 minutes)

It is for this reason that almost all Wave measurement buoys contain some Inertial Measurement System (IMS) coupled with a data processing strategy. The first part involves the component selection. Each system has a unique methodology that begins with its choice of IMS as shown in the table below:

Device Name	# of IMUs	Measurand	Device
WII Buoy	1	Vertical Acceleration, Pitch, Roll	VN100
WIIOS	2	3 Axes acceleration. 3 Axes Gyro, 3 Axes Magnetometer	Kistler 8330B3 ServoK-Beam, TDK Ivensense IMU MPU-9250
DOBLE	2	Heave, Roll, Tilt, 3 axes Acceleration	SBG IG-500
SKIB	1	3 axes Acceleration	STM32 LIS3DH
SWIFT	1	Heave, GPS	SBG Elipse (Inertial Measurement System)
SIMB	1	Device Tilt and Orientation	Bosch BNO055

Table 7: Comparison of Inertial Measurement Systems (IMS) employed by various devices. The list includes systems that have explicitly included an IMS. Systems such as Trident Buoy and MetOcean have been omitted

As mentioned previously, systems such as WIIOS and WII Buoy have built their purpose around wave measurements and therefore have specified High Powered, High Accuracy IMUs for wave measurements. However, WIIOS buoy separates itself from WII Buoy by having a cheaper complimentary 9 d0f IMU to complement the measurements. SWIFT Buoy and the DOBLE buoy use an integrated system known as an Inertial Navigation System. This device contains a GPS and an Onboard processor for RTK fusion and Kalman filtering whereas other devices use an external processor for filtering. The SIMB Buoy is the only buoy on the list that has an IMU for non-wave related measurements. It uses a cheaper Bosch BNO055 which is used solely for measuring the orientation of the device.

Ocean State Sampling must be performed with careful consideration of the sampling frequency and sample window. For remote systems, it is important to optimize performance and data acquisition with Power Consumption and Storage constraints. It is also important to include only the important parameters in the data set depending on the measurand of interest. For this reason, sea state measurements systems have different sample parameters that are shown in the table below

Device Name	Number of Axes	Sample Frequency (Hz)	Sample Period (minutes)
WII Buoy	6	10	25
WIIOS	9	64	11
DOBLE	6	1	Continuous
SKIB	3	25	10
SWIFT	2	5	9
SIMB	9	N/A	N/A

Table 8: Comparison of Sampling strategies utilised by each system showing the number of axes sampled during an active window, the sampling frequency as well as the sample period.

From the table, all systems chose a data sample frequency of at least 1Hz (2 x the Wave frequency upper band). However, most systems chose to sample for periods 10 minutes or less. A notable point from the table is that all the systems have a finite sample period except for the DOBLE. As mentioned previously, the data strategy for this system is to transmit the Raw sample points over the Iridium network once every minute. The system is continuously sampling until it loses contact or runs out of power. Another exception is the SIMB buoy which only samples to determine the orientation of the frame. Insufficient information is provided in the literature regarding the sampling strategy. Of the Ocean Wave Measurement devices, the WII Buoy samples for the longest period followed by The Wiios Buoy. It should be noted that the WIIOS and WII Buoy are both designed specifically for waves in ice and should share similar sampling strategies. However, the WIIOS buoy has the highest sampling rate before processing whereas the WII Buoy has the longest sample window. SWIFT Buoy measures data in bursts of 9 mins every 12 mins for 5 hours. Each burst is recorded as a bin and coupled with other sensors. Finally, SKIB measures data at a frequency of 25 Hz for 10 minutes.

Finally, The Data processing strategy for each system is discussed below:

7.3.1 WII Buoy

Raw Time series is passed through an Extended Kalman Filter running at 800Hz than a low pass filter. Wave Spectral data is calculated using the method by Earle et. al. (1996) where Co-Spectra is calculated using the Method by Kuik et al. (1988). Significant Wave Height is calculated through double integration. A Fast Fourier transform is applied to the data series to achieve this.

7.3.2 WIIOS Buoy

Data is filtered using a Butterworth filter with a cut-off frequency of 2Hz. Significant wave height is calculated by double integration using a Fast Fourier Transform. Spectra is calculated using the method by Earle et. al. (1996)

7.3.3 Doble Buoy

The double buoy is unique as it does not directly calculate wave parameters. However, the raw time series is filtered using an Extended Kalman Filter running at 10Hz

7.3.4 SKIB

Data collected from a sample window is processed using a classical RC filter to attenuate frequencies below 0.04Hz. M.D. Earle et. al. (1996) Spectra and Co-Spectra Calculation is then applied.

7.3.5 SWIFT

The Swift buoy is the only device that uses multiple sensors for sea state calculation. First, data is collected more frequently in short intervals (9 minute sample periods every 12 minutes) which include Doppler Profiles, Camera images and IMU data. The INS System outputs a Real-time kinematic (RTK) fusion data series where IMU data is passed through a Coning & Sculling Extended Kalman Filter running at 1KHz while doppler profiler is sampled at 8Hz. Turbulence profile is calculated through time-averaged data fitting of the doppler profiler. The current state is calculated using the Stokes drift Equation over time-averaged velocity series. Finally, Wave information is calculated from an image of the sea state.

7.3.6 SIMB buoy

No Clear Data processing strategy is available in the literature. This may be due to the non-critical nature of the IMU.

8 CONCLUSION

In Conclusion, the motivating choices for each system are heavily influenced by the measurement objectives of each System. This motivates the architecture, component choice and power rating for each device as well as the processing complexity. Systems that focus on wave variable measurements tend to have increased processing capabilities with more than one processor present in the system. Specialised systems can easily be identified by their sensor components often opting for state of the art, high accuracy sensors that drive up the cost of the system exponentially. Most Wave measurement systems have opted for Earl et. Al. or Kuik et. al. as the foundation for their Spectrum and Co-Spectrum measurements which require an IMU with vertical acceleration and at least 2 orthogonal vectors for accuracy. Finally, reliance on iridium shows a fundamental lack of infrastructure. We require iridium as a reliable, global network if we wish to deploy SHARC Buoy. This network, however, allows for high bandwidth transmission, but this comes at the cost of more expensive, higher-powered modems which could drive up the cost of system significantly. Using a narrow bandwidth modem is more ideal, however, more advanced processing techniques will be required. For SHARC Buoy to be a low-cost solution to the Polar Climate observation problem, we need to put these factors into consideration to develop our solution to be as robust as possible.

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10 WEBSITES USED

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2. https://www.iridium.com/
3. https://github.com/robynverrinder/trident-sensors