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SHORT ABSTRACT FOR DISSEMINATION PURPOSES

Abstract

This report documents the setup and data collection of a moored Directional Wave Spectra Drifter (DWSD) buoy network deployed offshore of Livorno as part of the AIMS project. The campaign aimed to create an experimental 3 x 3 buoy grid, positioned at 1.5 km intervals, to study wave dynamics in a confined area and evaluate the accuracy of numerical wave models. Each buoy, equipped with GPS and real-time data transmission via satellite, recorded wave and meteo-marine parameters at three-hour intervals over approximately five months. The data, though partially affected by buoy losses, provide a high-resolution view of wave behaviour and serve as a valuable resource for wave energy studies and forecasting models. This report includes detailed descriptions of the dataset and its structure, offering insights into data quality, operational challenges, and guidelines for future campaigns.

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ABBREVIATIONS

Acronym	Description
CSV	Comma Separated Values
DWSD	Directional Wave Spectra Drifter
MEM	Maximum Entropy Method
SLP	Surface Level Pressure
SST	Sea Surface Temperature
SVP	Surface Velocity Program

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EXECUTIVE SUMMARY

This report, title *D1.3 - Report and dataset from moored gridded wave buoys*, presents the research conducted under the AIMS project, which seeks to enhance marine conditions monitoring through the integration of artificial intelligence and satellite data. Funded by the European Union's NextGeneration EU program, the project focuses on the understanding of wave phenomena by combining satellite and in-situ data from wave buoys, specifically addressing current limitations in satellite data management, spatial-temporal discontinuities, and limited measurable parameters.

The report primarily covers the deployment of Directional Wave Spectra Drifter (DWSD) buoys arranged in a grid pattern offshore of Livorno, Italy. These buoys, equipped with GPS technology to capture real-time data on wave height, direction, and energy, are essential for validating satellite observations. The collected data has been processed into CSV format for analysis, enabling the assessment of wave parameters that are vital for climate models and wave energy studies. The GPS-based buoy data, characterized by long-term historical series and configurable to capture spatial and temporal variability, remains the most comprehensive and valuable dataset for the project, as it allows for comparisons with both satellite observations and numerical models.
While this report does not detail other planned in-situ data sources, the project will also acquire data from an Autonomous Surface Vehicle (ASV), which will complement the buoy data. Additionally, a dedicated measurement campaign is planned to capture the variation of satellite parameters (wave height and, prospectively, wave period) along satellite tracks, further enriching the dataset.

Despite numerous technical issues, such as the loss of some buoys during the campaign, the dataset provides valuable insights for the AIMS project, aiding in the refinement of numerical models and maximizing the potential of satellite data in marine monitoring. The report highlights the critical role of artificial intelligence in integrating diverse data sources, enhancing marine forecasting, and strengthening environmental monitoring.

1. Directional wave measurements from moored buoys

Wave buoys are widely regarded as a highly reliable source of offshore and coastal wave data and often serve as a reference standard. They are extensively used in wave forecasting, particularly for validating and calibrating numerical models and satellite altimetry. These buoys provide independent data sets that are frequently employed in a variety of wave-related research. A wave buoy operates by floating on the water surface, tracking its motion in all three dimensions over time, allowing for the computation of wave field statistics from this time series or the resulting spectrum.

The first wave buoy, the Datawell Waverider, launched in 1968, was designed specifically for measuring wave height. Later models, such as the Datawell Wavec introduced in 1983, and more advanced versions of the Waverider, expanded capabilities to include both wave height and direction measurements. The Waverider remains a preferred reference for evaluating waves in deep and intermediate waters (Jensen et al., 2011; Luther et al., 2013). The methodology for calculating directional wave spectra from buoy movements was first described by Longuet-Higgins et al. (1965).

Due to their capacity for accurately measuring sea movements, Directional Wave Spectra Drifter (DWSD) buoys provide essential data for studying ocean dynamics, enabling precise monitoring of local sea conditions.

While moored buoys offer high-quality data, their geographic coverage is limited to the locations where they are deployed, and they may be vulnerable to damage or malfunction due to harsh oceanic conditions. Nevertheless, by capturing detailed directional data on wave dynamics, these instruments are invaluable resources for validating numerical models and enhancing large-scale sea forecasting.

1.1 Directional Wave Spectra Drifter (DWSD)

At the core of the Directional Wave Spectra Drifter (DWSD) is a high-precision GPS engine, coupled with proprietary software algorithms that compute the directional wave spectrum in real time. This system is designed to serve as a comprehensive, turnkey solution for all wave monitoring needs, providing a reliable platform for both coastal and open-ocean applications. The DWSD's hardware builds on the same principles as the SVP (Surface Velocity Program) drifter, widely used to measure ocean currents. Unlike the SVP drifter, which typically includes a drogue to reduce wind influence and

follow subsurface currents, the DWSD is optimized for surface measurements, operating without a drogue. This design allows the DWSD to float freely at the surface for deep-ocean wave tracking or be restrained for near-shore, shallow water studies, offering flexibility based on the monitoring environment.
While the DWSD and SVP drifters share essential components, such as GPS for precise location tracking, they differ in functionality: the SVP focuses on current velocity, whereas the DWSD is equipped with onboard accelerometers and tilt sensors to capture detailed wave dynamics. The DWSD logs and transmits data, which can be stored on a microSD card or relayed in real-time to a shore station via Iridium SBD satellite communication.
Field validation of the DWSD's performance has been conducted through comparison studies, including mooring comparisons with the Datawell DWR3 in San Diego, California, and the RDI ADCP in the Gulf of Naples, Italy. Ongoing assessments, such as those in the equatorial Pacific comparing results with Wave Watch III, further affirm the DWSD's reliability and accuracy for oceanographic research.

1.2 Directional Fourier coefficients and wave parameters

Advanced onboard processing allows the DWSD to compute the first five Directional Fourier coefficients (a0, a1, b1, a2, b2). These coefficients facilitate the calculation of crucial wave parameters such as significant wave height, swell direction, and directional spread, providing comprehensive understanding of wave behavior. This capability makes the DWSD invaluable for studies on wave energy and climate models.

Each coefficient serves a specific role in characterizing the wave field:

- **a0 – Wave Energy**: The coefficient a_0 represents the total wave energy or variance of the wave surface displacement. It is directly related to the significant wave height (SWH) measures the overall wave energy, which can be derived from a_0. The significant wave height H_s is commonly calculated as $Hs = 4\sqrt{a_0{}^2}$.

- ***a₁*, *b₁* - First-Order Directional Moments:**

The coefficients a_1 and b_1 are the first-order directional moments, describing the mean direction of wave propagation and how wave energy is distributed across different directions. The mean wave direction θ can be calculated as:

$$\theta = tan^{-1}\left(\frac{b_1}{a_1}\right)$$

- ***a_2, b_2* - Second-Order Directional Moments (Directional Spread):** The second-order coefficients a_2 and b_2 provide information on the directional spread of the wave field. A narrow directional spread indicates that most wave energy is traveling in a specific direction (e.g., swell waves), while a wider spread suggests a more chaotic or multi-directional wave field, often associated with wind-driven waves.

The directional distribution of a wave energy can be calculated using the Maximum Entropy Method (MEM) of Lygre & Krogstad (JPO V16 1986) with input a_0, a_1, b_1, a_2, b_2.

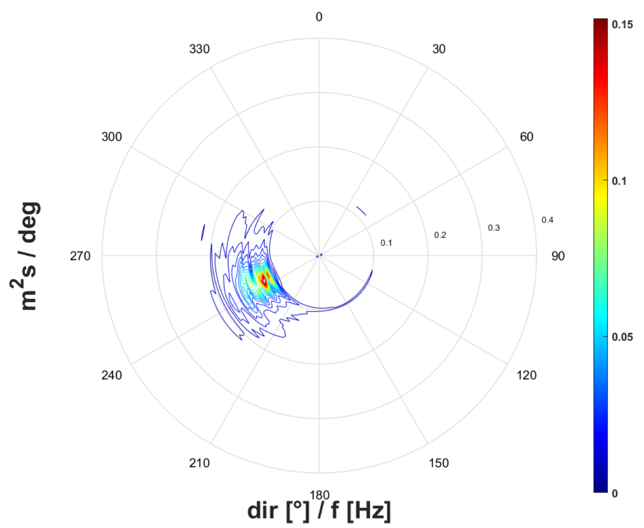

Figure 1 - Example of the wave spectrum averaged over two days (April 13-14, 2023).

2. MOORED DWSD SURVEY IN LIVORNO OFFSHORE

The goal of this measurement campaign was to establish an experimental network of buoys positioned at a specific distance from the shore to study wave dynamics within a confined area. This setup aims to improve understanding of how wave processes are represented in the numerical models in use. The buoy positions correspond to the grid nodes of a numerical model, effectively creating a digital twin of the buoy field. The network consists of nine buoys arranged in a 3 x 3 grid with 1.5 km spacing

(Figure 2). Data were collected at varying temporal resolutions and transmitted in real time to a land-based station via Iridium satellite link. Signaling systems (strobe lights) comply with Marifari's guidelines and were periodically checked throughout the campaign. The deployment area was selected to minimize interference with maritime traffic, avoiding marine protected areas (e.g., AMP Secche della Meloria), navigation-restricted zones (e.g., the vicinity of the OLT regasification terminal), and major shipping routes (e.g., ferries to and from the islands). The bathymetry in this area ranges from 70 to 100 meters. The buoy deployment configuration is illustrated in Figure 3; the campaign began on November 7, 2022, and lasted approximately five months.

Pts	Lat [°]	Lon [°]	Bat. [m]
BB1	43.559	10.007	86.1
BB2	43.559	10.023	71.1
BB3	43.559	10.038	72.2
BB4	43.543	10.007	80.2
BB5	43.543	10.023	65.9
BB6	43.543	10.038	72.8
BB7	43.527	10.007	96.8
BB8	43.527	10.023	83.7
BB9	43.527	10.038	79.1

Figure 2 – Detail of the buoy field.

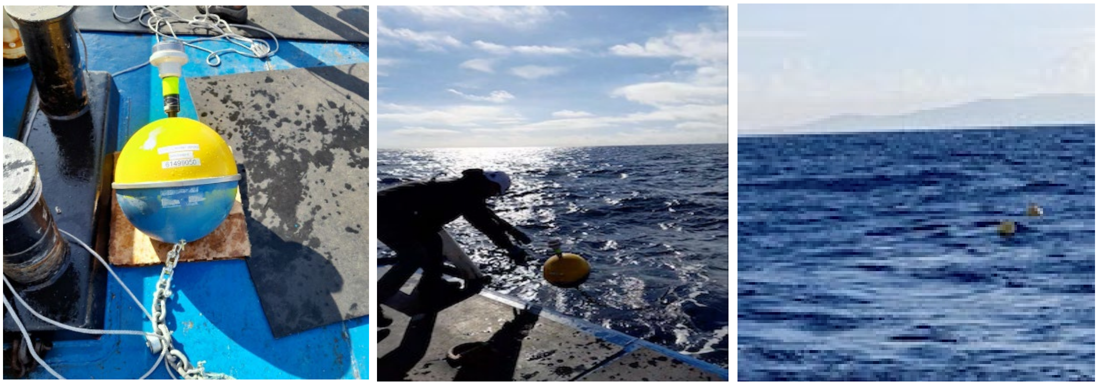

Figure 3 - Some photos of the positioning of the DWSD buoy field.

3. AIMS MOORED DWSD DATASET

All the data, recorded in summarized records, were accessible through the web site of Scripps Institution of Oceanography ([4]) for the entire duration of the campaign. The complete raw data (directional spectrum dataset) were downloaded later, following the recovery of the buoys and are not available here.

During the survey some buoys were lost. Only one of the unmoored buoys was recovered using GPS and repositioned, while another buoy was replaced with a spare one. Only 4 of the 10 buoys deployed (including the spare one) were retrieved at the end of the campaign. The acquisition period for the various buoys was as follows:

- **ID code: 300534061498830**, from 2022-11-07 to 2023-04-19
- **ID code: 300534061499000** from 2022-11-07 to 2023-04-06
- **ID code: 300534061499040** from 2022-11-07 to 2023-04-05
- **ID code: 300534061498940** from 2022-11-07 to 2022-11-15
- **ID code: 300534061498950** from 2022-11-07 to 2023-03-06
- **ID code: 300534061499130** from 2022-11-07 to 2022-11-18
- **ID code: 300534061499050** from 2022-11-07 to 2023-02-16
- **ID code: 300534061499080** from 2022-11-07 to 2023-02-18
- **ID code: 300534061499110** from 2022-11-07 to 2023-02-21
- **Spare buoy (unusable data due to mooring issues): ID code: 300534061499070** – from 2023-02-06 to 2023-04-04

3.1 CSV files description

These datasets contain three-hour interval measurements of various meteo-marine parameters (e.g., SST, SLP, Height, Period, and Wave Direction) transmitted in real-time by the DWSD buoys. The dataset consists of nine files, each corresponding to a different buoy, with varying lengths due to some buoys becoming unmoored before the campaign's end.

Data are stored in CSV format, a simple, tabular structure that is both human-readable and easy to process. Each line in a CSV file represents a data record, with fields separated by commas, allowing straightforward data handling with tools like Microsoft Excel.

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[4] https://ldl.ucsd.edu/

The columns in the CSV files are as follows:

- **Platform-ID**: Identification code for each buoy.
- **Timestamp (UTC)**: Timestamp of the acquired data (three-hour average), ordered from the most recent to the oldest record.
- **GPS-Latitude (deg)**: Latitude at the data acquisition point.
- **GPS-Longitude (deg)**: Longitude at the data acquisition point.
- **SST (°C)**: Sea Surface Temperature measured at the bottom of the surface float.
- **SLP (mB)**: Surface Level Pressure measured at the top of the float.
- **Battery (volts)**: Battery voltage.
- **Drogue (counts)**: Drogue counter, tracking the buoy's mooring status.
- **Hs (m)**: Significant Wave Height.
- **Tp (sec)**: Wave period (peak).
- **Ta (sec)**: Wave period (average).
- **Dd (deg)**: Dominant wave direction.

Example .csv file format:

Platform-ID, Timestamp(UTC), GPS-Latitude(deg), GPS-Longitude(deg), SST(degC), SLP(mB), Battery(volts), Drogue (cnts), Hs (m), Tp (sec), Ta (sec), Dd (deg)
300534061498950, 2023-03-06 18:00:00, 43.5597462, 10.0079313, 13.93, 850.00, 6.8, 13, 1.51, 6, 4.95, 237.80
300534061498950, 2023-03-06 15:00:00, 43.5599086, 10.0077231, 13.95, 850.00, 6.8, 13, 1.53, 6, 4.75, 251.10
300534061498950, 2023-03-06 12:00:00, 43.5600964, 10.0072448, 13.96, 850.00, 6.8, 13, 1.50, 4, 4.60, 206.10
300534061498950, 2023-03-06 09:00:00, 43.5601066, 10.0069155, 13.90, 850.00, 6.8, 13, 1.53, 7, 4.65, 259.20
300534061498950, 2023-03-06 03:00:00, 43.5598296, 10.0081417, 13.84, 850.00, 6.8, 13, 1.85, 7, 5.45, 250.00
300534061498950, 2023-03-06 00:00:00, 43.5594714, 10.0085338, 13.84, 850.00, 6.8, 14, 2.11, 7, 5.80, 239.70
300534061498950, 2023-03-05 21:00:00, 43.5592956, 10.0087566, 13.86, 850.00, 6.8, 14, 2.21, 7, 5.80, 241.10
300534061498950, 2023-03-05 15:00:00, 43.5594089, 10.0086473, 13.96, 850.00, 6.8, 13, 1.96, 7, 5.50, 233.50
300534061498950, 2023-03-05 12:00:00, 43.5596946, 10.0083129, 13.99, 850.00, 6.8, 15, 1.35, 6, 4.70, 234.60

3.2 Dataset location

The Dataset is freely accessible at the following links:

- https://doi.org/10.5281/zenodo.14039005
- https://morenergylab.polito.it/aims/

4. CONCLUSIONS

The AIMS project's moored DWSD survey off the coast of Livorno successfully established a dense network of buoys, providing a valuable dataset for studying wave dynamics and validating numerical models. Although several buoys were lost during the campaign, the data collected offer critical insights into wave behaviour and local sea conditions. This experience has been instrumental in informing the design of future AIMS campaigns, particularly for measuring wave parameters along satellite tracks. Given the importance of buoy recovery to obtain the complete spectral data, it is recommended to limit the duration of future campaigns to 3-4 weeks. This approach will maximize data density and improve the reliability of observed wave parameters.

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Luther, L., Meadows, G., Buckley, E., Gilbert, S., Purcell, H., & Tamburri, M. (2013). Verification of wave measurement systems. Marine Technology Society Journal, 47(5), 11. https://doi.org/10.4031/MTSJ.47.5.11

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