Validation and application of a Physics-Based Digital Twin for enhanced Monitoring and analysis of wind turbines

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1: France Energies Marines, Brest, France

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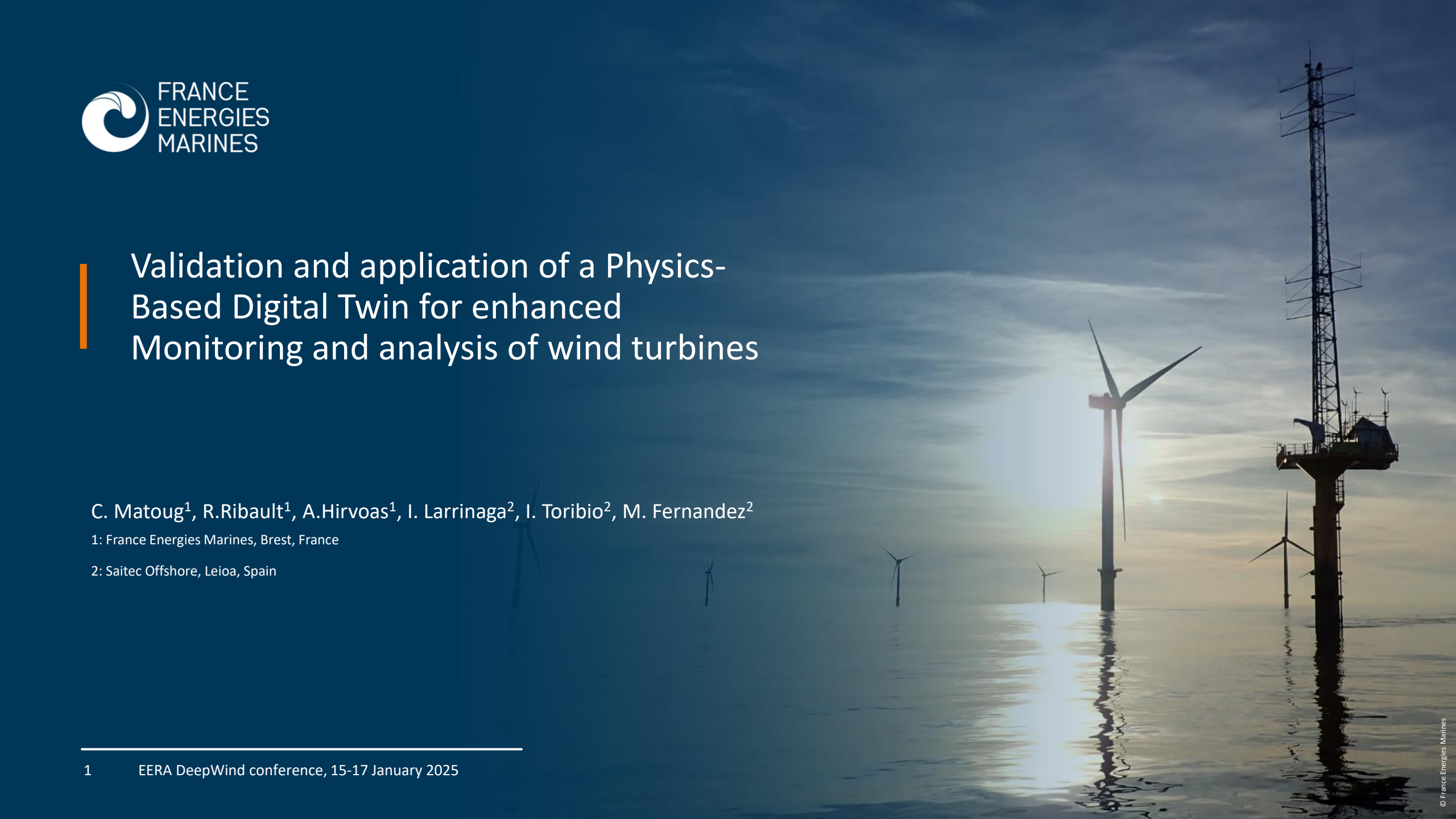

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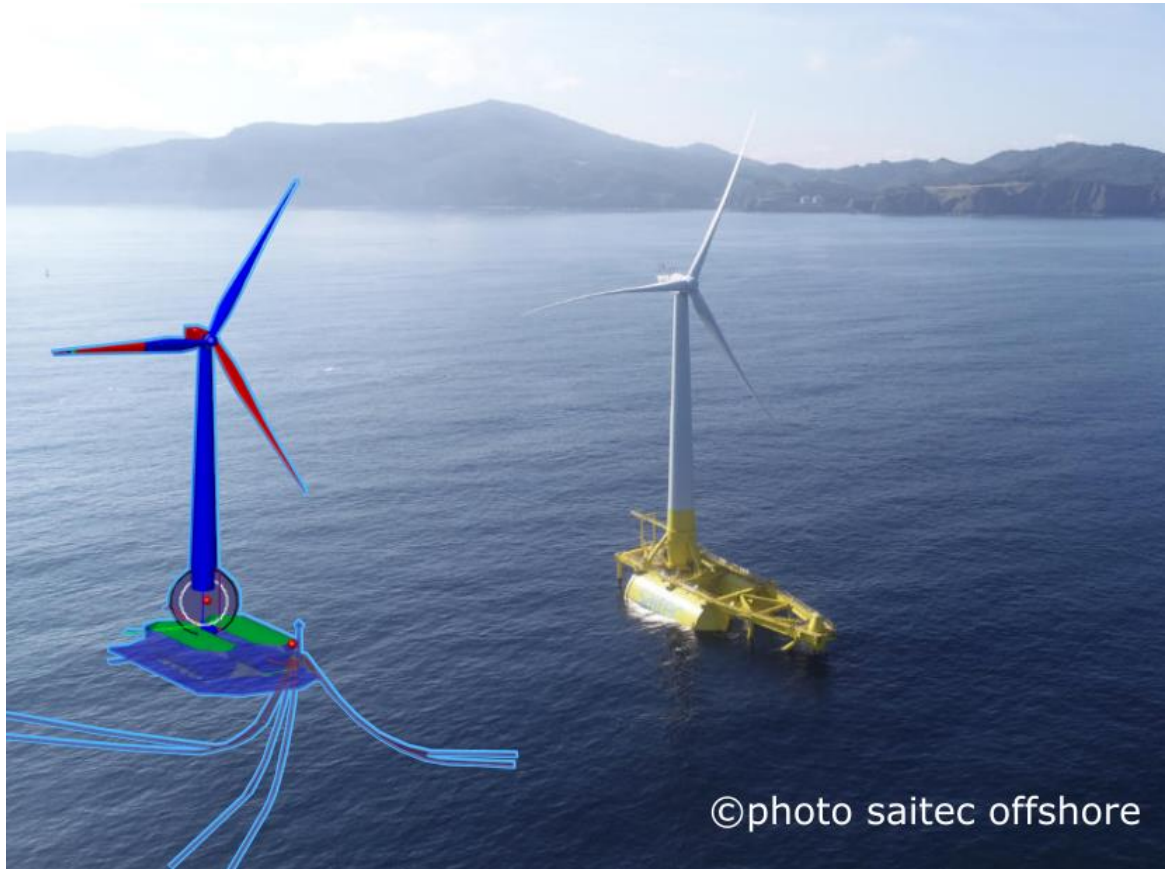
Introduction

- Digital Twin tool applied to DemoSATH
  - Concrete twin hull
  - Single Point Mooring
  - 2MW demonstrator at BiMEP, Spain
- High level Digital Twin presentation & Model-measure comparisons
- Base off previous work during DIONYSOS project
  - Adaptations for SIMA
  - Deployed on 2 FOWT demonstrators
- with SAITEC data
  - SIMA numerical model
  - SCADA with 20 channels, 400h of data at 1hz



Agenda

1. France Energies Marines in short
2. SIMA model presentation & integration
3. Digital Twin global process overview
4. Dataset presentation
5. SIMA model precision
6. Conclusions & perspecives

France Energies Marines in short

French National Research Institute fully dedicated to Offshore Wind

Staff 85

Since **2012**

€8M budget in 2022
100% allocated to R&D

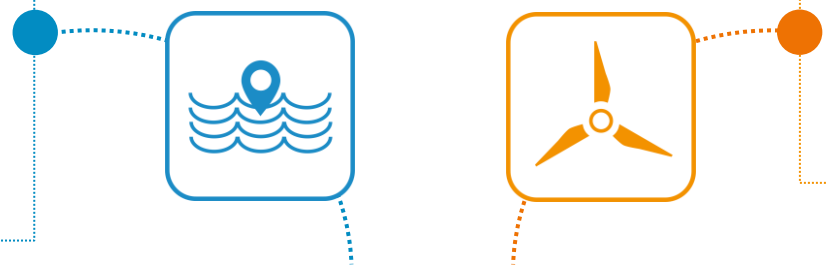
Headquarters in **Brest**
Offices in **Le Havre**, **Nantes** and **Marseille**

Institute supported by **France 2030** investment plan

France Energies Marines in short

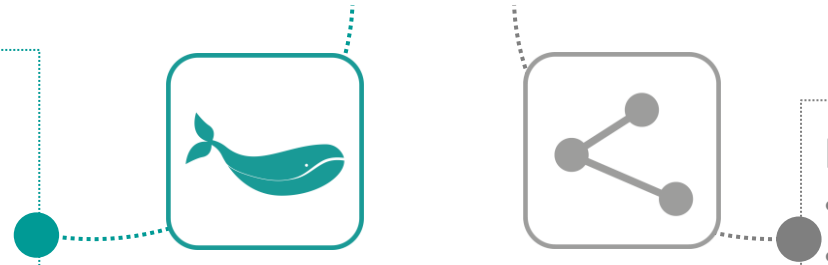
SITE CHARACTERISATION
- Spatialisation of observations
- Characterisation of sea states
- Wind characterisation at sea
- Climate change
- Hydrosedimentary processes

SYSTEMS DESIGN AND MONITORING
- Structure, mooring and electrical cable
- Hydrodynamic and structural coupling
- Digital twins and in-service monitoring
- Technological innovation



4 cross-cutting and complementary R&D programmes

ENVIRONMENTAL INTEGRATION
- Effects on ecosystem compartments
- Changing scale in terms of socio-ecosystem, space and time
- Tools for environmental integration



FARM OPTIMISATION
- Farm architecture
- Grid integration (hydrogen...)
- Installation, operation and maintenance

France Energies Marines in short

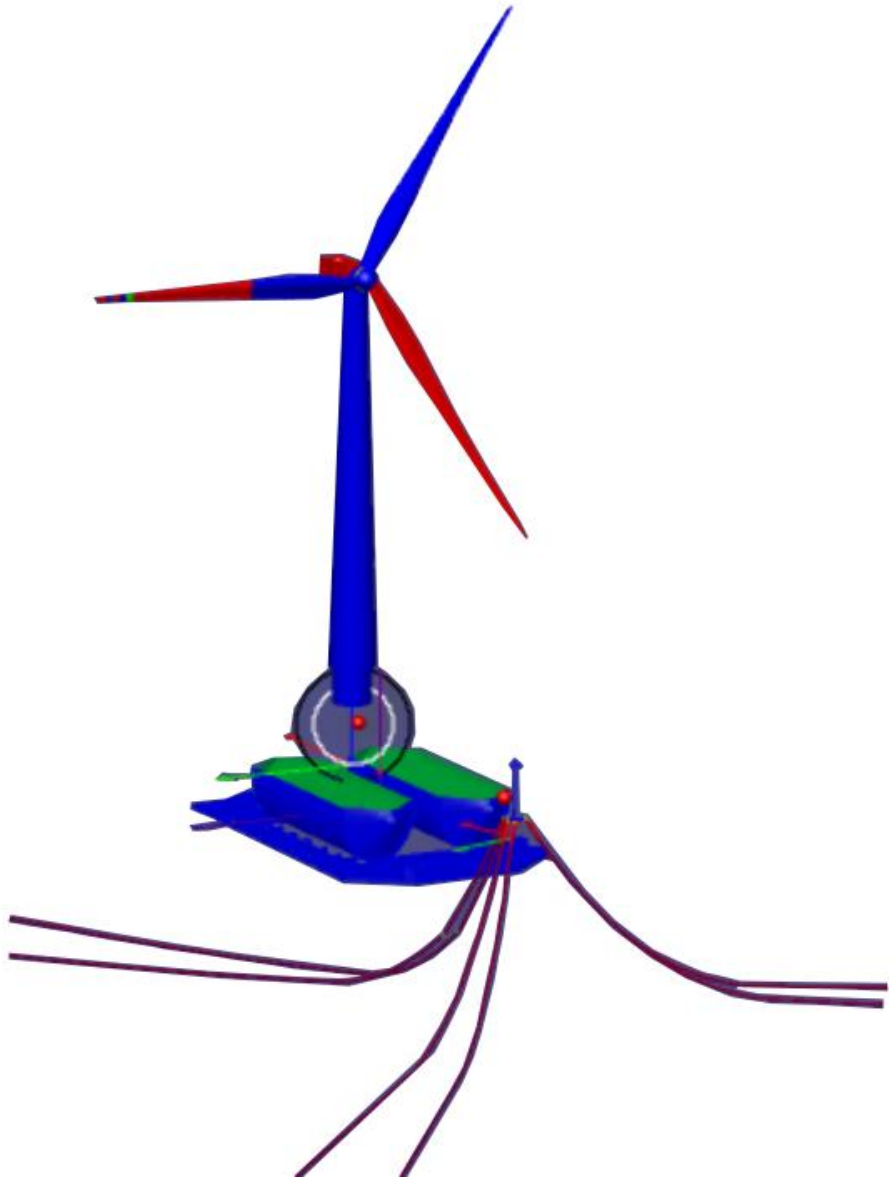
Ownership
50% public
50% private

A joint-stock company with a capital of
€699,000

SIMA MODEL: presentation & integration

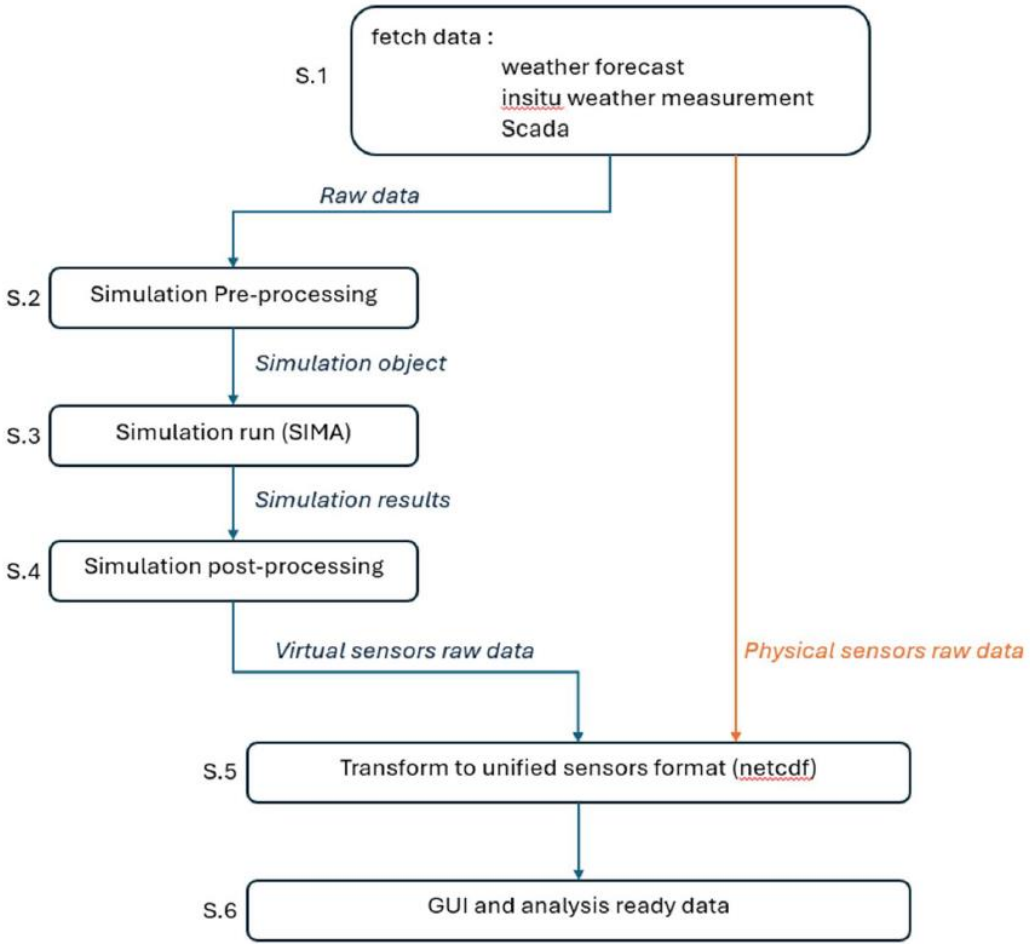
- SIMA fully coupled model provided by SAITEC
  - Mooring
  - Hydrodynamics
  - Structure
  - Aerodynamics
  - Controller

- Input parameters
  - Quadratic damping
  - Waves & current conditions
  - Turbsim input
  - …



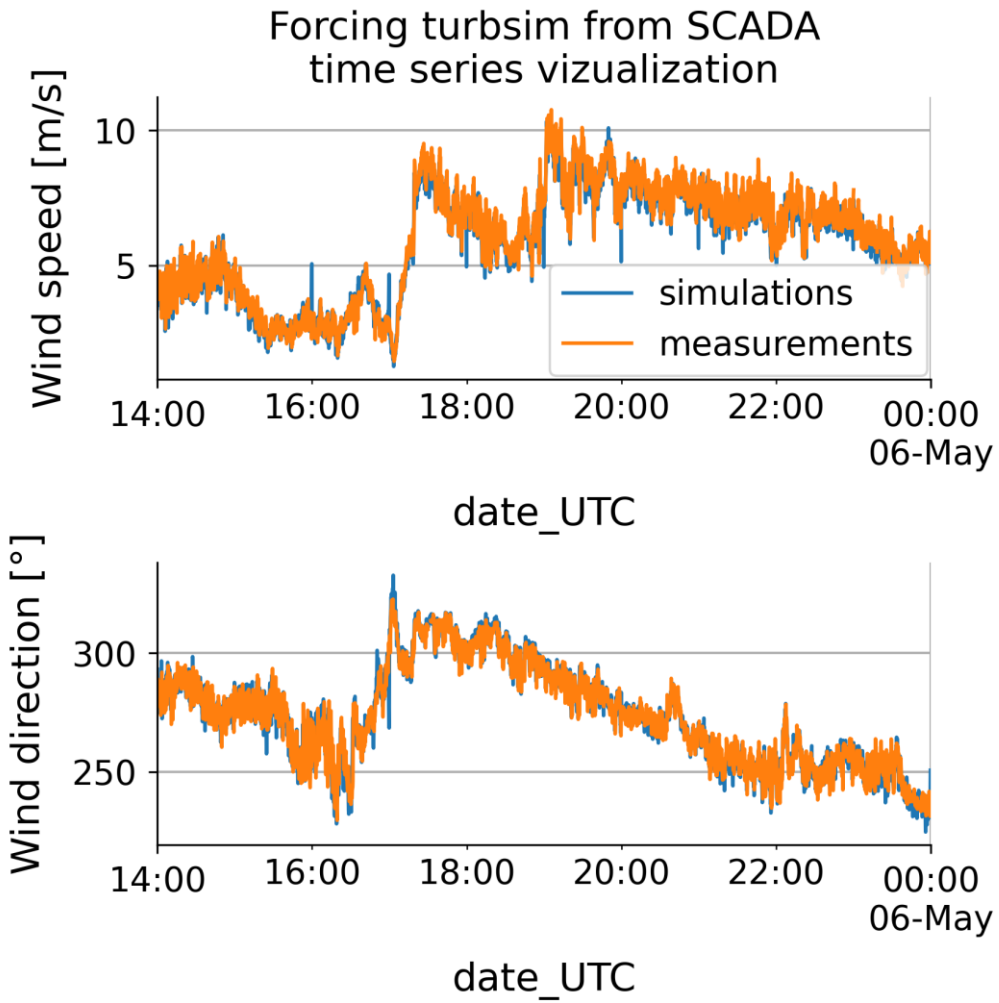
Digital Twin: global process presentation

- Automated fetching & simu. Runs
  - Weather forecast
  - In-situ measurements
  - SCADA
- Simulation run
  - Pre-processing inputs
  - Run simulations
- Automated data post-processing
  - Units changes
  - Unified naming channels & reference frames
  - Automated cleaning
  - Merge data
- All data unified in a single database



Digital Twin: global process presentation

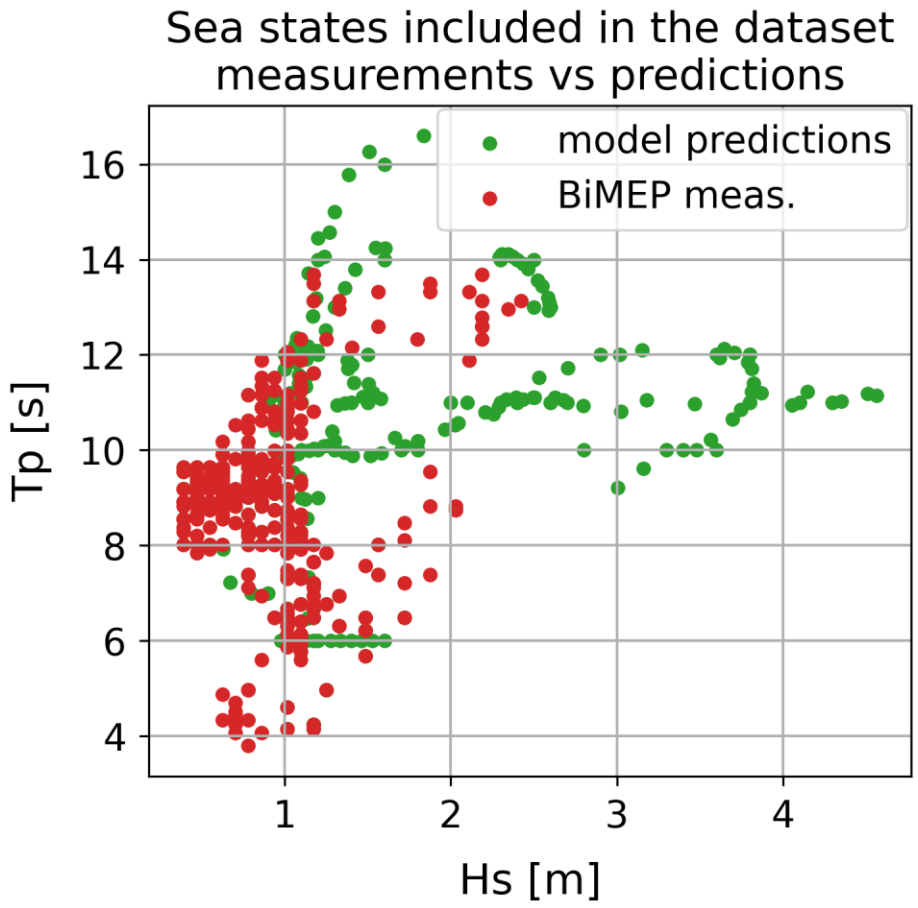
- Adapted for SPM application
- Forcings wind time series with SCADA
  - Acknowledged limitations
    - Wind turbine blockage
    - Floater motion
    - No LiDAR for comparison
- Forcing floater & nacelle heading at simulation initialization



Dataset presentation

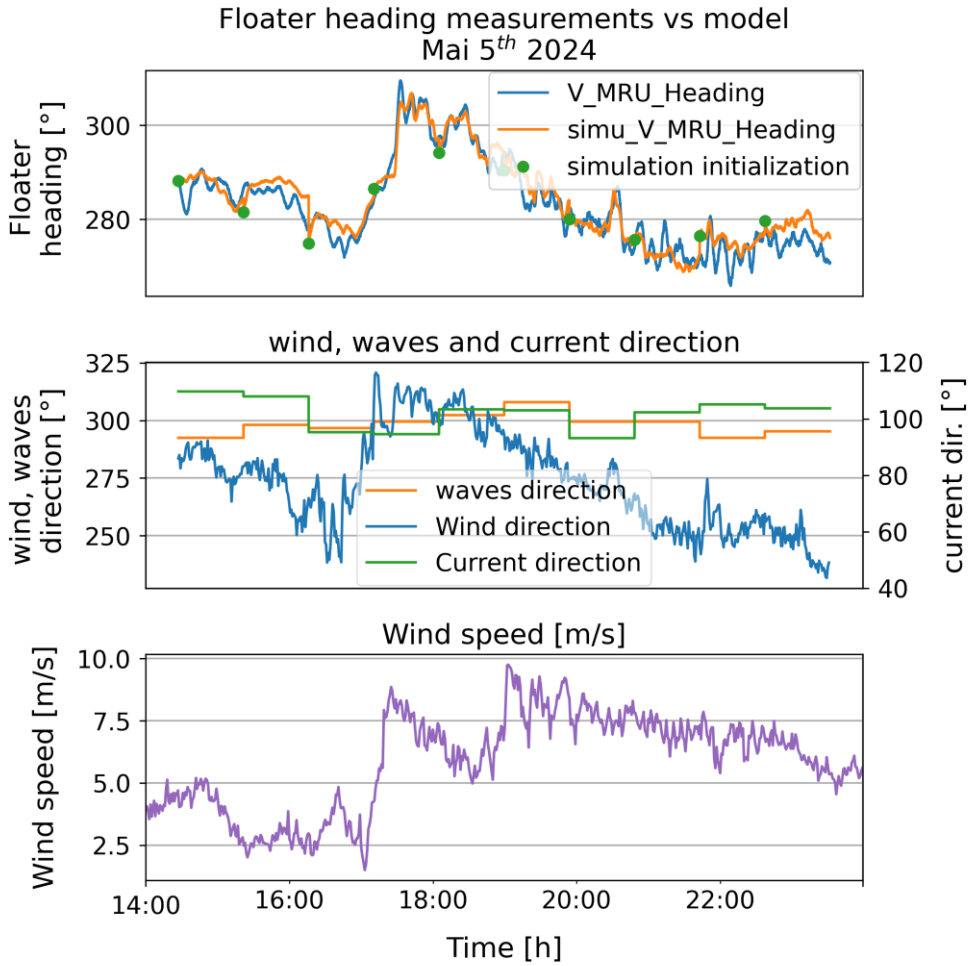
- 486h dataset
  - 287h with BiMEP measurements & SCADA data
- Operating the DT in best conditions only Priority 1 inputs
- Model – Measurements comparisons focus of a subset
  - Milder conditions

	Priority 1	Priority 2	Priority 3
Wind	1Hz time series from turbine anemometer	1h wind from weather buoy anemometer	1h mean wind speed & direction from ARPEGE
Wave	1h stats from buoy wave sensor	3h stats from WWIII forecast	
Current	1h stats from surface measurements of wave buoy	1h stats on surface velocity from MARS 2D	



SIMA model precision

- Illustration with a time-series
  - Selected for its strong wind direction variations
- Statistics on the subset (1Hz sampling)
  - Average error = 1.3°
  - Std error = 2.6°
  - Max error = 7.5°
- Key points
  - Initiating floater heading
  - Heading dynamics well captured
  - Finer resolution on current direction could help



SIMA model precision

- Methodology: process a big dataset
  - Statistically representative waves conditions
  - Most relevant for Heave, Pitch and Roll

- Statistical approach
  - Computed over 1 hour window (1 Hz sampling frequency)
  - Then aggregated over the dataset
  - Remove outliers defined as 5th and 95th percentile

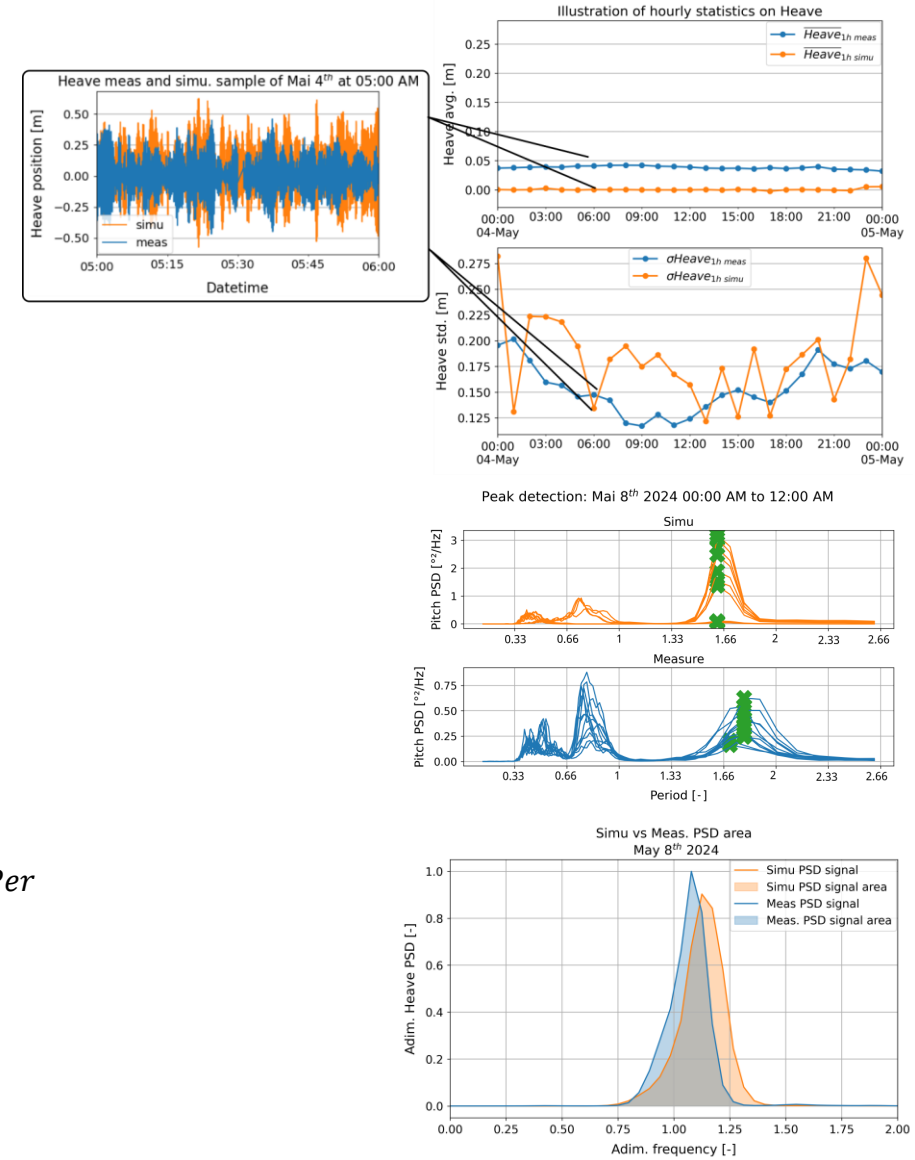
- Several metrics selected here
  - average, std, min/max
  - Natural frequencies
  - PSD area
  - Correlation

$$\overline{Dof_{error}} = \overline{DoF}_{1h\ simu} - \overline{DoF}_{1h\ meas}$$

$$\sigma_{error} = \sigma\ DoF_{1h\ simu} - \sigma\ DoF_{1h\ meas}$$

$$\Delta_{PSD} = \int_5^{40} PSD_{simu}.dPer - \int_5^{40} PSD_{meas}.dPer$$

$$r = \frac{Cov(x,y)}{\sigma_x \sigma_y}$$



SIMA model precision

- Globally good results are observed
  - Error is similar to censors' uncertainties
  - Statistics in the 5th to 95th percentile interfave

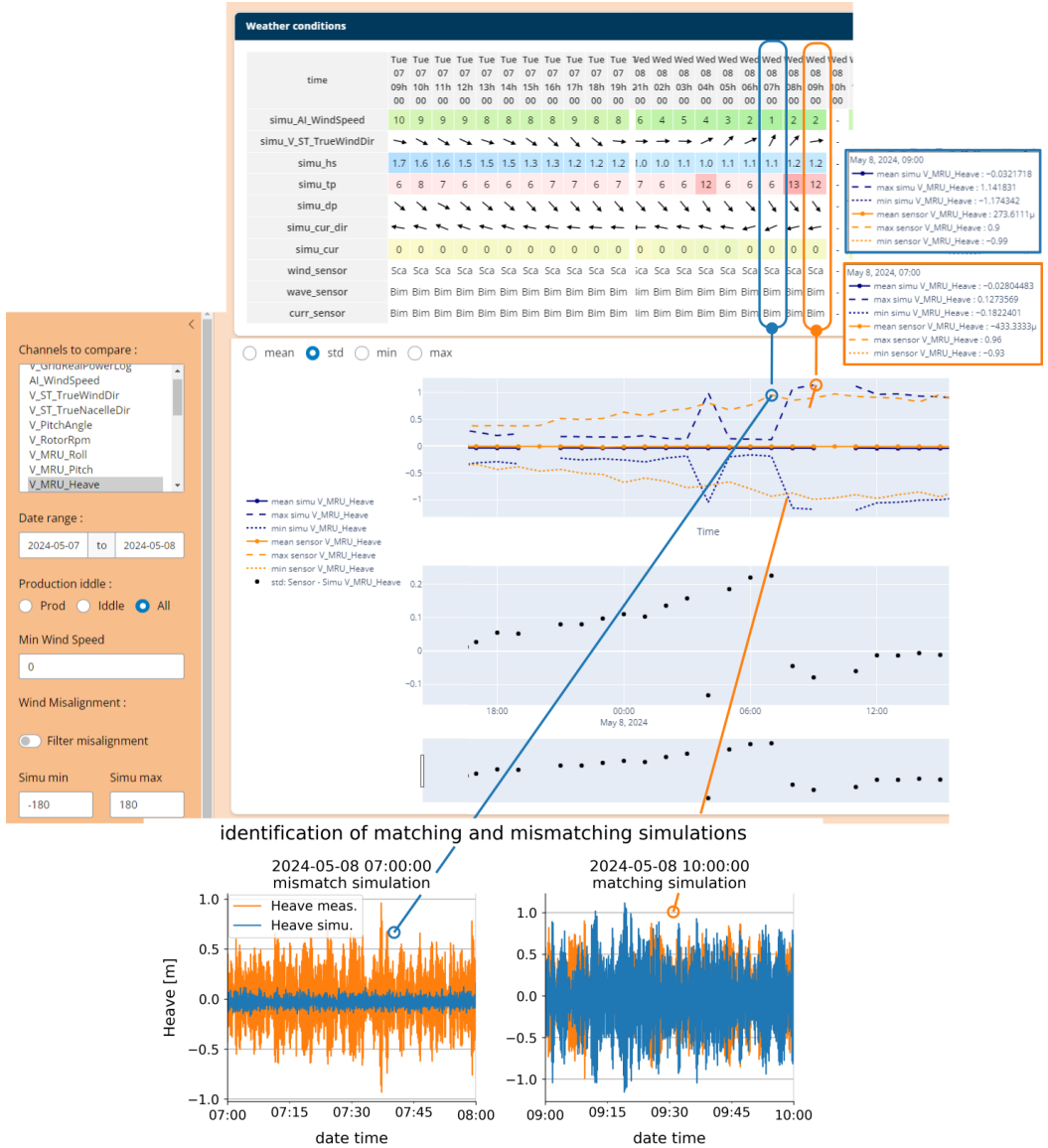
	Hourly average error: $\overline{\mathrm{Dof}_{\mathrm{error}}}$				Hourly standard deviation σ_{error}			
metric	$\overline{\mathrm{Heading}_{\mathrm{error}}}$ [°]	$\overline{\mathrm{Pitch}_{\mathrm{error}}}$[°]	$\overline{\mathrm{Heave}_{\mathrm{error}}}$ [m]	$\overline{\mathrm{Roll}_{\mathrm{error}}}$ [°]	heading σ_{error} [°]	Pitch σ_{error} [°]	Heave σ_{error}[m]	Roll σ_{error}[°]
mean	**1.87**	0.788	0.019	-0.523	-0.911	**0.032**	**0.024**	**-0.026**
std	9.3	0.228	0.030	0.212	1.973	0.024	0.057	0.022

SIMA model precision

- Outliers study
  - Strange T_p variation on Mai 8th
  - σ_{heave} diverging

	outlier simulation	matching simulation
σ_{meas}	0,27 m	0,31 m
σ_{simu}	0,04 m	0,39 m
error	85%	25%

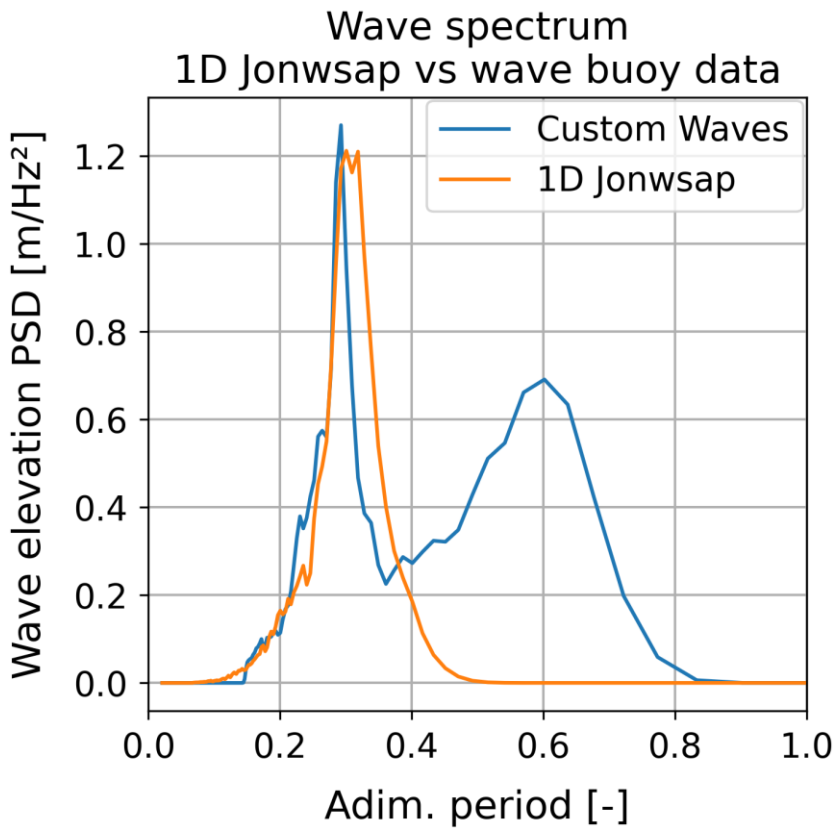
- Waves conditions modelled as 1-D Jonwsap
  - Might be to strong of an assumption
  - Generates misreading of Tp in some conditions
    - Observed a 6 am
    - Influences the Heave motion



SIMA model precision

- Refined waves model for SIMA:
  - Before : 1D Jonswap
  - After : 24 dir measured - custom spectra

- Warning - methodology issue for viscous damping:
  - Model with Morison elements not well suited for double peak

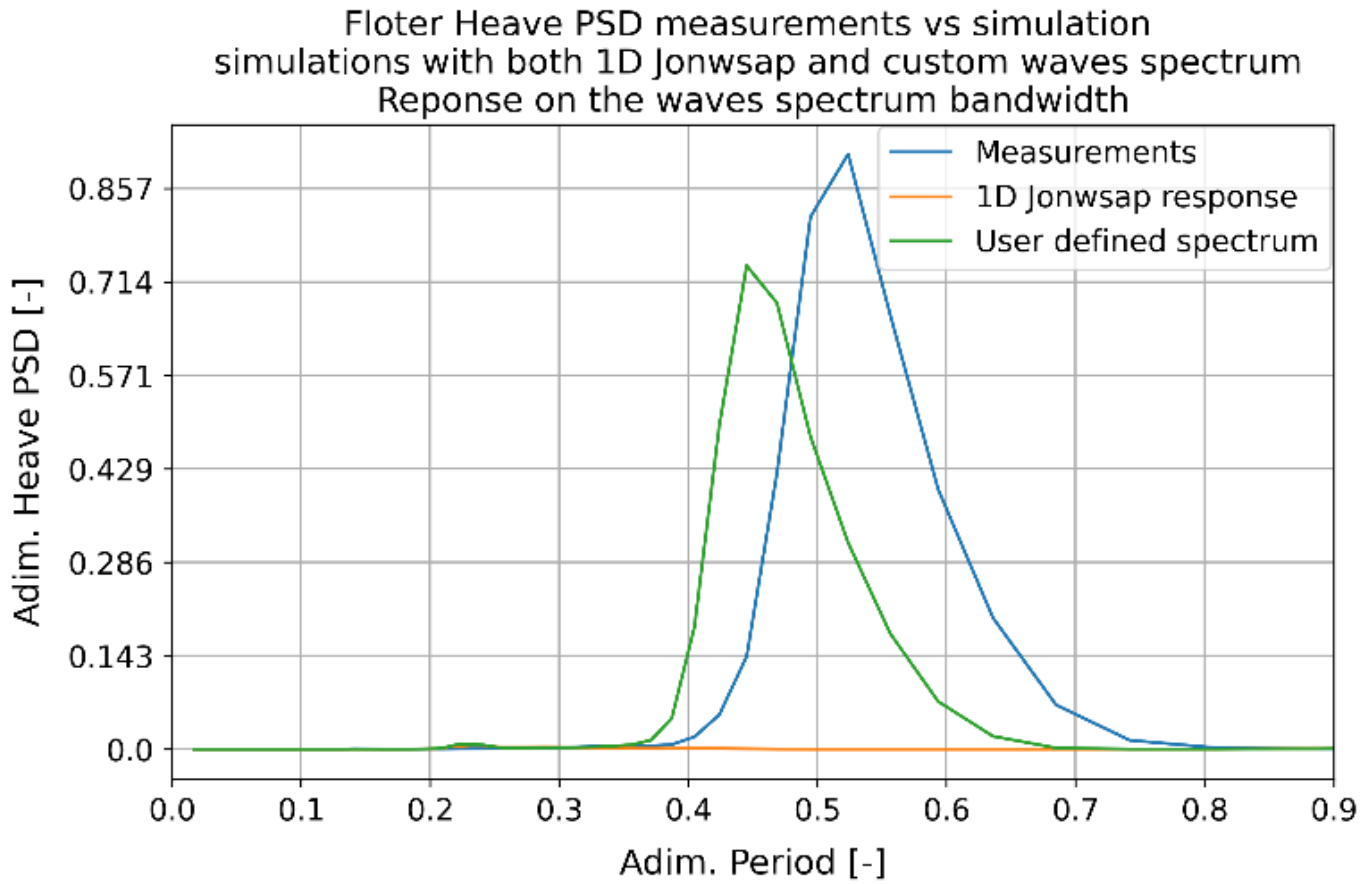


SIMA model precision

- Enhanced Heave modelling :
  - Now capture Heave response
  - Slight shift & amplitude mismatch

Heave PSD area error on wave response	
Meas.	13.13
1D JONSWAP	0.24 (n/a)
Custom	11.58 (12%)

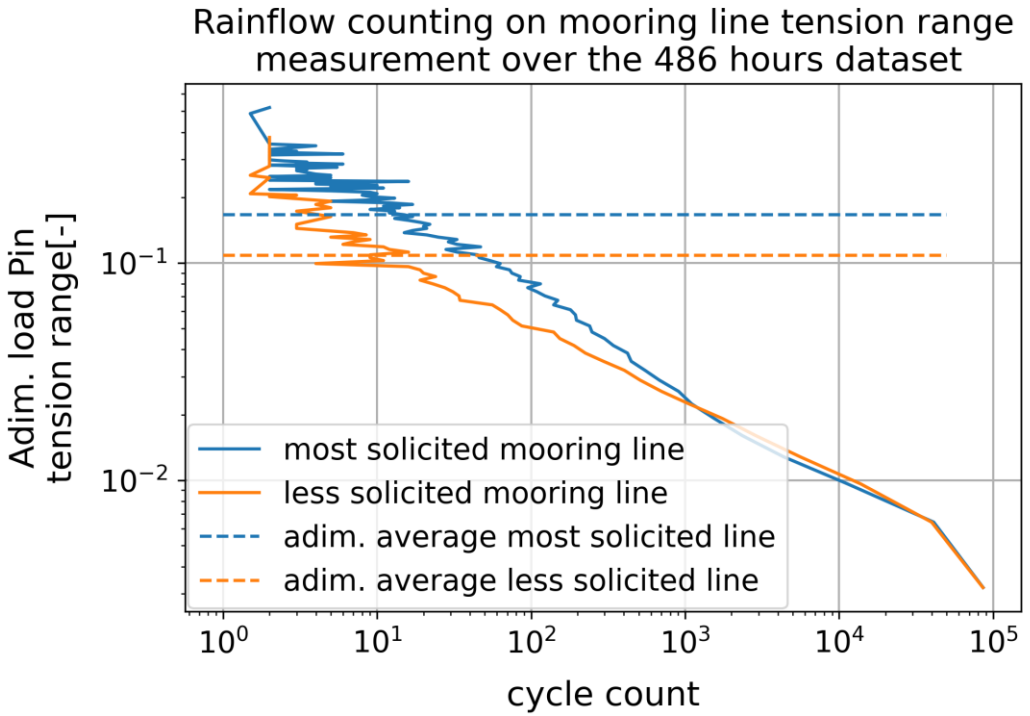
- Other DoF also show improvements



Conclusions & perspectives

- An operational digital twin for wind turbines
  - Deployed on two demonstrators
  - Processing various inputs
  - Software agnostic (currently OpenFAST & SIMA)
  - Tools for dataset visualization

- Perspectives
  - Investigate other outliers
  - Virtual sensor applications
  - Deploy on other offshore systems
  - European projects submitted for DT continuation
  - Prestation for data recovery, processing & reporting
  - …



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Any questions?

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Annexes

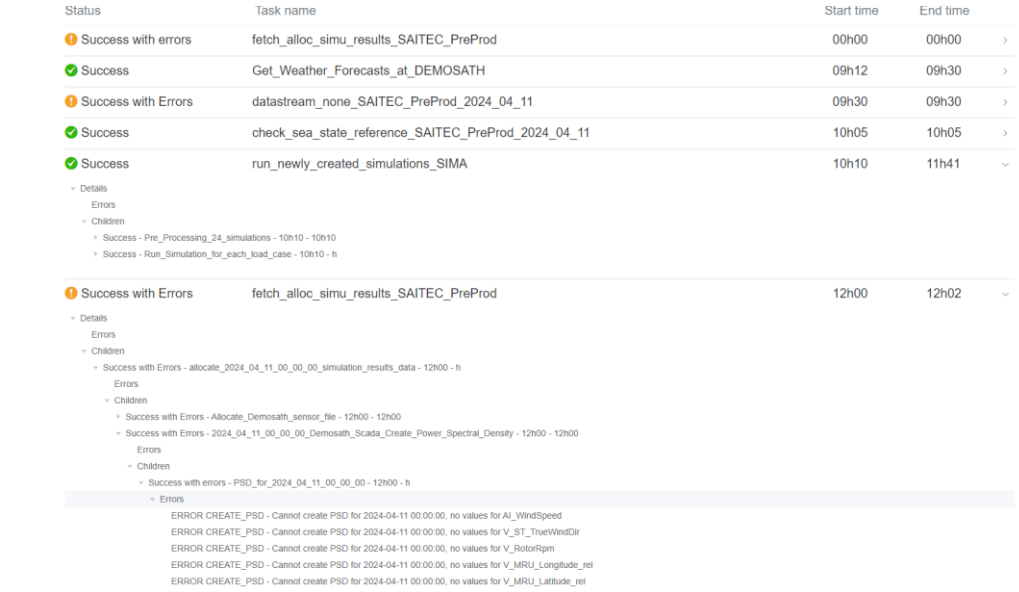
- Single file for all data sources: generic sensors
  - Unified naming scheme
  - Unified units & reference frames
  - All informations are condensed in one file

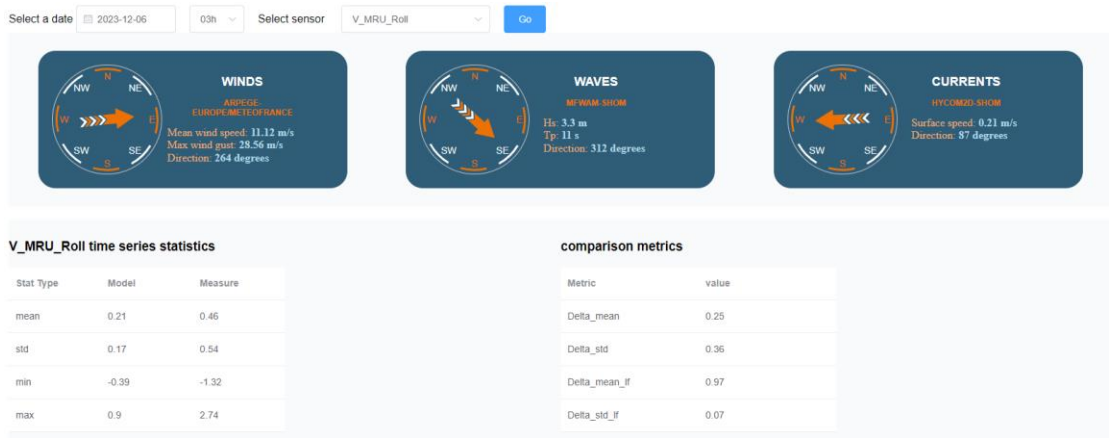

```
    "AI_WindSpeed": {
        "__type__":
"subsee4D:inputs:environment_sensors_catalogue:generic_sensors:channel",
        "name": "AI_WindSpeed",
        "description": "wind speed measurements by sonic anemometer",
        "values": "values",
        "Position": "ultrasonic anemometer above the nacelle, behind the blades",
        "unit": "m/s",
        "valid_min": 0,
        "valid_max": 80.0,
        "short_name": "AI_WindSpeed",
        "allowable_interpolation_seconds": 1800,
        "source": "Sima simulation",
        "Channels": 1561889327,
        "virtual_name": "WindSpeed"
    }
```

Annexes

- Will include a first data cleaning
  - Interpolations
  - Out of range data cleaning

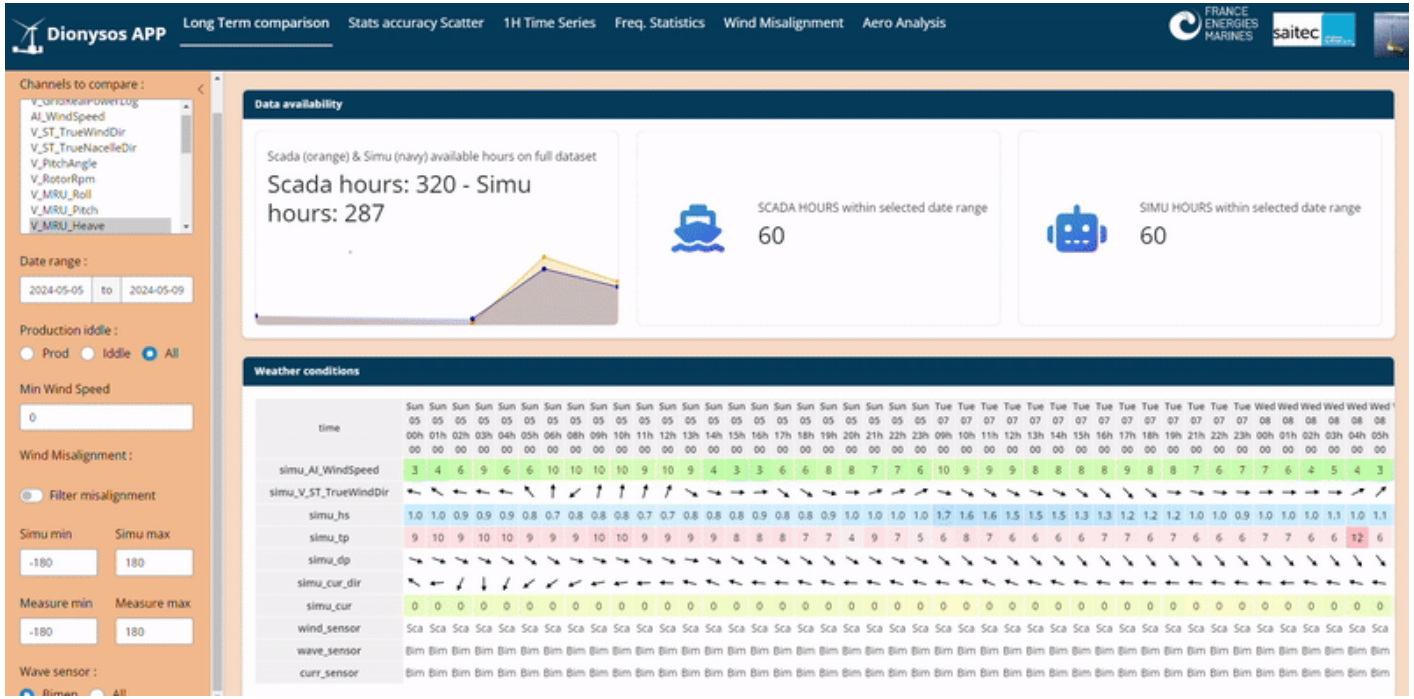
- Graphical User Interfaces
  - Tasks status
  - First visualizations
  - Erroneous inputs / outputs





Annexes

- Simple metric: outlier detection
  - Strange T_p variation on Mai 8th
  - σ_{heave} diverging



Annexes

- Illustration of the resulting file
  - All data concaneted
  - Time series & frequency domain

```
import xarray as xr
path = r"X:\DIONYSOS\03 Documents Internes\Lot_5\DEMOSATH_monitoring\preprod\storage\2024\05\05\Sensors\Demosath_Scada\Demosath_Scada_2024-05-05.nc"
dataset = xr.open_dataset(path)
dataset
```

► Dimensions: (**time**: 24, **time_sensor**: 3600, **time_psd**: 24, **Frequency_psd**: 508)

▼ Coordinates:

time	(time)	datetime64[ns]	2024-05-05 ... 2024-05-05T23:00:00
time_sensor	(time_sensor)	float64	0.0 1.0 2.0 ... 3.598e+03 3.599e+03
time_psd	(time_psd)	datetime64[ns]	2024-05-05 ... 2024-05-05T23:00:00
Frequency_psd	(Frequency_psd)	float64	0.0 0.005013 ... 0.4762 0.5

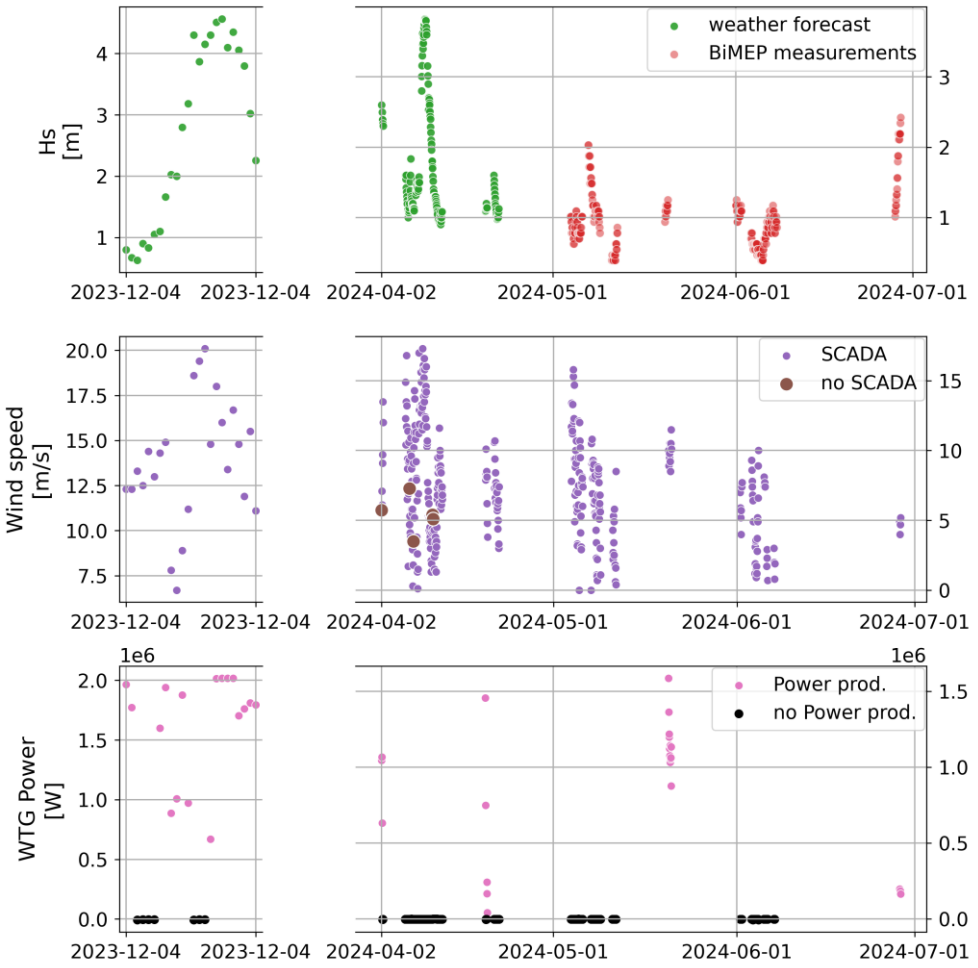
▼ Data variables:

status_Demosat...	(time)	object	...
V_GridRealPower...	(time, time_sensor)	float64	...
V_GridRealPower...	(time_psd, Frequency_psd)	float64	...
AI_WindSpeed	(time, time_sensor)	float64	...
AI_WindSpeed_p...	(time_psd, Frequency_psd)	float64	...
V_ST_TrueWindDir	(time, time_sensor)	float64	...
V_ST_TrueWindD...	(time_psd, Frequency_psd)	float64	...
V_ST_TrueNacell...	(time, time_sensor)	float64	...
V_ST_TrueNacell...	(time_psd, Frequency_psd)	float64	...
V_PitchAngle	(time, time_sensor)	float64	...
V_PitchAngle_psd	(time_psd, Frequency_psd)	float64	...
V_RotorRpm	(time, time_sensor)	float64	...
V_RotorRpm_psd	(time_psd, Frequency_psd)	float64	...

- For database integration & data analysis
  - Nc files for loading only relevant data
  - Cross-compatibility
    - Python panda dataframe
    - Python xarray
    - Matlab ncread
    - MongoDB
    - …
- Used for model measure comparison

Annexes

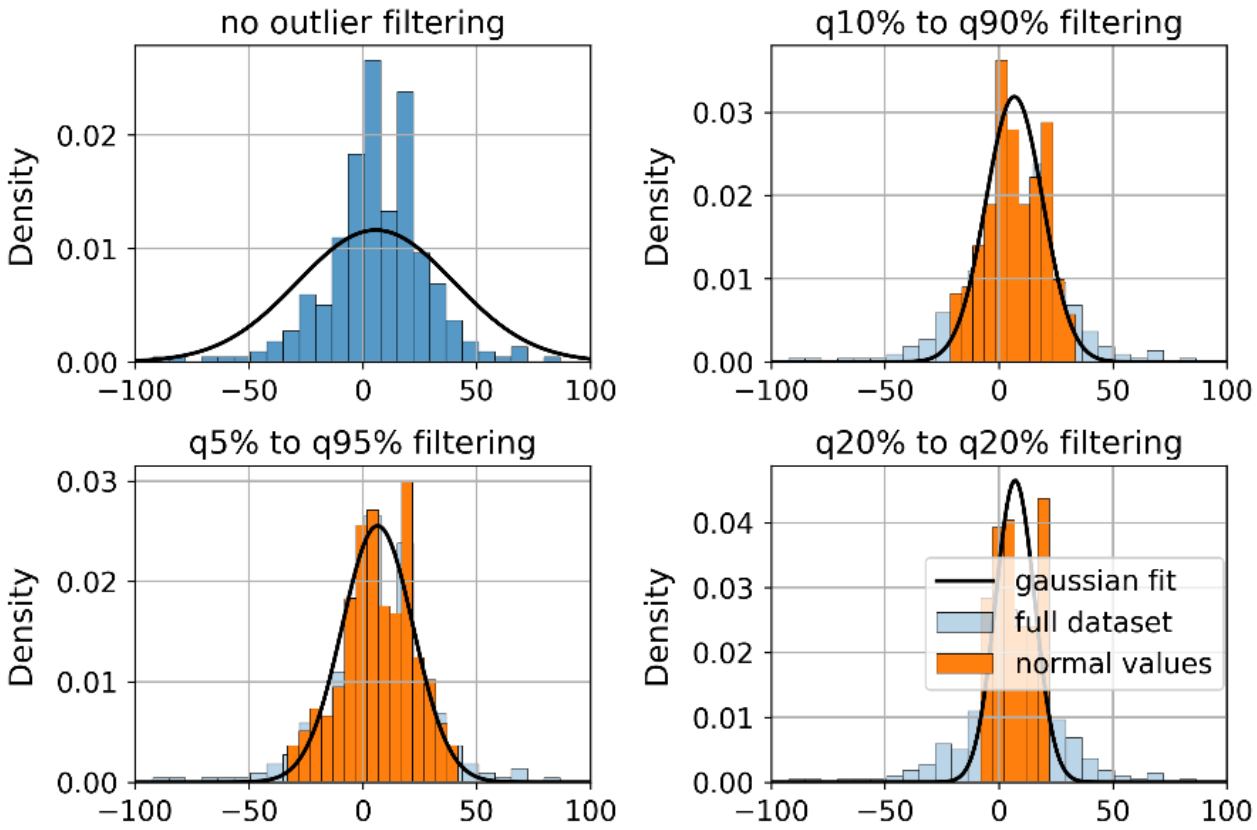
- 486h dataset
- 287 hours with BiMEP in-situ environmental measurements
- 370h provided by SAITEC in hand picked conditions
  - Mostly May to end of June
  - Confident with turbine operation & measurements
  - End of project limited processing time
- DT operation
  - Has been running automatically generating a lot of points
  - Allows for subset selection & outlier identification
- An operational Digital Twin



Annexes

- Distributions fitted with Guassian for outliers' rejection

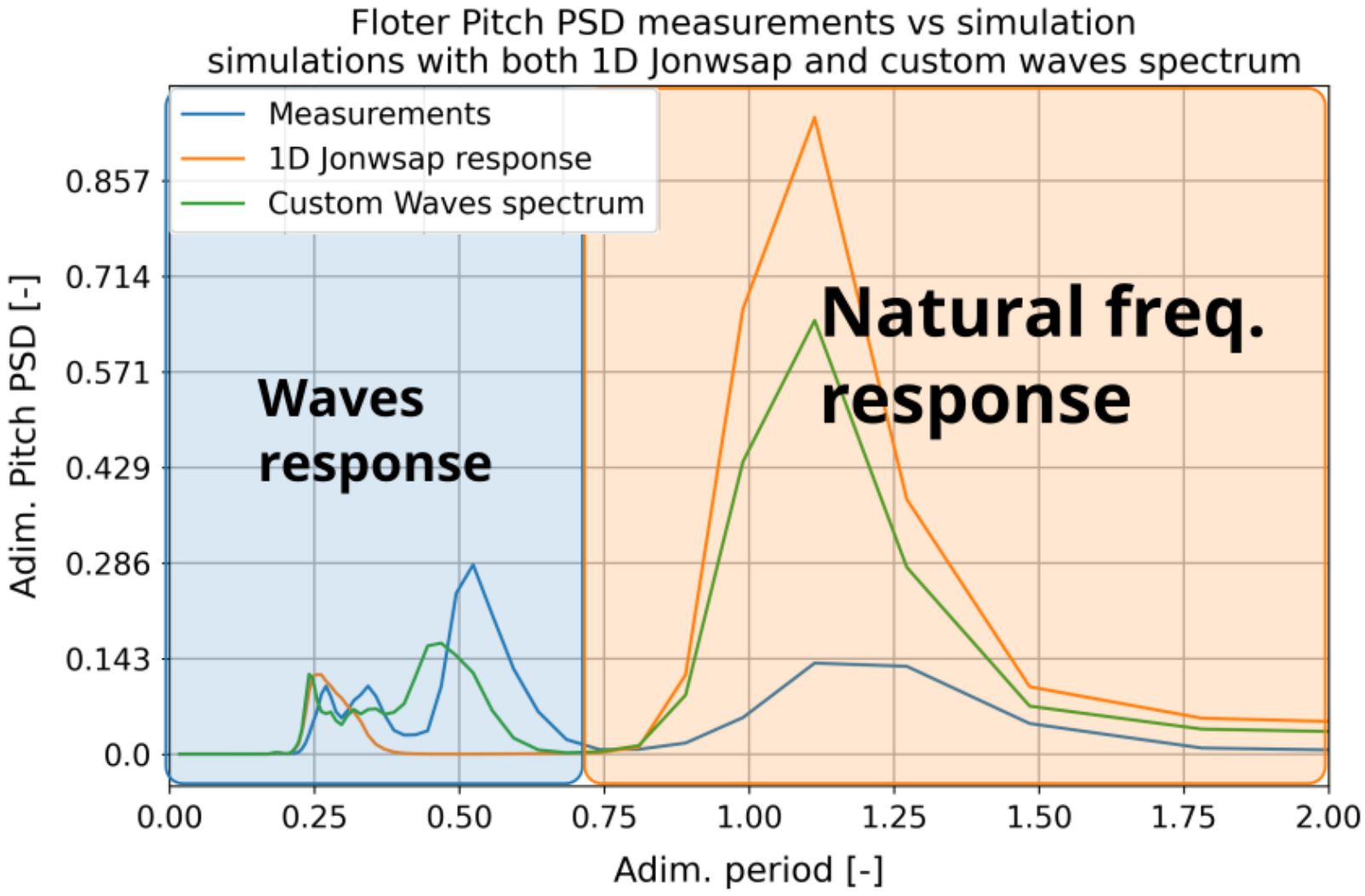
- Illustration with floater pitch histograms



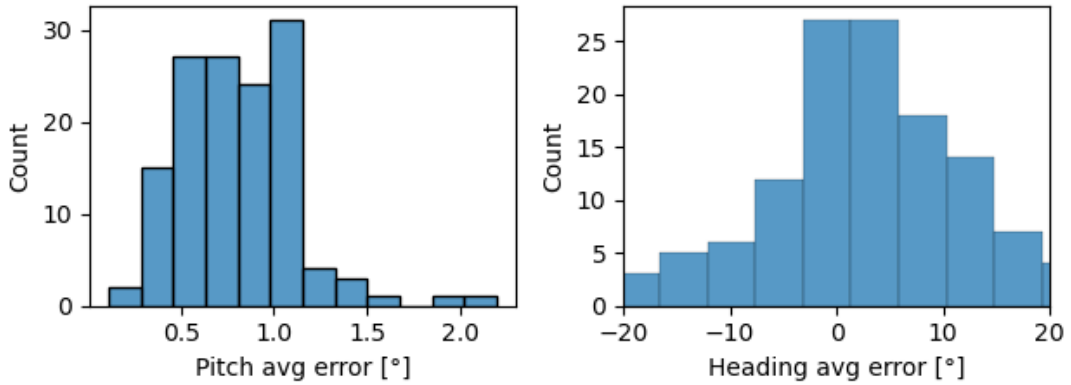
Annexes

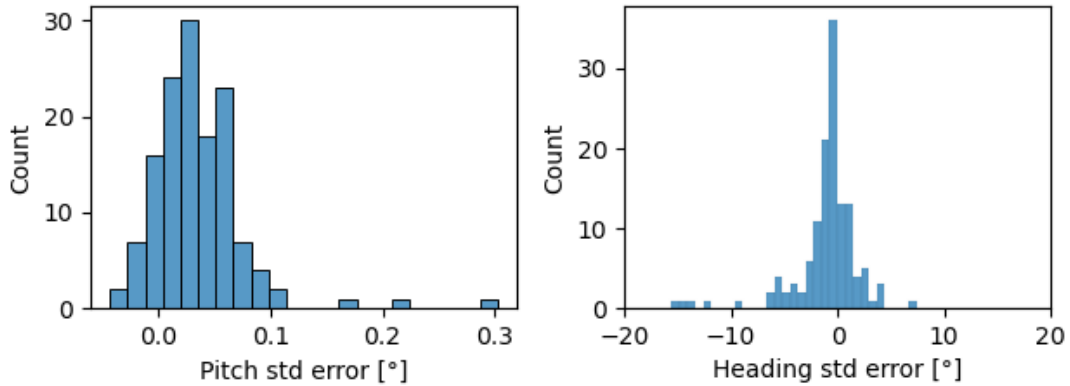
- Enhanced Heave modelling
  - Now capture Heave response
  - Slight shift & amplitude mismatch
- Enhanced pitch modelling
  - Good wave response .
  - Improved pitch n.f. Response.

	Waves response	natural freq. Response
Meas.	3.91	0.72
1D JONSWAP	2.12 (46%)	4.29 (496%)
Custom	3.64 (7%)	2.96 (311%)



Annexes


Count
Pitch avg error [°]
Heading avg error [°]
Heave avg error [m]
Roll avg error [°]

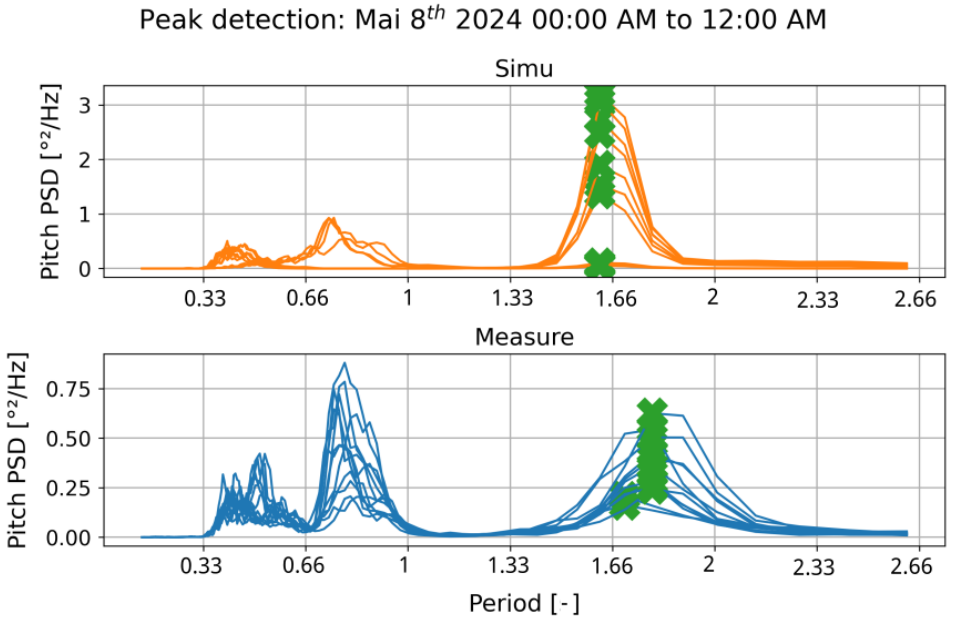

Count
Pitch std error [°]
Heading std error [°]
Heave std error [m]
Roll std error [°]

Annexes

- Statistics results
  - Heading, Heave and Pitch well captured.

- Natural frequency
  - Good result for heave
  - Average Pitch & Roll result

	Average error	Std error	Max error	Natural freq. error
Floater heading	5,72 °	34,38 °	279°	n/a
Heave	0.048m	0.056m	0.168m	-3.7%
Pitch	0.024°	0.039°	0.112°	-9.5%
Roll	-0.048	0.047	0,027	-11.8%



Annexes

- Statistics results
  - Heading, Heave and Pitch well captured.
- Natural frequency
  - Good result for heave
  - Average Pitch & Roll result
- Scatter plot Hs, Tp, WSPD vs natural period errors