Wind resource assessment uncertainty for a TLP-based met mast

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Abstract. The current work presents wind resource assessment results of a complete one-year offshore measurement campaign in the Aegean Sea, at 65 m deep waters, with a floating tension leg platform (TLP) equipped with a met mast reaching the height of 44 m above mean sea level (AMSL). Wind conditions uncertainty is evaluated according to the existing standards and guidelines and the additional uncertainty, due to the platform motion, is addressed with two different methods: First by performing wind tunnel experiments, in which the wind sensors are submitted to various controlled motions and second by comparing results of the onboard lidar to a nearby onshore one. Both methods converge that the motion effects are minimal and the additional uncertainty of the mean values due to the TLP motion is ≤1%.

1. Introduction

Offshore wind farms tend to be larger installations than onshore ones, both in terms of wind turbines sizes and numbers. Wind resource assessment plays a crucial role in the design of offshore wind farms, as small deviations between estimated and real wind conditions, can cause significant discrepancies in energy yield and consequently important financial losses. Published standards and guidelines ([1], [2]) describe methodologies to assess all possible sources of uncertainties. New solutions such as TLP-based met masts equipped with a lidar unit, although represent IEC-allowable and established configurations for resource assessment, lack data and published information concerning the effect of the TLP motion on the wind speed measurements and the related uncertainty.

Floating met masts represent a cost-effective alternative to more expensive hub-height fixed-bottom met masts and to floating lidars. All three solutions have strengths and weaknesses. As an example, fixed-bottom hub-height met masts are structures of considerable size, disturbing the flow and inducing wind speed errors of the order 2-3 %, due to aerodynamic blockage and boom mounting [3], [4], [5], [6] and [7]. On the other hand, the motion of floating lidars induces errors in the wind speed measurement [8] and motion compensation algorithms are often necessary, introducing additional uncertainties in the wind speed measurements [9], [10] and [11]. Additionally, when the ZX300 lidar is deployed at sea level, the well-known 180 deg ambiguity appears in the measured wind direction [12], [13] and [14]. These wind direction errors are considerably reduced when installed on a platform.

This paper aims to position this new measurement setup (short met mast with lidar), which is already successfully established onshore, relative to the two offshore existing alternatives: fixed-bottom met masts and floating lidars. It aims mainly to assess the additional uncertainty, introduced in the classical wind sensors (cup, sonic, vane), due to the motion of the TLP platform.
2. Platform description
FloatMast® [15] is a TLP divided into one main vertical central pontoon and four pontoons arranged radially and rigidly connected to the central pontoon. The peripheral pontoons are connected via tethers to the concrete blocks anchorage. All five vertical pontoons and part of the lower connecting beams may be used for efficient pressure controlled ballasting/de-ballasting of the platform in order to enhance deployment and transportation capabilities. Dimensions of the platform are 22 m x 22 m x 25 m. A deck is arranged on top of the central pontoon, 10 m above mean sea level (AMSL), utilized for electrical cabinets, electric production and outfitting. Fuel cells, wind turbines and solar panels provide the required electrical power, making the platform autonomous and environmentally friendly.

The meteorological mast arranged on top of the deck is a 30 m Carl-C A/S self-supporting lattice mast, especially designed for this deployment, reaching a height of 44 m AMSL.

3. The test site
The test site is located offshore, NE of the Makronissos island, in the Aegean Sea, at a depth of 65 m. Makronissos island is located close to the coast of Attica, facing the port of Lavrio. The selected location allows FloatMast to be exposed to the prevailing northern winds with minimal effects from the island. The WGS84 coordinates of the test site are: latitude: 37.7290805° N and longitude: 24.1555972° E.

![Figure 1: Geographic location of the site.](image)

4. Measurements setup
FloatMast’s met mast was equipped with 4 First Class Advanced X cup anemometers at 44 m, 40 m and two at 30 m AMSL, a 3D ultrasonic anemometer at 40 m AMSL, two First Class wind vanes at 38 m and 28 m AMSL, one thermo-humidity sensor at 38 m AMSL and one barometer. All sensors were calibrated before installation and sensor positioning were compliant to [1]. All wind sensors were sampled at 1 Hz except the ultrasonic which was sampled at 10 Hz. Figure 2 shows two different views of the instrumented met mast.

The onboard ZX300M lidar located 3 m north of the mast, was set to measure at 9 preset heights from 30 m to 185 m AMSL. The platform height was measured to be 9.84 m AMSL and an independent performance verification for the ZX300M lidar has been issued [16] before its deployment.

Waves height was measured with a MIROS SM-140 radar and sea water properties (temperature, salinity, dissolved O₂ and chlorophyll-A) with a dedicated AML Plus-X blue sensor. Platform dynamics were monitored through motion sensors (Xsens MTi-G-710 and MTi-20) at two heights (40 m AMSL and platform level), strain-gauges for the central pylon’s and mast legs bending moments and torsion, vibrating wires for the tension leg forces, all sampled at 80 Hz. Finally, the water level and pressure was monitored in all the submerged pontoons.

The total 113 analogue and digital signals were acquired in the FPGA level of a single CompactRIO real-time controller, a technique assuring μsec-order of signal synchronization and maximum reliability.
The current FloatMast deployment, near Makronissos island, offered the possibility to perform an additional comparison of its measurements, against a coastal measurement station. Various reasons excluded the erection of a tall met mast (insufficient terrain space, permissions and archaeological authorities), hence a lidar campaign was the only available option. Therefore, a Windcube v1 lidar unit was operated for 4.5 months in order to provide reference wind measurements, for comparison to those taken on the offshore platform. Note that before deployment, both lidars operated for three weeks next to each other, at CRES premises, in order to establish the initial correlations (figure 11).

![Figure 2: View of the prevailed wind direction (left) and of the instrumented met mast (right).](image)

5. Meteorological conditions

Measurements cover the period from July 12, 2019 8:10am to July 12, 2020 8:00am UTC. The onboard ZX300M lidar was installed later in October 30, 2019. The 10 min-averaged mean wind speed of the site (as measured by the top cup anemometer 44 m AMSL) was 7.9 m/s, the maximum 28.8 m/s and the maximum 1-second gust 35.3 m/s. Turbulence intensity at 15 m/s was found 7.5 %. Air-temperature ranged between 4.5 °C and 31.8 °C (at 38 m height AMSL) and average air-density was calculated 1.222 kg/m³. Data availability after data filtering reached 96.7 % in compliance with [2].

![Figure 3: Overview of the site measured wind conditions.](image)

Wave heights, as measured by the onboard wave radar, reached 4.9 m and 3.03 m maximum and significant heights respectively. The occurred wave periods as function of wave heights are presented in figure 4, grouped with different colors according to the mean wind speed.
Figure 4: Wave regime characteristics of the site per wind speed range.

FloatMast configuration allows continuous verification of the lidar operation against met mast mounted anemometers. In this configuration three common measurement heights exist: 30 m, 40 m and 44 m AMSL. Figure 5 shows the performance verification results, performed for the two predominant free flow direction sectors (N, NNE), according the requirements of [1] Annex L.3. Similar results obtained for the other two common measurement heights.

Figure 5: Performance verification of the ZX300M lidar at 44 m height. (Left: 10min averages, Right: in 0.5 m/s bins).

6. Operation regime of TLP

The motion characteristics of the TLP were derived from Inertial Measurement Unit (IMU) sensors integrating accelerometers, gyroscopes, magnetometers and a Kalman Filter sensor fusion algorithm, along with TLP-specific developed filtering, for the resultant integral magnitudes for angles, velocity and displacement.

The top IMU sensor of the met mast was used for the assessment of the motion characteristics, so that the wind speed and motion measurement points coincide. Specifically, for the translational magnitudes a pass-band filter was utilized, whereas for the rotational magnitudes the sensor internal filtering was used.

Figures 6 and 7 summarize the main results describing the FloatMast motion during the current deployment. The graphs present the probability distributions of the mean and standard deviation values, for pitch/roll inclinations and x/y translations.
Figure 6: Distribution of TLP pitch and roll movements (mean and sdv values).

Figure 7: Distribution of TLP translation movements (mean and sdv values).

It appears that motion is of typical TLP motion pattern, under wave and wind excitation, presenting the following characteristics (reference to 10min statistics):
• Low structure inclinations (roll/pitch). Pitch angle average value is up to 0.5° over static value and
its variation (σ) is limited to 0.15° Roll angle average value is up to 0.3° over static value and its variation (σ) is limited to 0.1°. Although yaw angle is not relevant to the cup wind speed measurement, its variation was below the wind direction uncertainty (<4°). This was verified by the wind direction comparisons with the onshore Lidar (see §7.2).

- Wave excitation dominates the dynamics of the platform. The dynamics of the platform is governed (in energy considerations) by the wave motion. The dominant wave period regime is from 3 to 9 seconds. The higher wave heights occurred during the presence of the high wind speeds are within the 6 to 8 seconds region.

The main motion of the platform is a translational one in resonance with the wave. The motion’s maximum amplitude reaches 1 m up to 16 m/s and at higher winds can exceed 2 m but only in rare cases. The major parameter that may affect the wind speed measurements is the motion velocity variation, during the translational motion. Up to 16 m/s, the variation (σ) of the motion velocity is under 0.2 m/s in either directions, while at higher wind speeds this value may exceed 0.3 m/s but only in rare cases.

During the campaign the IMU was operated with two different settings for angular calculation optimization (which basically affects the filtering band). This is reflected on the binomial distribution of the angular variance (right figures of Figure 6), without any effect on average angle estimation.

7. Uncertainty assessment due to motion
The total wind speed uncertainty of the measurement was found to be 0.18 m/s or 2.28 % (at the mean wind speed), calculated according to Annexes D and E of [1]. It includes an additional term due to platform motion. Two methodologies were used for its assessment and are described below.

7.1. Wind tunnel tests
For the assessment of the uncertainty of the wind speed measurements on FloatMast a series of tests were performed at CRES wind tunnel which is used for accredited anemometer calibrations. The tests were tailored to address the motion pattern of TLPs (a structure that presents low stiffness in sway, surge and yaw and high stiffness in heave, roll and pitch) that as far as wind measurements are considered, is characterized by: a) very low pitch and roll angles b) horizontal motion in resonance with wave excitation.

Considering the above, the tests are performed for one dimensional reciprocating translation with primary characteristics the motion velocity variation (σ_v) and the motion period (T). The motion amplitude is a dependent parameter and although limited by the wind tunnel capacity (up to 1m peak-to-peak), still addresses a large part of the target window. The motion amplitude does not affect directly the wind measurements but the motion velocity. The motion velocity has an effect on the sensors, but in the case of the limited reciprocating motion of TLPs, this effect on the averaged values is insignificant.

This setup allowed us to perform test with the following oscillation motion characteristics:

- Velocity variation (σ_v): 0.1 – 0.8m/s
- Period (T): 0.8 – 15.0s
- Maximum amplitude : 0.95m

7.1.1. Mean deviations
The experiments were performed at four wind tunnel wind speeds (4 m/s, 8 m/s, 12 m/s and 16 m/s) for the cup and ultrasonic anemometer and at one (8 m/s) for the wind vane. All three sensors were prior calibrated according to [17]and then the average deviations of the moving versus static test cases were examined. The two scatter plots (one for the cup and the other for the ultrasonic anemometer) of figure 8 present all motion patterns marked and colored according to the resultant wind speed deviation.

Table 1 summarizes the wind tunnel results. It appears that the applied motion cases cause deviations that remain below each sensor calibration uncertainty.
Cup anemometer  | Sonic anemometer  | Wind vane
---|---|---
Wind speed range [m/s] | Calibration Uncertainty [m/s] | Mean deviation due to motion [m/s] | CalibrationUncertainty [m/s] | Mean deviation due to motion [m/s] | Calibration Uncertainty [deg] | Mean deviation due to motion [deg]
4-16 | < 0.11 | 0.01 – 0.05 | < 0.08 | 0.01 – 0.07 | 1 | < 0.5

Table 1: Summary of Wind Tunnel results for the three sensors

Based on the application range of these tests and considering a conservative approach for the uncertainty estimation, we propose a generalized uncertainty estimation for TLP structures as a function of wind speed:

\[ u_c = \left(0.08 + 0.005u_i\right) \frac{1}{\sqrt{3}} \]

The application of the above formula on the FloatMast entire operation leads to a typical error ranging from 0.10 m/s to 0.13 m/s, at 4 m/s and 16 m/s respectively, averaging to ~1 % wind speed uncertainty due to motion.

![Cup anemometer response](image1)

![3D Ultrasonic anemometer response](image2)

Figure 8: Wind speed deviations of the applied motion cases relative to the static case.

7.1.2. Turbulence intensity deviations

The induced turbulence intensity due to the motion, for all the test cases, is given in the scatter plots of figure 9. Here, we note that higher turbulence intensities values are measured for the cup anemometer relatively to the ultrasonic anemometer and this is attributed to the sensors different measuring methods.

It is reminded here, that in the present FloatMast deployment case, the measured motion operational window was in the period range of 2.5 to 10 seconds and up to 0.5 m/s in velocity variation. This range corresponds to the grayed areas in the two plots, signifying that the induced turbulence intensity error due to motion was less than 1 % for the ultrasonic and somehow higher for the cup anemometer.

When considering turbulence intensities, the following points should be highlighted:

- Wind tunnels are generally characterized by low turbulence, unless built or configured for that purpose. Therefore, it is very difficult to apply the examined motion test cases under real ambient meteorological conditions considering turbulence intensity.
- For sensors with different measuring principles (frequency of rotating cups versus time of travelling sounds), different types of fluctuations are expected when the sensor is subject to motion, on contrary to the mean level response.
• The observed relation between cup and sonic standard deviations (figure 10) during the current FloatMast deployment is characterized by a slope practically 1.0 as expected in onshore campaigns with fixed met masts. This indicates that the excitation created by the TLP motion was not sufficient to trigger the higher turbulence intensity values expected for the cup anemometer, according to the wind tunnel results.

• In the same figure 10 we note the usual trend [24], [25] appearing onshore, of higher lidar wind speed standard deviations, due to the spatial wind speed fluctuations (captured only by the lidar and missed by the cup anemometer, because of the different principle: volume versus point measurement).

Figure 9: Turbulence intensity deviations of the applied motion cases relative to the static case.

Figure 10: Turbulence intensity comparisons of the FloatMast sensors

7.2. Offshore versus onshore lidar results comparisons
An alternative method to assess FloatMast’s measurement uncertainty due to motion, consists in performing comparisons between its onboard lidar and a fixed one installed onshore at 350 m distance (figure 1). The two lidars had operated side-by-side before deployment (and right after the ZX300M’s verification test), in order to establish the initial correlation at all heights. Figures 12 and 13 present the comparisons of 10min-averaged wind speeds and directions.
Figure 11: Side-by-side (left) and deployed (right) operation of the onboard and onshore lidar units.

In order to quantify differences, the methodology defined in Annex L.3 of [1] is followed, with the following modification: the reference uncertainty is zeroed as the investigated parameter is the relative increase of the ZX300M uncertainty between the two cases (side by side versus deployed). After all, it is generally accepted that in this methodology, lidar’s wind speed uncertainty is dominated by the reference cup’s uncertainty [18]. Therefore, when comparing two lidars, this term would add an unnecessary “noise level” in the results.

Here, it is noted that the increase in the lidar wind speed uncertainty, should not be attributed entirely to the platform motion. Factors like: lidars different probe volumes, the in-between distance and the terrain difference (offshore vs coast), are also deviation sources. It is expected however, that the influence of the last two factors decreases with height.

Consequently, at 200 m height, the observed 1 % increase of wind speed uncertainty (from 1.82 % to 2.76 %) should be mainly attributed to the platform motion, supporting the first method’s output. Similarly, wind direction deviations between the two lidars tend to be insignificant as deduced by the repression coefficients of figure’s 13 plots.

Figure 12: Comparison of lidars wind speed side by side (left) and on site (right).
The observed TLP motion characteristics, along with the estimated uncertainties on wind speed measurements, are low and do not justify any need for applying correction procedures.

These correction procedures are often applied in the case of floating lidars, due to their large amplitude motion patterns that significantly affect the measured wind parameters [10], [11], [21], [22]. In these cases, the introduced correction surpasses the inherent uncertainty of the correction procedure. Floating lidars major correction uncertainties regard not only the motion parameter measurement (especially bias effects and phase response of IMUs fusion filtering), but also its transfer from the IMU to the wind measurement point (rotational magnitude uncertainties are magnified).

Contrary to floating lidars, FloatMast’s motion parameters are measured at 40 m height AMSL where the reference wind speed is recorded, therefore the possibility exists to further reducing wind measurement uncertainties, using a phase consistent motion filtering procedure (specific for the TLP motion pattern).

Finally, table 2 displays the main key performance indicators (KPIs) dealing with the two lidars performance verification, following the established methodology, described in IEA’s Wind recommended practices for floating lidars [19] and Carbon Trust Offshore Wind Accelerator roadmap [20]. Given the (mild) flow complexity induced by the Makronissos island, the provided results concern the highest height of lidar measurement.

| KPI | Definition | Acceptance criteria |
|-----|------------|---------------------|
| Xmws | Mean Wind Speed – Slope | 0.97–1.03 | 0.98 – 1.02 | 1.02 |
| R2mws | Mean Wind Speed – R$^2$ | > 0.97 | > 0.98 | 0.996 |
| Mmwd | Mean Wind Direction – Slope | 0.95 – 1.05 | 0.97 – 1.03 | 1.00 |
| OFFmwd | Mean Wind Direction – Offset | < 10° | < 5° | 2° |
| R2mwd | Mean Wind Direction – R$^2$ | > 0.95 | > 0.97 | 0.99 |
| OSA$_{CA}$ | Overall System Availability Campaign Average | > 95% | > 97% | 98.4 % |
| OPDA$_{CA}$ | Overall Post-processed Data Availability | > 85% | > 90% | 90 % |

Table 2: Key Performance Indicators (KPI) for the FloatMast case
8. Conclusions
One year of offshore wind measurements have been performed with a TLP-based met mast deployed in the Aegean Sea at 65m sea depth, according the strict requirements of [1] and [2]. Three different types of anemometers (cup, ultrasonic and lidar) using three different principles of measurements were used to assess the wind speed uncertainty related to the TLP motion.

Results show that FloatMast motions are low and compensation algorithms are not necessary. The calculated additional uncertainty of mean values due to the TLP motion is ≤ 1%.

Wind tunnel tests revealed that the ultrasonic anemometer is better adapted than the cup for traceable turbulence intensity measurements, due to its operation principle and its fast sampling rate.

Experience gained showed that motion sensors should be adapted to limited motion amplitudes; they are indispensable equipment not only for platform dynamics, but also for wind measurements as they provide a traceable reference system.

Overall, it appears that such a configuration has many advantages for offshore wind resource assessment, especially for deep seas where only floating structures can be deployed, as it provides continuous verification of wind data from sensors of known accuracy and different operation principle, reducing thus the measurement uncertainty and the financial investment risks.

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