How to analyse blade aerodynamics on an operating wind turbine with low-cost pressure sensors?

WESC2023 Mini Symposia: Wind Turbine Blade Aerodynamic Measurements

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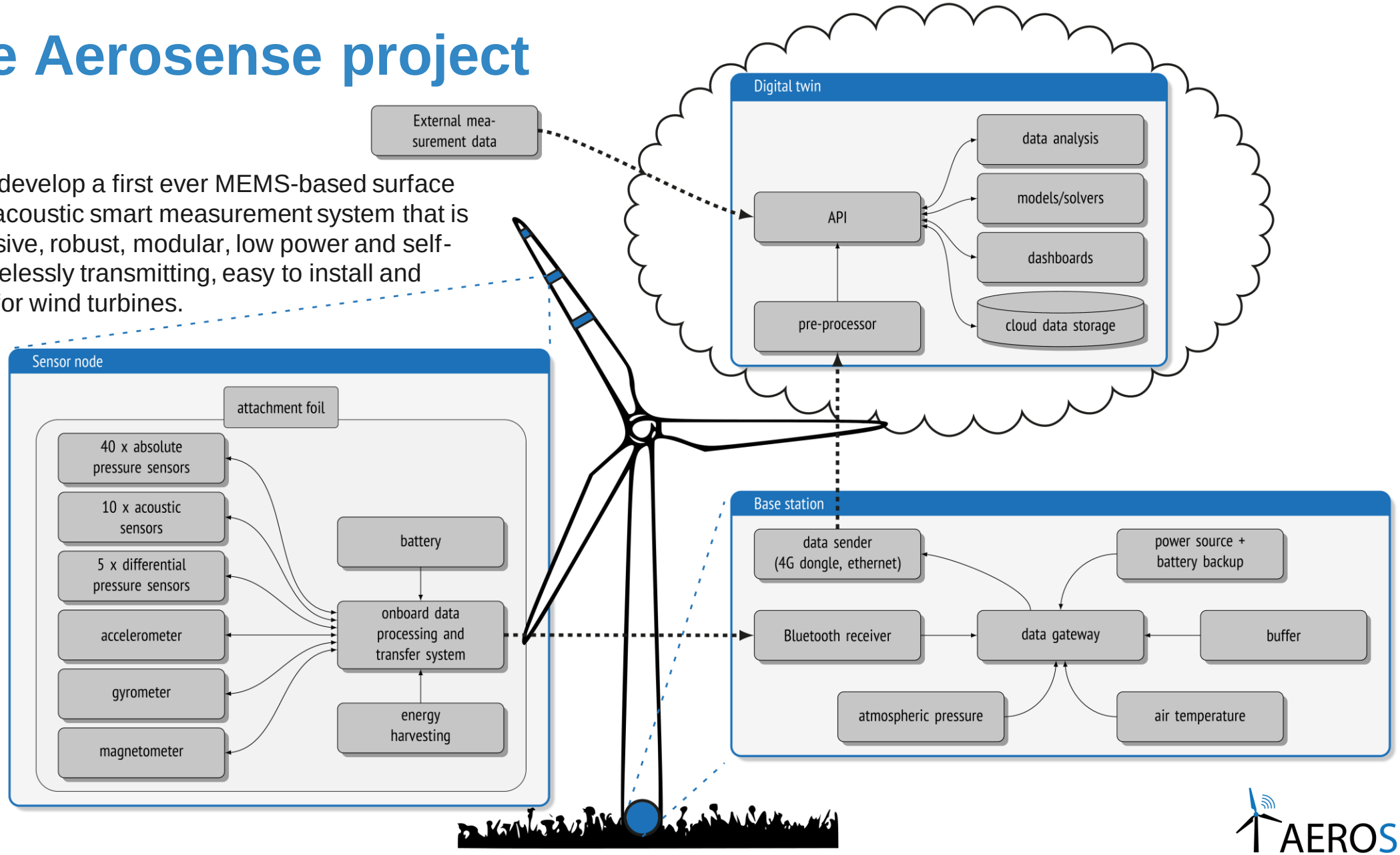
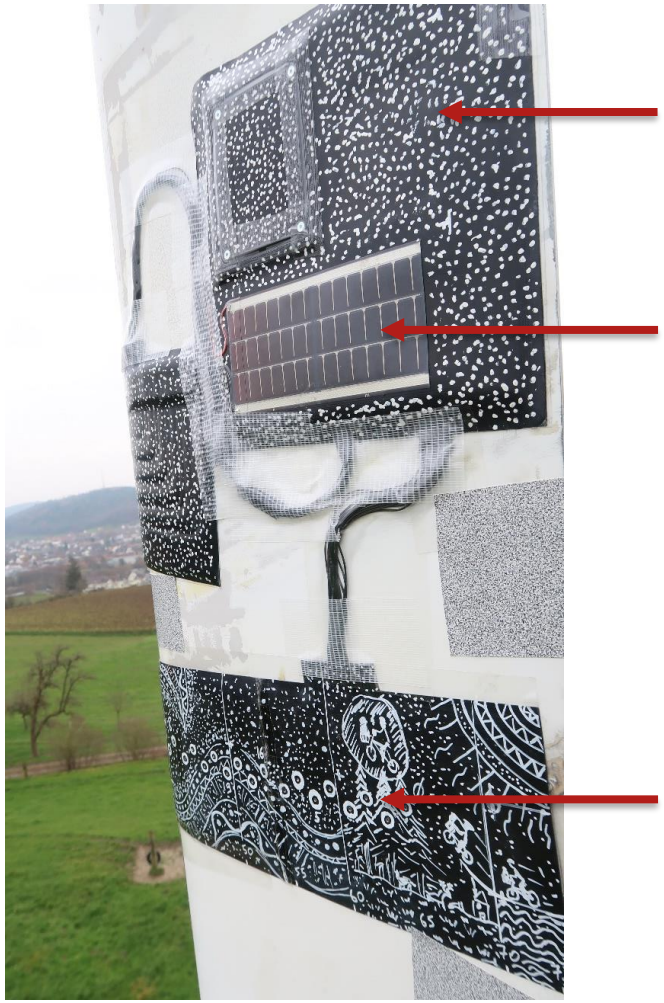
The Aerosense project

Project goal: develop a first ever MEMS-based surface pressure and acoustic smart measurement system that is thin, non-intrusive, robust, modular, low power and self-sustaining, wirelessly transmitting, easy to install and cost-effective for wind turbines.



1. Installation



Test on a 6kW wind turbine

- Simple installation process (~2h) with no damage on the blade
- Automatic measurement and data storage on a cloud
- Cheap barometers
  - **Accuracy**: 100 Pa by default.
  - **10 Pa** after thorough calibration.
- IMU: accelerometer and gyrometer
- Photogrammetry

Challenge

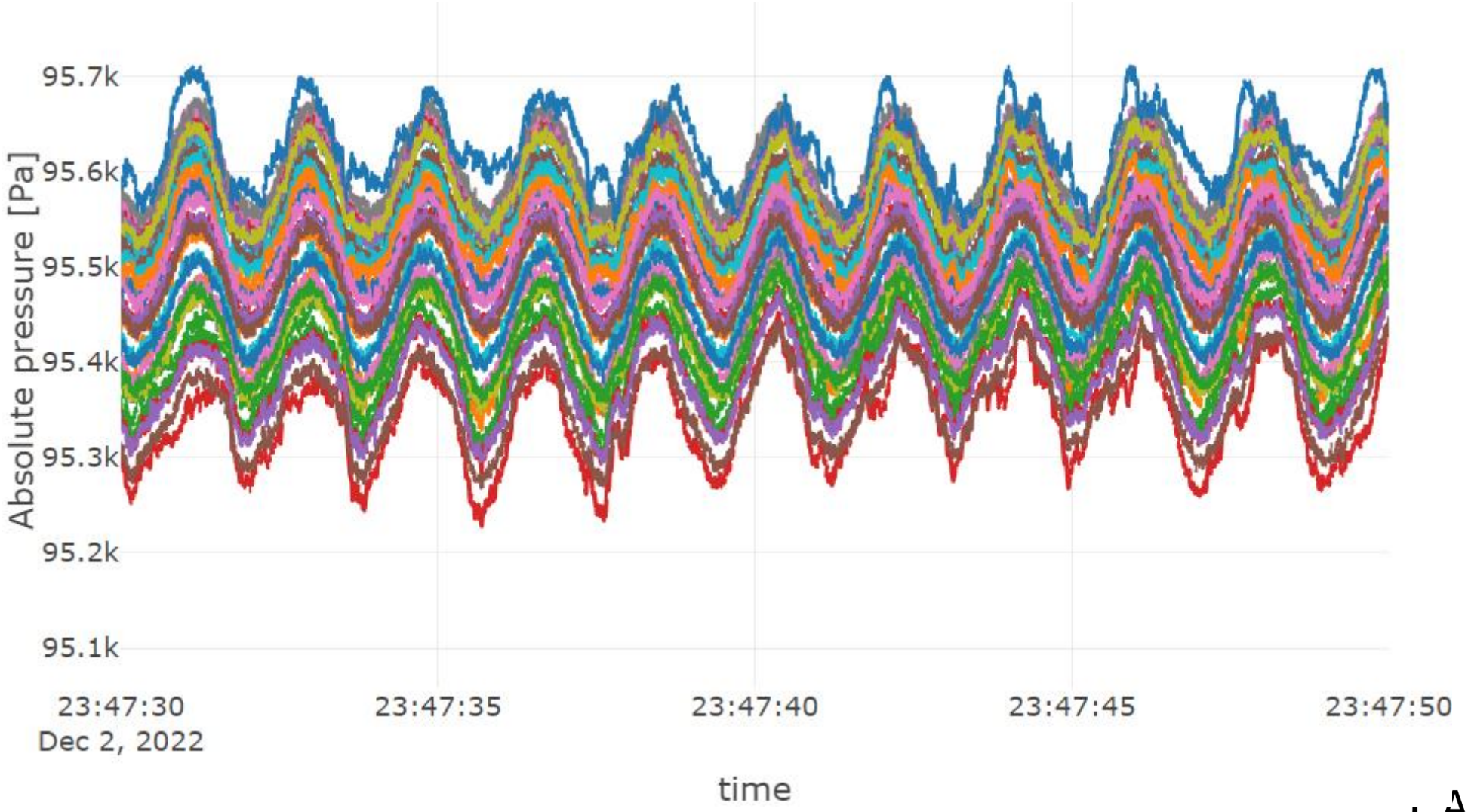
For a 5MW wind turbine

What we measure	Name	Order of magnitude	Ratio with dynamic pressure
Dynamic pressure	P_{dyn}	2’000 [200 – 7’000] Pa	1
Atmospheric pressure	P_{atm}	100’000 Pa	50
Daily atmospheric pressure variations	ΔP_{atm}	5’000 Pa	2.5
Pressure drift of barometers	ΔP_{drift}	100 Pa/year	0.05
Height variation	ΔP_{height}	800 Pa	0.4
Acceleration influence	K_{acc}	20 Pa	0.01

Challenge

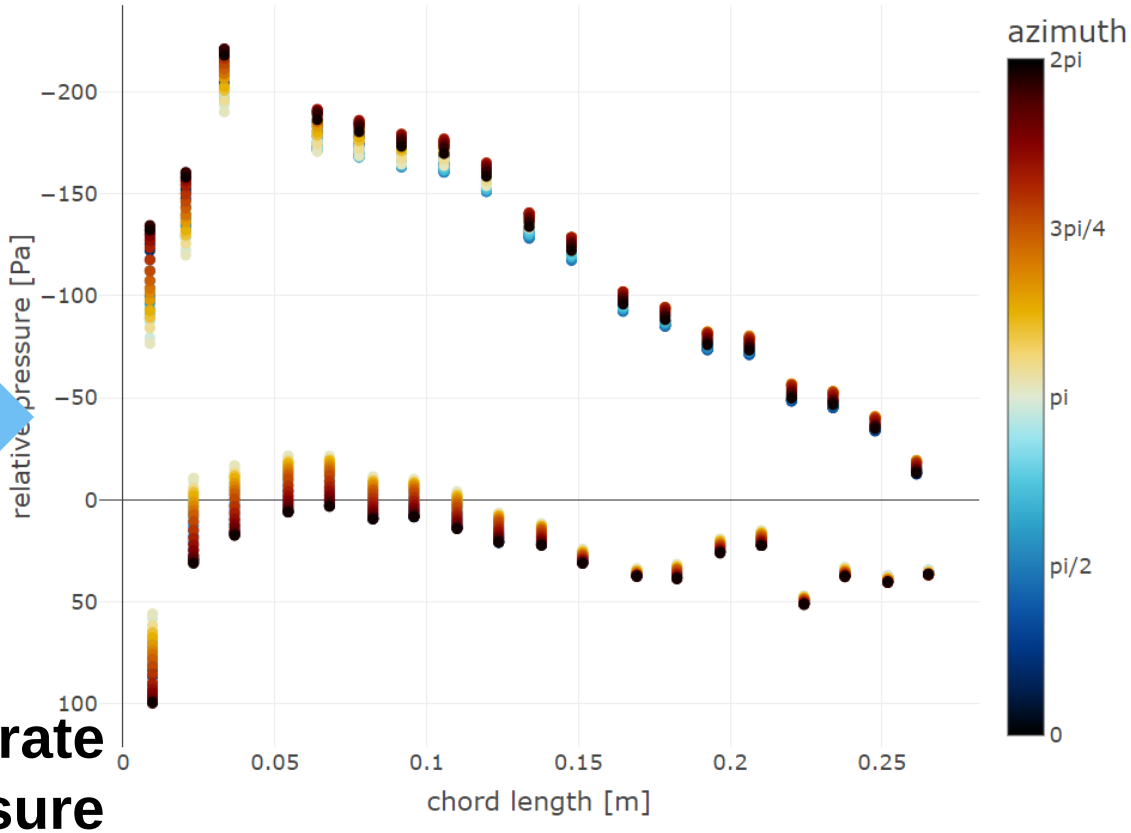
Example on a 6kW wind turbine

- blade length: 6m
- hub height: 18m



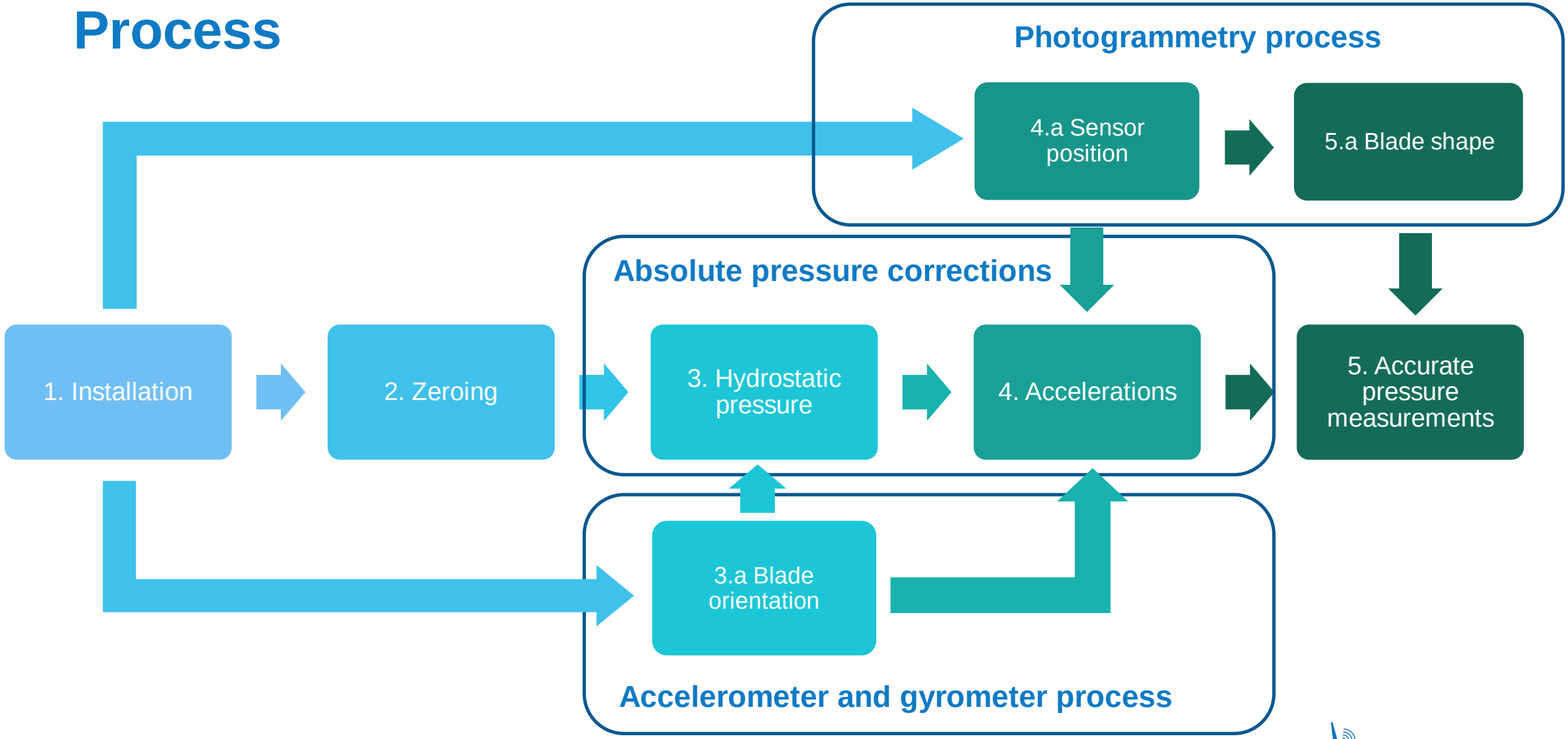
Goal

How to move from low-cost pressure sensors…



… to accurate pressure distribution on a wind turbine blade?

Process


Photogrammetry process
4.a Sensor position
5.a Blade shape
Absolute pressure corrections
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2. Zeroing
3. Hydrostatic pressure
4. Accelerations
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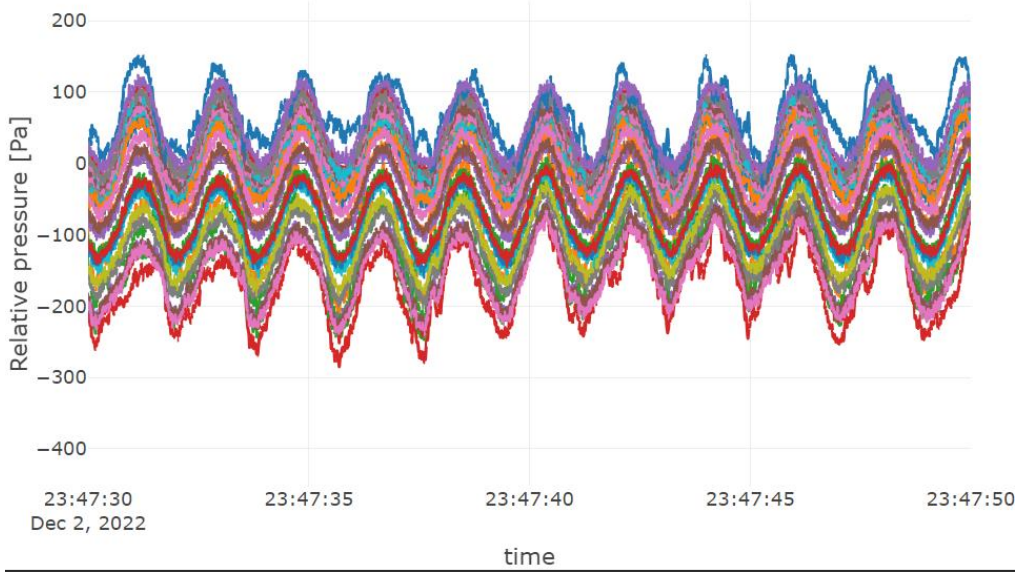
3.a Blade orientation
Accelerometer and gyrometer process

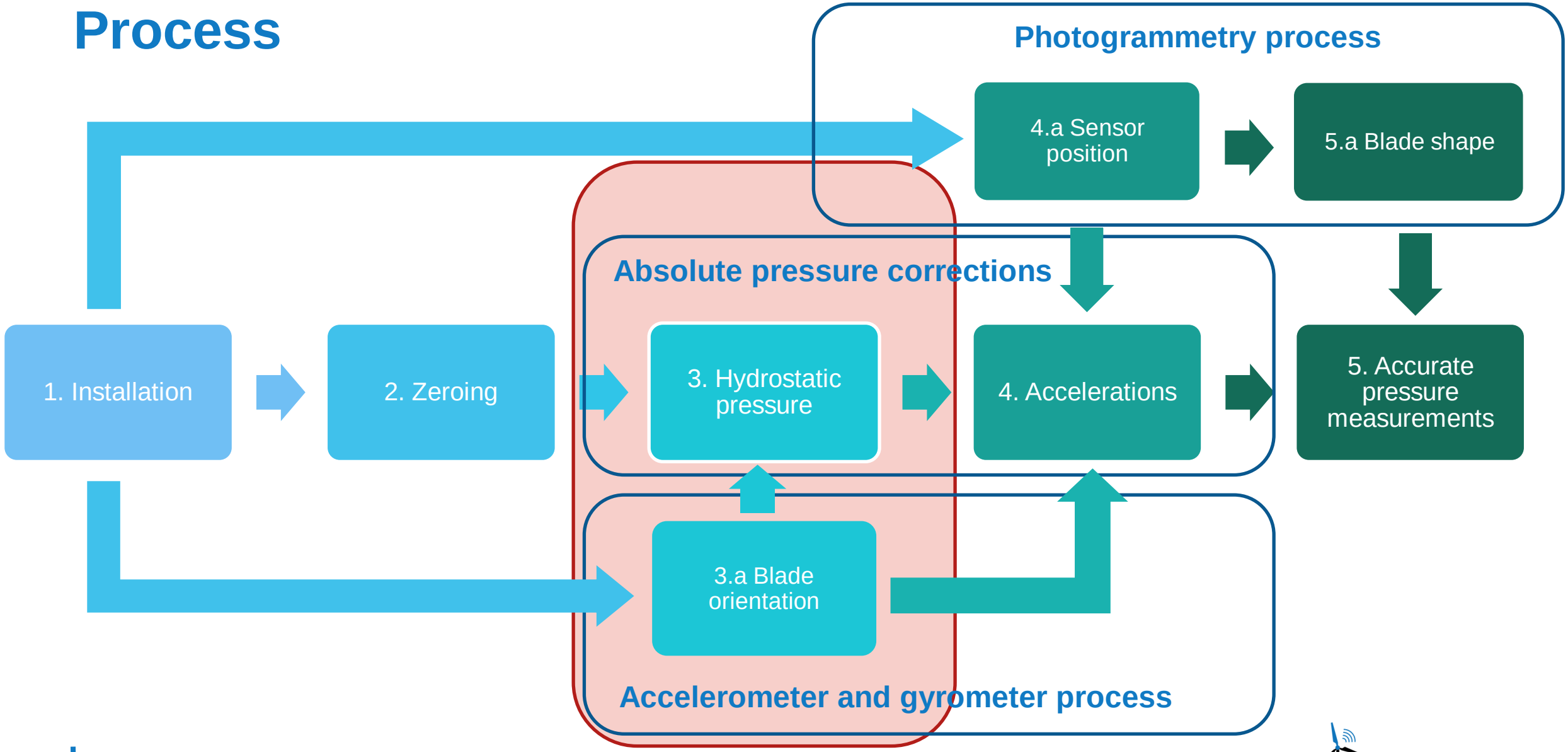
2. Zeroing correction

- Find sessions with little wind and no rotations from our database
- Relative correction of :
  - Atmospheric pressure
  - Pressure drift
- Relative difference between sensors

start	duration	mean_pressure	std_pressure	mean_temperature	gyroscope	std_acc	mean_rpm
2022-12-02 09:53:33.663631	480	95113.824876	326.935147	8.106889	[0]	0.050617	0.133815
2022-12-02 10:31:35.007711	480	95083.733127	6.482925	7.955537	[1]	0.013412	0.065113
2022-12-02 12:08:22.618608	480	95057.806414	32.226074	4.685416	[5]	0.092360	0.071528
2022-12-02 12:33:32.840333	479	95033.063217	10.201531	4.241900	[6]	0.034068	0.064507
2022-12-02 12:53:15.657502	479	95017.090737	7.006266	4.110043	[7]	0.012852	0.069223
2022-12-02 14:09:50.948549	479	95238.321433	24.455049	4.908247	[8]	0.013734	0.064297
2022-12-02 14:25:57.762371	480	95257.654980	142.454404	5.363431	[9]	2.351149	0.424414
2022-12-02 15:11:39.683384	480	94739.239758	7.033385	3.157717	[11]	0.012176	0.070494
2022-12-02 15:41:39.801353	480	94719.861944	5.208073	1.966692	[12]	0.013054	0.070970
2022-12-02 16:41:39.934881	479	94736.208188	5.660486	0.880029	[14]	0.012078	0.071347
2022-12-02 17:11:40.045713	480	94724.795245	4.923346	0.494632	[15]	0.012340	0.074264
2022-12-02 17:41:40.155745	149	94724.327813	4.524175	0.283309	[16]	0.012228	0.071891
2022-12-02 18:11:40.170866	480	94234.622836	5.853671	0.504328	[17]	0.012718	0.066860
2022-12-02 18:41:40.283832	480	94715.182081	5.702075	0.423394	[18]	0.012640	0.074765
2022-12-02 19:11:40.396008	479	94701.474600	6.003236	0.518154	[19]	0.013604	0.074647
2022-12-02 19:41:40.706974	480	94730.502776	39.908504	1.061341	[20]	5.002533	15.100004
2022-12-02 20:11:40.620222	480	94723.295231	39.916624	1.082309	[21]	4.992649	13.872053
2022-12-02 20:41:40.737368	480	94715.402428	40.888662	1.136787	[22]	5.211964	15.523809
2022-12-02 21:11:40.949848	479	94709.675919	40.979524	0.992811	[23]	5.216050	17.218507
2022-12-02 21:41:40.756255	480	94672.549734	39.165002	0.919825	[24]	5.140681	23.539741
2022-12-02 22:11:40.972521	479	94660.716321	40.559811	0.692972	[25]	5.187389	24.857924
2022-12-02 22:41:41.132717	480	94673.650613	41.947093	0.503004	[26]	5.695656	22.348665



Process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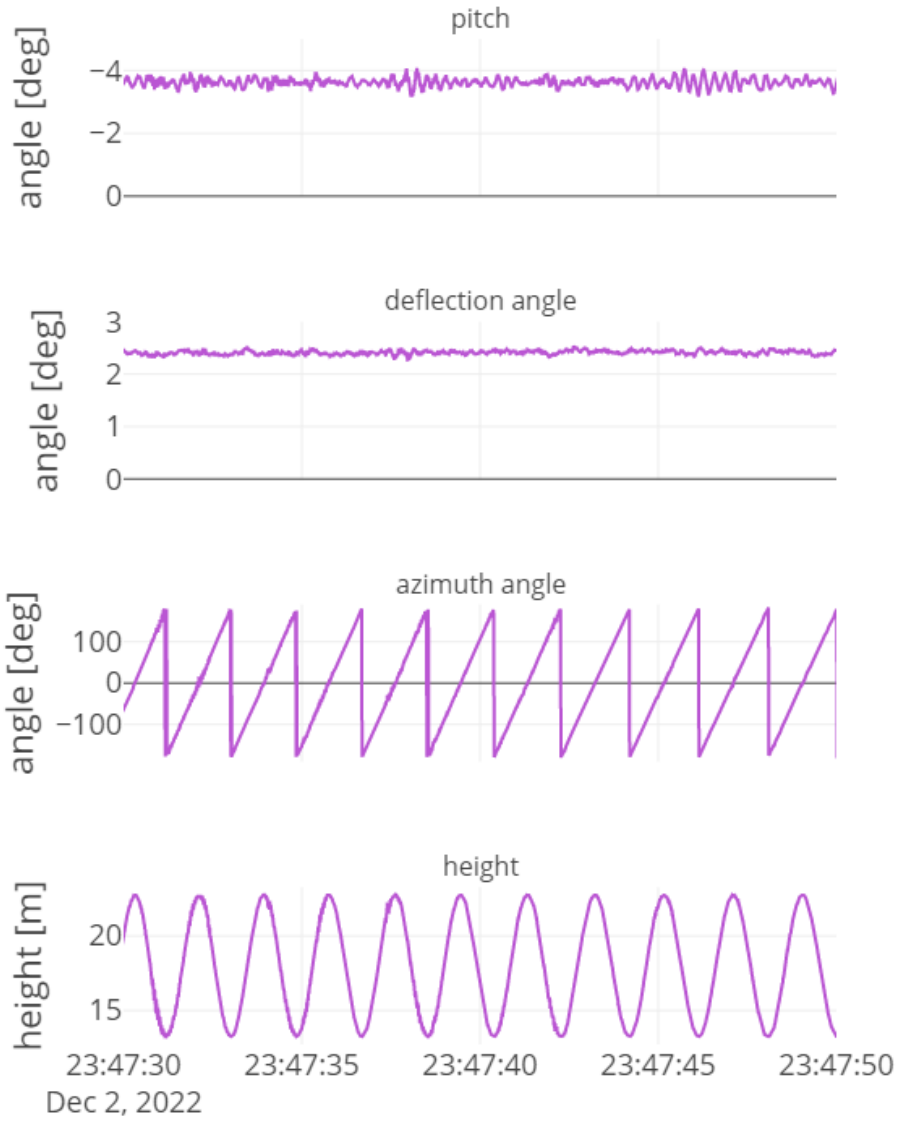
Accelerometer and gyrometer process

3. Hydrostatic pressure correction

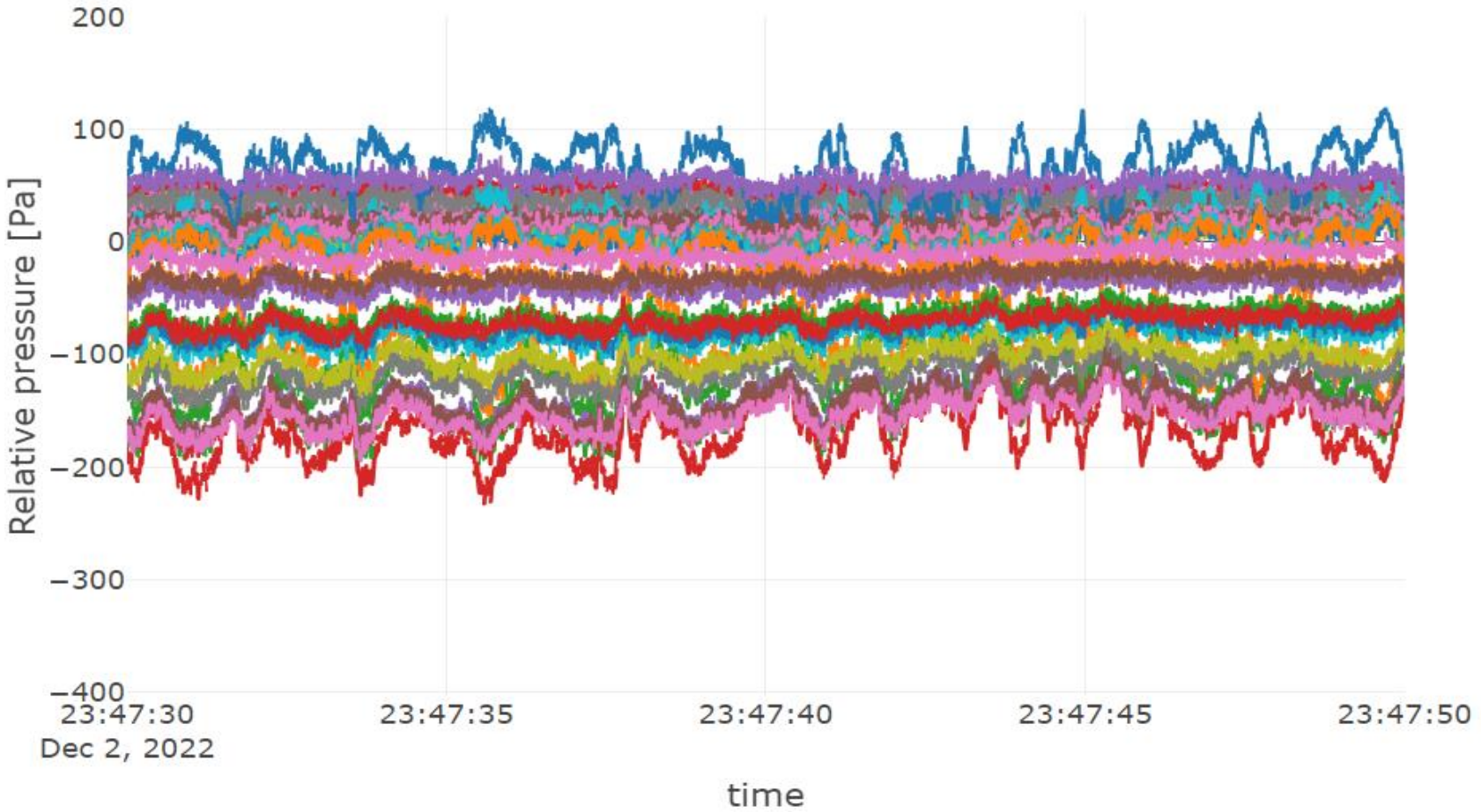
- Process of IMU data (accelerometer + gyrometer) independent of barometers
- $\Delta P_{height} \approx 100\text{Pa}\ (2\ P_{dyn})$
- Change frame of reference: rotational plane
  - Calculation of pitch and deflection angles
- Dissociate centrifugal force and gravity direction → azimuth position



3. Hydrostatic pressure correction

- So far:

$$P_i = \left(P_{measured,i} - P_{ref,i}\right) - \Delta P_{height}$$



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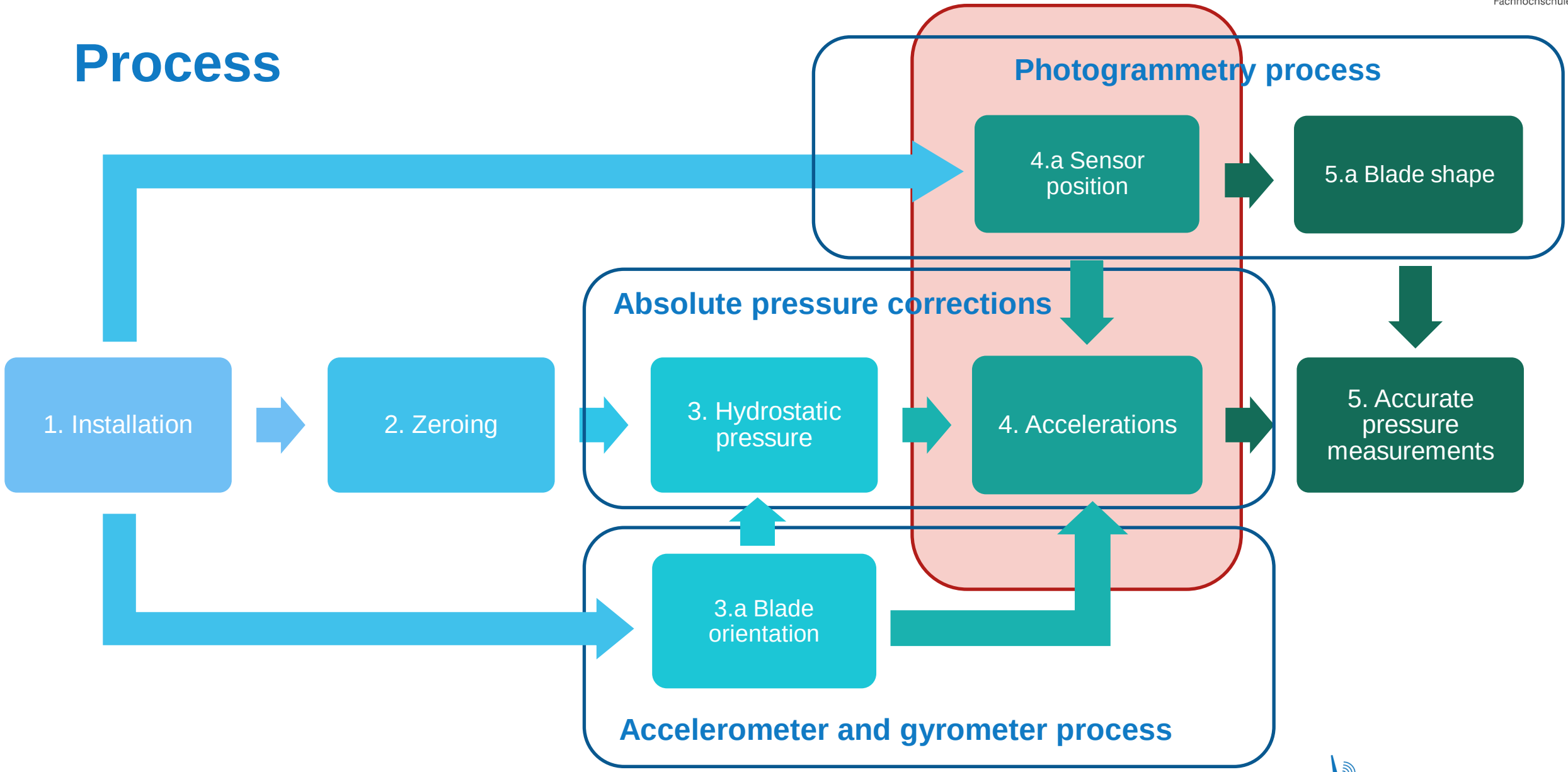
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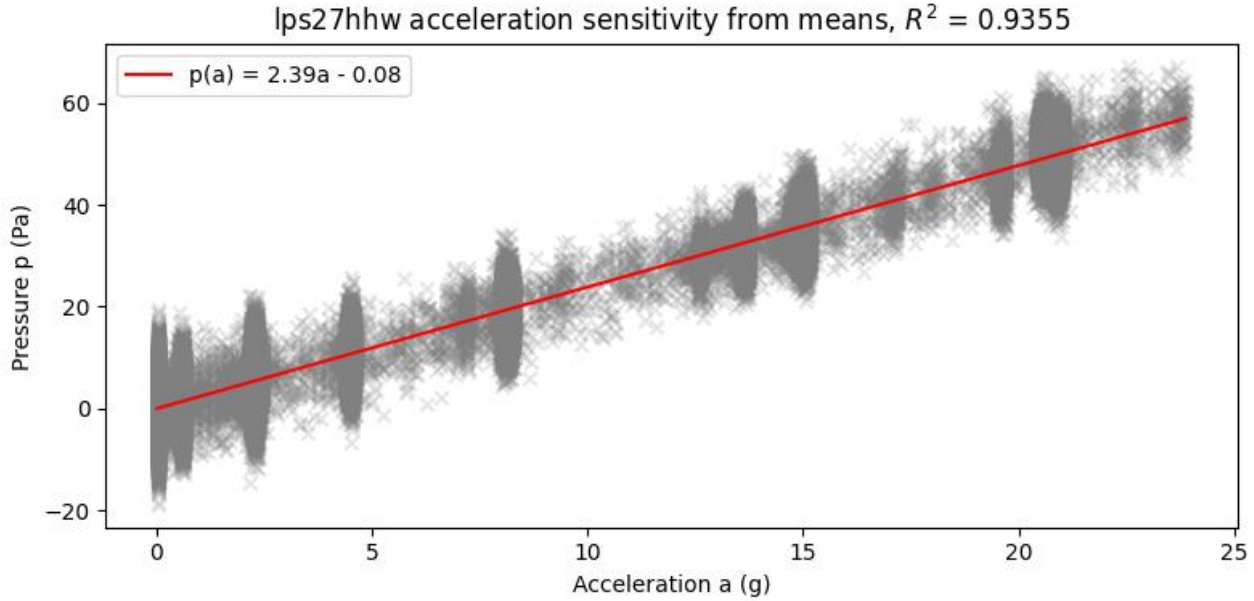
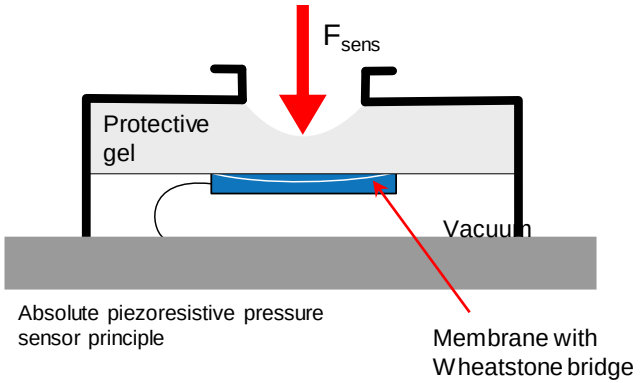
4. Acceleration corrections

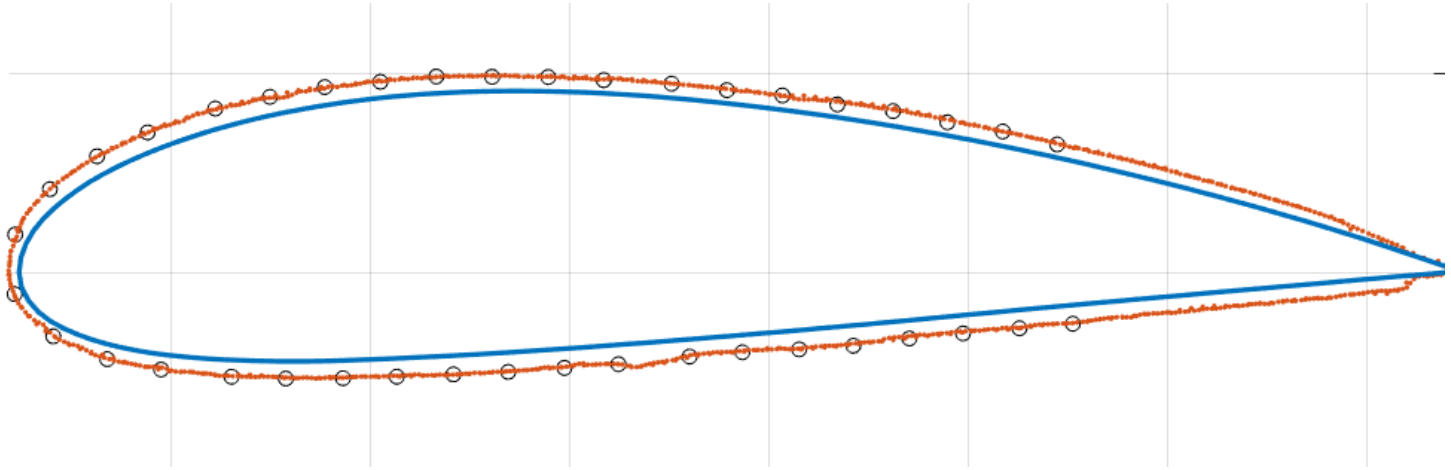
- Weight of the membrane influenced by acceleration
  - Centrifugal acceleration usually not normal to membrane.
  - But accelerations and vibrations affecting the measurements.
  - How to know position and direction of the sensors relative to accelerations?



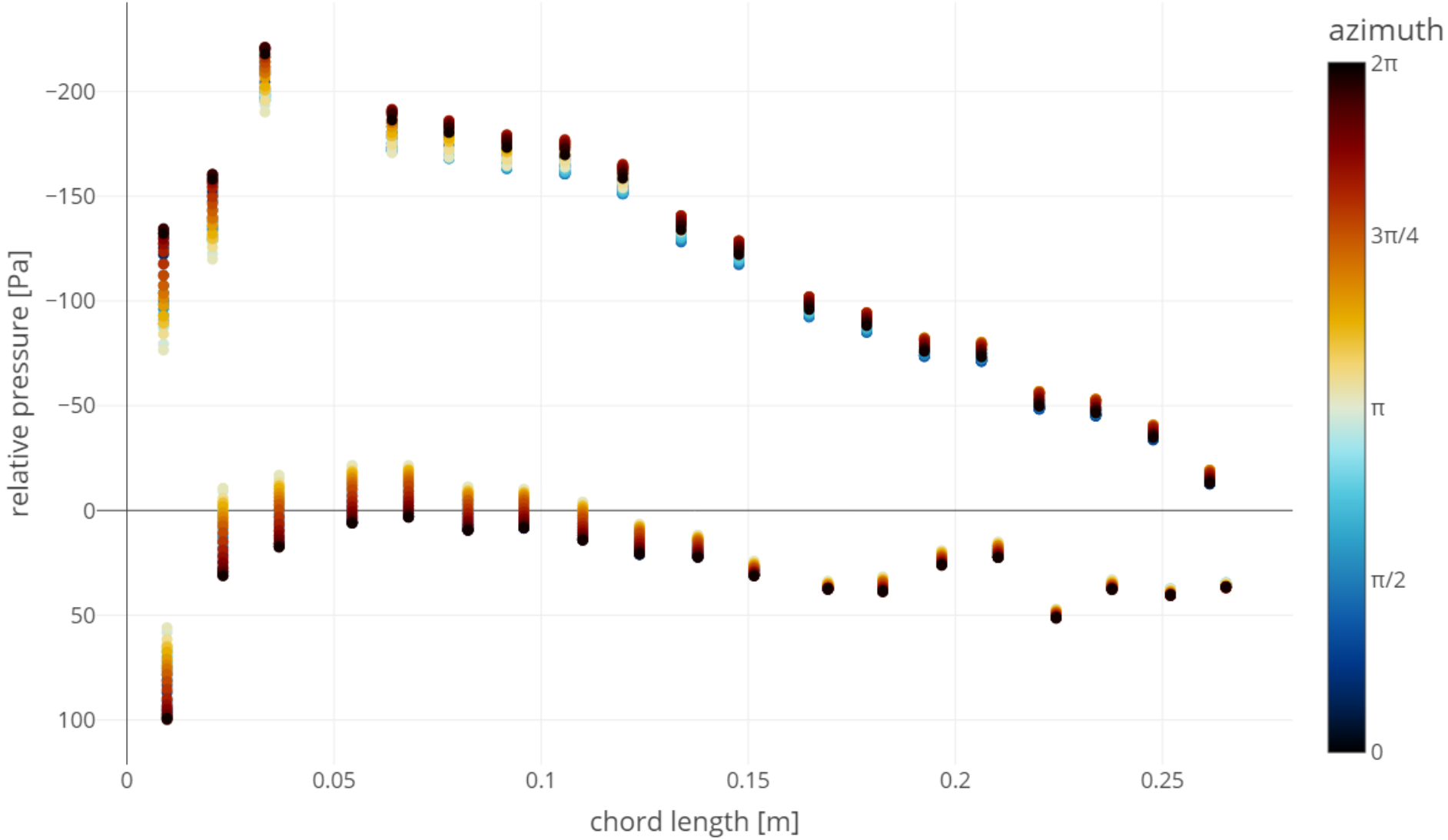


4.a Sensor position and blade shape

- Photogrammetry process when installing the sensors
- Accuracy on the 6kW wind turbine: ~1mm



5. Accurate pressure measurements



Conclusions

Absolute pressure measurements comprise:

- **Dynamic pressure P_{dyn}**

Relative zero pressure using session with no wind

- Atmospheric pressure P_{atm} $(50\ P_{\mathrm{dyn}})$
- Daily atmospheric pressure variation: ΔP_{atm} $(2.5\ P_{\mathrm{dyn}})$
- Pressure drift of the barometers ΔP_{drift} $(0.05\ P_{\mathrm{dyn}})$

Using IMU data

- Height variation: ΔP_{height} $(0.4\ P_{\mathrm{dyn}})$

Could be neglected? $(O(Precision))$

- Acceleration of the membrane ≈ K_{acc} $(0.01\ P_{\mathrm{dyn}})$

Thank you

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Find out more here:

https://aerosense.ai

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