Measurement Setup for Condition Monitoring on a Wind Turbine

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Introduction

Wind turbines are the dominant player of renewables energies in Germany and contributed more than 20% to the domestic net electricity production in 2021. At installation, the turbine receives an operation approval for 20 years. Condition monitoring can support the quality inspection and help to extend the approval, based on the determined residual useful life. Prolonged operation lowers the electricity generation costs and saves natural resources such as building materials.

Measurement Setup

The measurement setup consists mainly of a high-performance edge computer that is connected to measurement modules over UART (optic cable) and network over ethernet and Wi-Fi that covers the whole turbine.

Acceleration, strain, tilt, real-time kinematics and temperature sensors are installed throughout the tower and are further processed (see Coordinate Systems and Displacement Calculation), stored as binary data and distributed in real-time over MQTT.

Methods

Several types of independent sensor nodes are installed at a wind turbine for Structural Health Monitoring:

- Wired acceleration sensors with high sampling frequency and direct link to PC
- Battery-powered wireless acceleration sensors with micro-g resolution and compressed data transmission for low energy consumption
- Conventional strain gauges as well as FBG fiber-optic strain gauges
- Temperature sensors, seismometer, tilt sensors
- RTK real-time kinematic sensor
- Edge computing devices are available throughout the tower
- Network connection (Ethernet and Wi-Fi) is available in the whole turbine
- Real-time distribution of measurement data through platform independent data transfer

Results

By comparison and fusion of all independent recordings, the monitoring reliability is optimized. As tower and rotor blades form a coupled system, filtering the rotor bandwidths and blade passing bandwidths indicates changes of imbalance, most probably caused by ice growth.

Displacement Calculation

Based on acceleration data, displacement is calculated using two different techniques of numerical trapezoidal integration and integration in frequency domain. For batch processing, both methods perform without any issues.

Comparison of calculated displacement with simulated displacement and processed data of real-time kinematic shows the exact matching data as shown in figure 1.

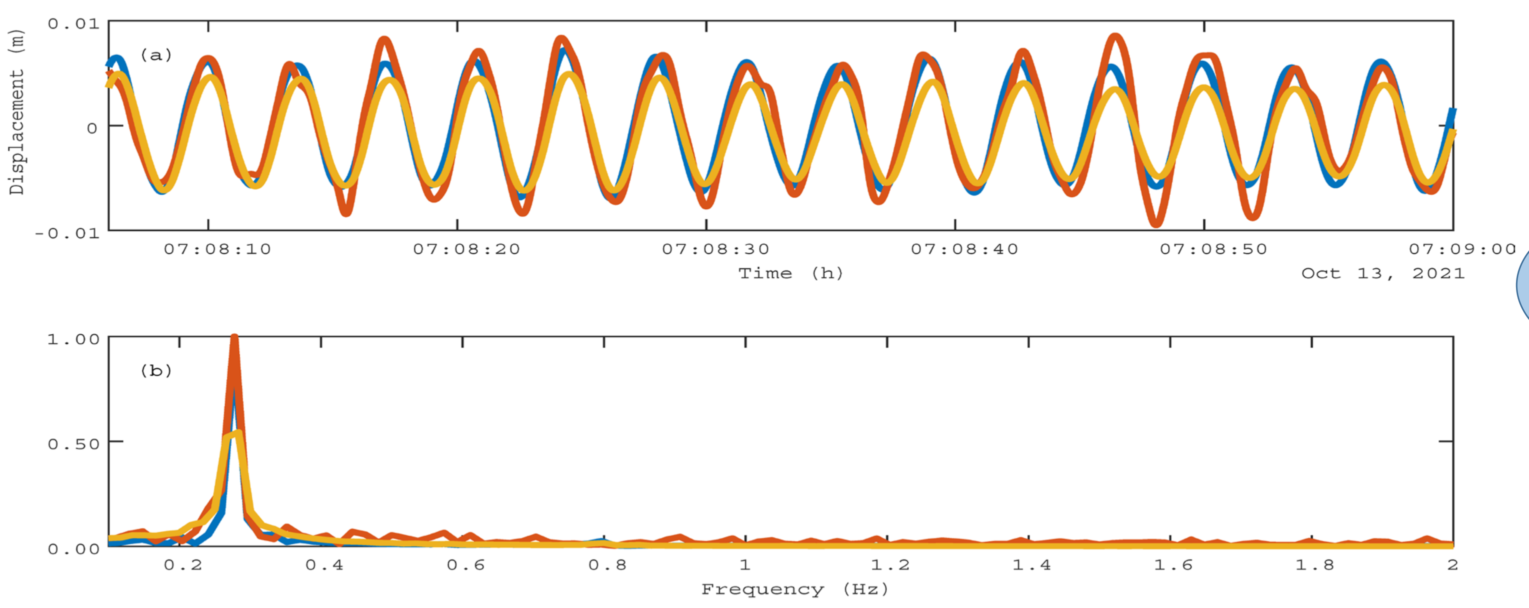
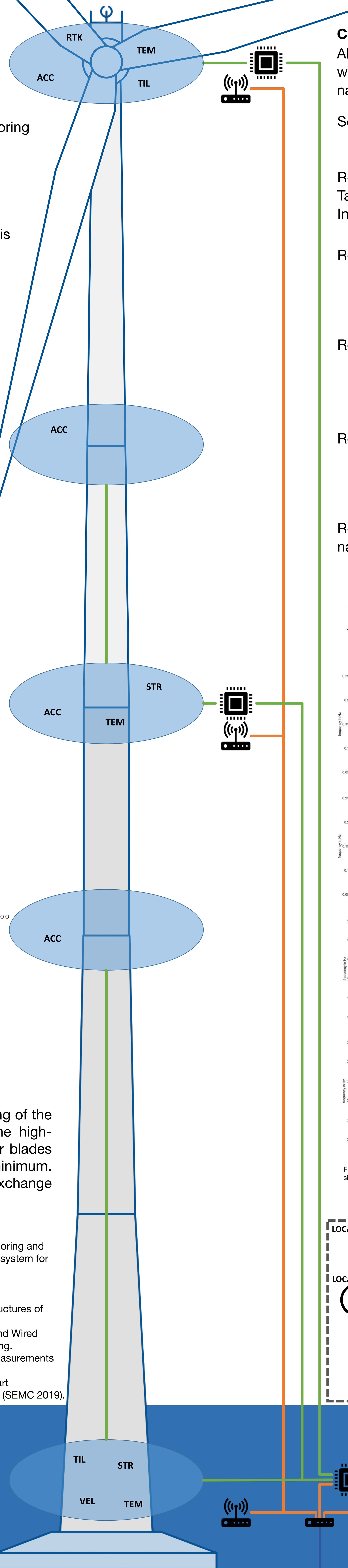


Figure 1. Comparison of dynamic displacement calculated using the three different approaches of vibration-based displacement in frequency domain (blue), processed RTK data (orange), and external forces based simulated displacement (yellow) [1]
(a) Comparison of time series.
(b) Normalized frequency spectra of the data sets with peaks at first bending Eigenfrequency of approximately 0.27 Hz.

Conclusion and outlook

The extensive monitoring system enables a sophisticated structural health monitoring of the wind power plant and supports the analysis of remaining lifetime. Moreover, the high-resolution acceleration sensors inside the tower can detect ice growth on the rotor blades and validate the ice alerts of the plant's SCADA system, limiting downtimes to the minimum. The fusion of all recorded data allows the setup of a digital twin by automatic exchange between a FEM model and the monitored turbine.



Coordinate Systems

All sensor data are converted to common coordinate systems, which allow an evaluation in tower coordinates or related to the nacelle position.

Sensor Fixed $\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \begin{pmatrix} E \\ N \\ Z \end{pmatrix}$

Tower Fixed $\begin{pmatrix} x \\ y \\ z \end{pmatrix}$

Nacelle Fixed $\begin{pmatrix} \xi \\ \eta \\ \zeta \end{pmatrix}$

Rotation Matrix determination
Tait-Bryan angles are used as composed elemental rotations. Intrinsic sequence X-Y'-Z" is used.

Rotation (α) around X-axis

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = R_X(\alpha) \begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix}$$

$$R_X(\alpha) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix}$$

Rotation (β) around Y'-axis

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = R_{Y''}(\beta) \begin{pmatrix} X'' \\ Y'' \\ Z'' \end{pmatrix}$$

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$$R_{Z''}(\gamma) = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Rotation Matrix to convert sensor fixed coordinates to tower and nacelle fixed coordinates

$$R_{S\to T} = R_{Z''}(\gamma) R_{Y'}(\beta)\, R_X(\alpha)$$

$$R_{S\to T} = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix}$$

$$R_{S\to T} = \begin{pmatrix} \cos\beta\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma \\ \cos\beta\sin\gamma & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma \\ -\sin\beta & \sin\alpha\cos\beta & \cos\alpha\cos\beta \end{pmatrix}$$

$$R_{S\to N} = \begin{pmatrix} \cos\beta\cos\gamma\cos\theta + \sin\alpha\sin\beta\cos\gamma\sin\theta - \cos\alpha\sin\gamma\sin\theta & -\cos\beta\cos\gamma\sin\theta + \sin\alpha\sin\beta\cos\gamma\cos\theta - \cos\alpha\sin\gamma\cos\theta & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma \\ \cos\beta\cos\gamma\cos\theta + \sin\alpha\sin\beta\sin\gamma\sin\theta + \cos\alpha\cos\gamma\sin\theta & -\cos\beta\cos\gamma\sin\theta + \sin\alpha\sin\beta\sin\gamma\cos\theta + \cos\alpha\cos\gamma\cos\theta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma \\ -\sin\beta\cos\theta + \sin\alpha\cos\beta\sin\theta & \sin\beta\sin\theta + \sin\alpha\cos\beta\cos\theta & \cos\alpha\cos\beta \end{pmatrix}$$

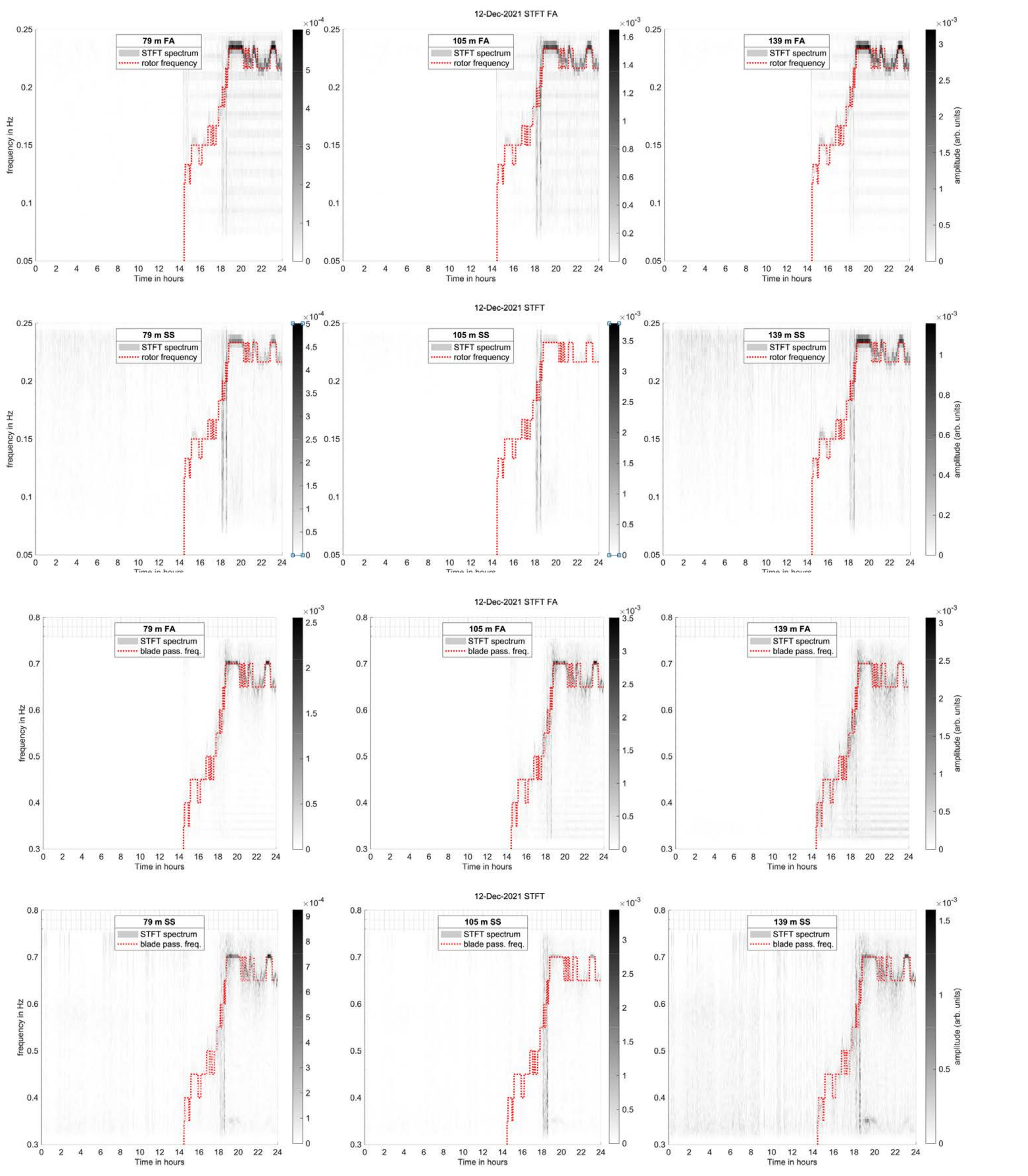
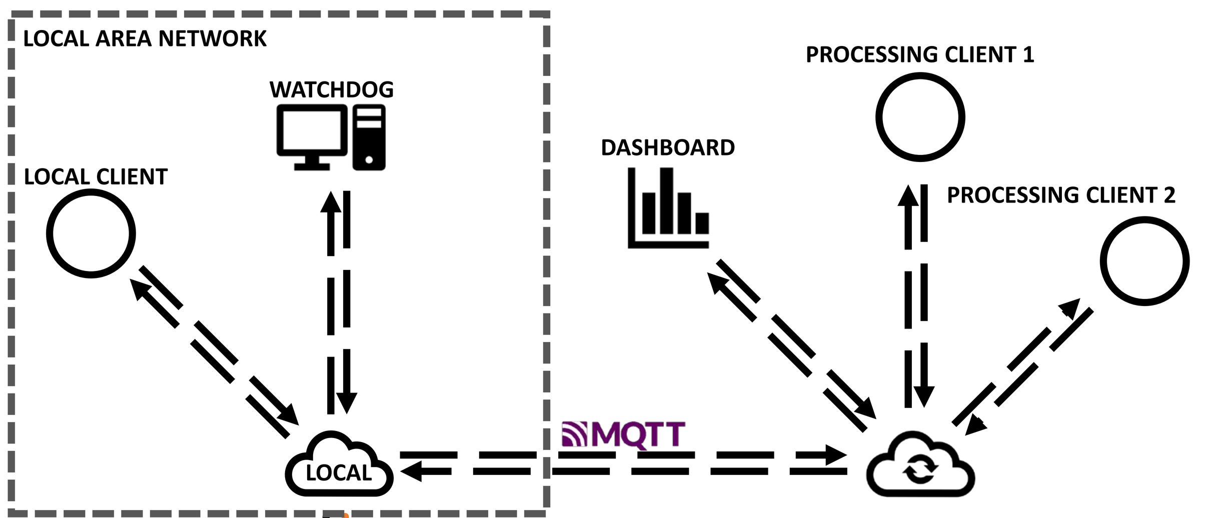


Figure 2: Short-time Fourier transfer frequency spectra on platforms at 79m, 105m and 139m, on Dec. 12, 2021, in fore-aft (FA) and side-side (SS) direction, after filtering to rotor frequency resp. blade passing frequency bandwidth.



Acknowledgement

We thank the German Federal Ministry for Economic Affairs and Energy for funding the projects MISTRALWind (Monitoring and Inspection of Structures At Large Wind Turbines) and IM Wind (Development of a sensor-based intelligent monitoring system for wind turbines).

References

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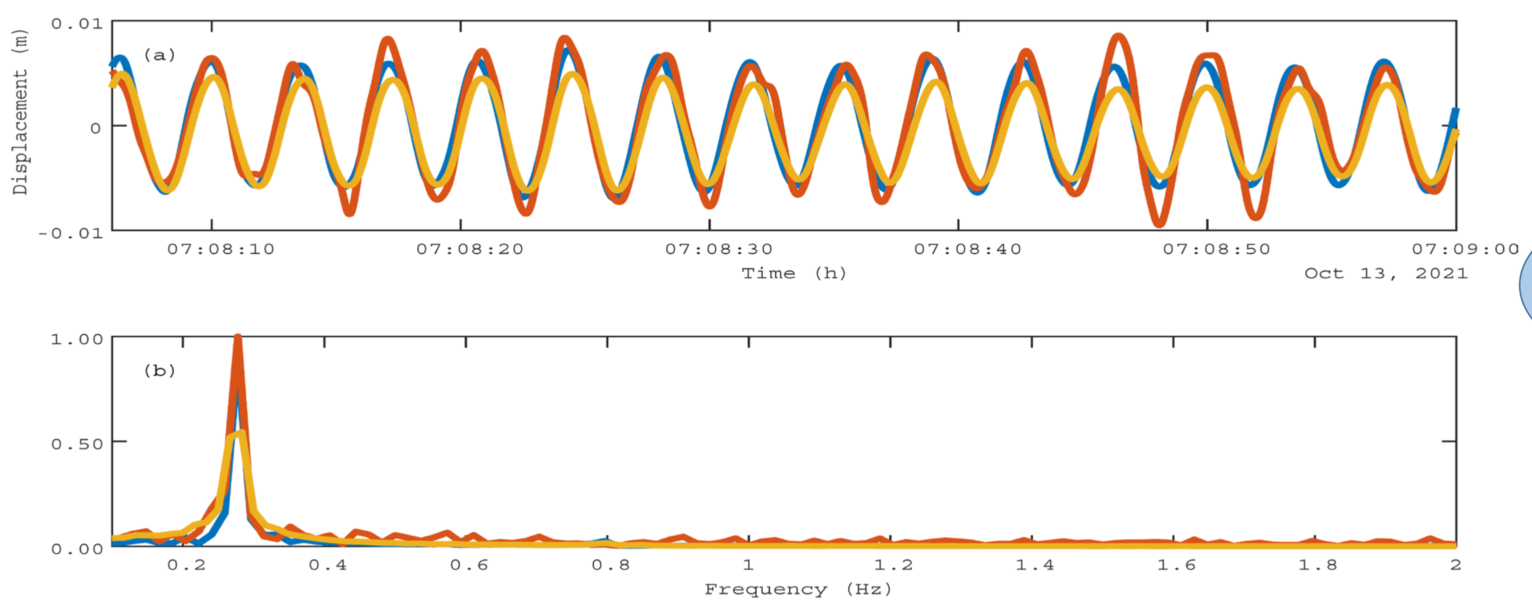

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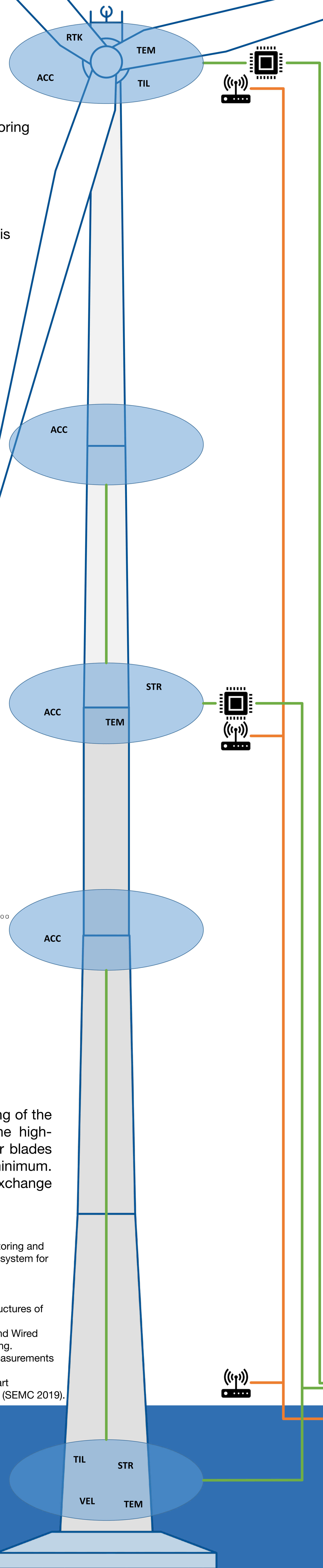

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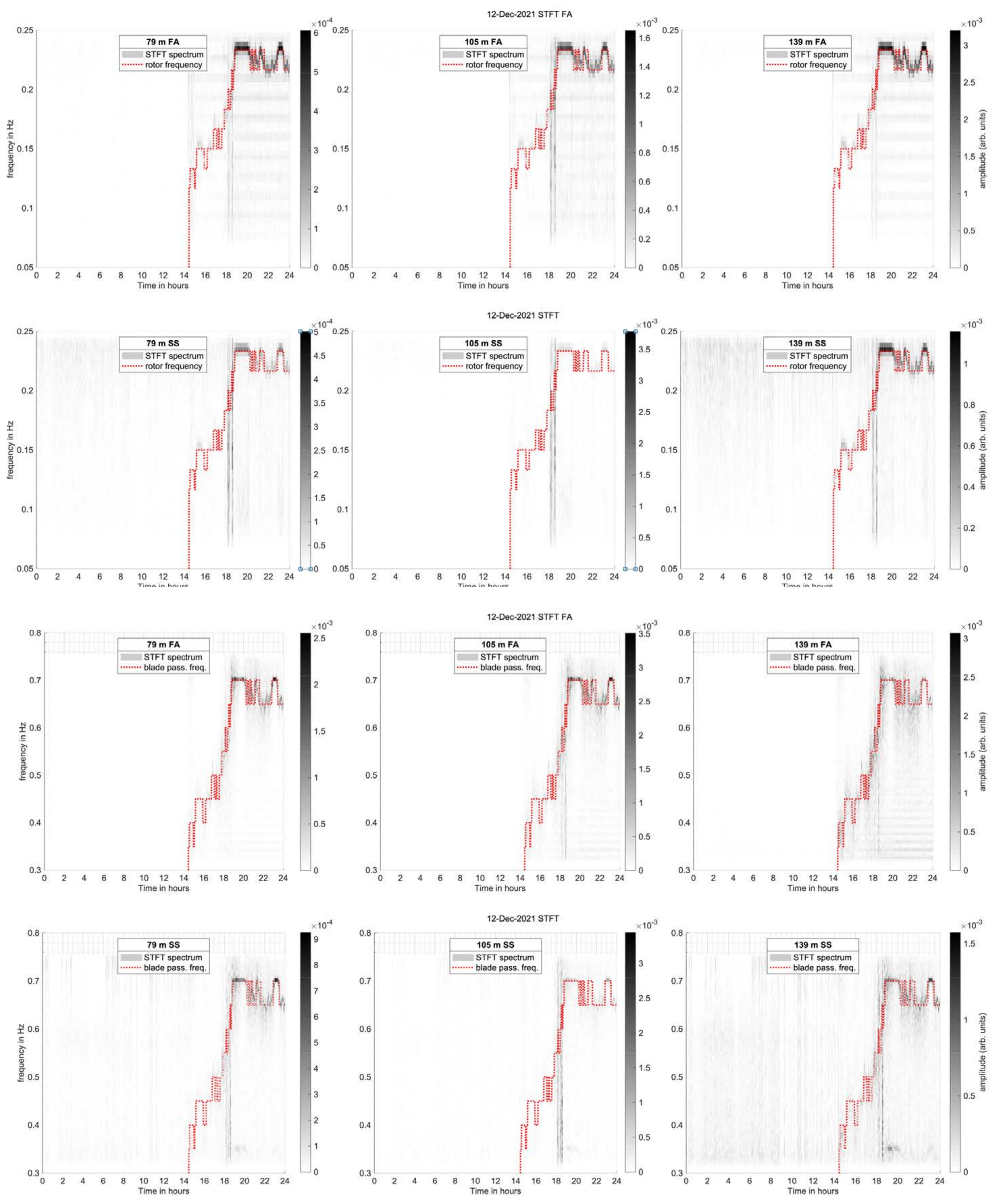

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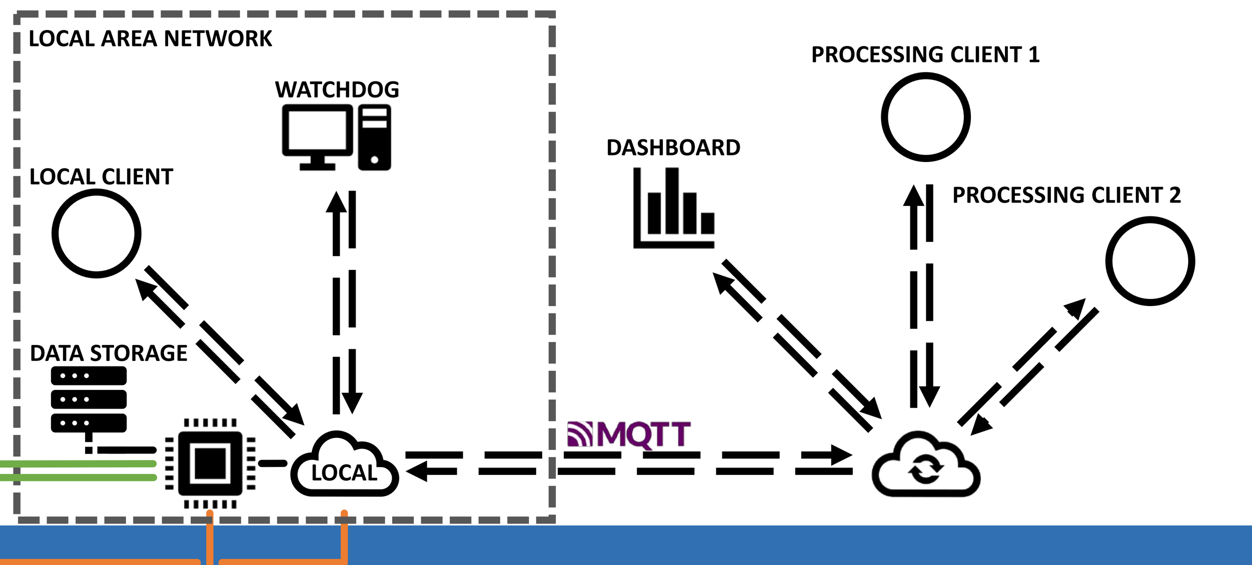

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