Acoustic Emission 24/7/365 remote monitoring of W/Ts

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PRESENTATION STRUCTURE

PART A

1. OVERVIEW of MG
2. OVERVIEW of W/T Apps
3. SENSORIA BLADES MONITORING – APP OVERVIEW

PART B

1. BACK to BASICS
2. SENSORIA Details
3. TOWER MONITORING

Presenter Background in Wind Energy

Back in 1996 @ Center of Renewable Energy Sources

>25 years ago @ Physical Acoustics Corp & Envirocoustics ABEE (now Mistras Group) participated in JOULE AEGIS and other EU funded projects

WORK PRESENTED TODAY IS MAINLY a COMPILATION of MISTRAS GROUP HELLAS RESEARCH and DEVELOPMENT the past 20 + years and the STATE of THE ART NEW PRODUCTS from MISTRAS GROUP in the Field of AE remote monitoring of W/Ts

CREDITS TO MISTRAS GROUP R&D, ENGINEERING DEPARTMENT, FIELDS SERVICES and PRODUCTION (H/W & S/W)

MISTRAS Group

MISTRAS' asset protection solutions support clients with cutting-edge, technology-driven mitigation of risks.

- **VISION**
  Be the **integrated-solution partner** to solve civilization's unmet asset protection needs

- **MISSION**
  We will deliver value by developing, integrating, and executing asset protection solutions that **maximize uptime and safety**

- Founded in **1978**
- NYSE: **MG**; IPO in 2009
- Global HQ in Princeton, NJ - USA
- **Over 106 Locations Worldwide**
- Over **5,000** Employees

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Certain industries operate in some parts of the world more than others. With locations all over the globe, we have the ability to operate wherever our customers are.

- OIL & GAS
- AEROSPACE & DEFENSE
- INFRASTRUCTURE
- POWER
- MANUFACTURING

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Individual spot inspections all the way up to evergreen inspection program management and execution

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Complementary light mechanical services to clean and repair assets after damages are discovered in inspections

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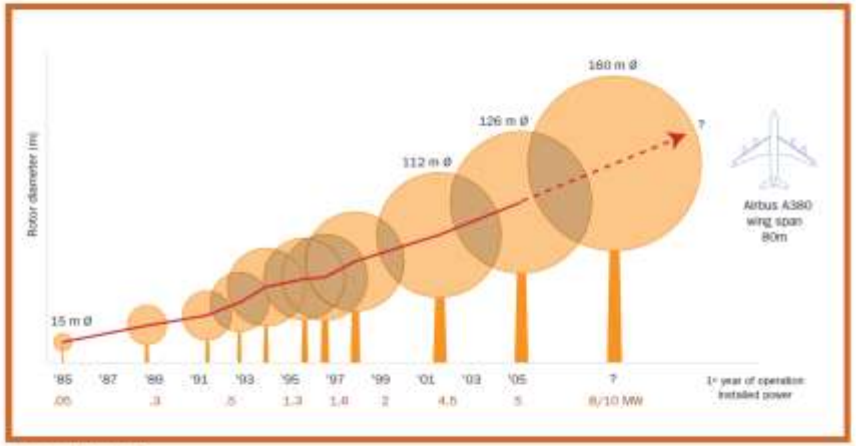
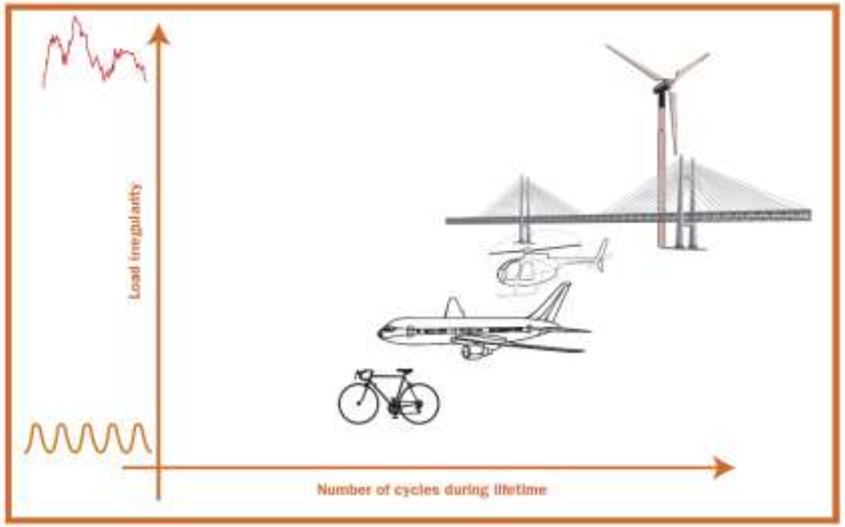
WIND ENERGY IS AN EMERGING AND FAST GROWING MARKET – OPPORTUNITIES & CHALLENGES



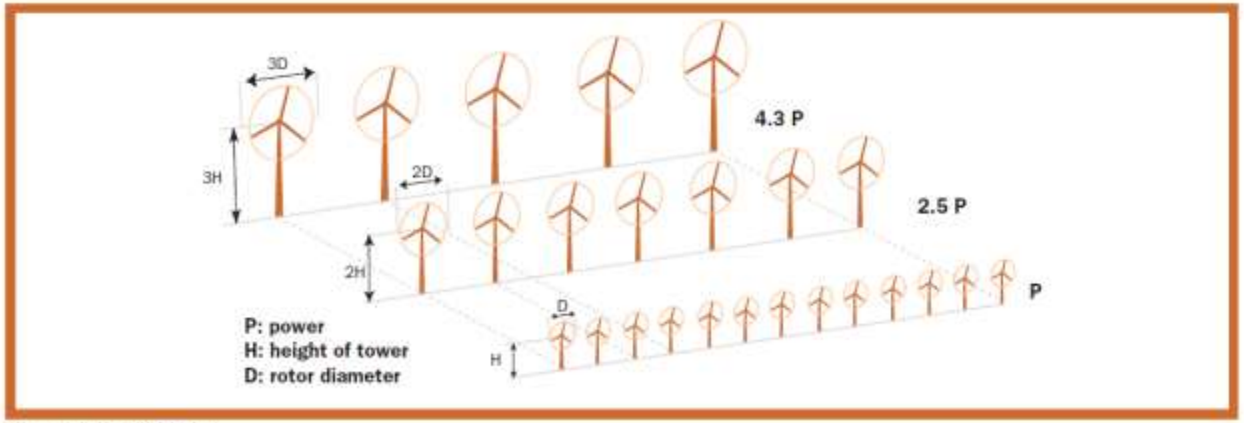
Source: Jos Beurskens, ECN

The fatigue loading of a wind turbine during its life time is large compared to examples bridges, helicopters, airplanes and bicycles.



Source: WMC (TU Delft ECN)

Depending on the roughness of the terrain, the total capacity of a line cluster is more than proportional to the size of the rotor. This is one reason to install wind turbines as large as possible.



Source: Jos Beurskens, ECN

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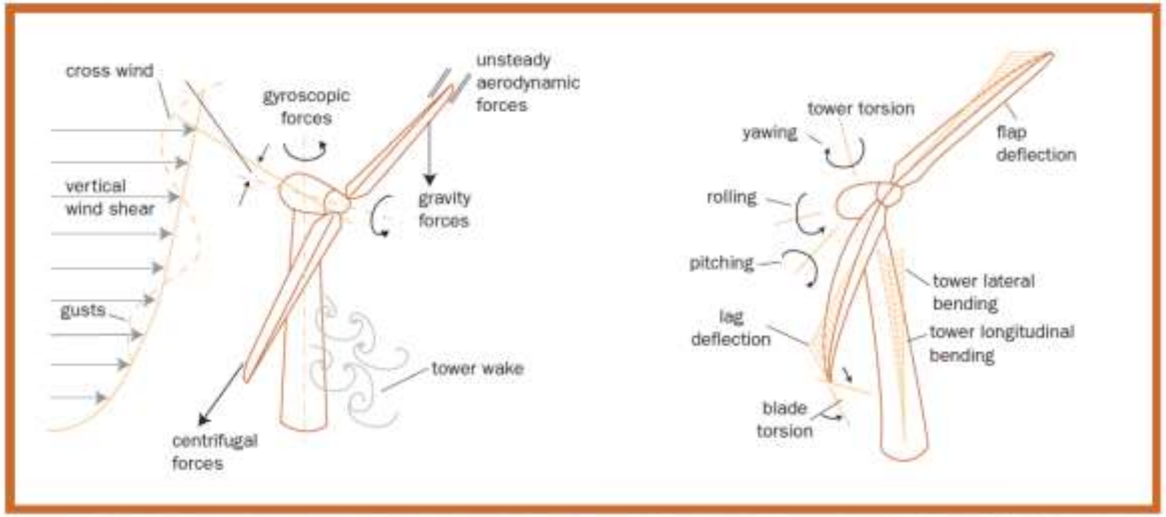
WIND ENERGY IS AN EMERGING AND FAST GROWING MARKET – OPPORTUNITIES & CHALLENGES

On the left all external dynamic forces are indicated that expose a turbine to extreme fatigue loading. On the right the various vibration and deflection modes of a wind turbine can be seen. From the dynamic point of view a wind turbine is a complex structure to design reliably for a given service life time.



Source: Kießling, F: *Modellierung des aeroelastischen Gesamtsystems einer Windturbine mit Hilfe symbolischer Programmierung*. DFVLR-Report, DFVLR-FB 84-10, 1984.

APPLIED REMOTE MONITORING SOLUTIONS IN WIND INDUSTRY

- ENVIRONMENTAL MONITORING IS WELL DEVELOPED AND APPLIED IN WIND INDUSTRY
- ELECTRICAL & OPERATIONS PARAMETERS MONITORING IS WELL DEVELOPED AND APPLIED IN WIND INDUSTRY
- SHM (STRAIN & VIBRATION) IS WIDELLY APPLICABLE THE PAST 20years in WIND INDUSTRY Together with WEATHER MONITORING STATIONS
- SCADA SYSTEMS & ADVANCE CONTROL ROOMS FOR REMOTE MONITORING WIDELY AVAILABLE

AE IS A POTENTIAL SOLUTION TO MANY OF THE SHM AND NDT NEEDS IN WIND INDUSTRY

THE KEY QUESTION IS WHAT IS THE SUCCESS PATH TO SOLVE INDUSTRY NEEDS

Structural Health Monitoring - SHM

- Structural health monitoring involves the periodically measurement and analysis of a data from a structure to detect damage to its components, material and/or changes to its geometric properties.

- Traditionally the method to inspect and ensure integrity of a structure during its service life is to periodically perform visual inspection. Now days drones are engaged for this purpose. This works only in cases where degradation is visible on the surface and provided access for close up is possible.
- However, in the majority of cases the degradation is not visible.
- Currently there are numerous sensing technologies that are used for structural health monitoring of critical infrastructures, most do not detect damage directly but indirectly (strain, displacement etc.)
- Acoustic Emission (AE) monitoring is used for inspection of larger areas in order to detect cracks and defects. AE is a direct damage detection method.

THE PROBLEM OF TIMELY and EARLY DAMAGE DETCTION, CHARACTERIZATION and PROPAGATION REMAINS.

TRADITIONAL STRAIN and DISPLACEMENT MEASUREMENTS CANNOT PROVIDE ANSWER

ACOUSTIC EMISSION MONITORING is a PROMISING ALTERNATIVE if ….

APPLIED CORRECTLY

AE & MG & MGH History IN WIND INDUSTRY

- AE is Well Proved for Testing Composite Materials
- MG Has Long Experience in AE Testing of Composites
- MG is a Pioneer in AE testing of W/T Blades

- >25ys / SINCE 1998 LABORATORY AE FULL SCALE BLADE TESTING
- >20ys / SINCE 2000 ON LINE AE BLADE MONITORING
- >25ys / SINCE 1998 MACHINE LEARNING AND ADVANCED AE DATA ANALYSIS SOLUTIONS

- AE as SHM technique is well suited for PDM od Rotating parts
- MG has Long Experience in AE Testing of Slow Speed Bearings, Couplings and Gear Box

- APPLIED IN BOTH RESEARCH AND OPERATING LEVEL
- MARKET EXPERIENCE FROM AZIPODS – HELLICOPTERS DRIVE AND OTHER ROTATING APPS

- AE is Well Proved for Fatigue Crack Monitoring of Metal Structures
- MG Has Long Experience in AE Fatigue Crack Monitoring

- REMOTE MONITORING OF OFSHORE STRUCTURES AND W/T TOWERS

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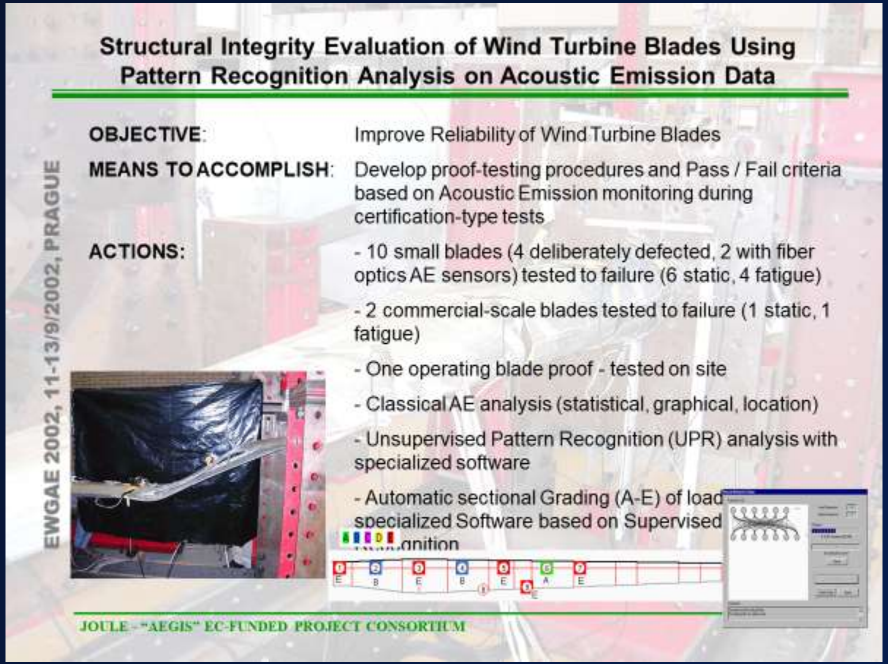
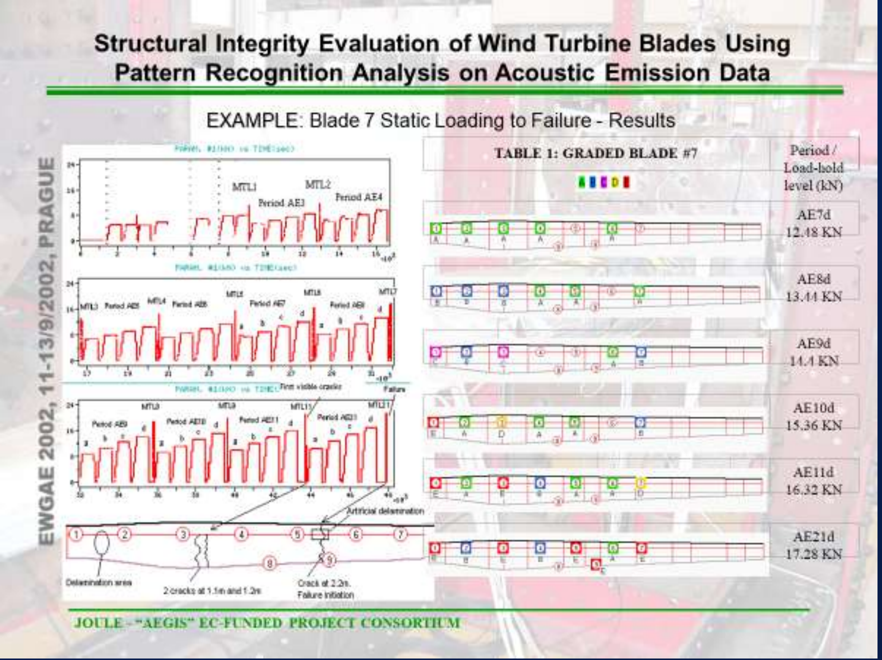
AE DURING LABORATORY FULL SCALE BLADE TESTING (DEVELOPMENT & CERTIFICATION - AEGIS)





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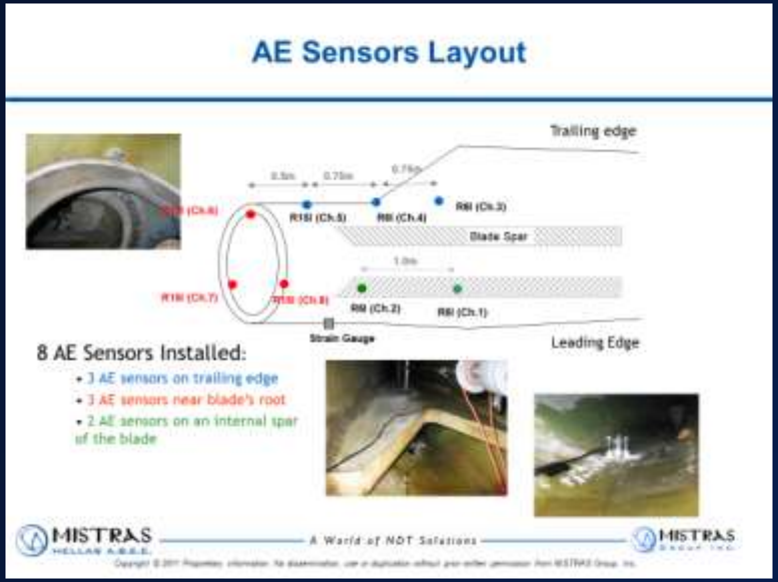
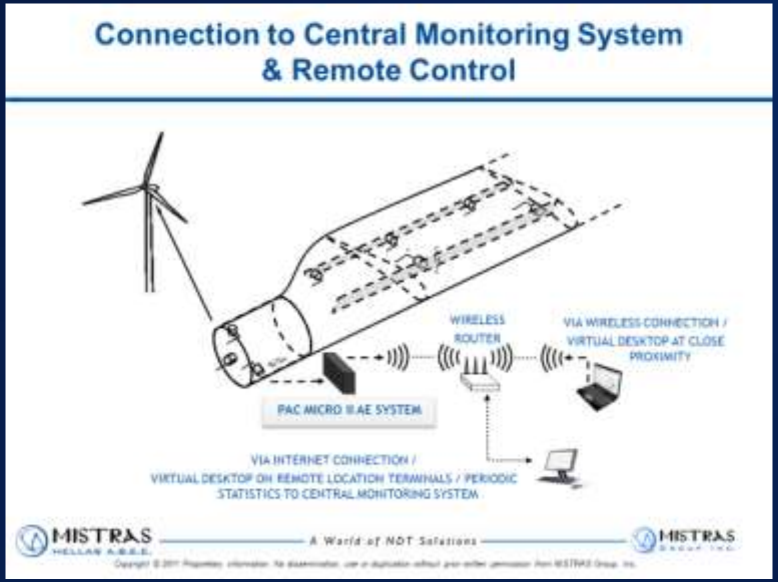
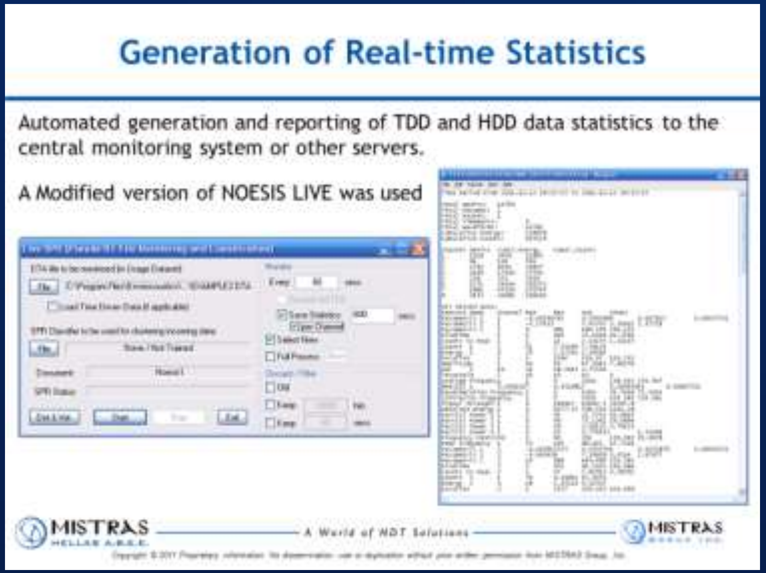
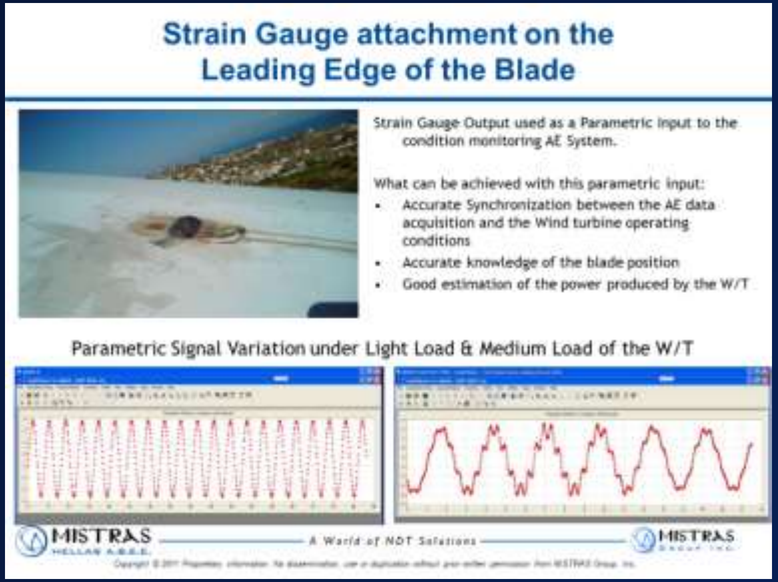
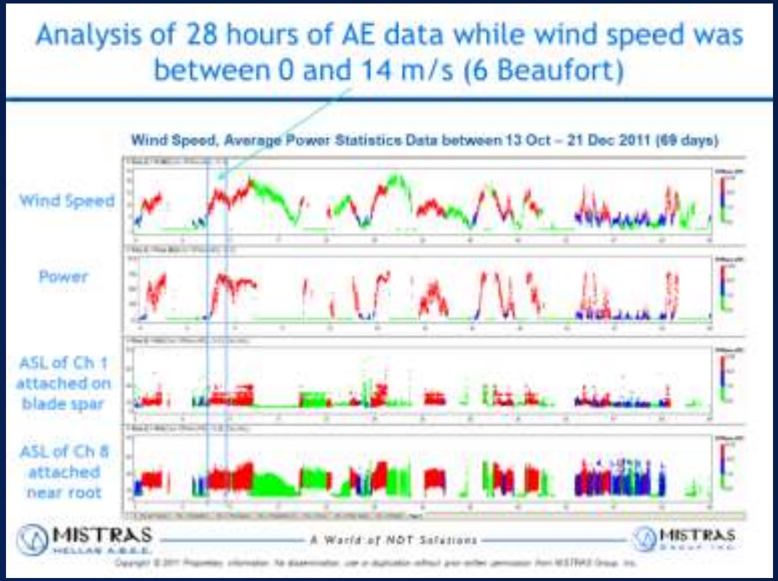
R&D AND W/T BLADE MONITORING BACKGROUND (20years experience - NIMO)

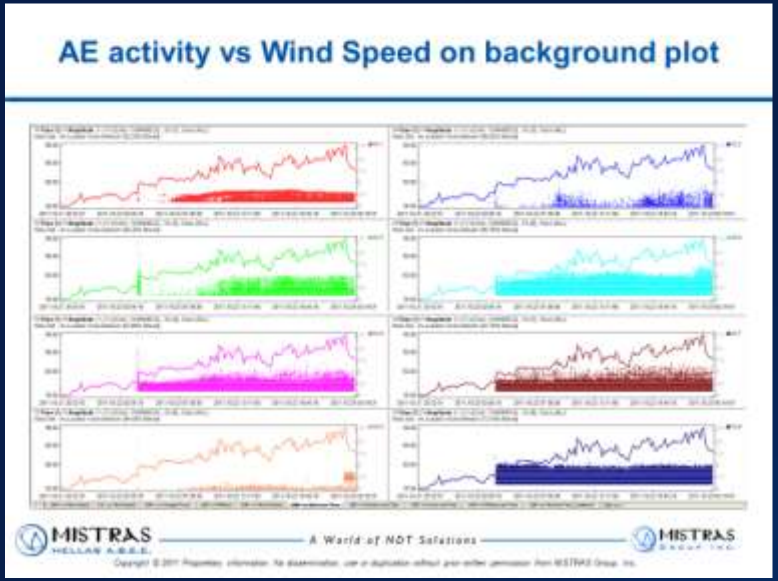












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WT AE Services

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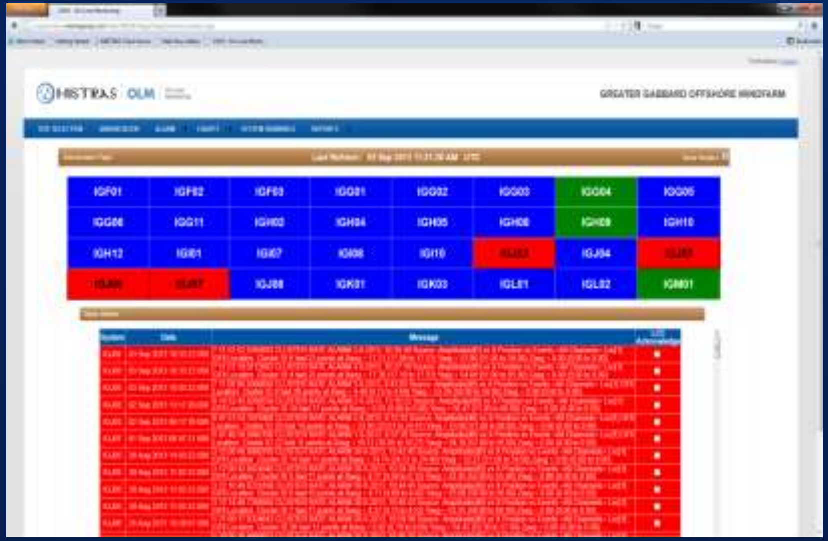
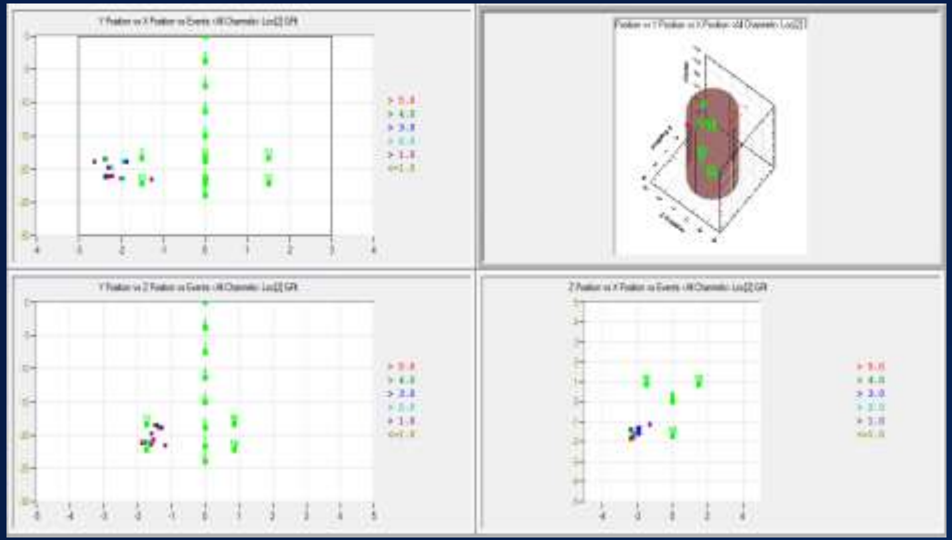
WT PRODUCTS – SERVICES & OLM





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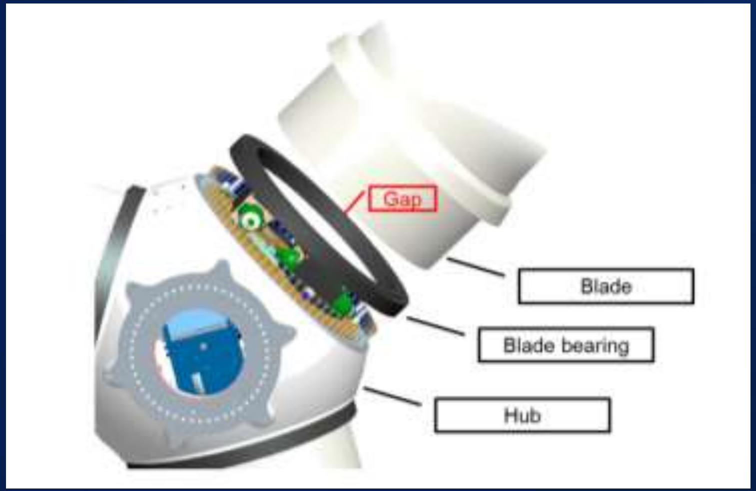
WT Products



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PURPOSE OF THE BLADE MONITORING SYSTEM

EARLY DETECTION

- ✓ Identify damage upon onset

DEFECT ACTIVETY OR STABLILITY

- ✓ Track acoustic signature to learn of growth or stability

ANALYZE TRENDS ACROSS SITE AND BLADE SETS

- ✓ Acoustically rank blades for repair & inspection prioritization

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Sensoria blade monitoring system components

- The system consists of a Data Acquisition Unit (DAQ) and three airborne acoustic sensors.
- The DAQ is installed in the turbine hub and connected to an uninterrupted power source.
- The acoustic sensors are mounted on the blade bulkhead pointing towards the blade tip.
- Sensor cables are securely routed to the DAQ

Sensoria DAQ installed in Hub

Sensor mounted on the blade bulkhead

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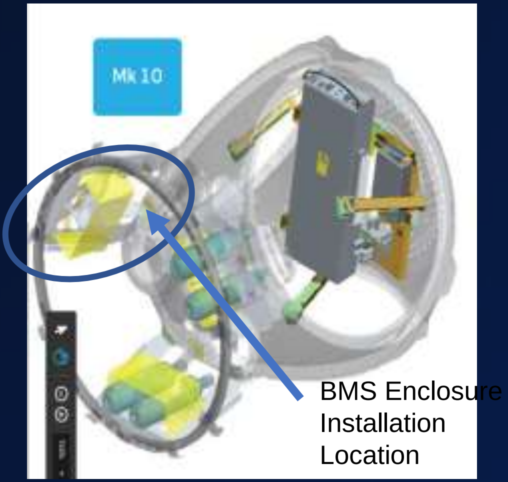
WT Products – SENSORIA™



(A) Details of sensor mounting with magnet and epoxy

(B) Sensor and cable gland

(C) Cable routing

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Sensoria is designed to Identify

- High energy / speed Impacts on the blade
- Rupture to the blade skin or formation of perforations
- Non-Penetrating defects
- Acoustic signal changes by blade or operational conditions

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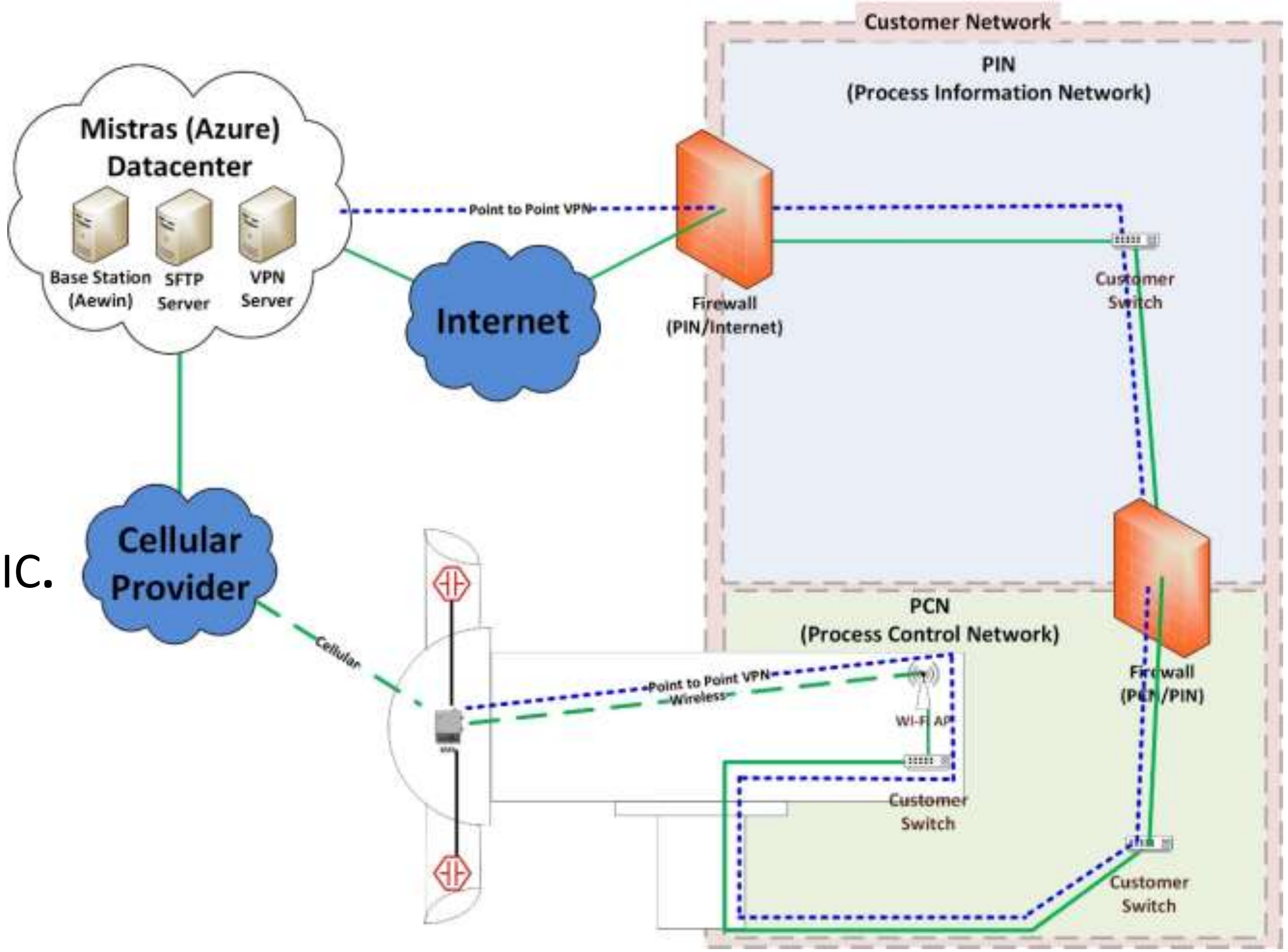
COMMUNICATION OPTIONS

- **CELLULAR NETWORK**
- **WI-FI ACCESS POINT IN THE NACELLE**
- **SENSORIA CYBERSECURITY**
  - ✓ Compliant with Standard IEC 62443.
  - ✓ DAQ protected by an integrated cybersecurity IC.



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Sensoria data flow

SYSTEM

Monitoring system installed in the turbine hub or nose cone

SENSORS

Sensor installed on the bulkhead of each blade

IMPACT ALARM

On board data processing

DEFECT ACTIVITY AND RESPONSE TO OPERATION

Data transfer for further postprocessing and analysis

DATA-DRIVEN WEB APP

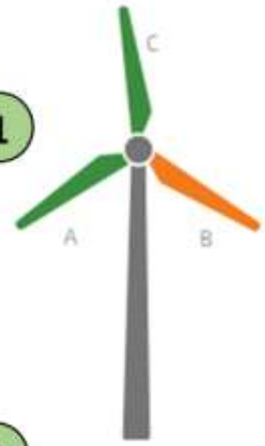
Back End Post processing

- Impact, lighting strike and blade skin rupture
- Characterization of acoustic activity and grading of blades over time and per period

ANALYST/MONITORING

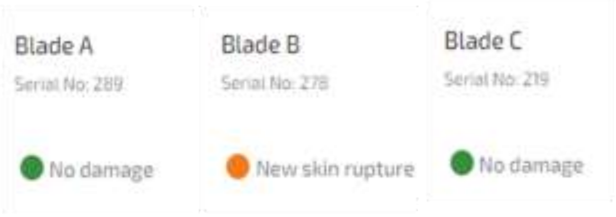
- Alarm verification and manage customer website communications
- Verification of acoustic signatures

1



"REAL TIME" INFORMATION ABOUT IMPACT ALARMS

customer communication via email with verified alarms



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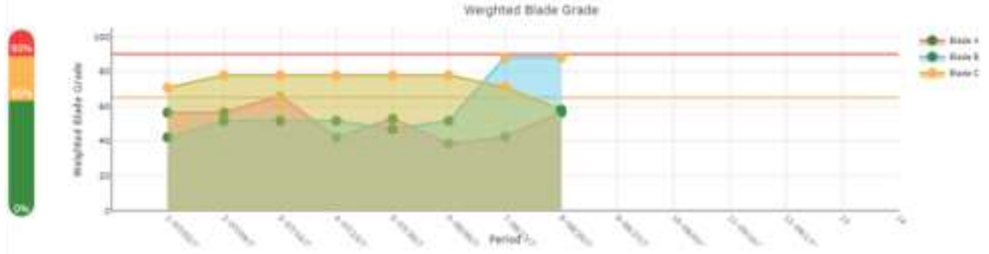
3

PROBABILITY OF DEFECT ACTIVITY

Based on acoustic response



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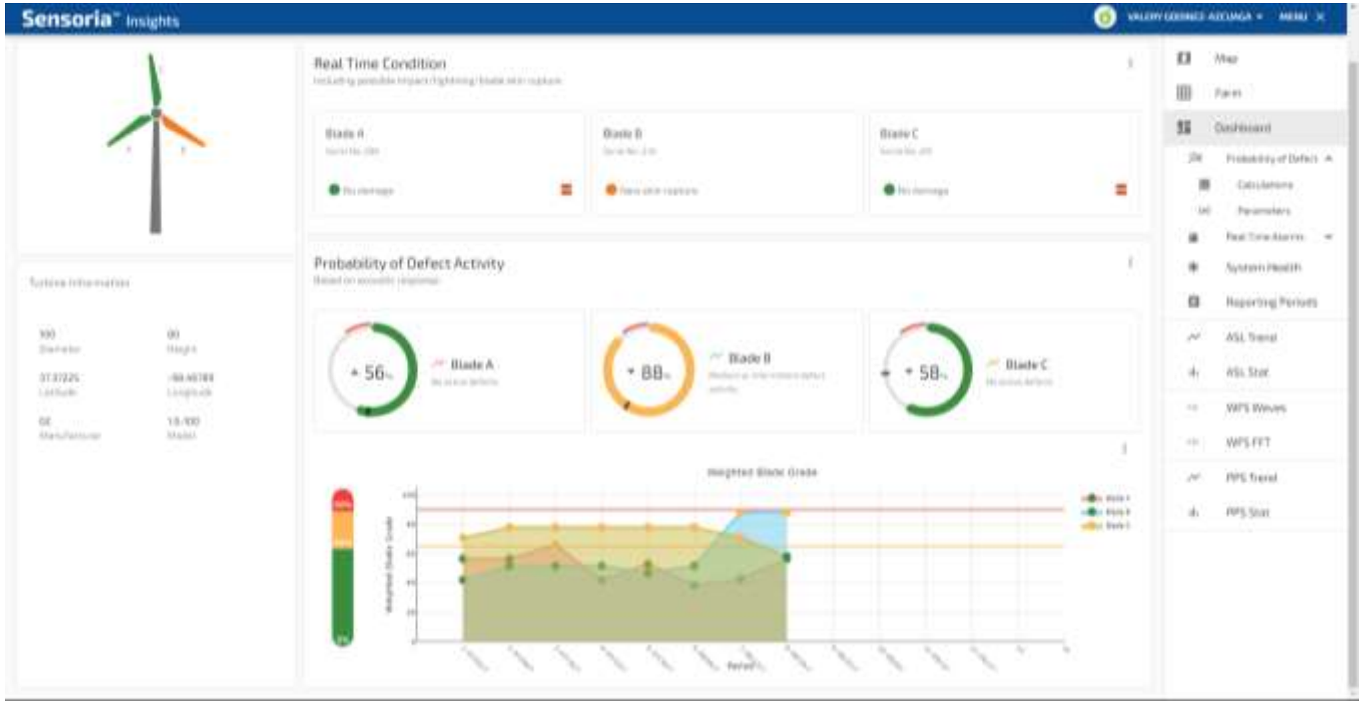
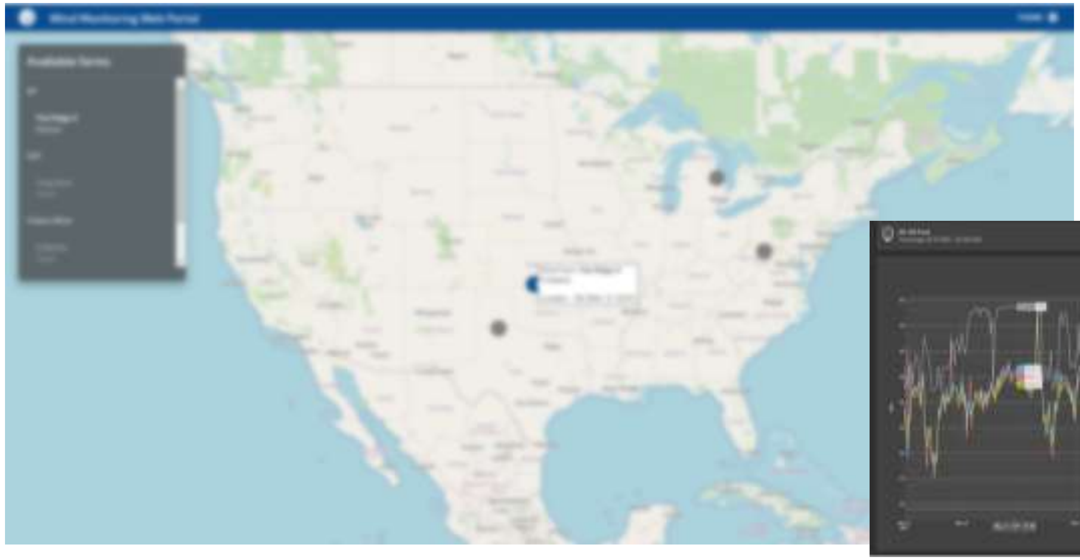
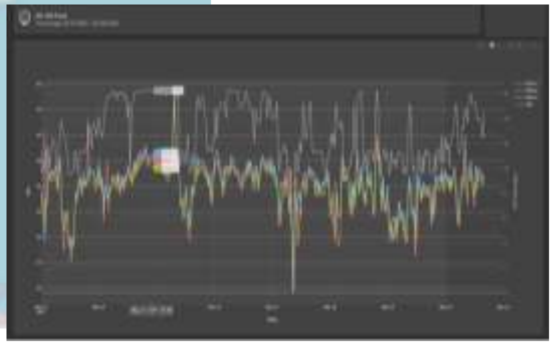
DATA-DRIVEN WEB APPLICATION

- Data-Driven web app provides a fleet wide, farm and specific asset view
- Periodic acoustic activity trend
- Historic blade grade calculations
- Real time asset status updated every 1.5hrs







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END of PART A

DISCUSSION …

WHAT ARE YOUR QUESTIONS ?

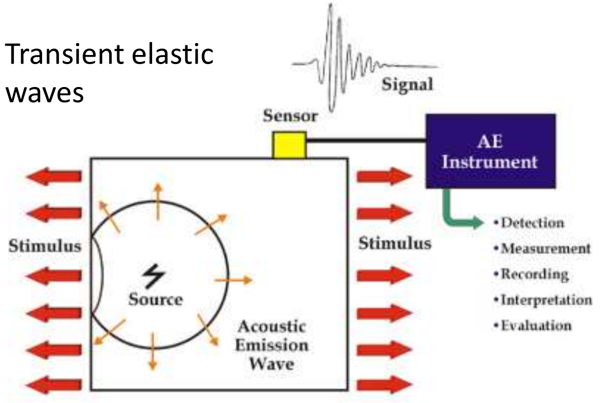
PART A

BACK TO BASICS

ACOUSTIC EMISSION ALSO CALLED MICROSEISMIC ACTIVITY

ACOUSTIC EMISSION IS NOT VIBRATION OR SOUND MEASUREMENTS

Transient elastic waves



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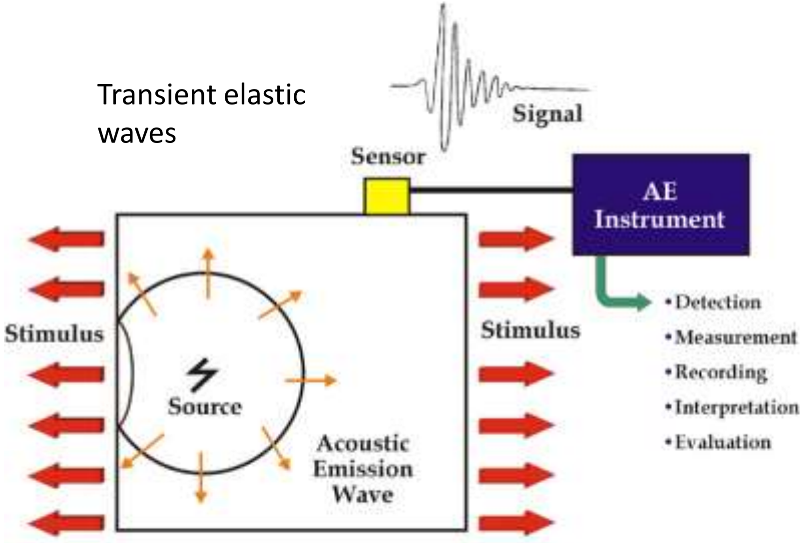
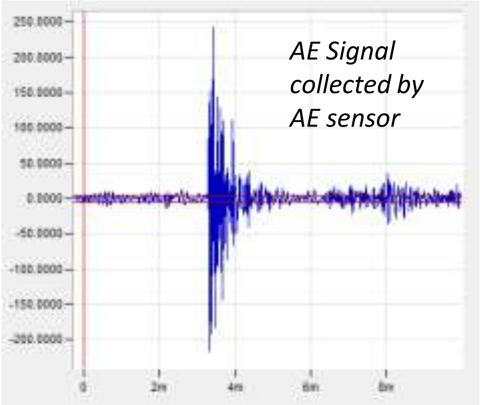
ACOUSTIC EMISSION ALSO CALLED MICROSEISMIC ACTIVITY

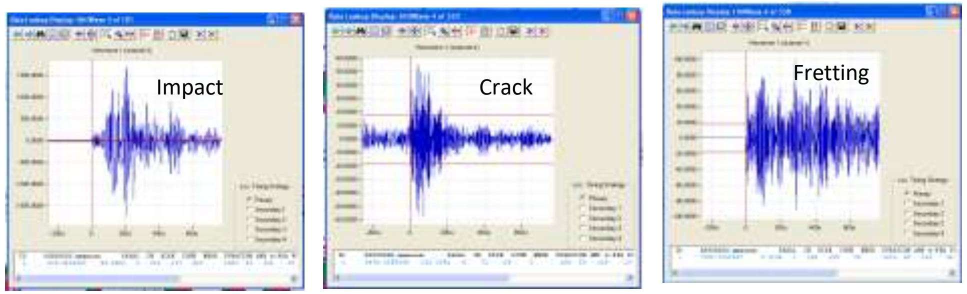
ACOUSTIC EMISSION IS NOT VIBRATION OR SOUND MEASUREMENTS





Number of Hits, Energy, characteristics of AE HITS change over time in response to:
Operation/Weather/Defect presence and status

Shape and characteristics (ranges for specific AE features) vary depending of the mechanism producing the emission.



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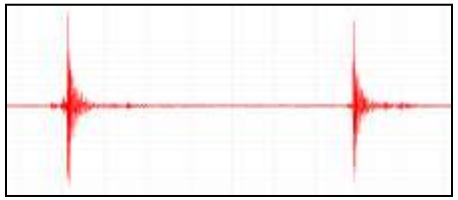
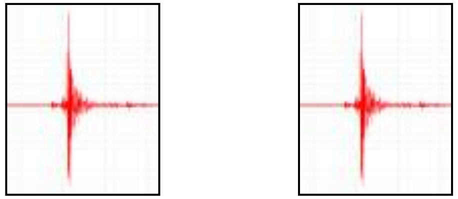
Four different AE data sets can be acquired simultaneously

1. Complete RF waveform



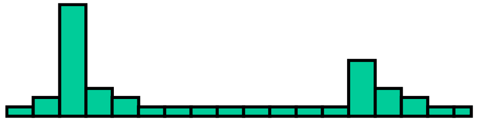
2. Discrete RF waveform



3. Waveform Feature Data

Channel, Time, Amplitude, Duration, Counts, Energy, Rise Time, etc.

4. Time Driven Data



Parametric

All analysis techniques can be conducted simultaneously in real-time and data stored directly to hard drive.

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Manufacture AE sensors, the acquisition systems to collect data, the software to optimize the data collection and analyze the signals

- Look for cracking signals
- Look for leaks signals
- Characterize background noise changes associated to processes

WHY?

Defects/damages and process changes produce acoustic signals

AE is dynamic irreversible phenomenon not readily repeatable.

Thus, Once the event occurs there is no other real time proof.

If we listen correctly….we can

- Guide Maintenance
- Extend Asset Operation Periods

- Attenuation result in different sensitivity of sources …
- Noise (EMI, RFI, Impact, Friction, etc.) discrimination is sometimes a difficult task.
- Real Time Evaluation & Alarms during AE monitoring necessitates evaluation of genuine emission and real time noise filtering
- AE sources and/or failure mechanisms often progress simultaneously making analysis difficult.
- Complex wave propagation (Multiple paths, different media etc.) make source characterization difficult task

SIGNAL PROCESSING & PATTERN RECOGNITION HELPS A LOT …

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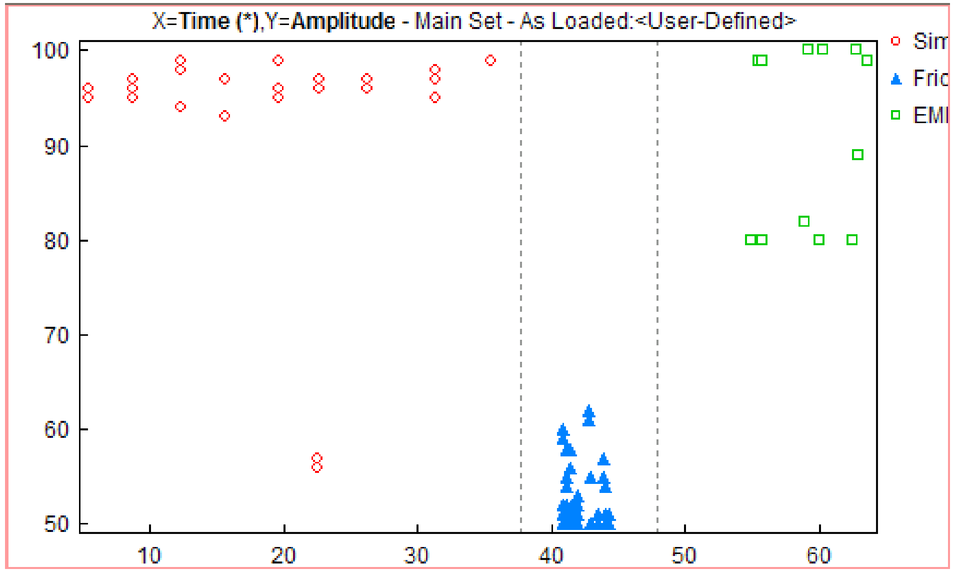
EXAMPLE of SPR using Artificial data



0 : Simulated AE (26.3 %)
1 : Friction (63.2 %)
2 : EMI (10.5 %)

- **The data due to the experimental procedure are separated in time.**
- **Overlapping is evident in Amplitude and other features (see next slide summarizing measured features, waveforms->extracted features)**

- Three MISTRAS-R15I sensors, mounted on a thick metallic plate in a triangular pattern (320mm X 540mm).
- 4ch MISTRAS AE unit was used for real time data acquisition and
- NOESIS pattern recognition s/w for the analysis and pattern s/w.
- AE signals produced by mechanical pencil lead breaks at various positions on the plate.
- Mechanical friction produced by sliding a small metal piece across the surface of the plate.
- (EMI) signals were generated by unplugging the sensor cable during acquisition.

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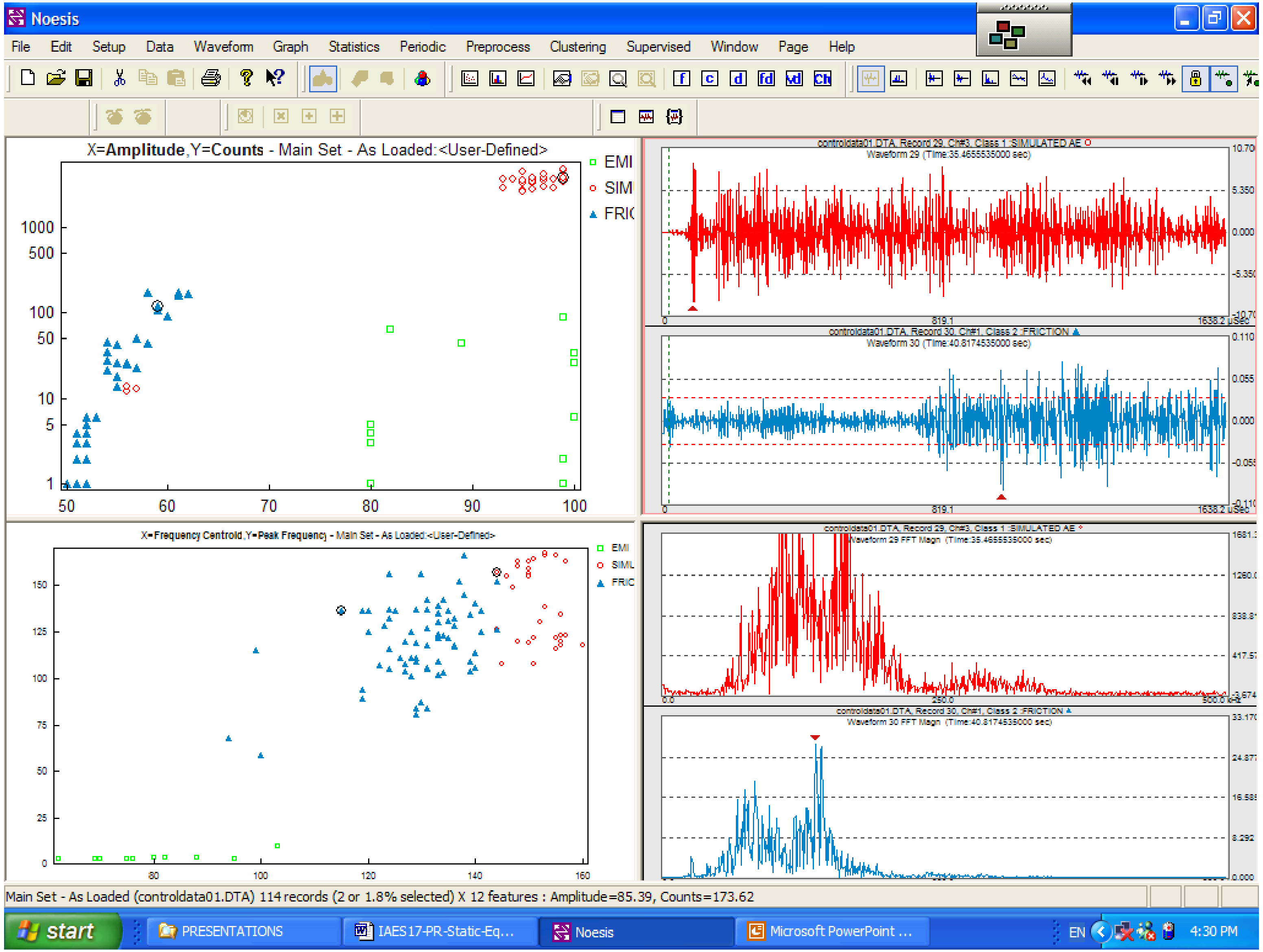


NN & PR S/W

- Signal processing
- Classification
- Supervised PR
- Unsupervised PR

BACKGROUND FOR AE DAMAGE ASSESEMENT OF W/T BLADES

History of AE Testing of FRP Wind-Turbine Blades

To the authors' knowledge:

1994 - First (in the world) application of AE during laboratory full-scale static and fatigue testing of Wind Turbine Blades at Sandia National Laboratories, NM, USA, by Alan G. Beattie et al[1],[2]

Feasibility proved, location capabilities demonstrated, etc.

1998 June – First (in Europe) application of AE during laboratory full-scale static and fatigue testing of Wind Turbine Blades at CRES W/T testing laboratory, Greece by CRES and Envirocoustics ABEE[3],[4]

Applied Pattern Recognition techniques to AE data

[1] Beattie, A.G., 1997, ''Acoustic Emission Monitoring of a Wind Turbine Blade During the Fatigue Test,'' 1997 AIAA Aerospace Sciences Meeting.

[2] Sutherland, H., Beattie A.G., Hansche, B., Musial, W., Allread, J., Johnson, J., and Summers, M., 1994, ''The Application of Non-destructive Techniques to the Testing of a Wind Turbine Blade,'' Report SAND93-1380, Sandia National Laboratory.

[3] Kouroussis, D., A., Anastassopoulos, A., A., "Analysis of Acoustic Emission Data from a 12m F.R.P. Wind Turbine Blade During Flapwise Bending", Envirocoustics A.B.E.E., Technical Report, Ref: TR-001-8/98, Athens, August 1998.

[4] Kouroussis, D. A., Anastasopoulos, A. A., Kolovos, P.V., Vionis, P., "Non Destructive Testing of W/T Blade by means of Acoustic Emission", Proceedings of the 1st National Conference of the Hellenic Society of Non-Destructive Testing (HSNT) entitled "The Contribution of NDT in Quality Assurance", Athens 23 November 1998, pp. 68-71 (in Greek)

History of AE Testing of FRP Wind-Turbine Blades

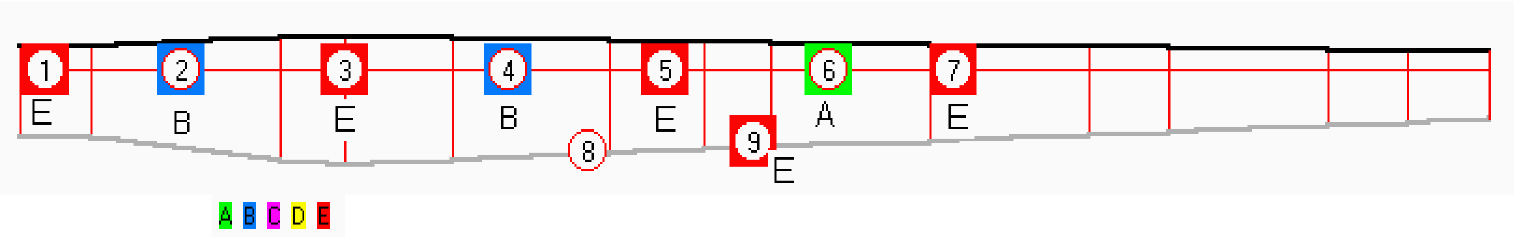
To the authors' knowledge:

1998 September to October 2002, "AEGIS*" EU-funded Research Project, extensive research (10 small and 2 large blades tested to failure while monitored with AE under static or fatigue loads in lab conditions) and first (ever?) AE test on an installed blade (not rotating – pulleys used for loading) with consortium members:

Energy Research Unit, CLRC Rutherford Appleton Laboratory, UK
Envirocoustics ABEE, Greece
Euro Physical Acoustics SA, France
CRES, Wind Energy Department, Greece
Delft University of Technology, WMC-Group, The Netherlands
Dept of Mechanical Engineering & Aeronautics, University of Patras, Greece
Geobiologiki S.A., Greece
Engineering Systems Department, Cranfield University (RMCS), UK

2002-2003 within AEGIS: semi-permanent installation (sensors attached on outer surface) and ATTEMPTS TO monitor rotating blade with Radio Telemetry system – AE logger on the ground at RAL's facilities
13 relevant consortium publications

OBJECTIVE:	Improve Reliability of Wind Turbine Blades
MEANS TO ACCOMPLISH:	Develop proof-testing procedures and Pass / Fail criteria based on Acoustic Emission monitoring during certification-type tests
ACTIONS:	- 10 small blades (4 deliberately defected, 2 with fiber optics AE sensors) tested to failure (6 static, 4 fatigue)
	- 2 commercial-scale blades tested to failure (1 static, 1 fatigue)
	- One operating blade proof - tested on site
ANALYSIS:	- Classical AE analysis (statistical, graphical, location)
	- Unsupervised Pattern Recognition (UPR) analysis with specialized software
	- Automatic sectional Grading (A-E) of load severity with specialized Software based on Supervised Patter Recognition



DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service
KIT Karlsruhe Institute of Technology
UNIVERSITY OF PATRAS

AE Testing of FRP Wind-Turbine Blades - AEGIS

Wind Turbine FRP Blades were Tested under Fatigue Loading and Monitored with Acoustic Emission.
Target was to investigate the possibility of distinguishing Critical Types of AE signals that indicate damage and possible failure.

AE Testing of FRP Wind-Turbine Blades - AEGIS

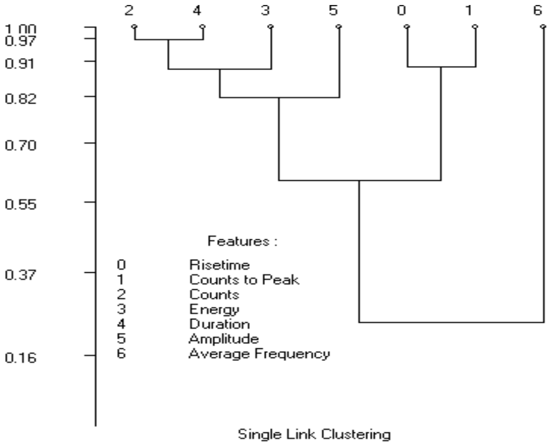
Unsupervised Pattern Recognition Analysis Performed

First-hit analysis for better representation of source characteristics

AE Feature selection, assisted by Feature Correlation Hierarchy. AE feature-vector non-dimensionalization: 0 to 1 range

Clustering with selected algorithms

Cluster validity assessment and optimization based on minimization of D&B R_{ij} criterion.



W/T Blade Testing procedures and special "Condition Grading" System developed for AE testing during "Proof" loading of the blade

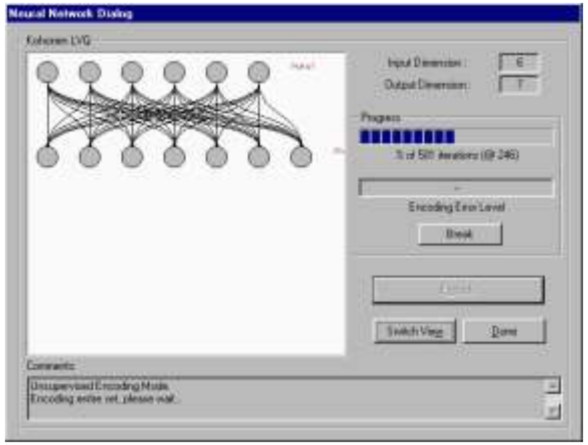
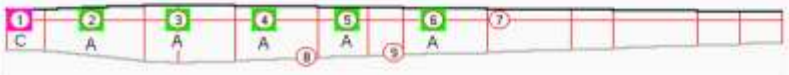
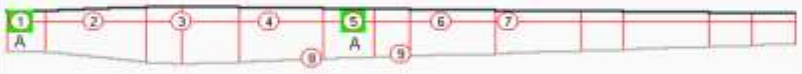
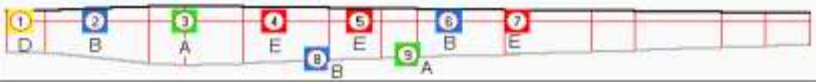
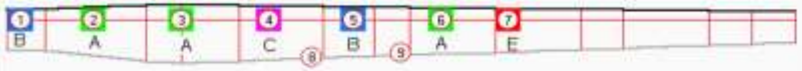
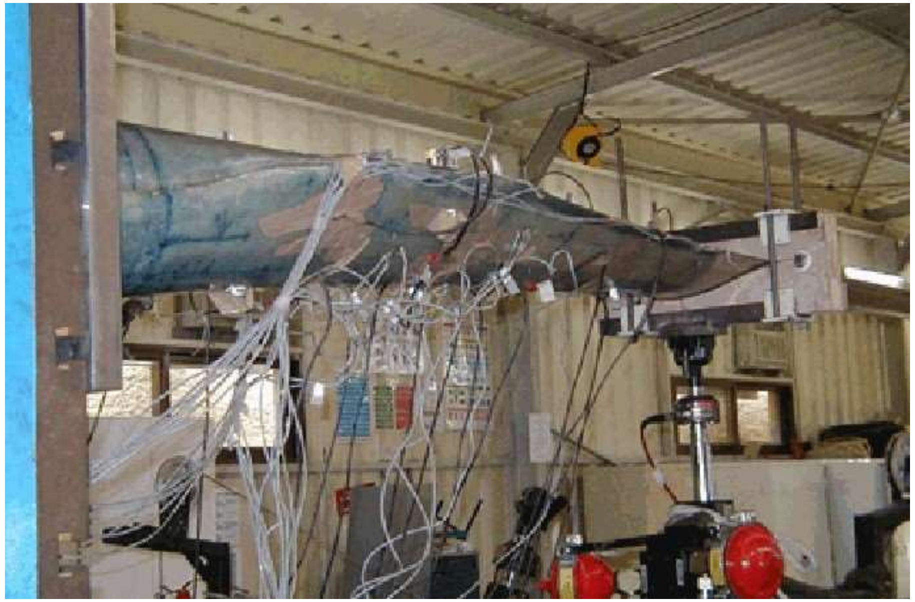
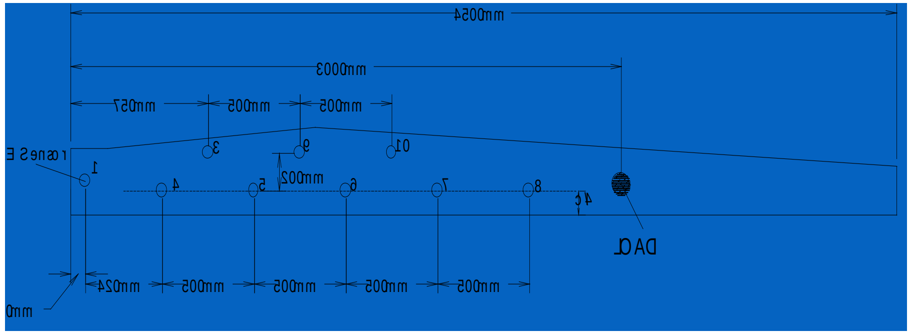
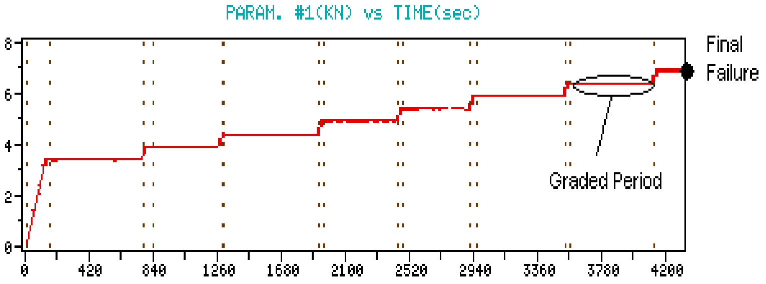


TABLE 2: GRADED BLADE #8 A B C D E	Period /Load-hold level (kN)
	AE1a 6 (50% of max. fatigue)
	AE1b 6 (50% of max. fatigue)
	AE2a 13.2 (110% of max. fatigue)
	AE2b 13.2 (110% of max. fatigue)

EXAMPLE: Blade 1 Static Loading to Failure – method calibration







- **Loading Envelope (to failure)**

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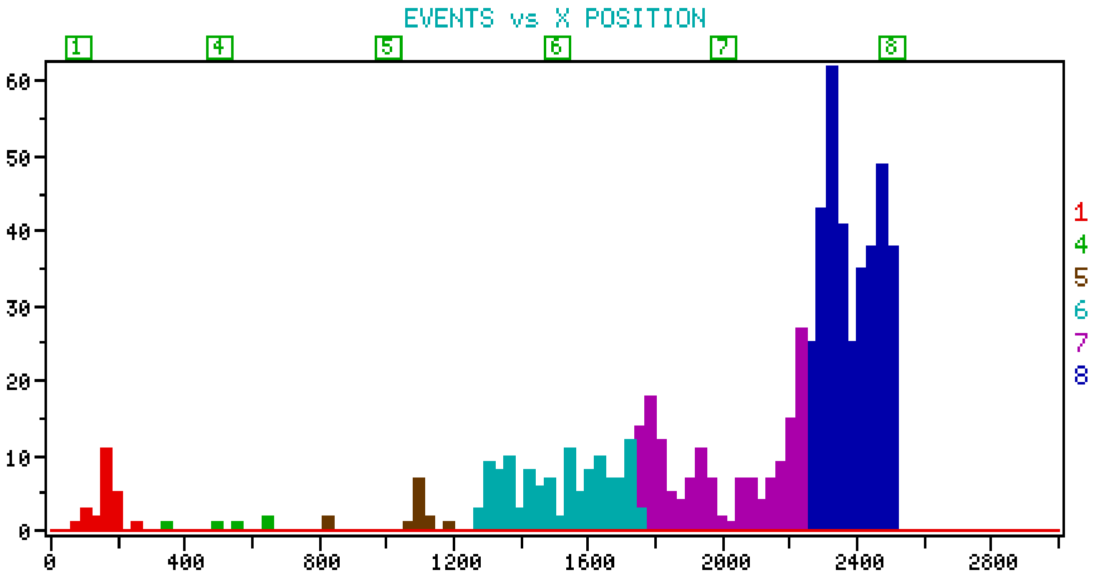
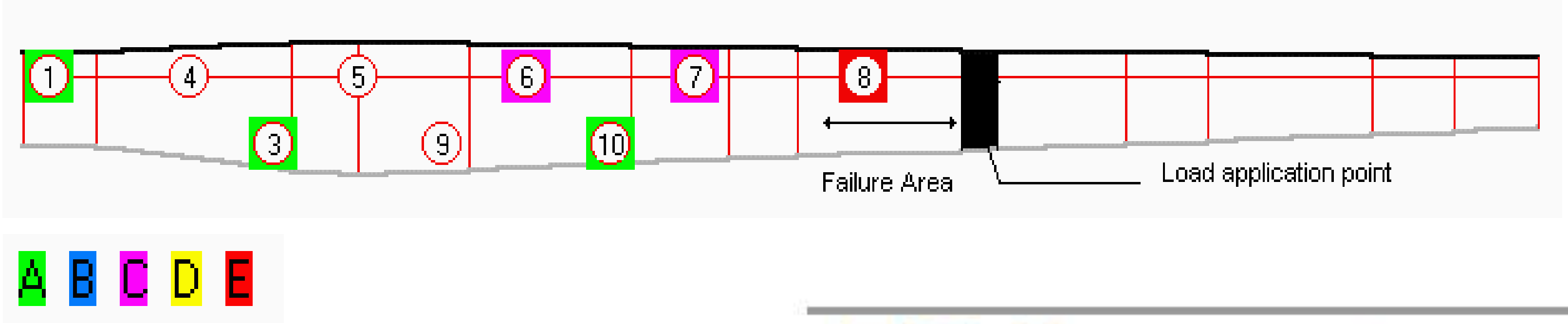
EXAMPLE: Blade 1 Static Loading to Failure - RESULTS



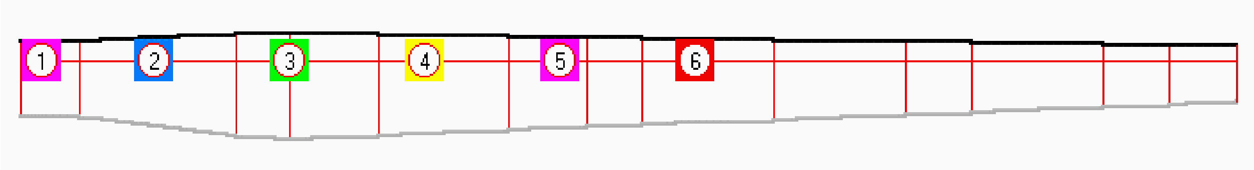
- Linear Location Results

- Automated Blade Grading Results (based on critical class)

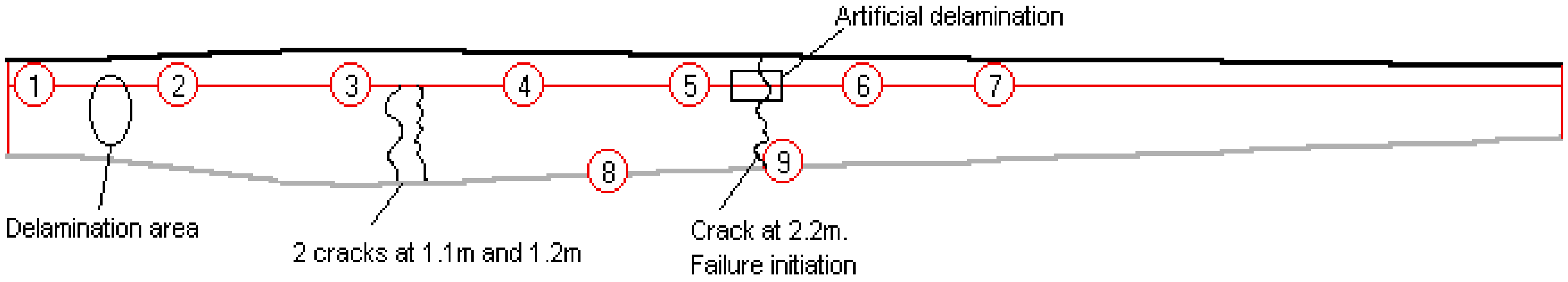


EXAMPLE: Blade 2 Static Loading to Failure – validation test

Automated Grading of Blade 2



EXAMPLE: Blade 7 Static Loading to Failure



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EXAMPLE: Blade 7 Static Loading to Failure - Results

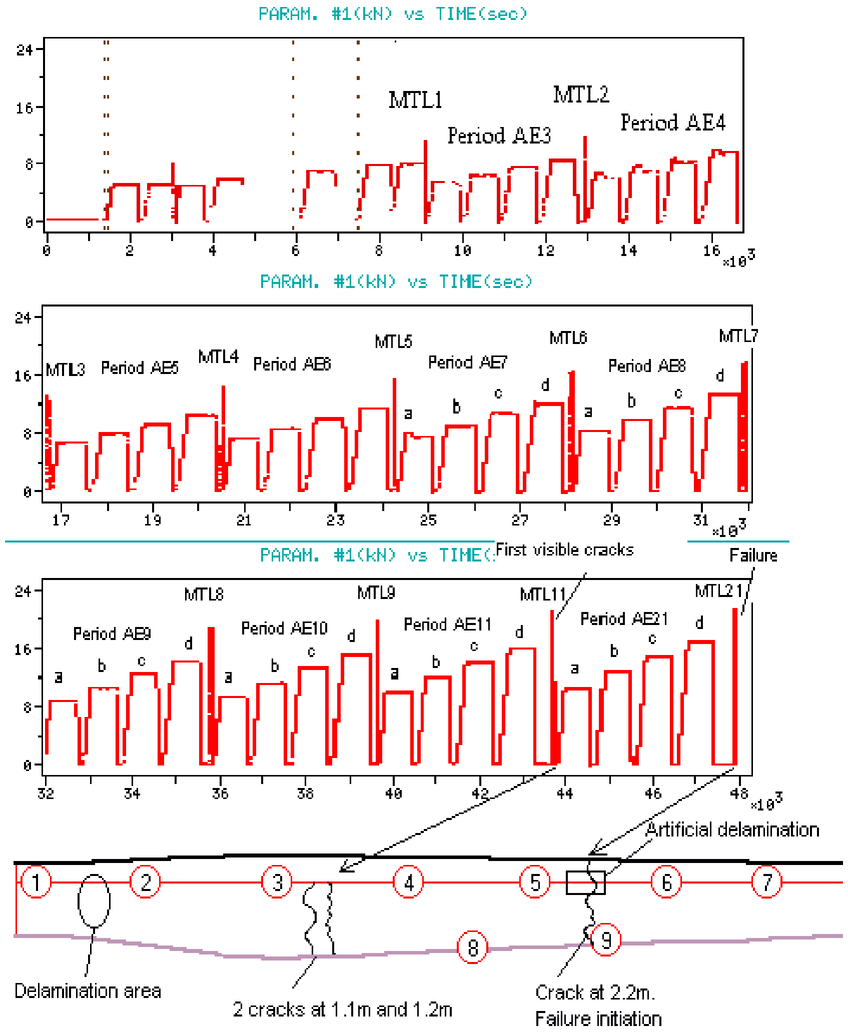
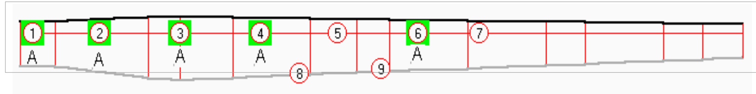
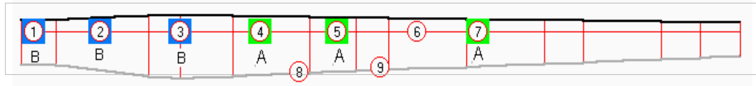
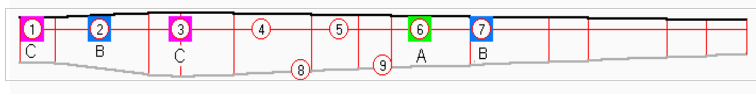
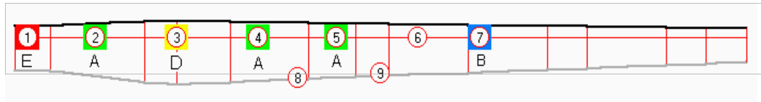
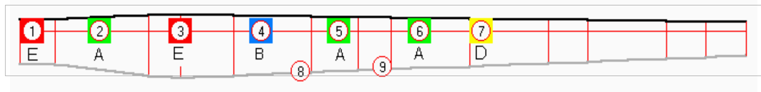
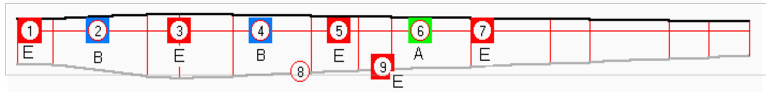


TABLE 1: GRADED BLADE #7 A B C D E	Period / Load-hold level (kN)
	AE7d 12.48 KN
	AE8d 13.44 KN
	AE9d 14.4 KN
	AE10d 15.36 KN
	AE11d 16.32 KN
	AE21d 17.28 KN

EXAMPLE: Large Blade 1 Static Loading to Failure

EXAMPLE: Large Blade 1 Static Loading to Failure - Results

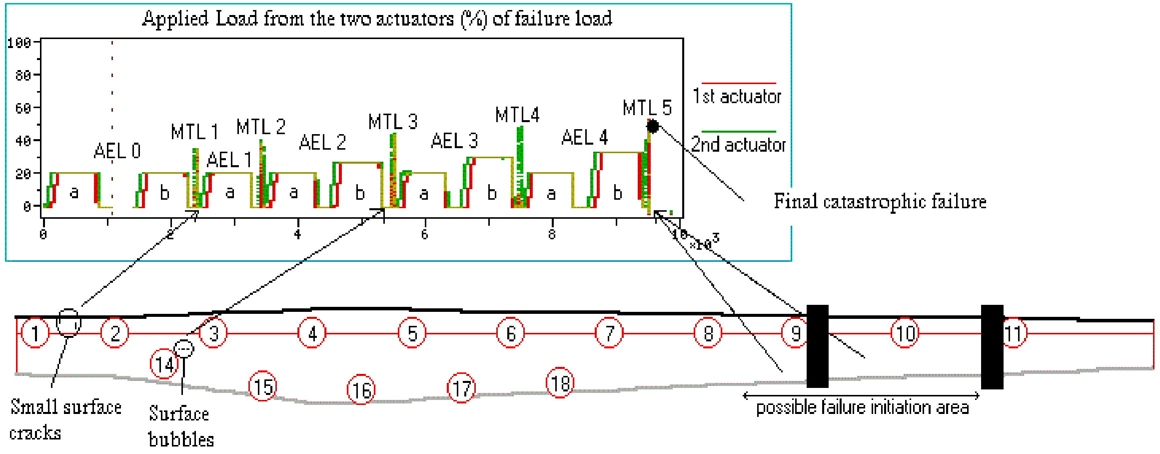
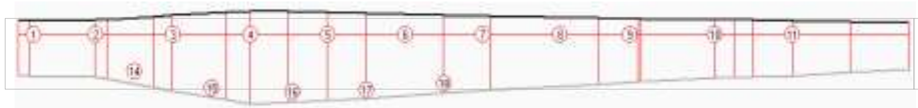
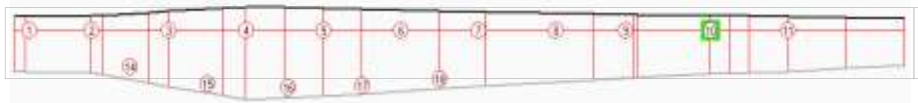
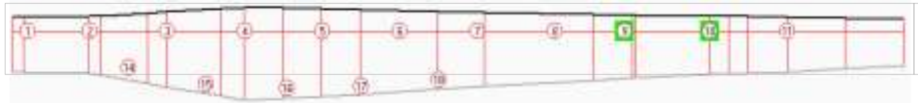
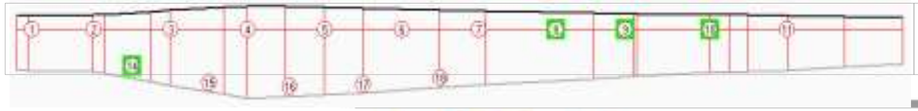
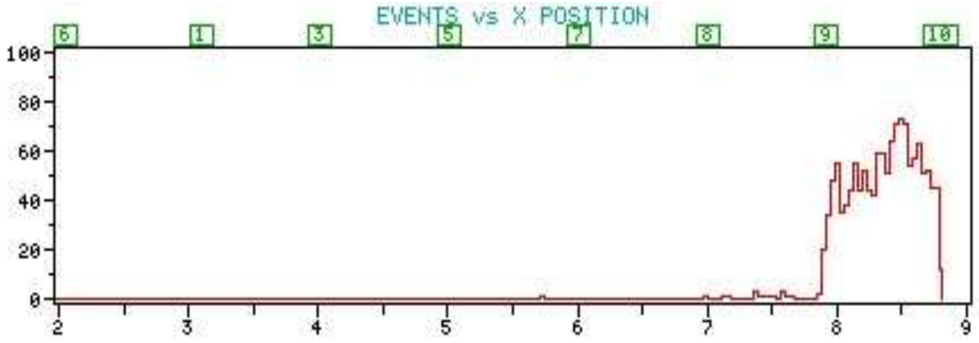


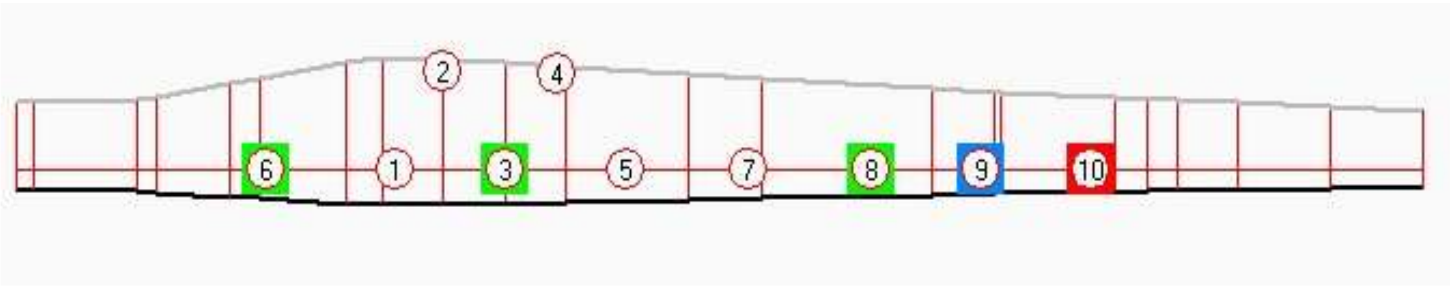
TABLE 2: GRADED LARGE BLADE #1 A B C D E	Period / Load-hold level (% of final failure load.)
	AEL3A (40%)
	AEL3B (58%)
	AEL4A (40%)
	AEL4B (64%)

EXAMPLE: Large Blade 2 Fatigue Loading to Failure

Failure damage developed just inboard of load application point

EXAMPLE: Large Blade 2 Fatigue Loading to Failure – Preliminary results





- Linear Location results fully coincide with damaged area of the blade introduced by the fatigue test (between sensors 9 and 10)
- Automated grading of the blade indicates that a static load to 110% of the maximum fatigue load is very severe for the blade

EARLY STAGES - ON AE LINE MONITORING OF W/T BLADES

Health Monitoring of Operating Wind Turbine Blades with Acoustic Emission

Stochastic nature of loading, Possible noise or irrelevant signals from blades' rotation

Identify the conditions contributing to damage accumulation. Transient (Early Warning)

Comparative analysis of TDD and HDD and Located AE data for each specific case. Different filtering/processing depending on conditions (Start/Stop Transients, Moderate - High Wind Load)

Case Specific (blade type etc.)

Successful On Line Monitoring for 8 months. Different filtering methodologies validated for the specific application. Able to set up early warning alarms by monitoring a W/T for 2 months.

1st Systems used for In-Service W/T blade AE monitoring

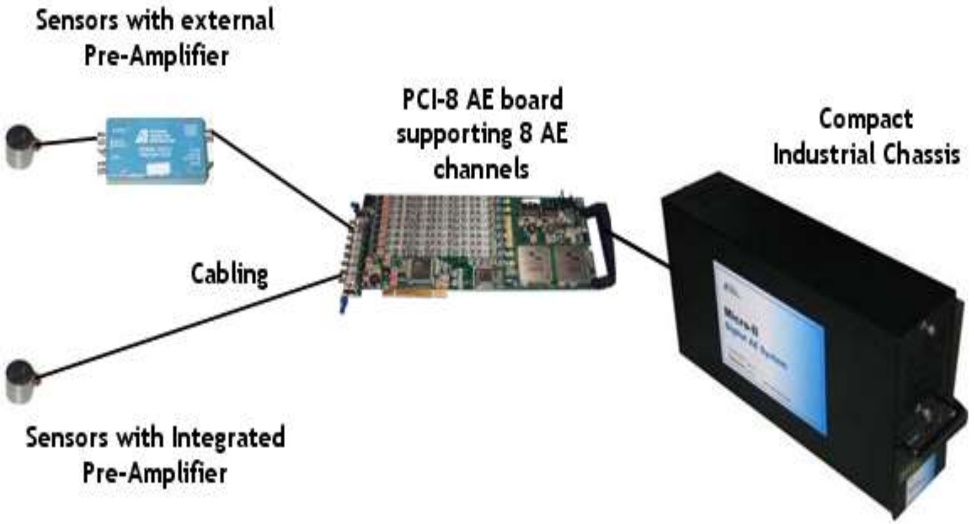
Pocket AE of Physical Acoustics Corporation

Operated by battery or low DC power or standard AC power

Offers full AE features and functions capabilities

Performs traditional AE feature extraction, as well as advanced waveform based acquisition and processing

Ideal tool for short-term AE monitoring applications



Micro-II AE of Physical Acoustics Corporation

Compact multi-channel and fully featured AE system based on a high performance industrial computer

Scalable to provide from a minimum 8 AE channels up to 32 AE channels, when multiple PCI-8 AE boards of Physical Acoustics Corporation are used

Support multiple analogue and digital parametric inputs

Powered by AC or DC input

Can be remotely controlled and also supports wireless data transmission

Instrumentation of an In-Service NEG MICON 48/750 at CRES wind farm in Greece using Pocket AE system – (NIMO project)

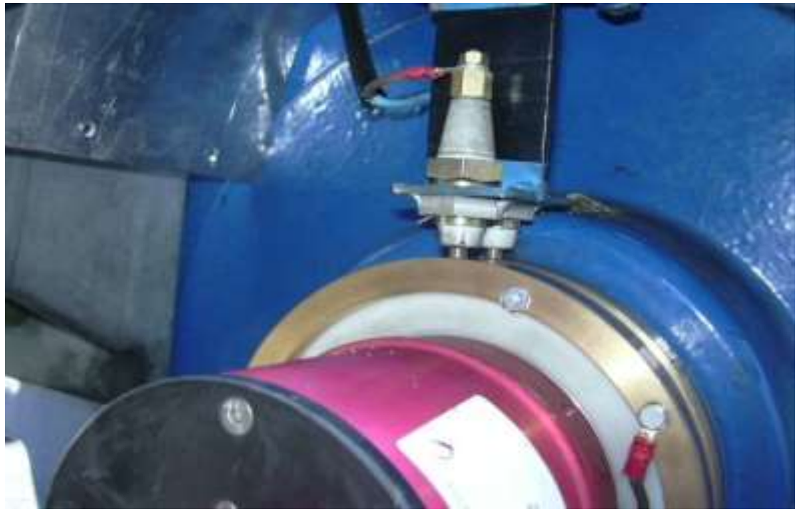
Installation of the **Pocket AE** system on the rotating blade's hub.

Waterproof enclosure for protecting **Pocket AE** system

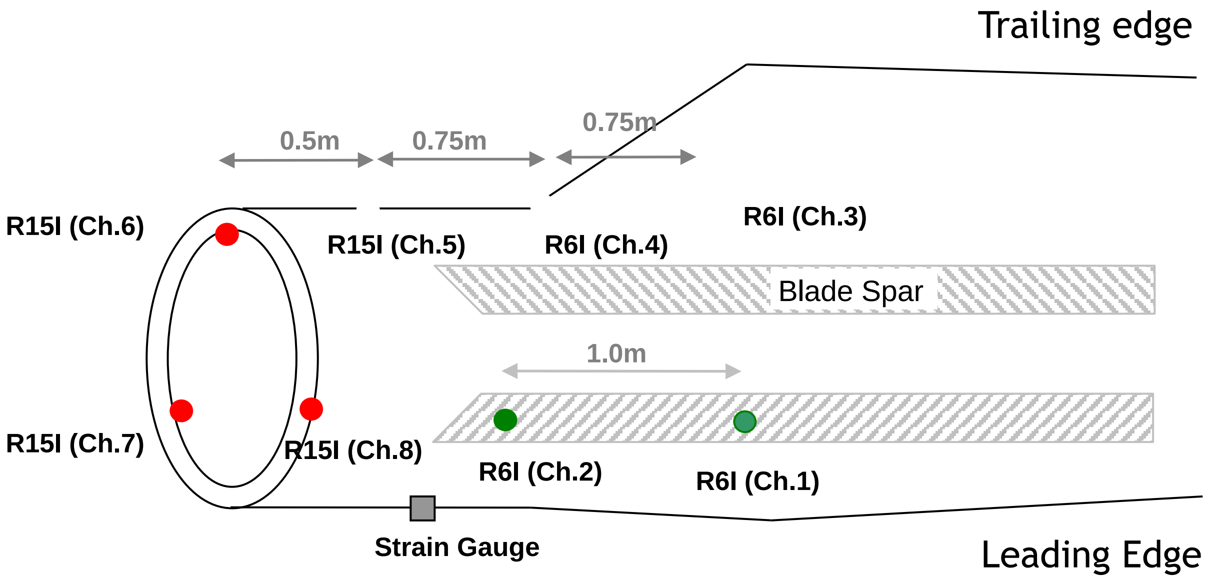
Instrumentation of an In-Service NEG MICON 48/750 at CRES wind farm in Greece using Micro-II AE system (NIMO)

An 8-channel Micro-II AE system installed inside the hub of the W/T
System powered through a slip-ring with 12V DC
System control and Data transmission, to the central monitoring server, performed through wireless connection

Slip-Ring installation for powering the multi-channel Micro-II AE system (NIMO Project)



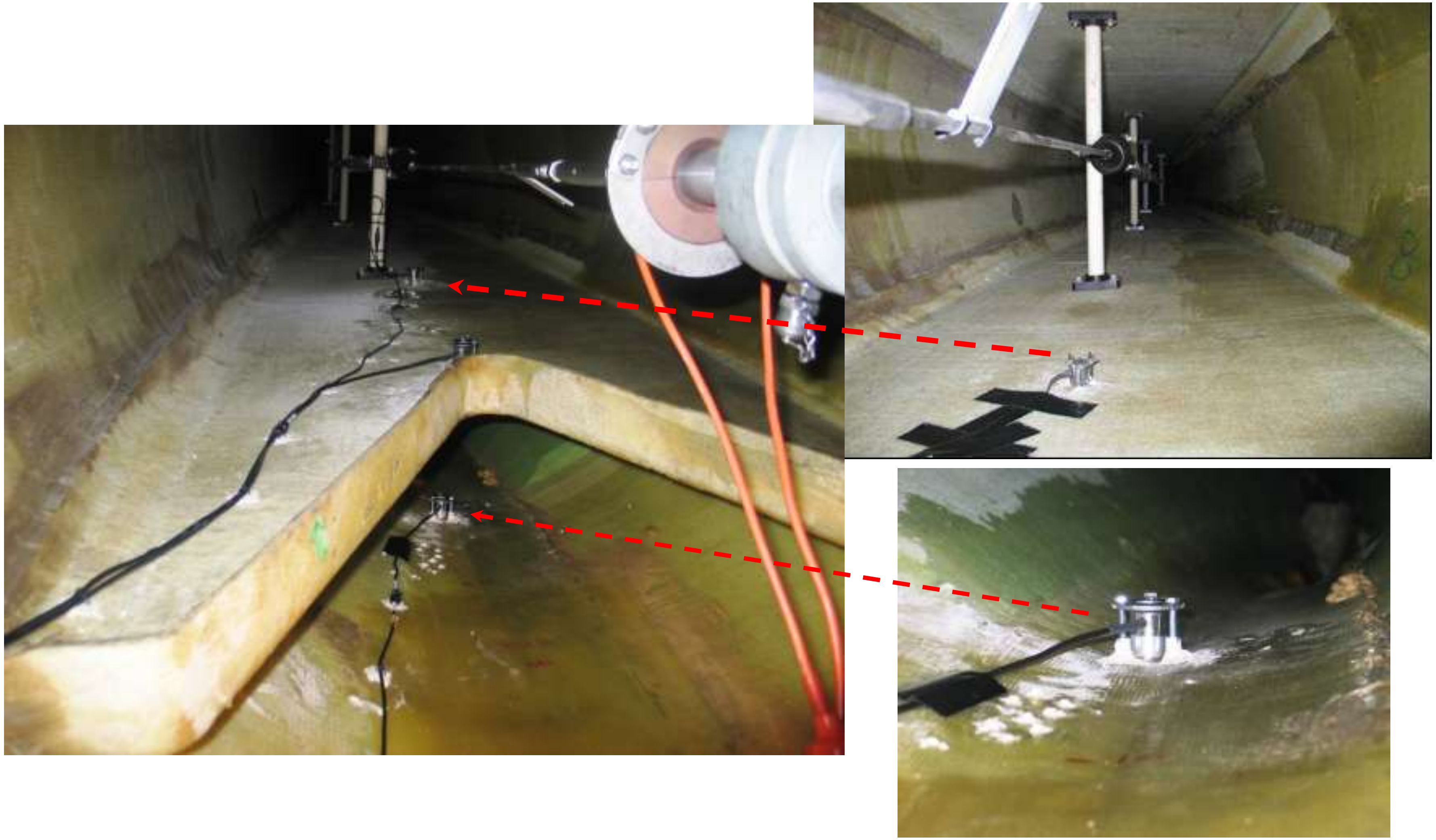
AE Sensors Layout



8 AE Sensors Installed:

3 AE sensors near blade's root
2 AE sensors on an internal spar of the blade

Attachment of AE Sensors on an Internal Spar of the blade and on the Trailing Side of the blade



Attachment of AE sensors near blade's root

Strain Gauge attachment on the Leading Edge of the Blade

Strain Gauge Output used as a Parametric Input to the condition monitoring AE System.

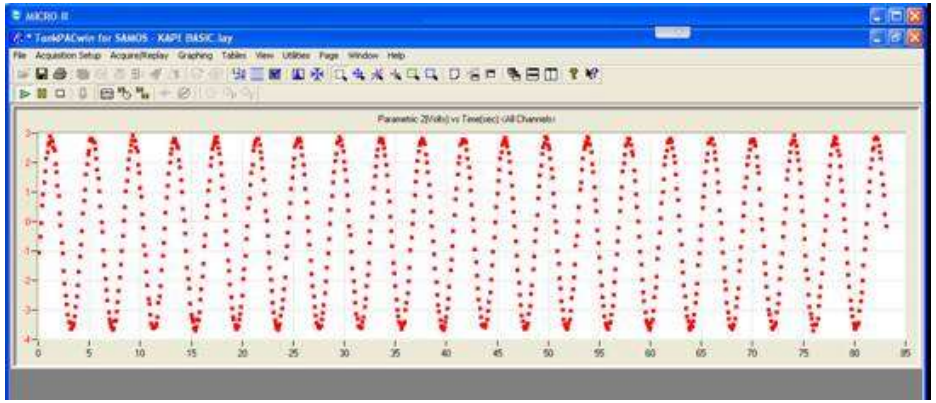
What can be achieved with this parametric input:

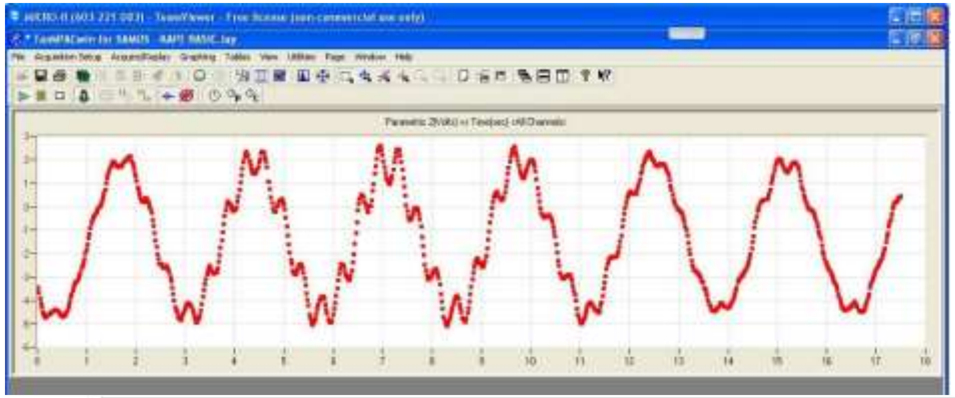
Accurate Synchronization between the AE data acquisition and the Wind turbine operating conditions

Accurate knowledge of the blade position

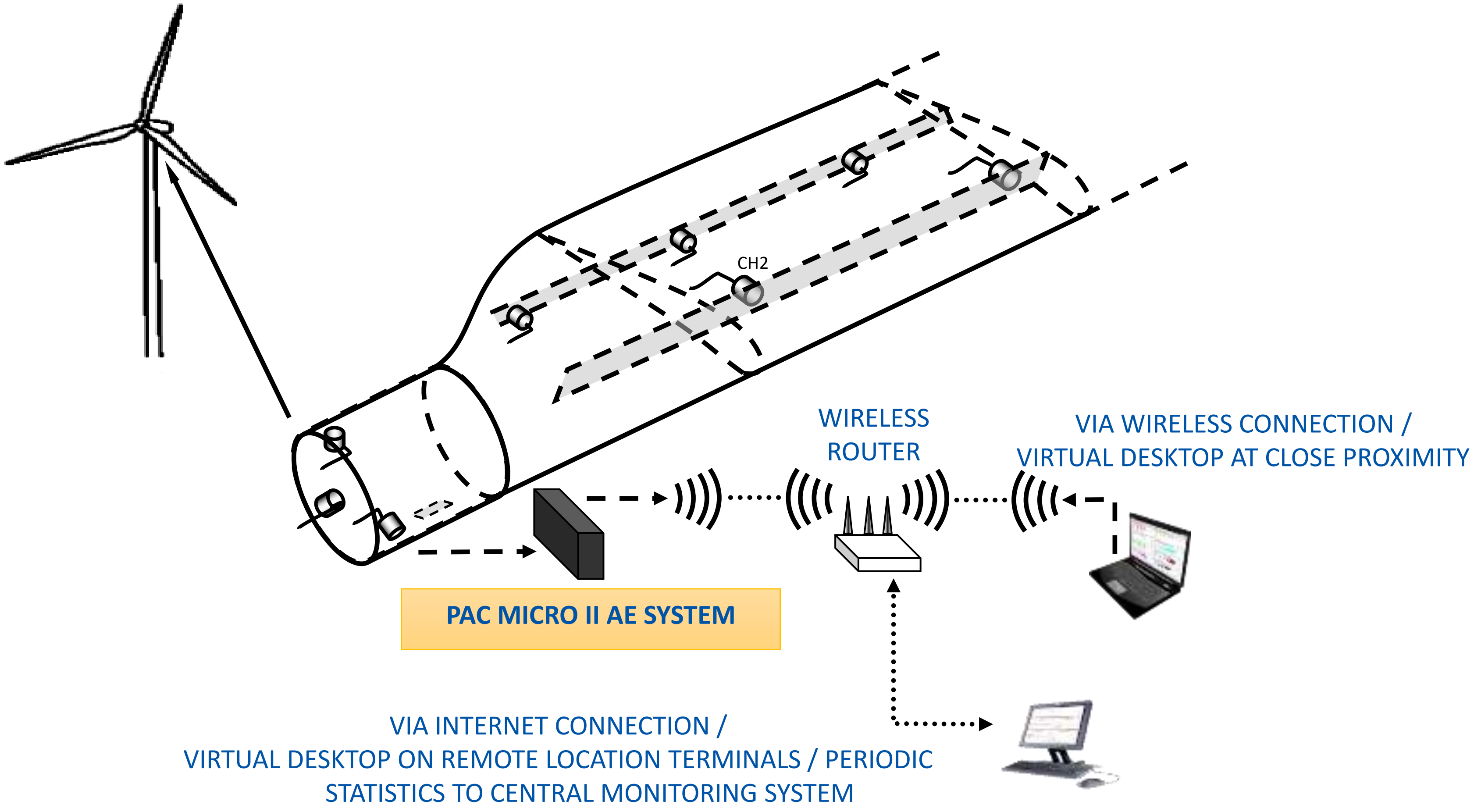
Good estimation of the power produced by the W/T

Parametric Signal Variation under Light Load & Medium Load of the W/T





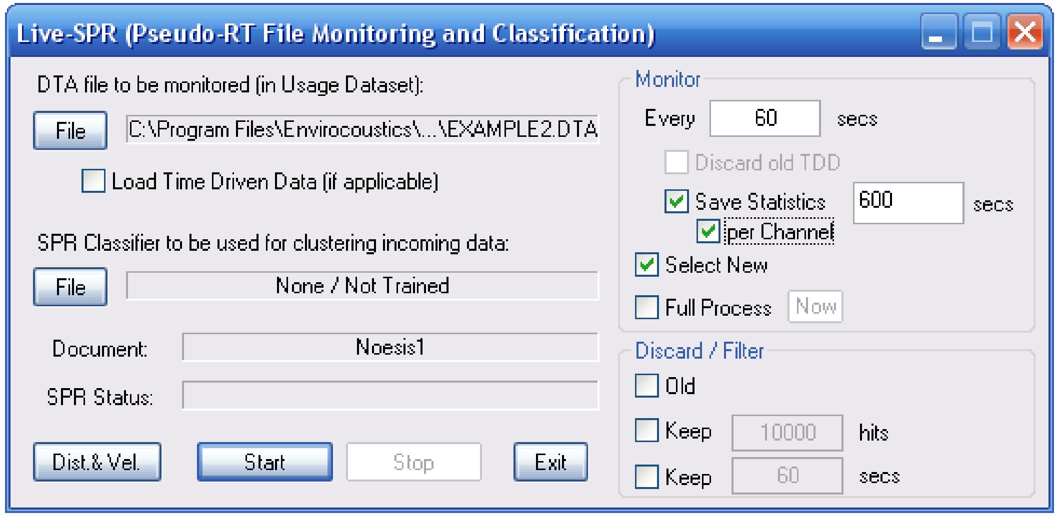
Connection to Central Monitoring System & Remote Control

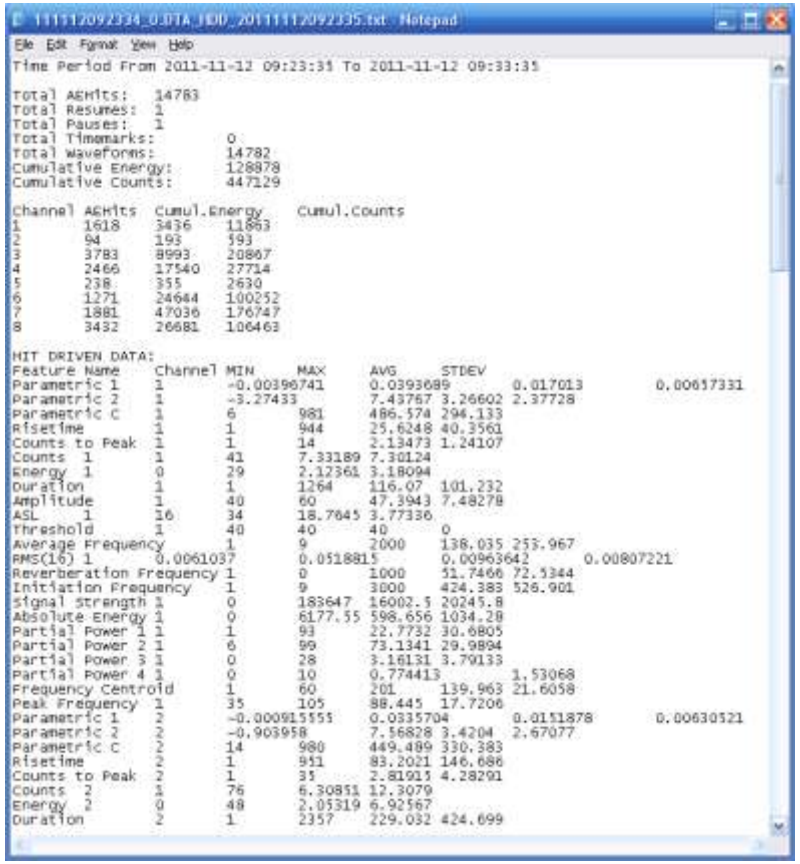


Generation of Real-time Statistics

Automated generation and reporting of TDD and HDD data statistics to the central monitoring system or other servers.

A Modified version of NOESIS LIVE was used



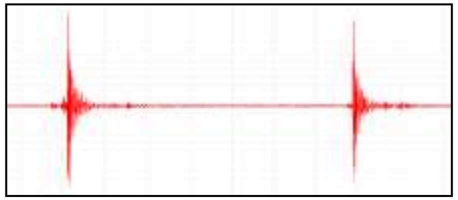


```
Time Period From 2011-11-12 09:23:35 To 2011-11-12 09:33:35

Total AEHits:   14783
Total Resumes:  1
Total Pauses:   1
Total Timemarks:        0
Total Waveforms:        14782
Cumulative Energy:      128878
Cumulative Counts:      447129

Channel AEHits  Cumul.Energy    Cumul.Counts
1       1618    3436    11863
2       94      193     593
3       3783    8993    20867
4       2466    17540   27714
5       238     355     2630
6       1271    24644   100252
7       1881    47036   176747
8       3432    26681   106463

HIT DRIVEN DATA:
Feature Name    Channel MIN     MAX     AVG     STDEV
Parametric 1    1       -0.00396741     0.0393689       0.017013        0.00657331
Parametric 2    1       -3.27433        7.43767 3.26602 2.37728
Parametric C    1       6       981     486.574 294.133
Risetime        1       1       944     25.6248 40.3561
Counts to Peak  1       1       14      2.13473 1.24107
Counts  1       1       41      7.33189 7.30124
Energy  1       0       29      2.12361 3.18094
Duration        1       1       1264    116.07  101.232
Amplitude       1       40      60      47.3943 7.48278
ASL     1       16      34      18.7645 3.77336
Threshold       1       40      40      40      0
Average Frequency       1       9       2000    138.035 253.967
RMS(16) 1       0.0061037       0.0518815       0.00963642      0.00807221
Reverberation Frequency 1       0       1000    51.7466 72.5344
Initiation Frequency    1       9       3000    424.383 526.901
Signal Strength 1       0       183647  16002.5 20245.8
Absolute Energy 1       0       6177.55 598.656 1034.28
Partial Power 1 1       1       93      22.7732 30.6805
Partial Power 2 1       6       99      73.1341 29.9894
Partial Power 3 1       0       28      3.16131 3.79133
Partial Power 4 1       0       10      0.774413        1.53068
Frequency Centroid      1       60      201     139.963 21.6058
Peak Frequency  1       35      105     88.445  17.7206
Parametric 1    2       -0.000915555    0.0335704       0.0151878       0.00630521
Parametric 2    2       -0.903958       7.56828 3.4204  2.67077
Parametric C    2       14      980     449.489 330.383
Risetime        2       1       951     83.2021 146.686
Counts to Peak  2       1       35      2.81915 4.28291
Counts  2       1       76      6.30851 12.3079
Energy  2       0       48      2.05319 6.92567
Duration        2       1       2357    229.032 424.699
```

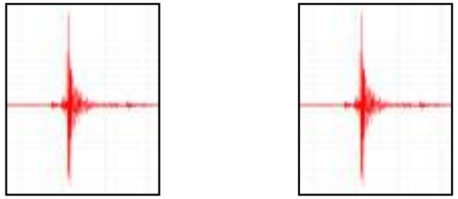
Data Analysis Principles

Four different AE data sets can be acquired simultaneously

1. Complete RF waveform



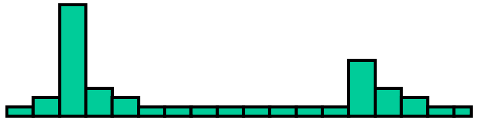
2. Discrete RF waveform



3. Waveform Feature Data

Channel, Time, Amplitude, Duration, Counts, Energy, Rise Time, etc.

4. Time Driven Data



Parametric

All analysis techniques can be conducted simultaneously in real-time and data stored directly to hard drive.

Analysis of 28 hours of AE data while wind speed was between 0 and 14 m/s (6 Beaufort)

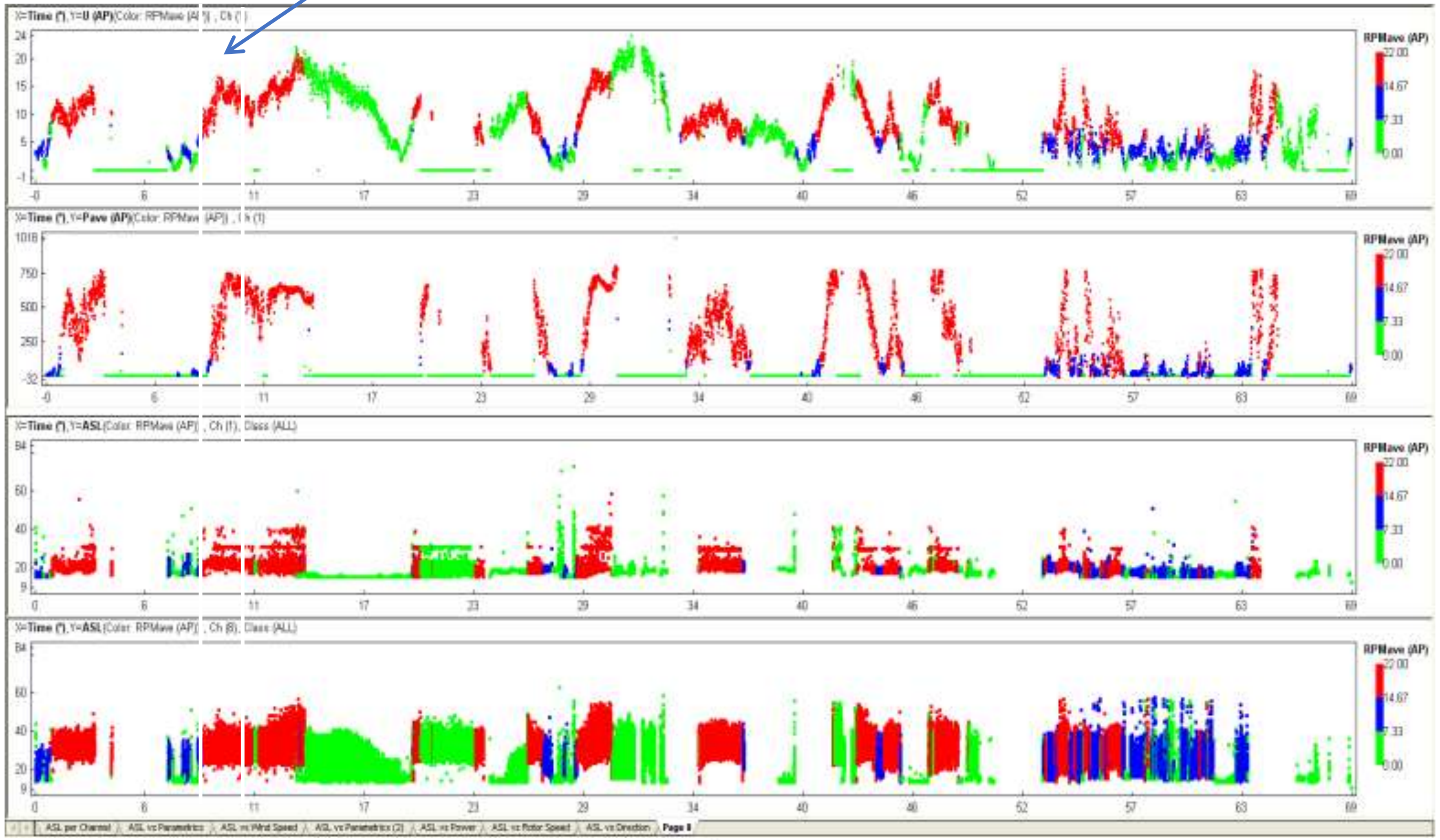
Wind Speed, Average Power Statistics Data between 13 Oct – 21 Dec 2011 (69 days)

Wind Speed

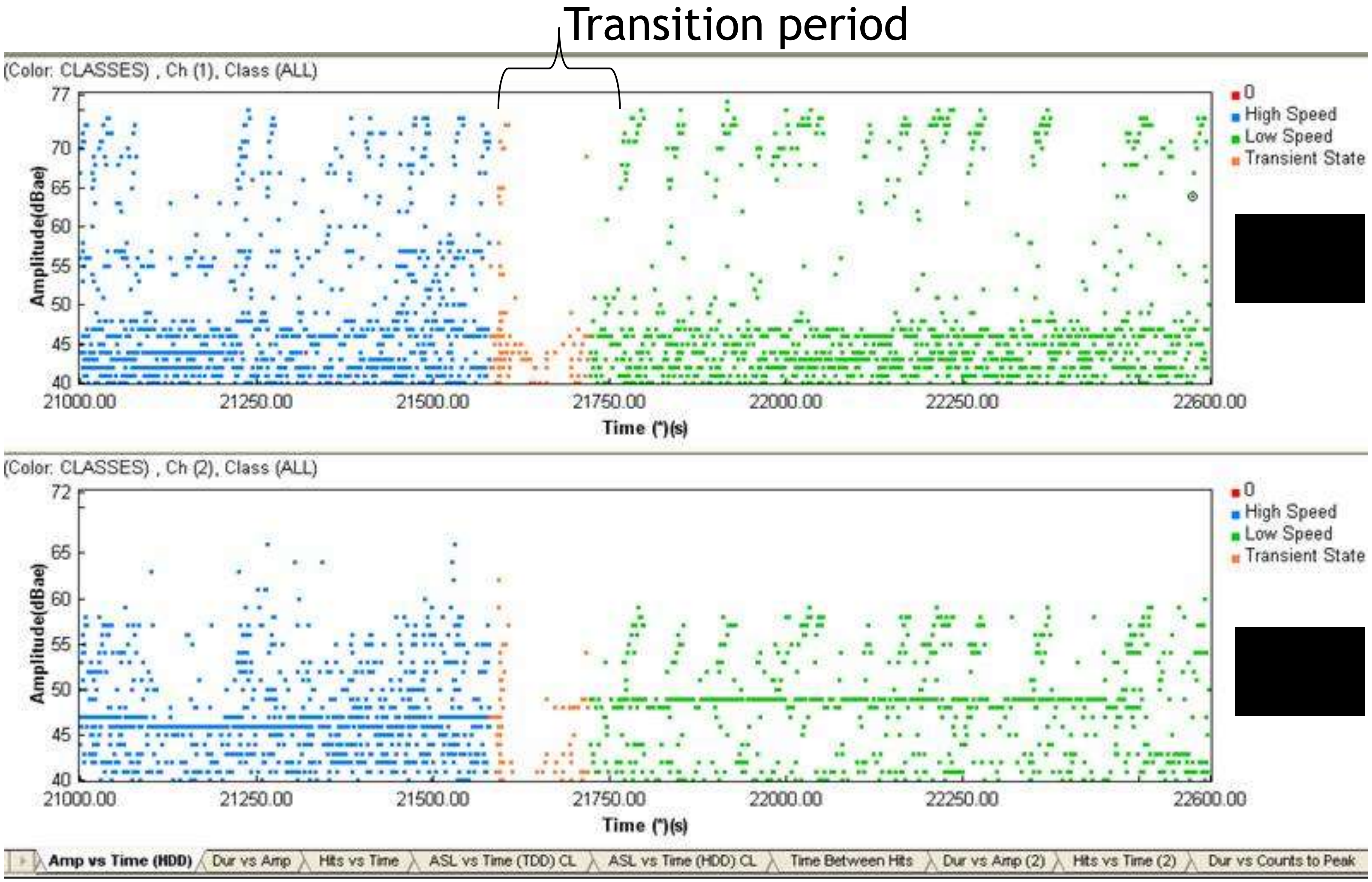
Power

ASL of Ch 1 attached on blade spar

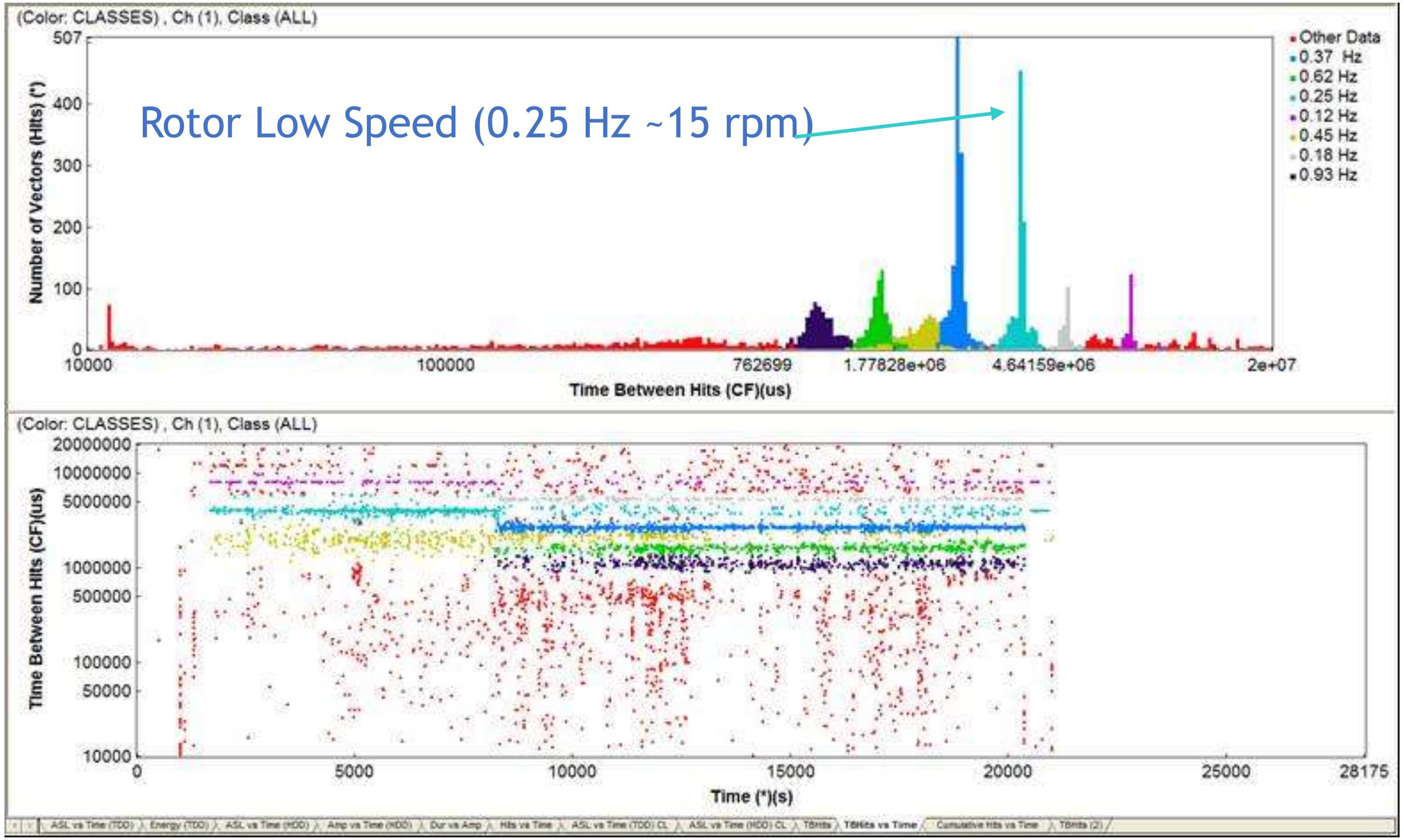
ASL of Ch 8 attached near root



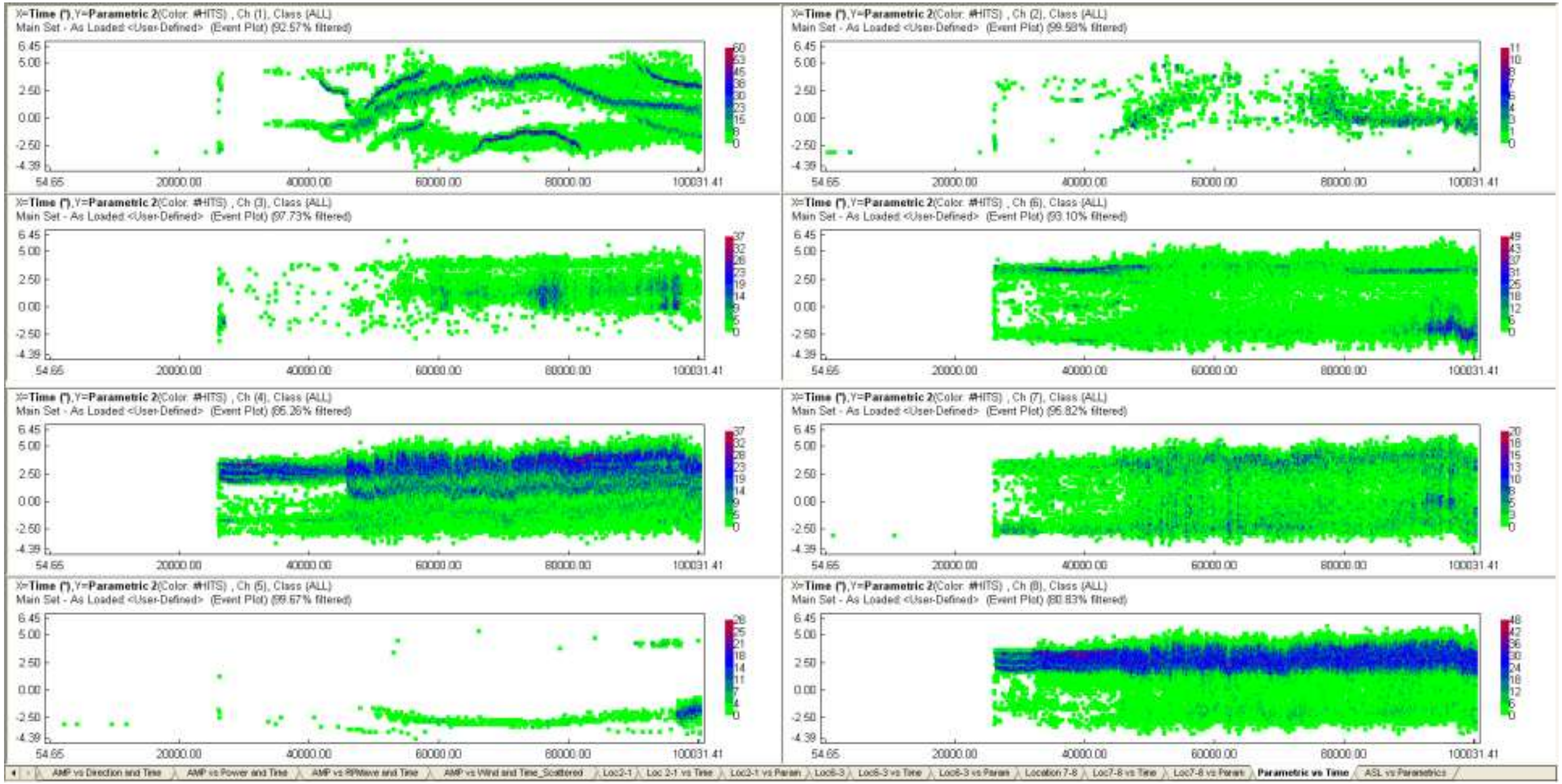
Amplitude of AE events during transition of Rotor speed from High speed to Low speed



Advanced Analysis of AE Data



Plot of Located AE hits density versus Strain Gauge value (Blade Position)



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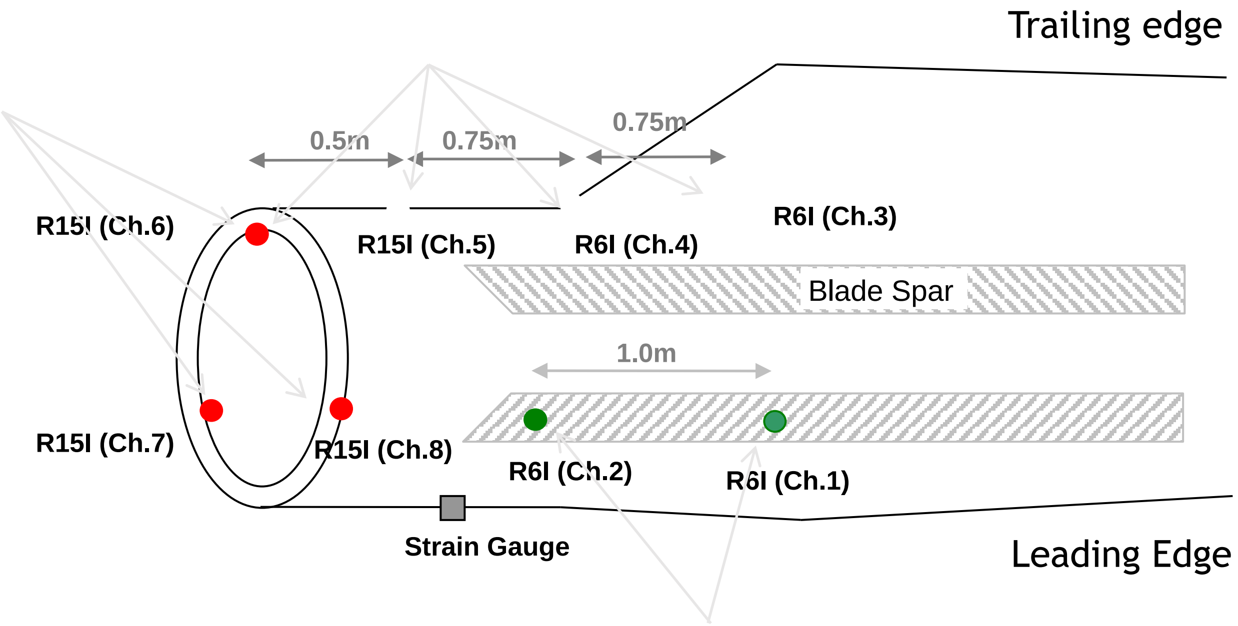
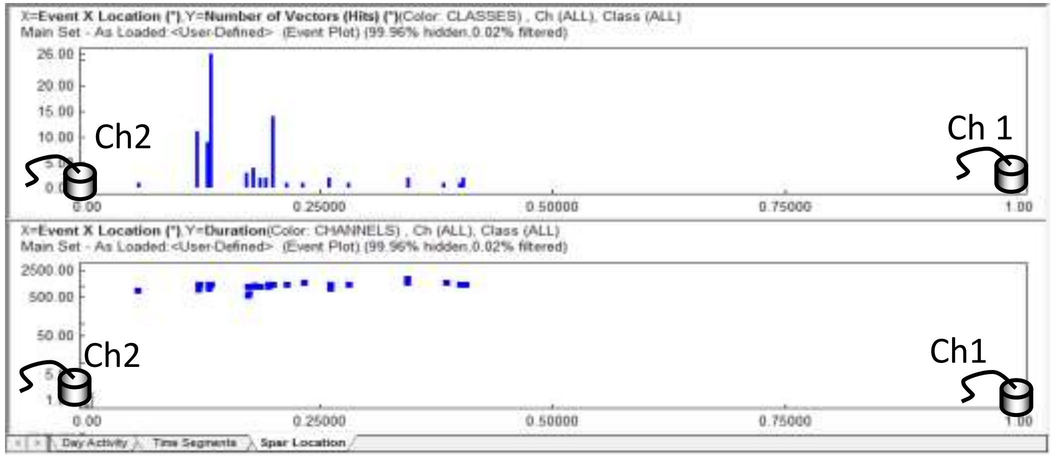
Linear Location Groups



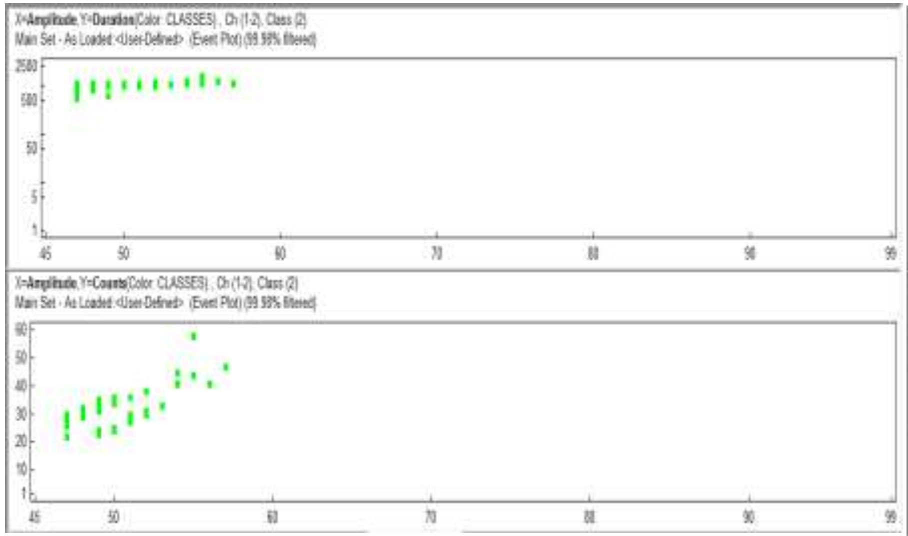
8 AE Sensors Installed:

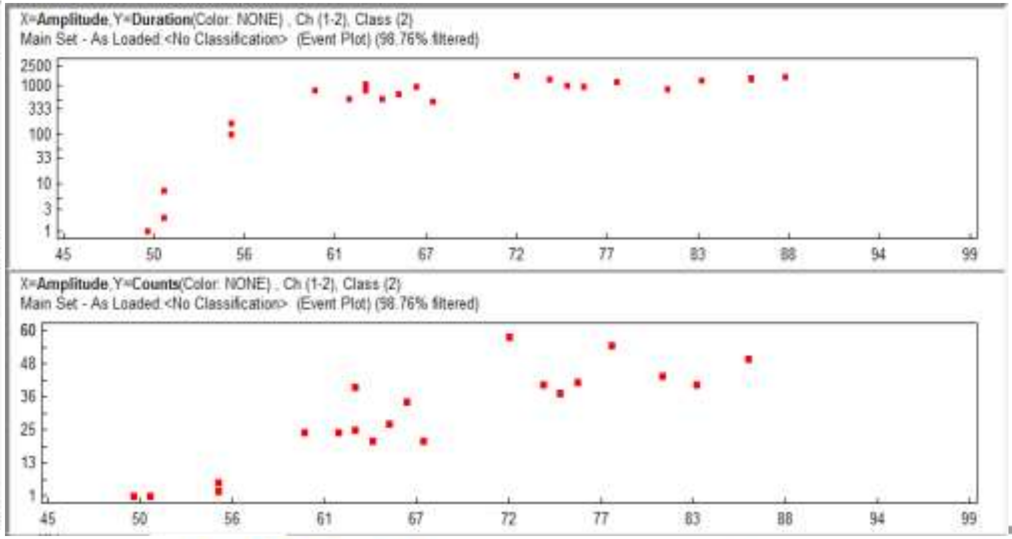
3 AE sensors near blade's root
2 AE sensors on an internal spar of the blade

Linear Located AE Events on Blade Spar
(Channels 1 & 2)

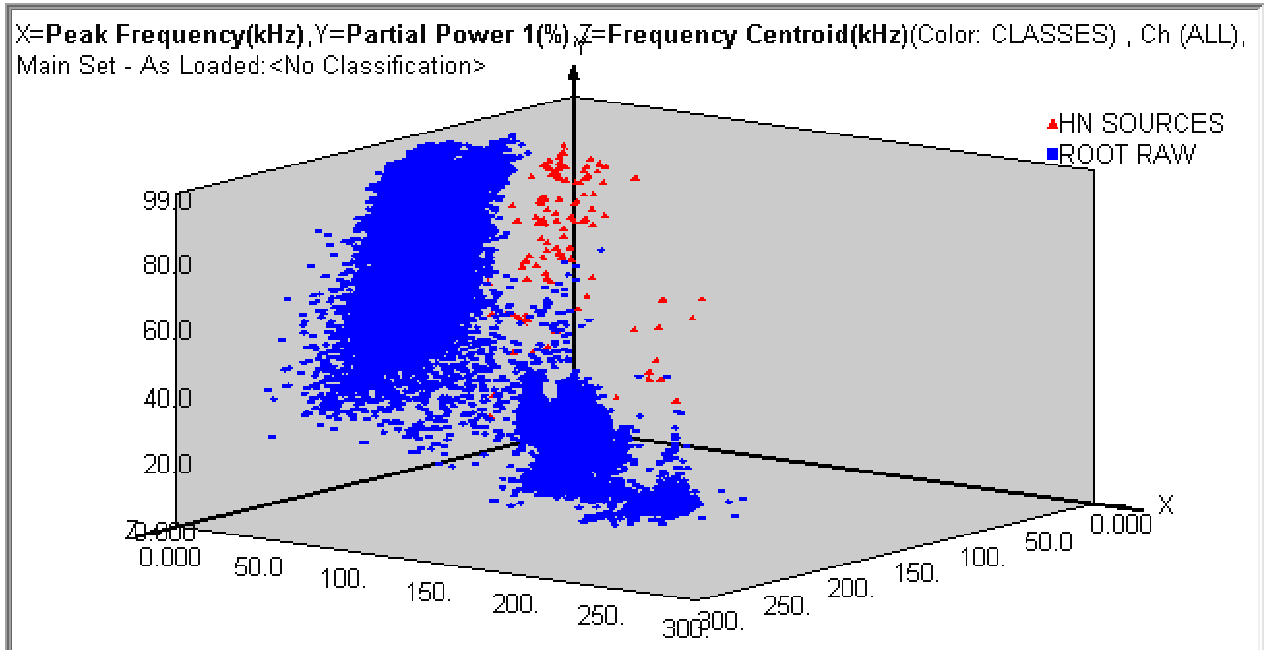


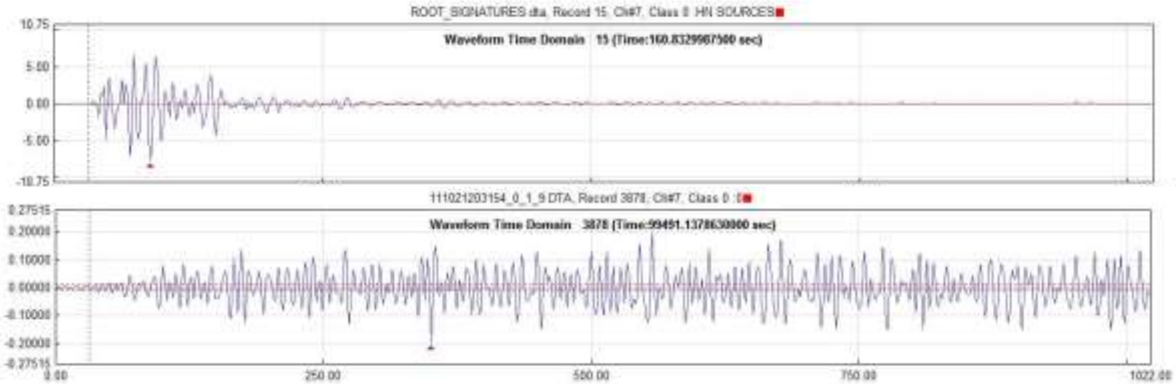
The number of located AE events & the comparison of their signatures with simulated sources signatures indicate that there is no obvious active damage mechanism under current operating conditions





Data Separation in 3D space between raw AE activity and simulated sources recorded near blade's root





Waveform of simulated AE source

Waveform of the majority of the signals acquired near blades root

Conclusions (extracts from NIMO project)

Successful On Line Monitoring for 8 months. Different filtering methodologies validated for the specific application. Able to set up early warning alarms by monitoring a W/T for 2 months.

AE data indicate an acceptable level of activity for the sensors located on the trailing edge and for the sensors located on the internal spar of the blade. Contrary, AE data indicate excessive activity for the sensors mounted near the blade’s root.

Correlations between the AE data rate and the Wind speed, Generated power, Rotor speed and Blade position have been identified, however they can’t be used the only features to set-up early warning alarms.

Increased amplitudes of AE activity can be observed during machine start/stop transition periods and on high loads (above 520 kW). Located AE events were not correlated with structural degradation, as the blade appears to be in good condition.

Advanced analysis in real-time of TDD and HDD data, using pattern recognition and events location can provide the means to train an AE system to generate early warning alarms, while keeping false alarms as low as possible.

FROM RESEARCH (over ambitious goals) to PRACTICE (application development to meet industry needs)

SENSORIA™ COMMERCIALLY AVAILABLE SYSTEM

Blade Failures are the Primary Cause of Insurance Claims

- **Lighting strikes**
- **Foreign object damage**
- **Fatigue material failure**
- **Manufacturing defects**

Blades O&M Challenge

- **Difficult to predict lifetime**
- **Stochastic loading**
- **Limited access - especially offshore**
- **Limited availability of data – mostly visual**

Challenges will Increase with Deployment of Larger Offshore Turbines

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Blade Maintenance

Fixed schedule

Historical data, failure and degradation information

Schedule based on blade condition

Real-time sensor measurements, data trends, models and ML & AI algorithms

Blade Maintenance Based on Blade Condition Requires Continuous Monitoring

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SENSORIA™ SHM of W/T BLADES

blade failures are the primary cause of insurance claims.

Blade failures account for over ***40% of insurance claims***, ahead of gearboxes (35%) and generators (10%).

The ***main causes of failure*** of rotor blades include:

- Lightning strikes,
- Foreign object damage,
- Material failure due to fatigue, and
- Manufacturing problems

Longitudinal crack at 25m

Longitudinal crack at 10m

PURPOSE OF THE BLADE MONITORING SYSTEM

EARLY DETECTION: Identify damage upon onset

DEFECT ACTIVETY OR STABLILITY: Track acoustic signature to learn of growth or stability

ANALYZE TRENDS ACROSS SITE AND BLADE SETS: Acoustically rank blades for repair & inspection prioritization

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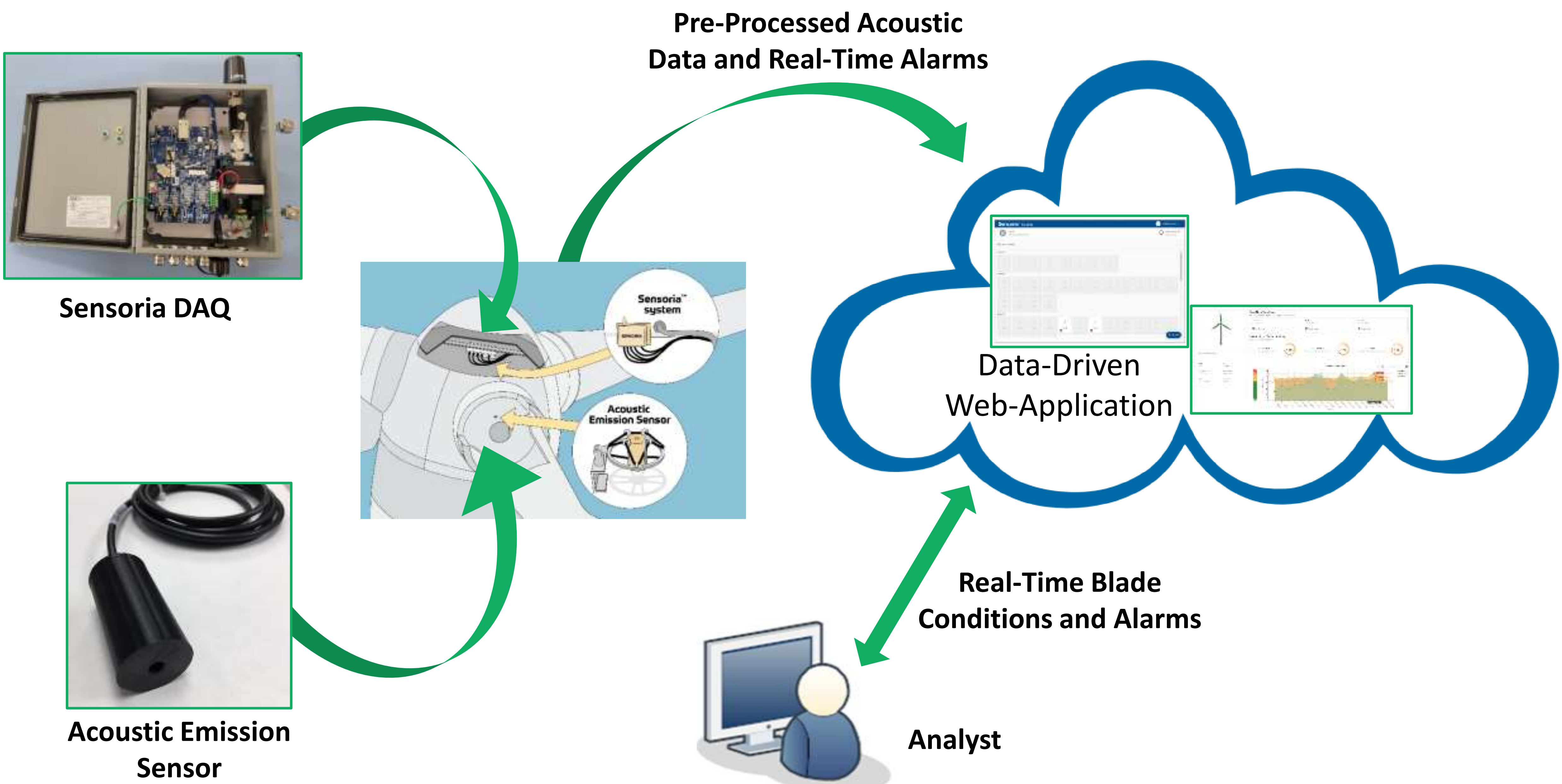
SENSORIA^{TM} TECHNOLOGY PACKAGE

MISTRAS



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Continuous Monitoring Data

Generate real-time alarms

Generate a grading system

Guide maintenance planning

Real Time Alarms

Normal Status	Event	Heightened Status	Time to inform alarm	How do we Inform
Normal	*Impact*	Impact no rupture alarm *(Clear after 24 hrs.)*	1hr -1.5hr (@ website)	web app only or email if ruptured blade
Normal	*Skin rupture*	Skin rupture alarm *(Cleared after 48 hrs.)*	8-12hr	Email after verification only
Normal	*Impact producing rupture*	Impact & skin rupture alarm *(Cleared after 72 hrs.)*	8-12hr	Email after verification only

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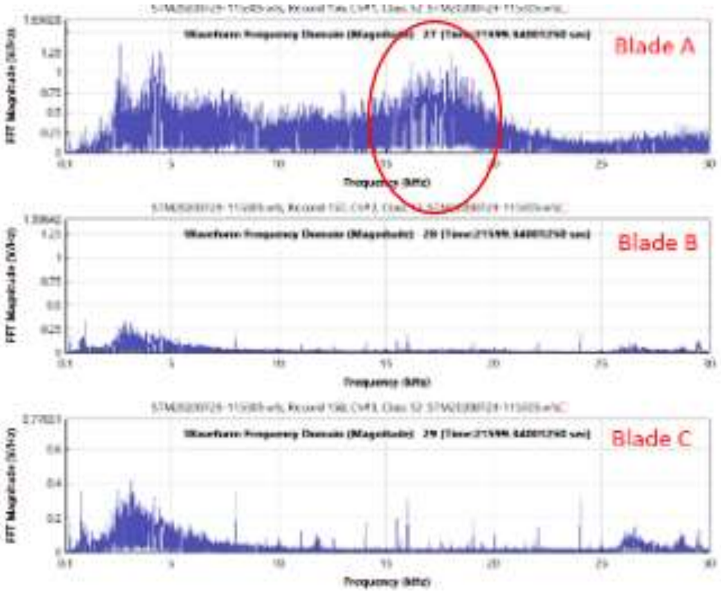
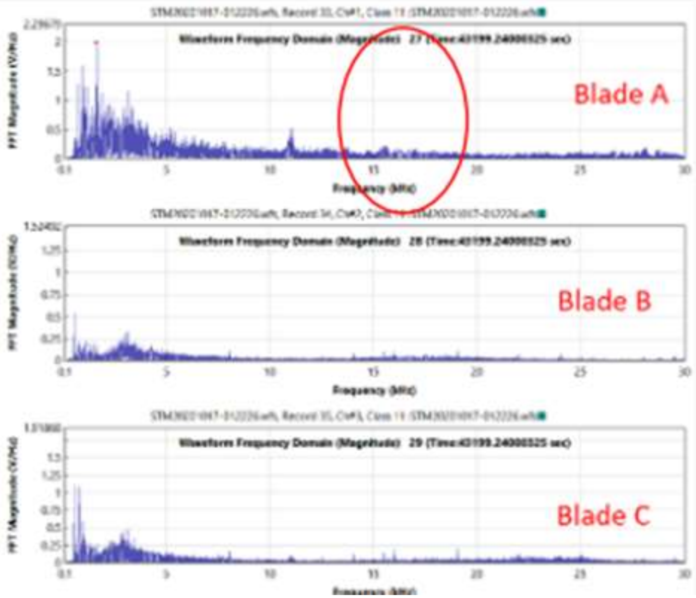
EXAMPLE - SPLIT TRAILING EDGE





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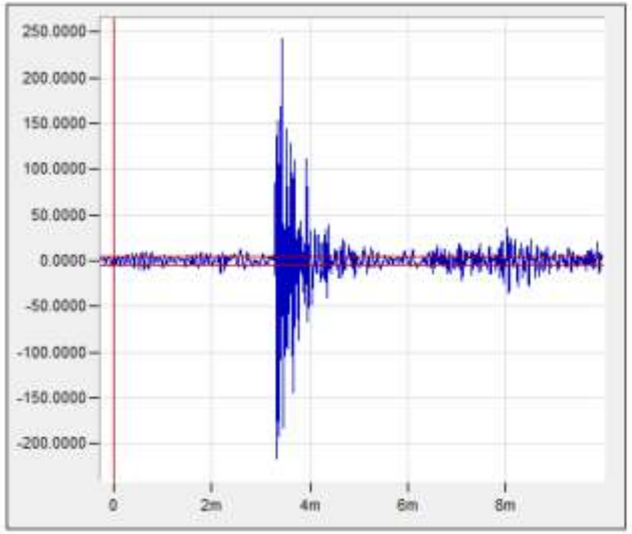

Acoustic Emission Hit
Recorded by the DAQ

Acoustic Activity change over time in response to

- **Turbine Operation**
- **Weather**
- **Defect Presence and Severity**

Acoustic activity collected over a 7-day period allows to generate Grading Metrics

- **Probability of Defect Activity (PDA)**
- **Crack-Like Activity (CLA)**
- **Delamination-Like Activity (DLA)**
- **Other Defect-Like Activity**

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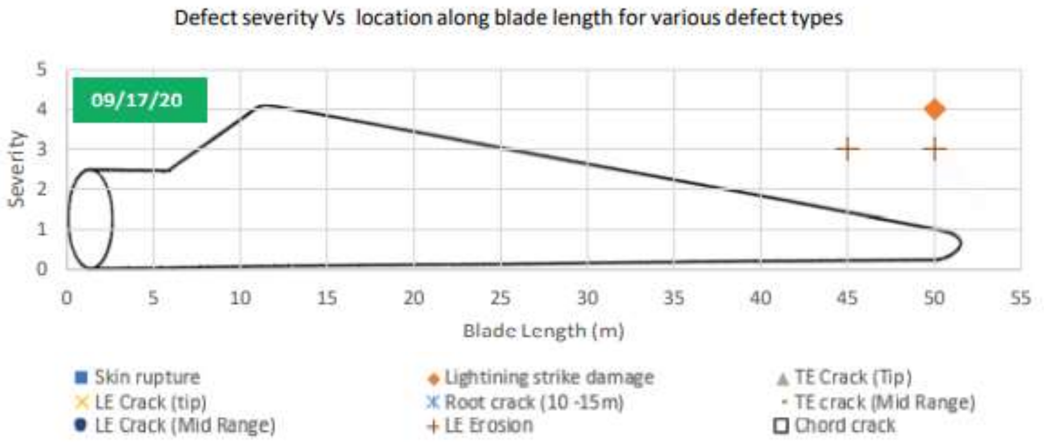
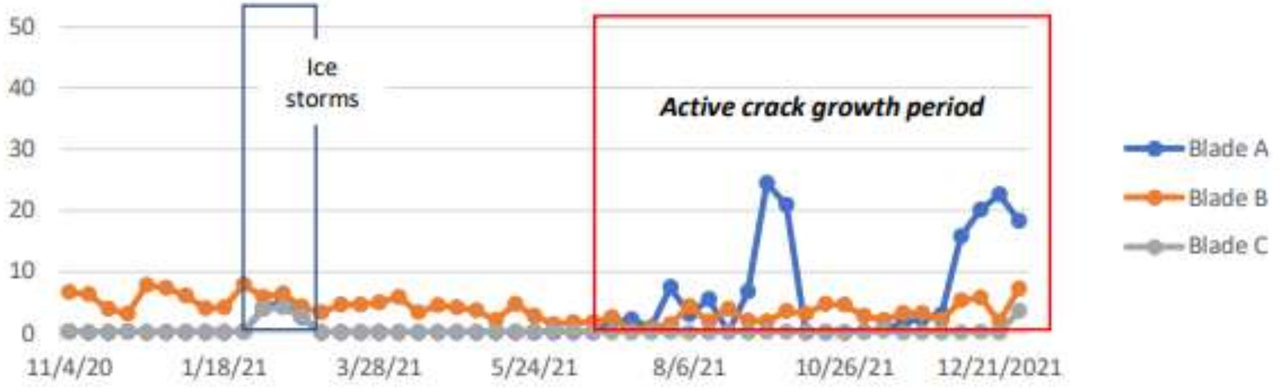
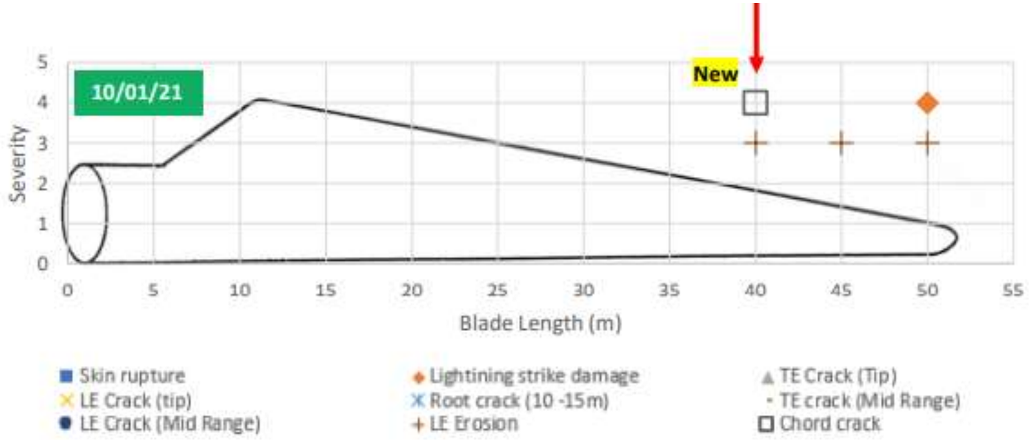
CRACK-LIKE ACTIVITY CONFIRMATION BY INSPECTION & ASSESSMENT TREND







Test Turbine No	Model	Blade	Defect Type-ID	List Severity Leve		Defect Location Info		Repair Date
T0004-B	V100-MK7	A/1	LE Crack - Mid Range	Other	✗	Tip		
T0006-B	GE1.6	B/2	Root Crack (10m)	S5	✓	10m	1	7/9/2021
T0002-B	Clipper 93	B/2	LE Crack - Mid Range	S4	✓	25m	2	
T0007-B	GE1.6	A/1	TE Crack - Tip	S4	✓	Bond line crack	3	
T0001-B	Clipper 93	A/1	TE Crack - Mid Range	S3	✓	23m	4	
T0002-B	Clipper 93	A/1	LE Crack - Mid Range	S3	✓	20m	5	
T0001-B	Clipper 93	C/3	LE Crack - Mid Range	S3	✓	20m	6	
T0006-B	GE1.6	B/2	LE Crack - Mid Range	S3	✓	30m	7	
T0007-B	GE1.6	C/3	Root Crack (10m)	S3	✓	10m	8	
T0003-B	V100-MK10	A/1	LE Crack - Mid Range	S2	✓	30m	9	
T0001-B	Clipper 93	B/2	TE Crack - Mid Range	S2	✓	30m	10	

✓ Activity passing filters ✗ Activity not passing filters

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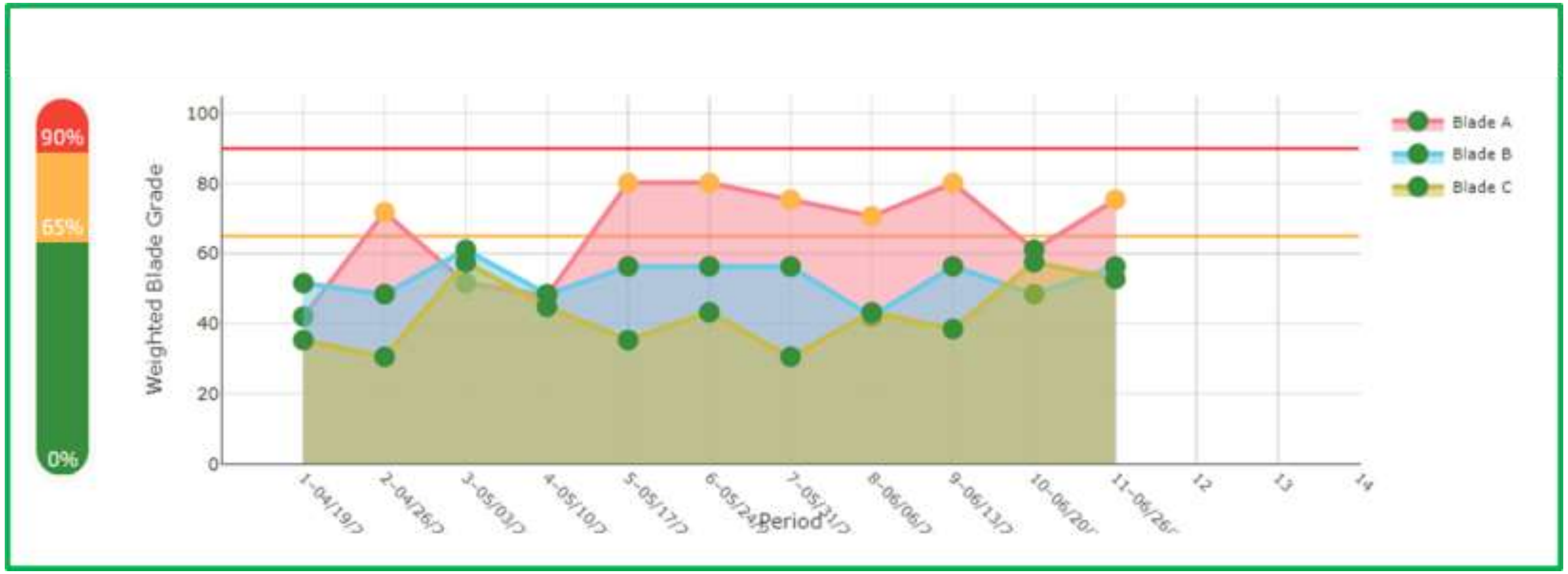

PDA Alarm

Normal Status

PDA (green or yellow)

➔

Event

New PDA calculation

Calculation is performed weekly or following the monitoring period.

➔

Heightened Status

High defect activity Alarm
(Cleared after 1 week)

Email Communication Summary

Email sent after **analyst verification** of the acoustic activity *(Analyst assisted verification expected within 24 hrs. of alarm onset).*

- Acknowledgement requested
  - Email reminding need to acknowledge (sent after 48hrs alarm verification)

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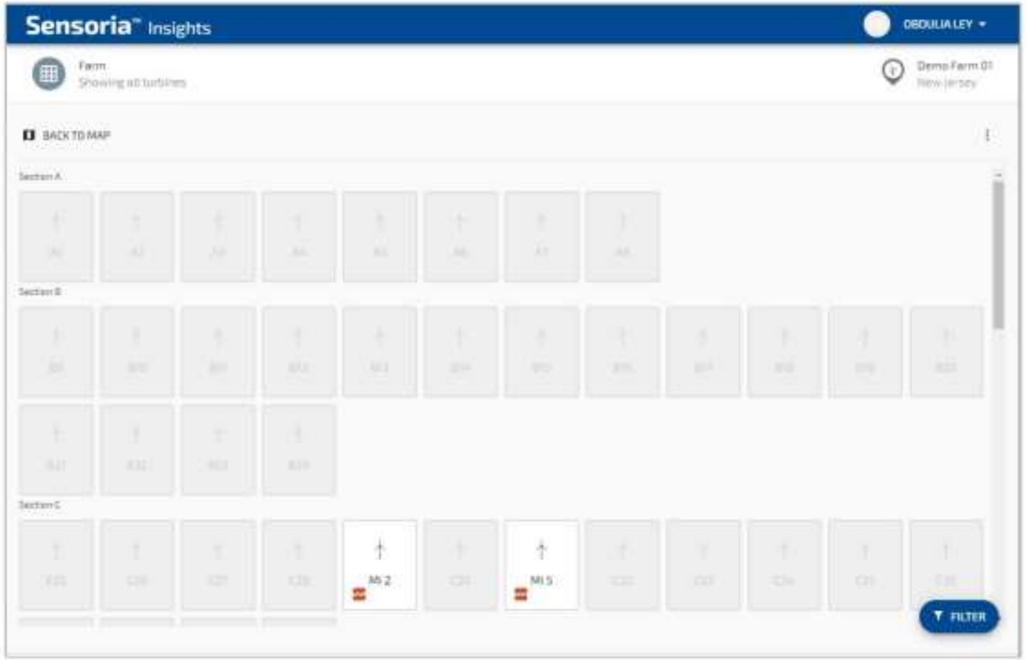

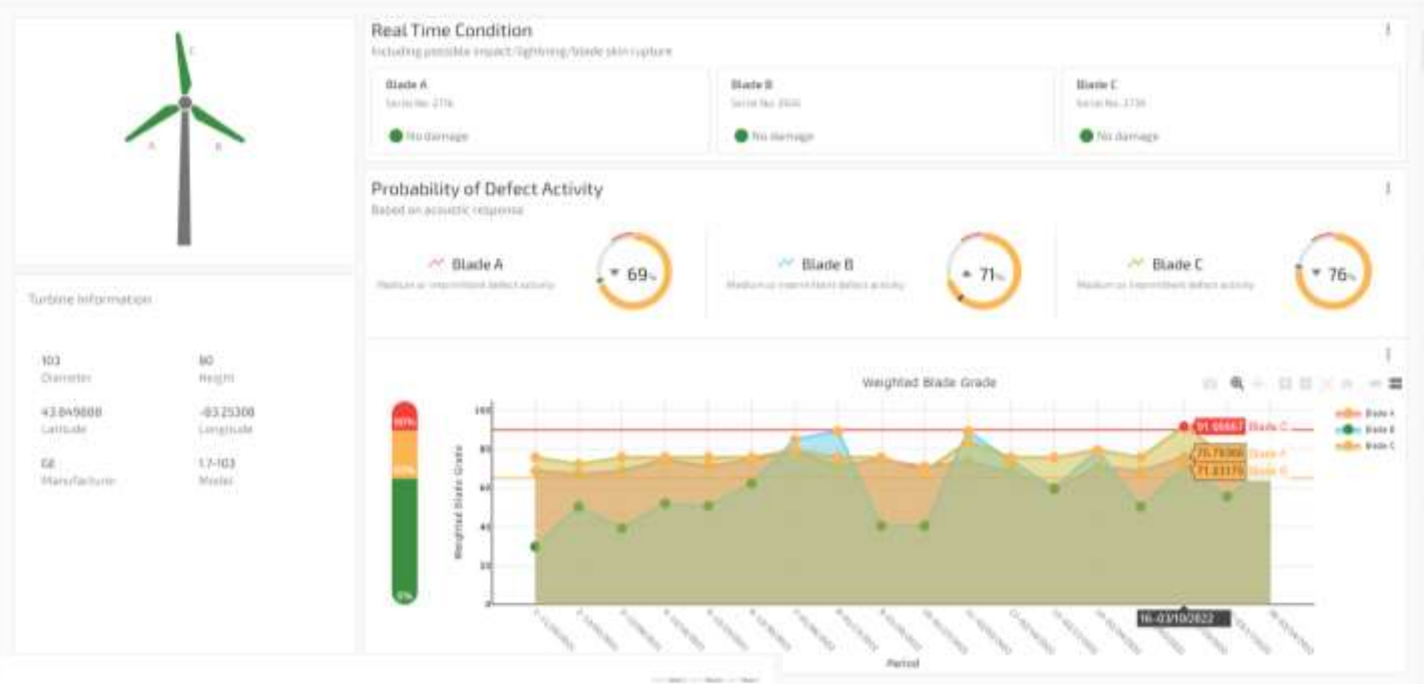

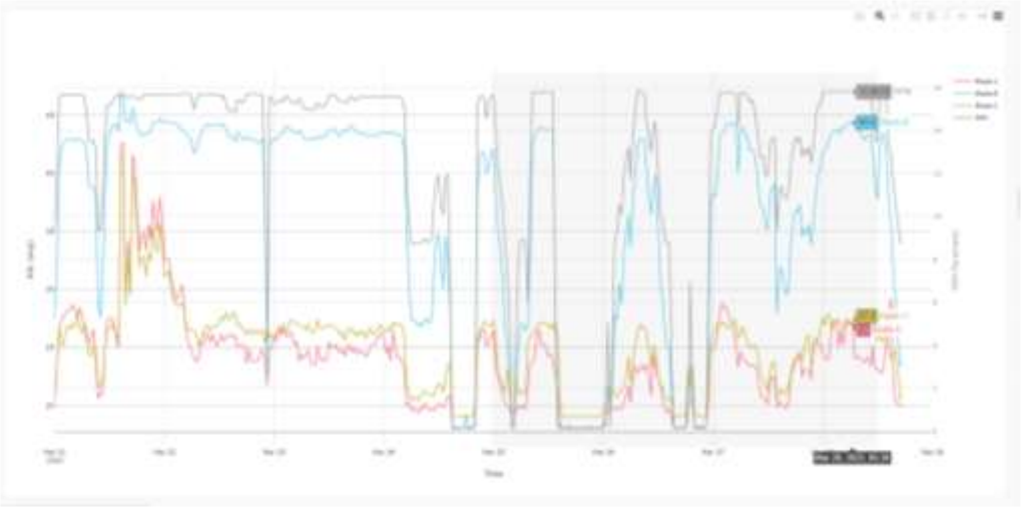

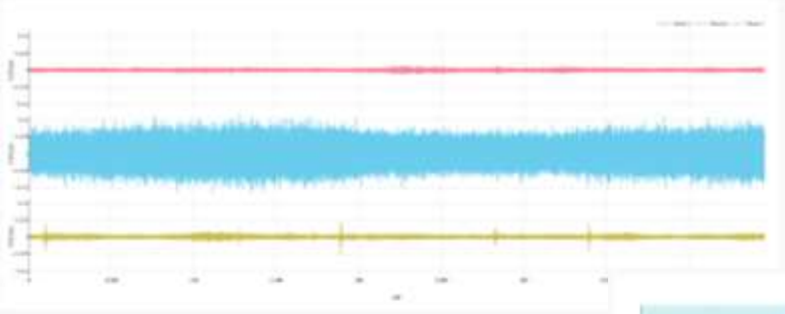

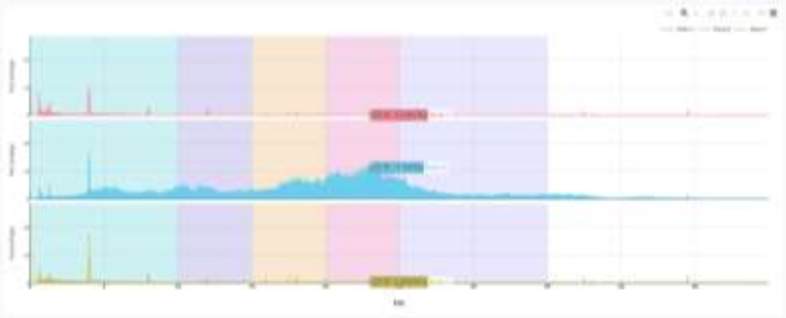

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CASE STUDIES

- **SPLIT TRAILING EDGE**
  - **BMS detected high level background noise in a blade split TE. After the TE was repaired, the background noise level was reduced**

- **ROOT TRANSVERSE CRACK**
  - **BMS detected specific frequency in a blade with a root transverse crack. After the crack was repaired, this frequency reduced significantly**

- **ASYNCHRONOUS PITCH OPERATION**
  - **BMS detected high energy bursts of acoustic activity on blade C during pitching which was not in synch with blades A and B**

- **ICE FORMATION**
  - **BMS data showed high energy and high frequency signals in the 02/01/21 to 02/16/21 period, when temperatures dropped below 20° F**

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1

Early information about defect activity and onset allows to proactively plan for repairs and reduce repair costs & risk.

2

The monitoring system can help prevent blade failures by providing early detection of damages.

3

The data driven web app communicates real time condition and alarms.

4

The monitoring system identifies damages when they happen and as they grow, by sending automated email alarms.

5

Data from the web app to compare blade condition across site & fleet, by using two MISTRAS proprietary quantities:

- Probability of Defect Activity (PDA) and
- Crack –Like Activity (CLA)

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TOWER MONITORING

Fatigue experience background

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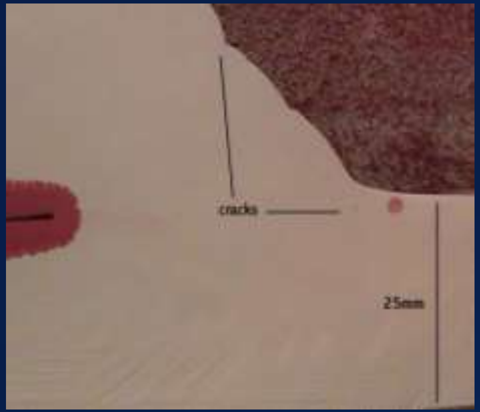
Verification trial



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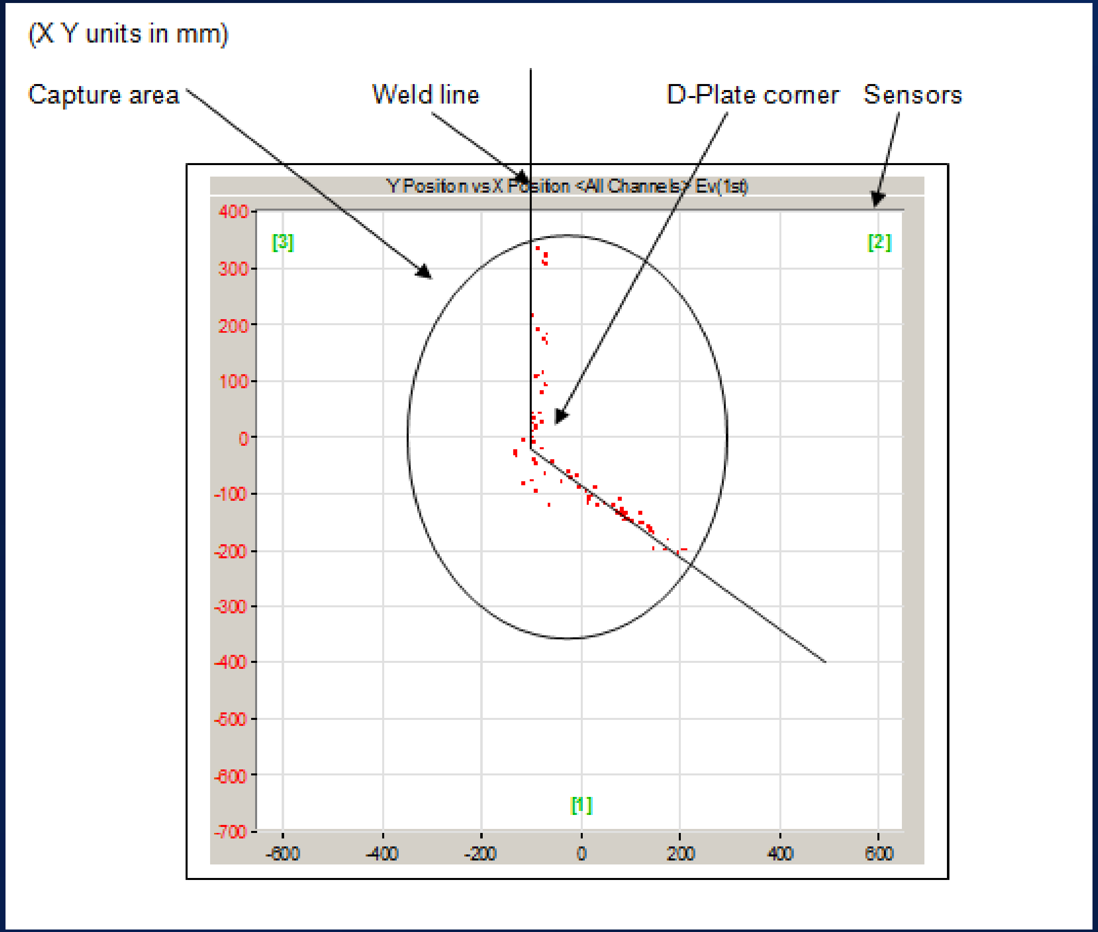
Installation



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Background Research

55m high wind turbine on Mires Hill

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TP WELD MONITORING

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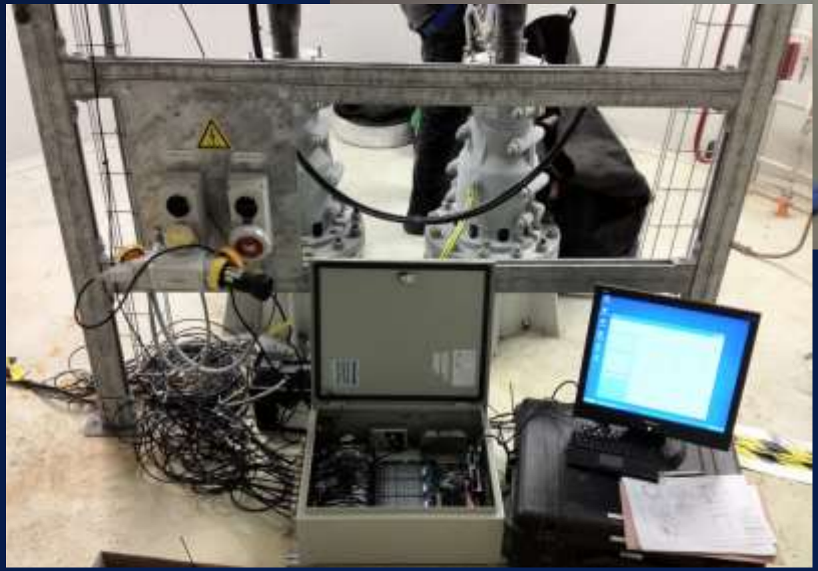
Source Location on welds



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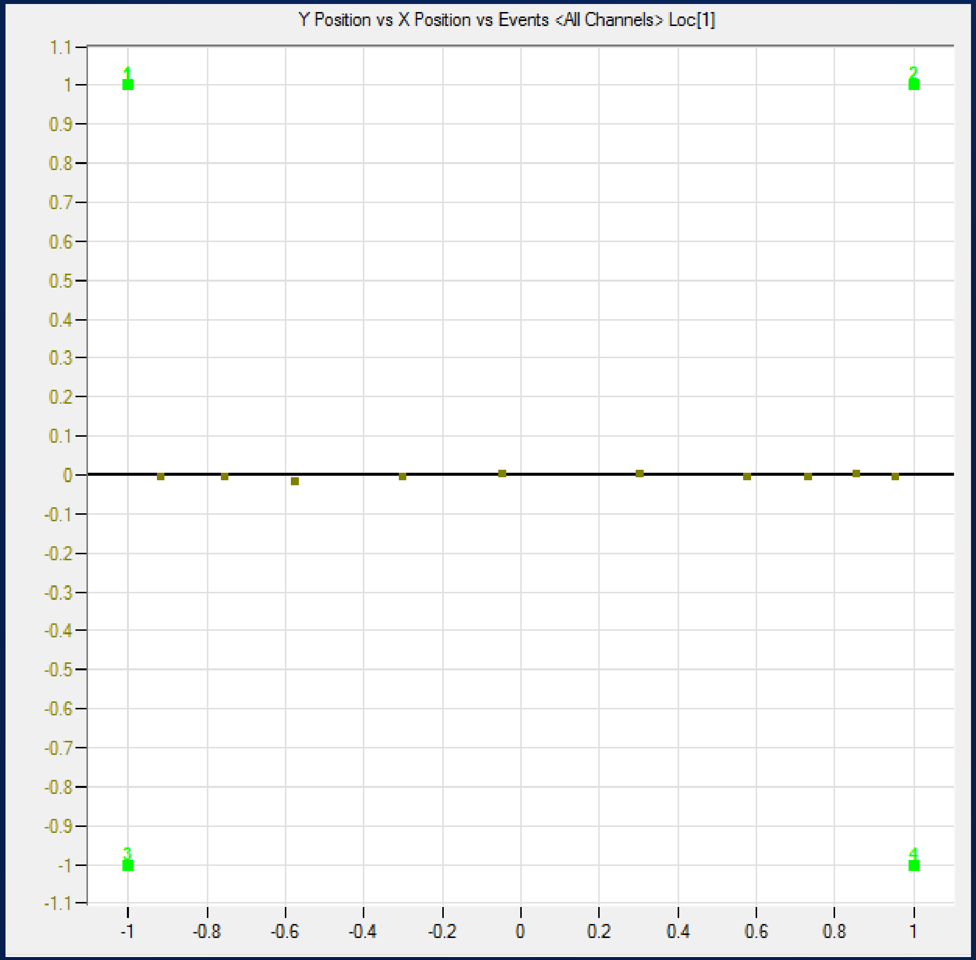
Source Location in TP Welds



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TP SUPPORTS WELD MONITORING

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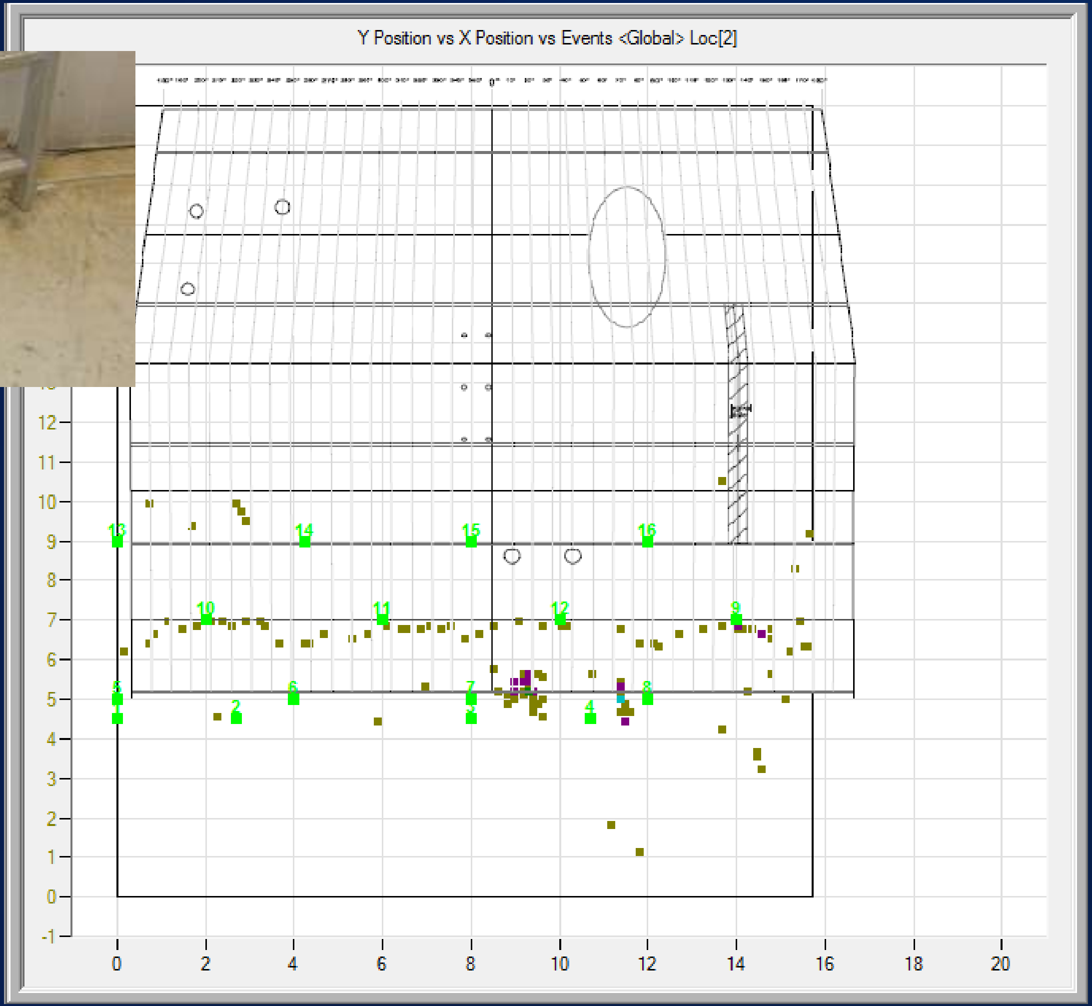
SOURCE LOCATION ON TP WELD



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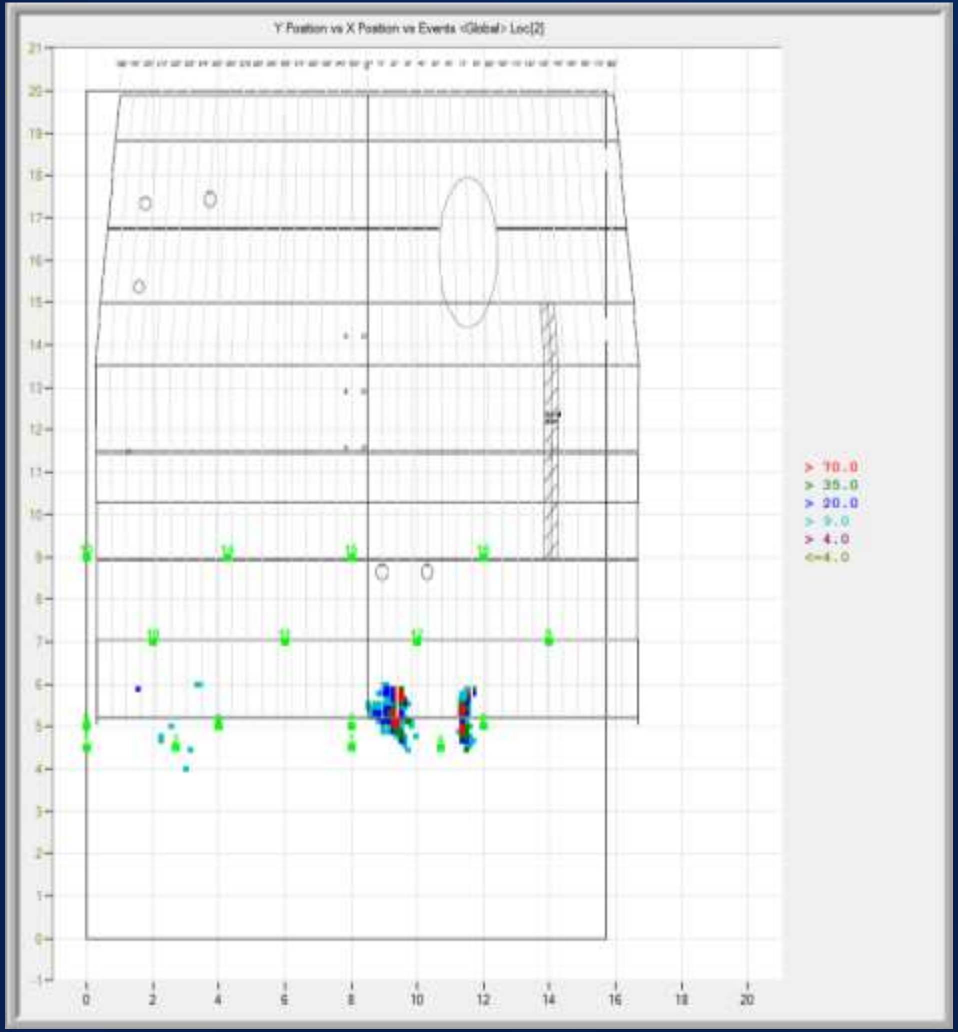
Source location on welds



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BOLT AND FLANGE MONITORING

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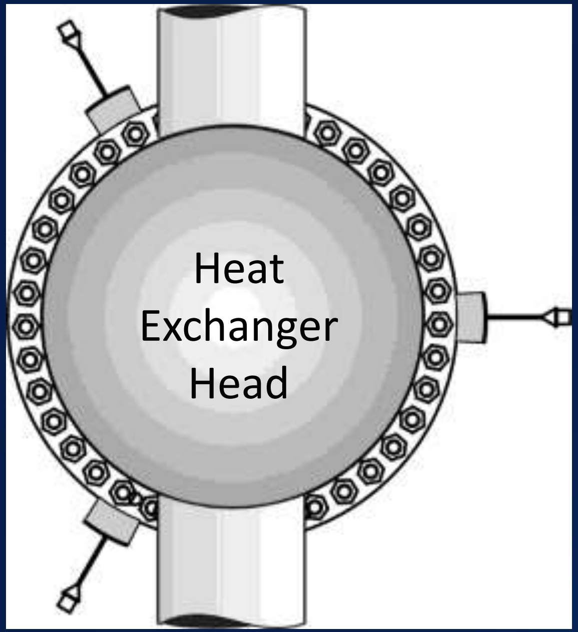
AE Flange experience – Heat Exchangers



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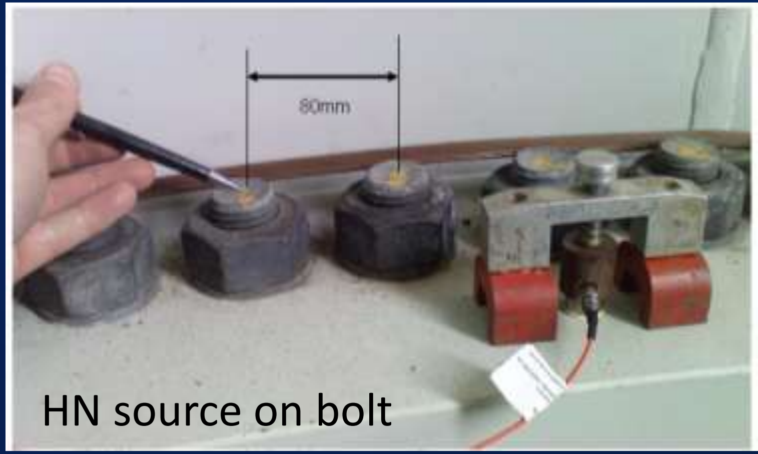
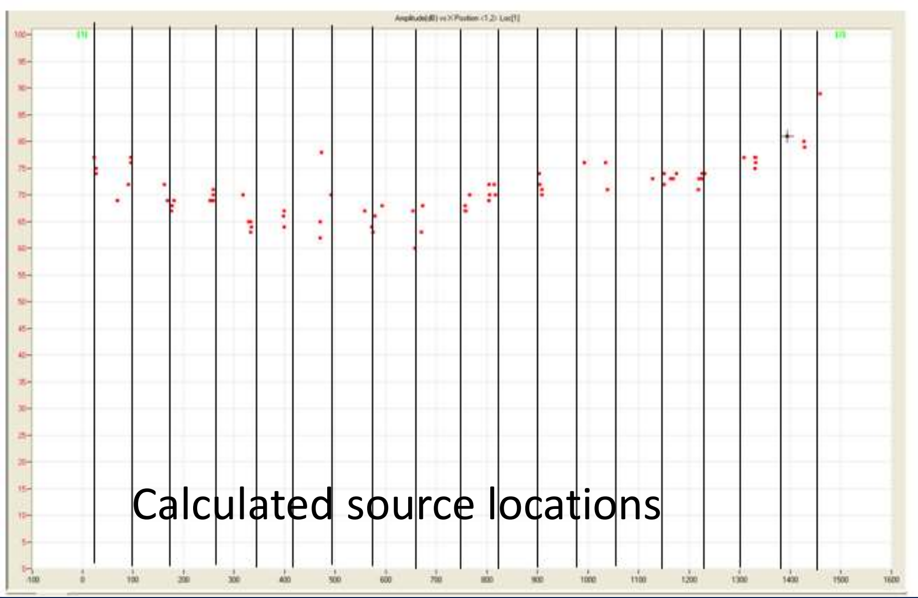
Source Location on Bolted Joints



Using sensors mounted on the bolted flange it was possible to demonstrate this application locating artificial AE sources to the area of each bolt. This was tried on the wall of the tower but the location provided was not as clear.



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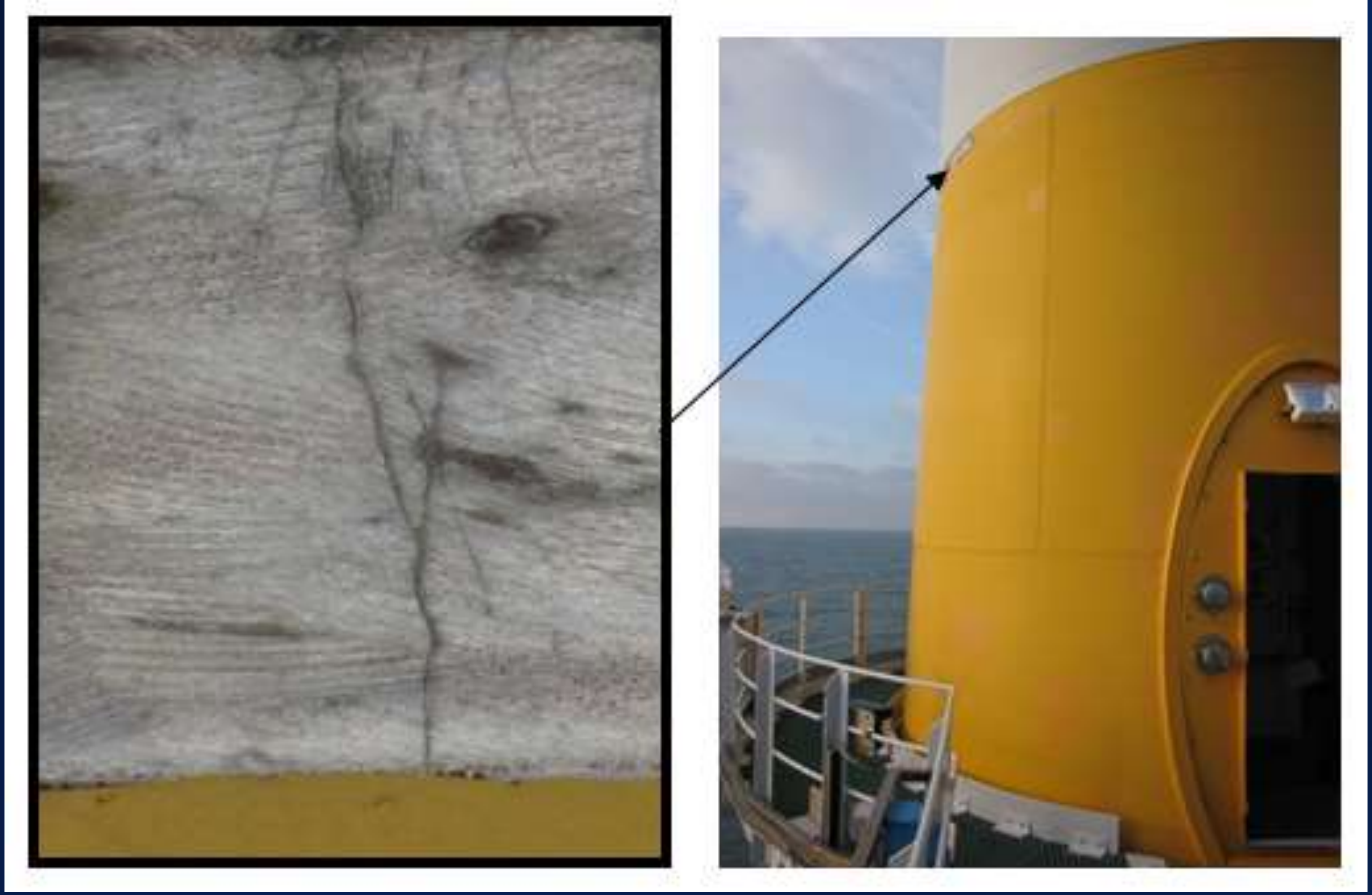
Source Location on flange



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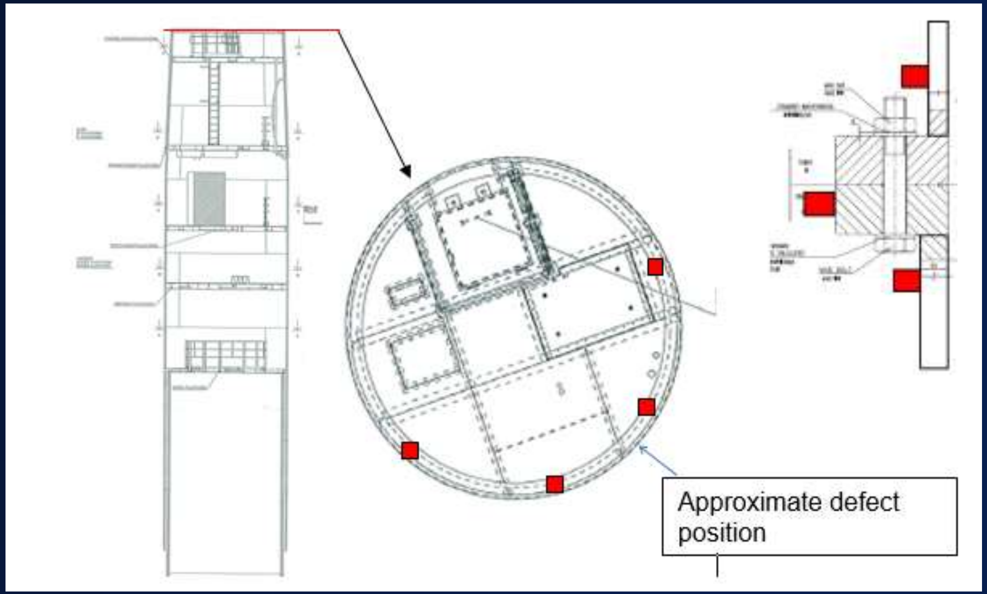
Source Location on flange



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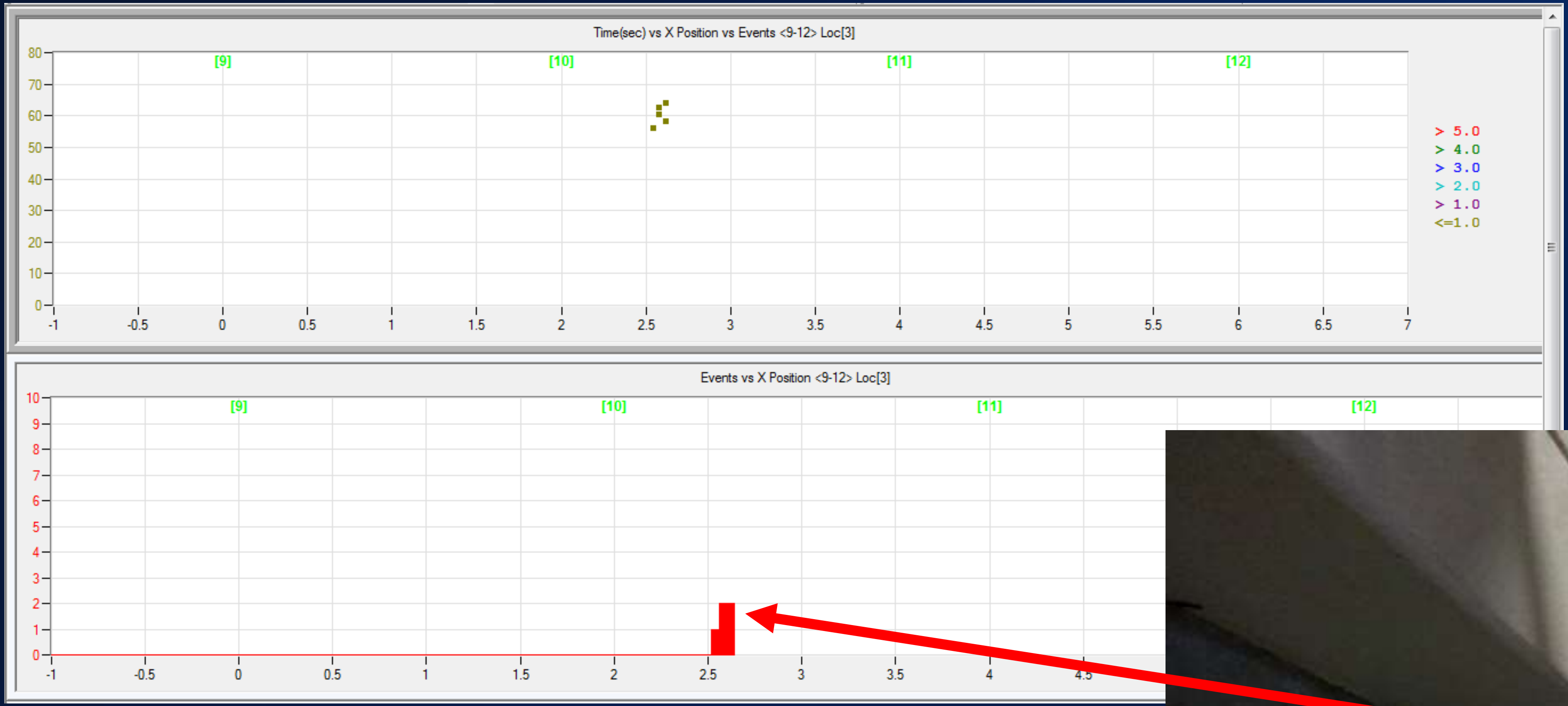
Source Location on flange



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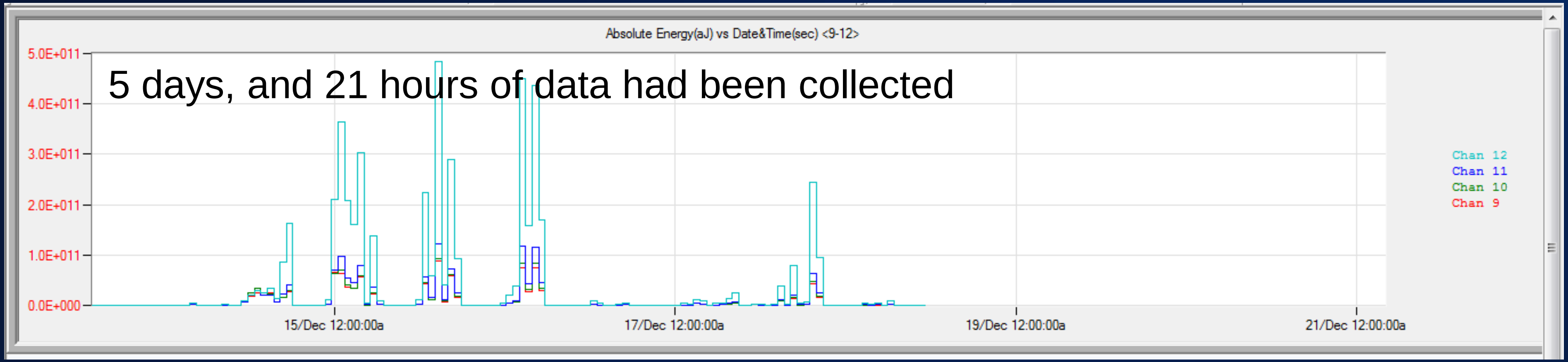
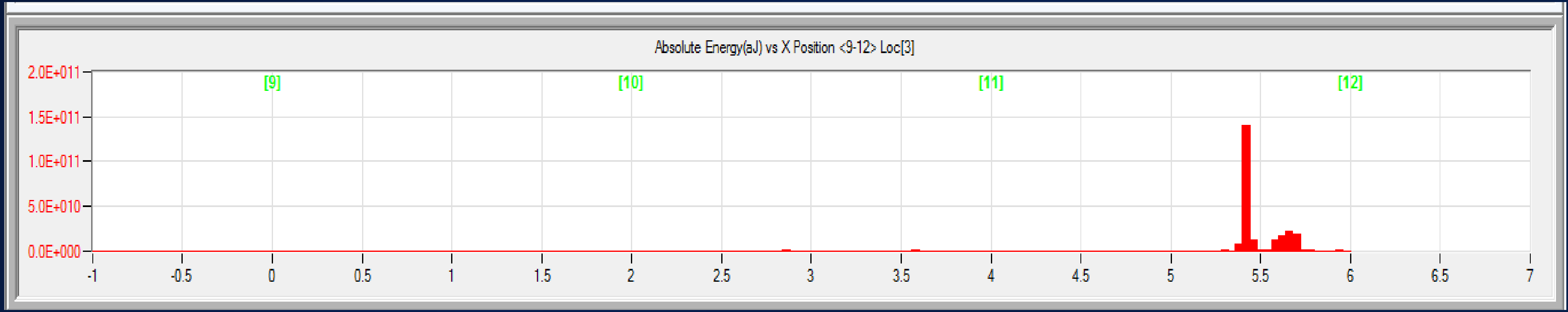
Source Location on flange





As can be seen there is no significant emission located around the defect position of 2.5m. There is an indication around 5.5m but following closer examination using guard sensors it was identified this is not located on the flange but outside and below the array.

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OFFSHORE MONOPILE MONITORING

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Monopile Monitoring

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Monopile Monitoring

Concept design and verification trials:

Hardware design, manufacture and supply:

Hardware installation offshore:

System remote monitoring:

Data management, visibility analysis and reporting:

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THANK YOU FOR YOUR ATTENTION

WHAT ARE YOUR QUESTIONS ?

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