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Work-Comittee No II
Characteristics and Inspection of Ropes

Gains and Limits of Magnetic Rope Testing

University of Stuttgart
Institute of Mechanical Handling and Logistics
Stuttgart, Germany

Dipl.-Eng. **Sven Winter/** Dipl.-Ing. **K. Kuehner**
sven.winter@ift.uni-stuttgart.de

STRMTG / French authority
Saint Martin d'Hères, France

Dr.-Eng. **Stephane PERNOT**
stephane.pernot@developpement-durable.gouv.fr

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Content

(1) Basics of MRT
(2) Experimental setup and testing
(3) Actions arising from an MRT report
(4) Wire break analysis (anomalies)
(5) Limits of MRT
(6) Beyond the limits
(7) Conclusions and prospects

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Basics of MRT

6-month old track-rope

lack of lubricant, indentation of Z wires

Failures of internal layers

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Brief History of MRT in Stuttgart

Origin: Invention of magneto-inductive coil by Prof. Richard Woernle in 1930s

Today: Research institute for MRT and rope technology, service provider for rope inspections, damage analysis, approval tests and regular inspection of ropeways

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Typical damages in ropeway wire ropes

How & why does a rope reach the discard criteria?

-<u>Bending cycles:</u> rope wear and material aging by repeated flexion over sheaves

-<u>Corrosion:</u> Material surface turns brittle and initiates cracks and wire breaks

-<u>External influences:</u> lightning strokes, accidents within construction works, derailments,…cause deformation, structural changes or wire breaks

-…and many more reasons



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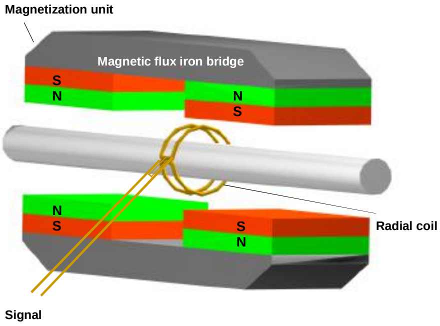
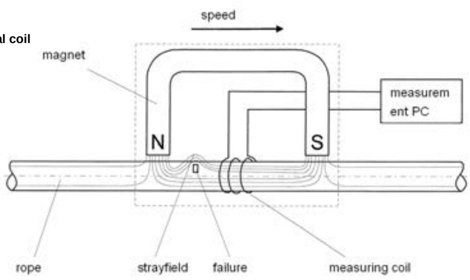
Magneto-Inductive Method and Results



– Permanent magnets create a saturating magnetization of the steel wire rope
– Resulting leakage field generates a voltage in the measurement coil

$$U = -\, n\, S\, v \frac{dB}{dx}$$

Lenz-Faraday law



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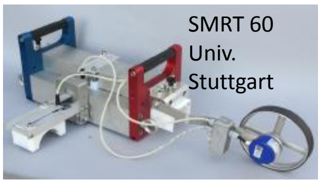
Examples of Basic Machine Designs


SMRT 40


Test head IWT


SMRT 60
Univ.
Stuttgart


Test heads TVFA-Wien

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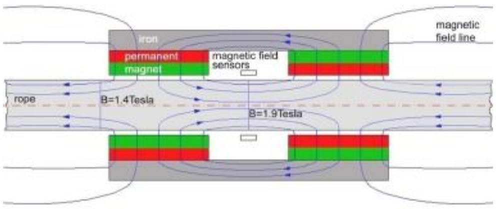
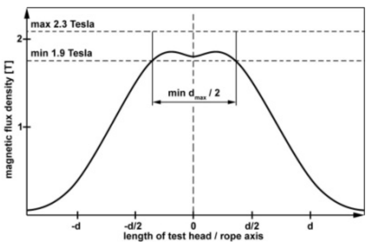
Magneto-Inductive Method and Results



Magnetic field circuits forming homogeneous magnetic flux all over the rope's cross section. The wire material has to be magnetically saturated by at least 1.9 up to 2.3 Tesla.



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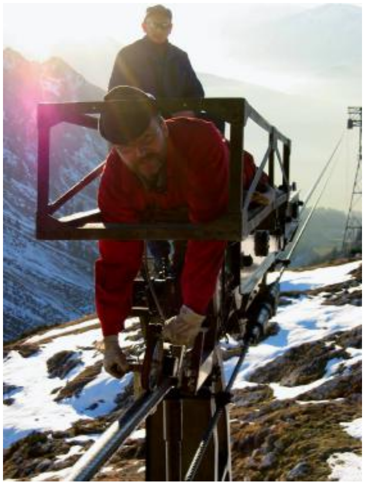
2. Experimental Setup



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Experimental setup on suspension ropes


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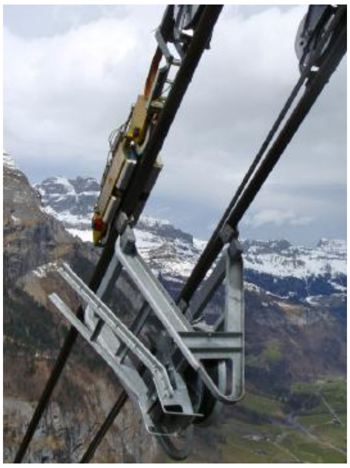
Experimental setup on track ropes



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Experimental setup on moving ropes

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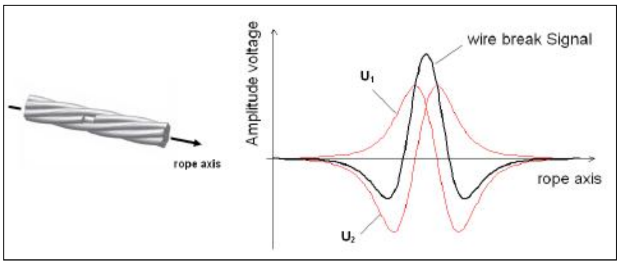
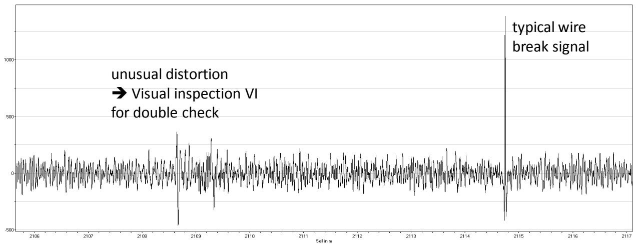
Magneto-Inductive Method and Results

Damage Signals:

Theory:



Practical experience:



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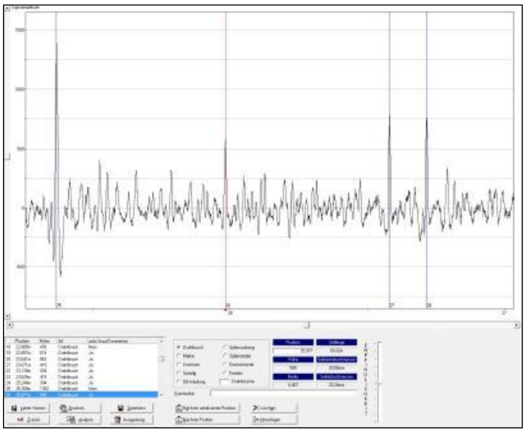
Magnetic rope test and Results



Software-Application:

- Automated labelling of suspicious patterns
- Evaluation by expert user
- Automated report creator
- Relating of damages to discard criteria (loss of tensile capacity on specific reference lengths)

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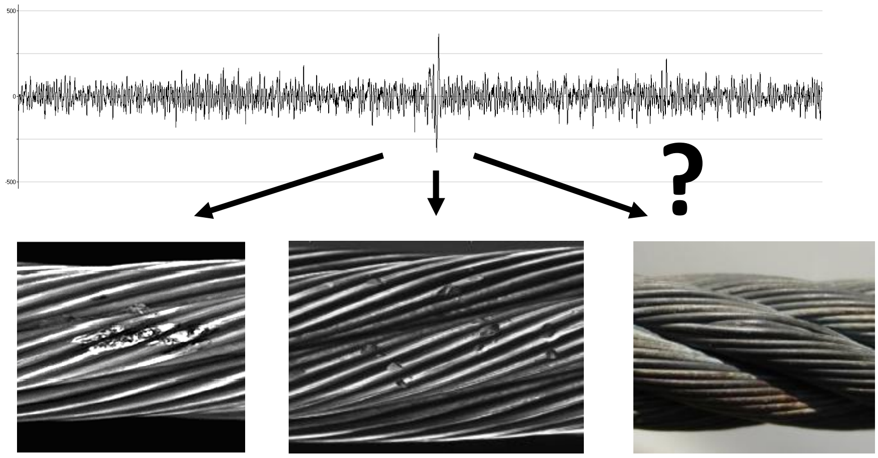
Visual verification

Magnetic signals are only a 1D image of the real damage. Signals can be ambiguous, so every pattern of doubt has to be clarified by visual inspection:



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3. Actions arising from an MRT report

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MRT report

test report shall include:

- comments about signature;
- rope identification (designation, name of manufacturer);
- rope details (rope diameter nominal and measured) / construction (diameter and number of wires);
- length of rope at rope end(s) not tested;
- the position, type and extent of any reportable indications and the conclusion on the wire rope condition;
- any increase in the size, number or extent of the indications shall be ascertained by comparison with previous test results.

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Report: additional data / local regulations

In several countries there are local regulations demanding additional information in an MRT report like:

- development of rope condition, a table showing a comparison to the values of at least the last MRT
- Additional Recommendations for the operator, e.g. visual or other further inspections, maintenance & repair,…
- Showing pictures of the results from visual inspection
- Showing diagrams of wire break progress
- Giving recommendations on maintenance and repair actions (e.g. cut-off of wire break ends, re-lubrication, splice restoration…)
- Setting restrictions for operation or requirements for further (visual) inspections

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Report: examples of repair of locked coil ropes

Fill-up of wire break gap using plastics:

- Protection of inner layers against moisture
- Stabilizing of surface wire compound

Shifting of wire breaks by brazing:

- Separation of two neighboring wire breaks
- Creation of distance to discard criteria

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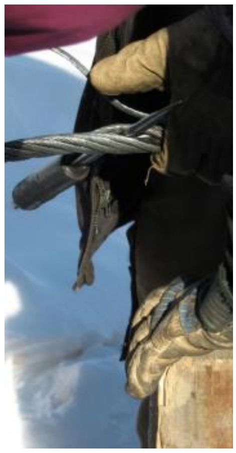
Report: examples of repair of stranded ropes

Grinding of a lightning stroke

Cut-off of out-sticking wires and broken ends



Strand repair / Splice-in part

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Discard criteria

Most important discard criteria is the loss of metallic cross section within the reference lengths, given as multiple rope diameters according as for instance to the EN standard :

- **Short reference length (e.g. 6xd):** local damage, usually external impacts
- **Mid-range reference length (e.g. 30xd):** mixed section of local defects, abrasion and corrosion
- **Long-range reference length (e.g. 500xd):** average damage development of rope within its life time (mainly fatigue wire breaks)

“If there is any doubt about the size of a broken wire indicated by MRT calculating the loss of metallic area, it shall be assumed to be with a larger cross section in the rope.”

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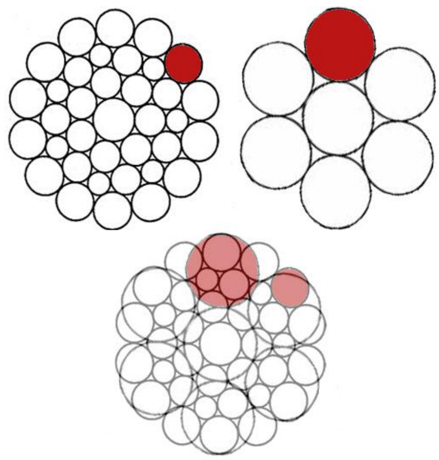
Discard criteria: relation to damage

Number of maximum allowed wire breaks on reference lengths depends on rope type:

Rope Type	Part of outer wire
6x7	2,38 %
6x19 Seale	1,27 %
6x36 Warr.-S	0,60 %

Example: number of broken outer wires at point of discard on 6xd according to EN 12927-6:

Rope Type	Number broken outer wires
6x7	3
6x19 Seale	4
6x36 Warr.-S	9



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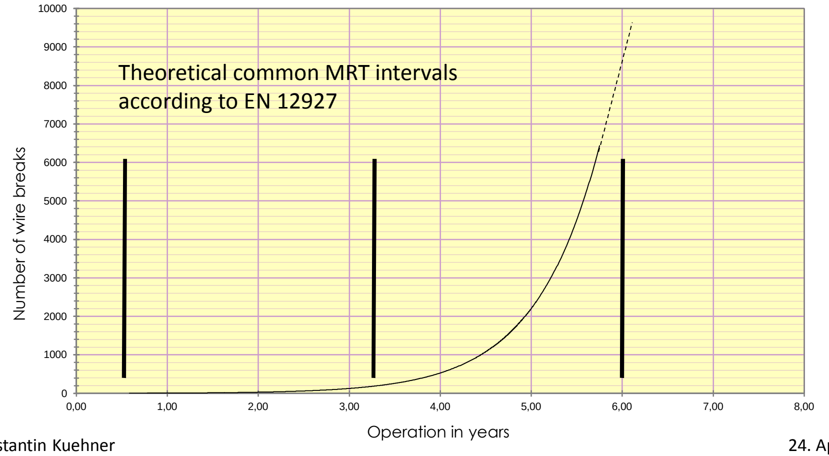
Rope-History and Increase of Wire Breaks

Example Funitel carrying-hauling rope: development of fatigue wire breaks is generally shaped exponentially → rope has to be inspected more often at advanced age!



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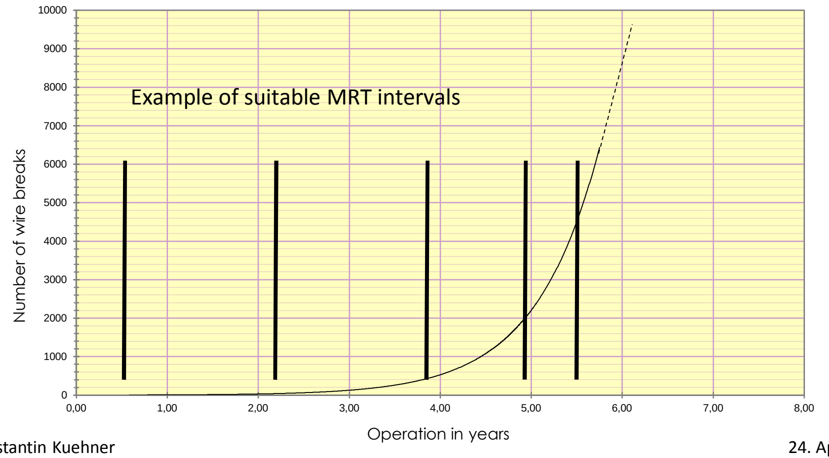
Rope-History and Increase of Wire Breaks

Sound magneto-inductive inspection intervals not to have to follow the figures given in the standards – they can be shorter!



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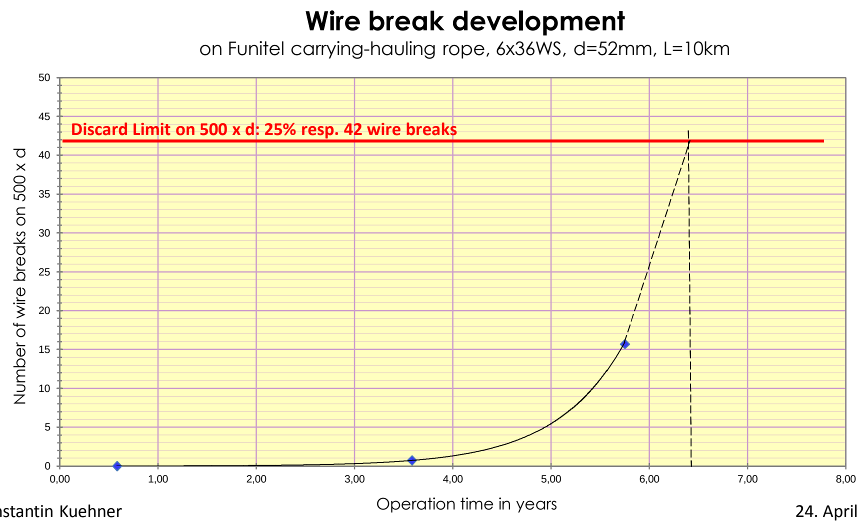
Increase of Wire Breaks on 500 x d



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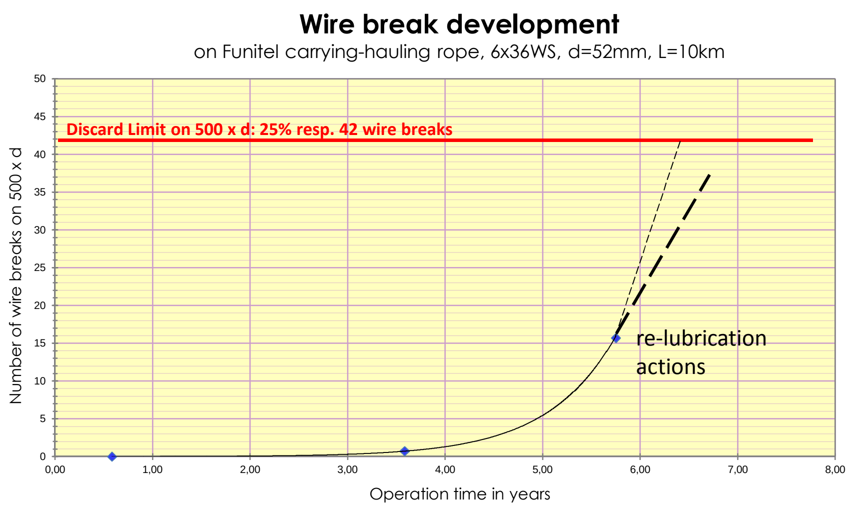
Increase of Wire Breaks on 500 x d



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4. Wire break analysis

1. **Single wire break**:
   - ✓ WB signatures and related damage
   - ✓ WB gap & depth versus signal shape & amplitude,
   - ✓ WB signature and rope ground signal

2. **Wire break clusters**
   - ✓ Multiple WB's versus single WB,
   - ✓ Ill-separated WBs → MRT history
   - ✓ Specific WBs like missing wire → visual verification

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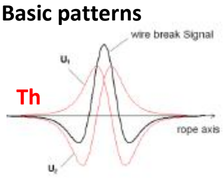
Single wire break

Basic patterns



1 wb = loss ⊕ recovery patterns

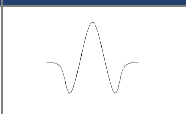
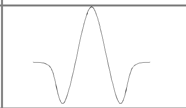
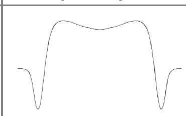
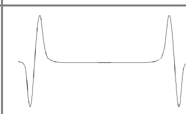
- **Small / medium size gap** = merged signals

→ averaging of measuring coils

- **X-Large gap** = detached signal patterns

→ coils are sensitive to variation of magnetic flux provoked by (dis)/appearing steel wires

WB signature and related rope damage

Gap	WB signal	Real default
small		
medium		
large		
XL		

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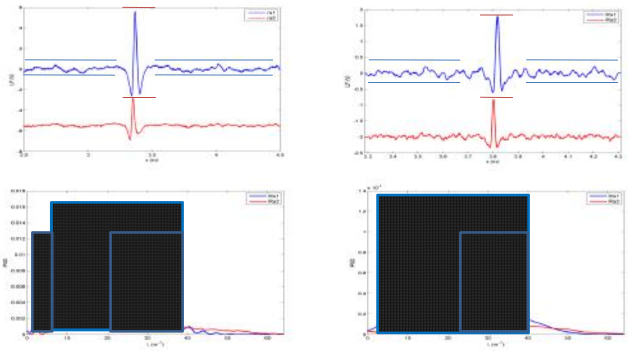
Single wire break: instances

WB signals:
LF 1 / LF2

Spectrum

Wire break
Ground signal



Puy de Sancy: track rope | Hoffmann hauling rope

- WB signatures are perturbed by rope ground signal
- Ground signal can't be filtered

WB signals shall arise well above ground signal to be analyzed !

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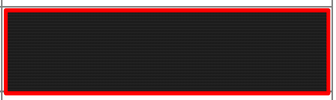
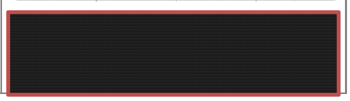
Wire break clusters

WB's versus single WB signal

2 WBs with gap	Effect of gap 2 WB's versus 1 WB	x WBs with 0.2m gap	Effect of number of WB's x WB's versus 1 WB
5 mm		11 WB's	
10 mm		21 WB's	
20 mm		41 WB's	

Various rope failures may give similar MRT signatures !

2 WB's with 10mm clearance may be interpreted as a single WB with large gap

high number of WB's may be analyzed as a missing wire over a x-large distance

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5. Limits of MRT

1. **MRT issues:**
   - ✓ Non-injective mapping: various rope defaults → similar signature
   - ✓ Masking effects
     - Ill-separated WB's ← issue of coil spatial resolution
     - Amplitude high-contrast ← tuck tail mask neighbouring wire breaks
     - Amplitude low-contrast ← WB's may vanish in ground signal
2. **Limits:**
   - ✓ MRT signal analysis of specific rope parts:
     - Saddle or tower section
     - Sheave or rolling chain section
   - ✓ MRT analysis of specific rope defaults
     - Lightning stroke ← no evidence
     - Wear / corrosion ← not obvious
     - Fatigue-cracking corrosion ?

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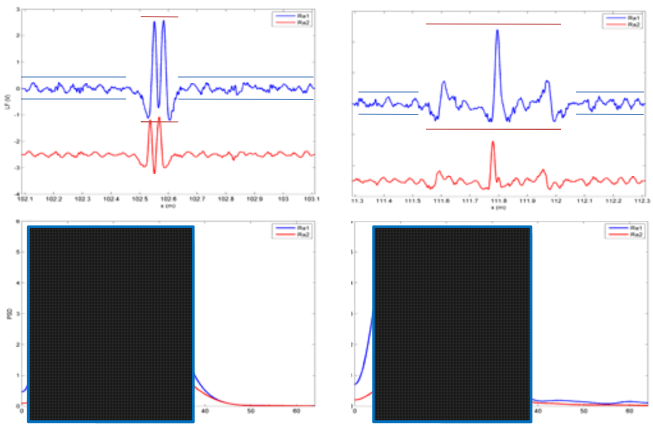
Masking effects: ill-separated WB's

WB signals:
LF 1 / LF2

Spectrum

WB's
Ground signal



a) single or double WB ?
b) missing wire + 1 WB ?

Answer:

- a) Unknown → **MRT history is required** to analyze the development of WB's during rope operation
- b) WB ? Missing wire ? : No → splice knot

  → **rope visual verification is required**

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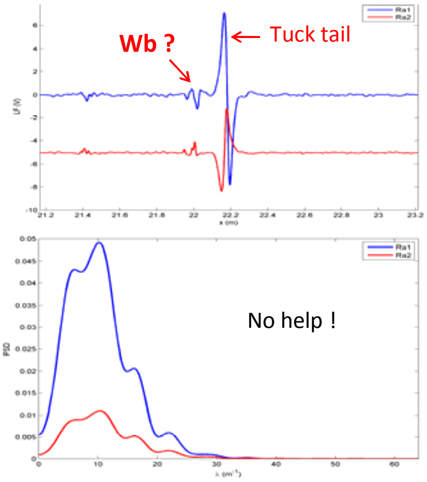
Masking effects: amplitude high-contrast

Splice section: tuck tail masking eventual neighbouring wire break

MRT Signals
LF 1 / LF2

Droset 2013
carrying-hauling
rope

Spectrum



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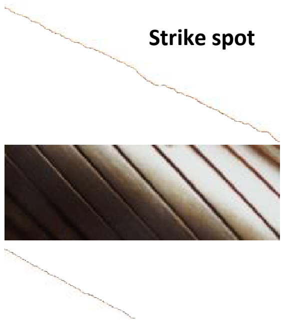
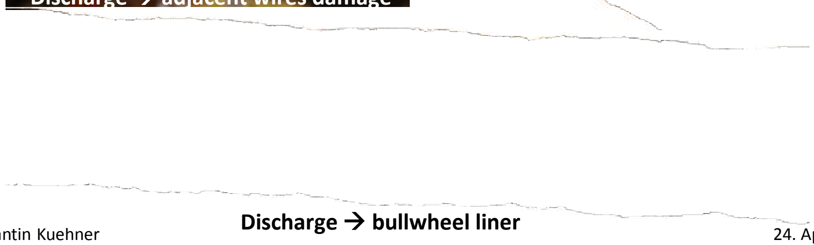
Limits: MRT analysis of lightning discharges / strikes

?





Discharge → bullwheel liner

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Limits: MRT analysis of a lightning discharge

6x7 stranded trackrope :
material tramway

Melted adjacent wires

Broken melted wires

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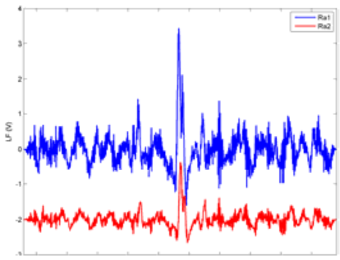
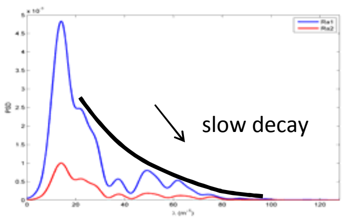
Limits: MRT analysis of a lightning discharge

MRT Signals
LF 1 / LF2



6x7 stranded trackrope

Spectrum



Broken melted wires

MRT signature ? not obvious
- similar with wire break signals
- noisy ground signal
- slow spectrum decay

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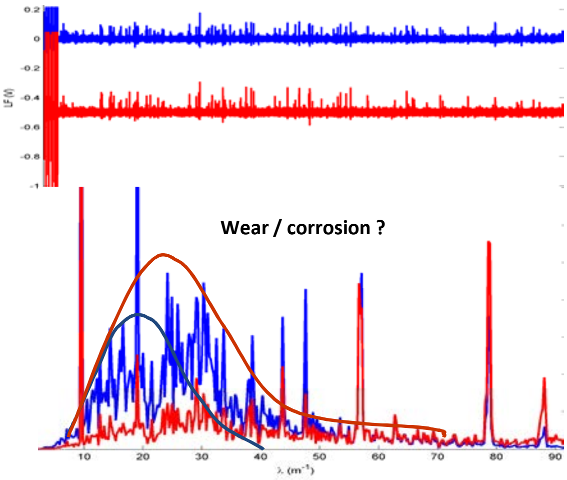
Limits: MRT analysis of wear / corrosion

WB signals:
LF 1 / LF2

Ruade 2012
carrying-hauling
rope

Spectrum



healthy → corroded

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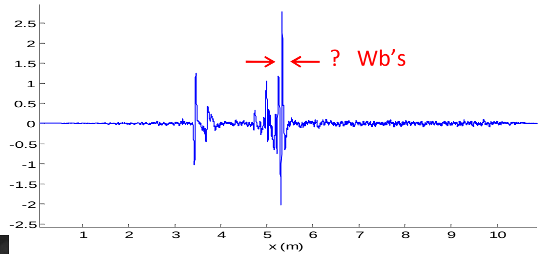
Limits: MRT analysis of saddle / tower section

Puy de Sancy, MontDore : 48 mm carrying rope, section over a saddle

rope : 1 – 6 – 12 – 18 – 23 – 29 – 32 Z – 39 Z → MRT : 3 wb's



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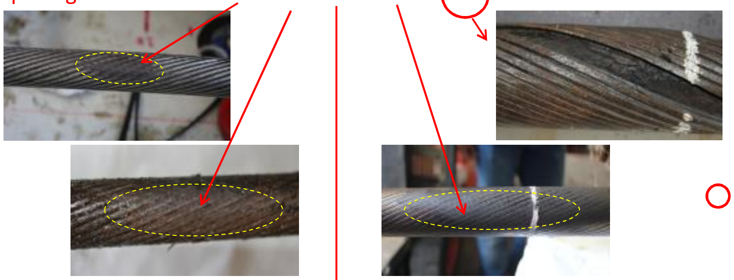
Limits: MRT analysis of saddle / tower section

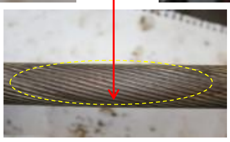
Puy de Sancy, MontDore : 48 mm carrying rope, section over a saddle

rope : 1 – 6 – 12 – 18 – 23 – 29 – 32 Z – 39 Z

opening: 1 – 6 – 12 – 18 – 23 – 29 – 32 Z – 3 Z



wb



Failure : fretting-corrosion

- steel-steel contact
- high pressure / low saddle radius
- lack of relubrication ?

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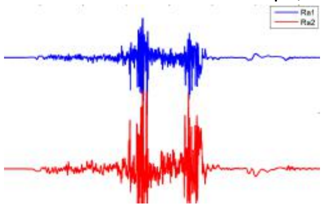
Characteristics and Inspection of Ropes

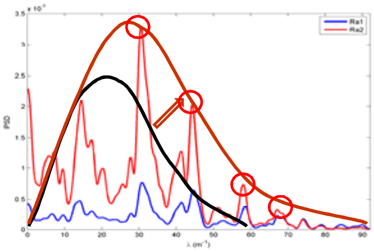
Limits: MRT and fatigue-cracking corrosion

TpH Ruillans, La Grave : 51mm tension rope, section over a sheave

WB signals:
LF 1 / LF2



Spectrum



MRT analysis : not obvious

- noisy ground signal
- low amplitude

Corrosion ? probably !

healthy ⟹ corroded

Fatigue-cracking corrosion ?

- peak distribution !

Further investigation is required ...

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Limits: MRT and fatigue-cracking corrosion

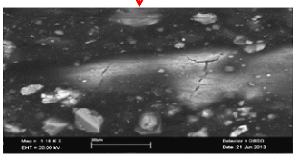
TpH Ruillans, La Grave : 51 mm tension rope, section over a sheave

rope : 1 – 7/7 – 7 – 14 – 24 – 30 – 33 Z – 38 Z

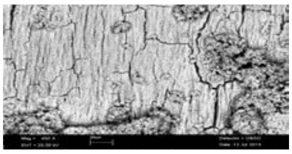
opening: 1 – 7/7 – 7 – 14 – 23 – 2 – 33 Z – 38 Z

○ wb

rusty - dry



Fatigue-cracking corrosion



Microfractures

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6. Beyond the limits

1. **High resolution inspection**
   - ✓ WB localization around rope section: coils → belt of hall sensors
   - ✓ separate WB's from corrosion, wear
2. **Visual inspection with technical support**
3. **Wavelet scalogram analysis**
   - ✓ To highlight interaction between MRT signatures and ground signal,
   - ✓ To separate closed WB's,
   - ✓ To assess the occurrence and severity of corrosion.

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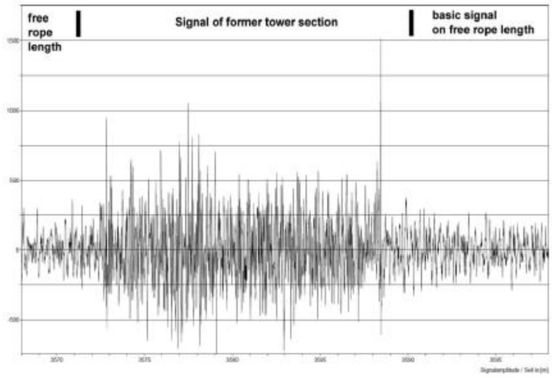
Magnetic high resolution test



Problem: Corrosion-/wear-signals can cover wire break signals, e.g. in former tower sections

➔ Another more-dimensional inspection-method is needed to clarify the state of the rope

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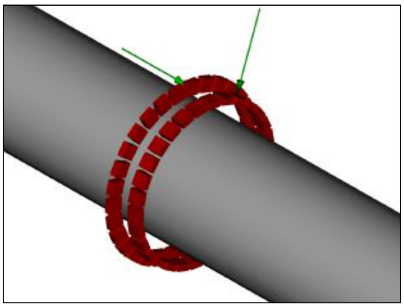
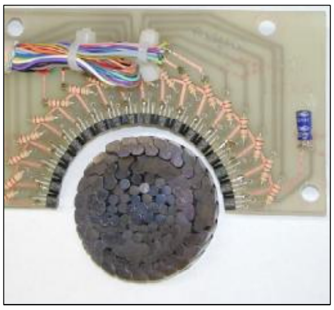
Magnetic high resolution test

- Instead of an averaging coil, a large amount of hall-effect sensors is installed around the rope
- By recording each sensor as a measuring channel, the defect can be better localized in the cross-section of the rope
- This allows to separate wire breaks from wear or corrosion
- Cheaper, less dangerous alternative to x-ray examination





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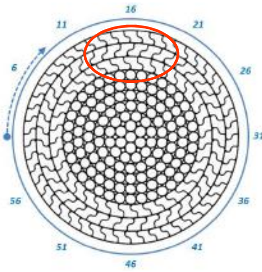
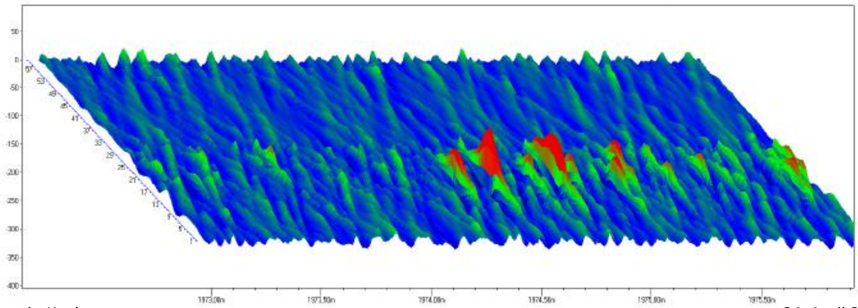
Magnetic high Resolution test

- Software-Application allows to rescale color-scheme and amplification to work out points of interest
- Damage can be closely localized and evaluated to plan further special treatment, inspection and repair





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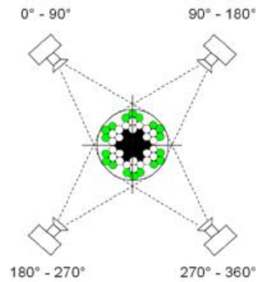
Characteristics and Inspection of Ropes

Visual Inspection with technical device

Inspection can be carried out manually - or by technical device with following advantages:

- higher result reliability by overlapping cameras
- better documentation by digital images and automated report editor
- less danger and physical stress for inspection operator
- less downtime of cable car due to higher inspection velocities (up to 3 m/s)



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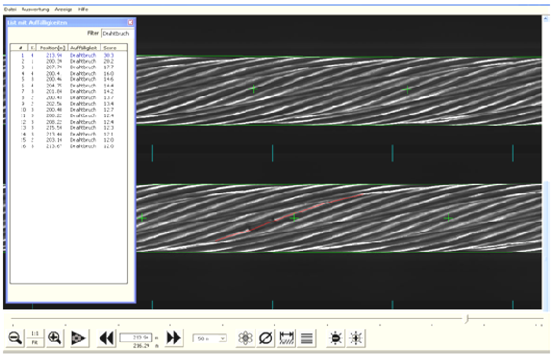
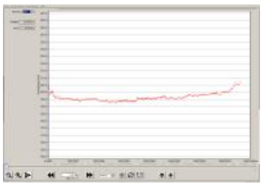
Visual Inspection with technical device

Analyze of the wires and rope surface:



Diameter and rope lay length along the rope



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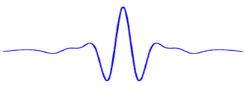
Wavelet scalogram

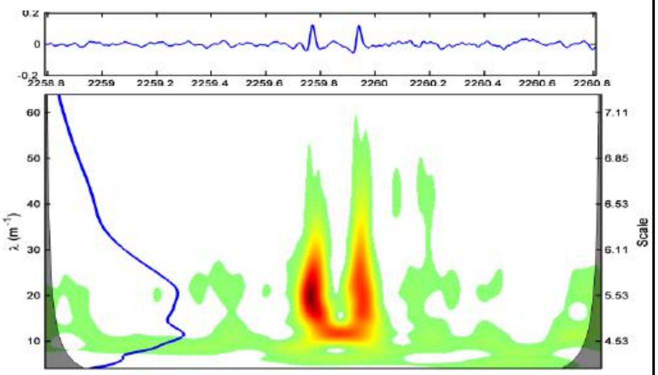


Wavelets : mathematical entity Ψ aimed to analyze main signal components

Transform : $W_{\psi}^{s}(a,\,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} s(t)\overline{\psi\left(\frac{t-b}{a}\right)}\,\mathrm{d}t$

MRT signal : splice knot

Scalogram: colormap of wavelet representation



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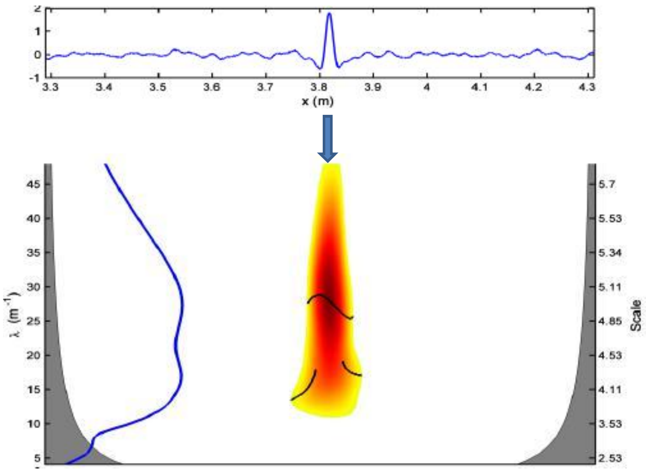
Scalogram : single wire break

Wire Breaks signal

Hoffmann rope test

Scalogram



1 WB: space-localized cluster crossing ground signal

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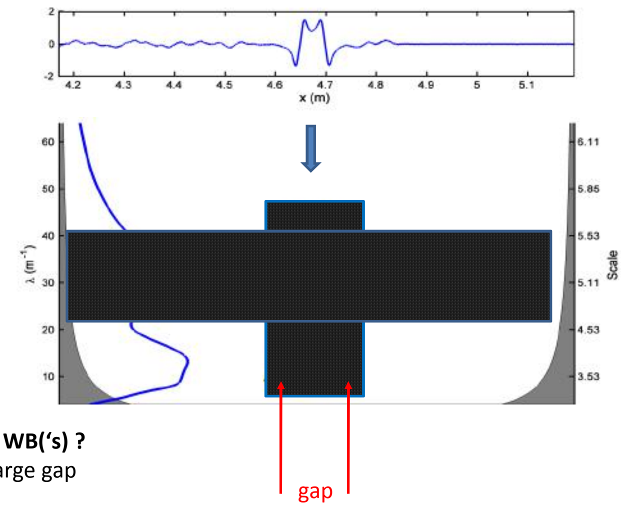
Scalogram: multiple wire breaks

WB signals:
LF 1

Hoffmann rope test

Scalogram



Q: single or double WB('s) ?
A: single WB with large gap

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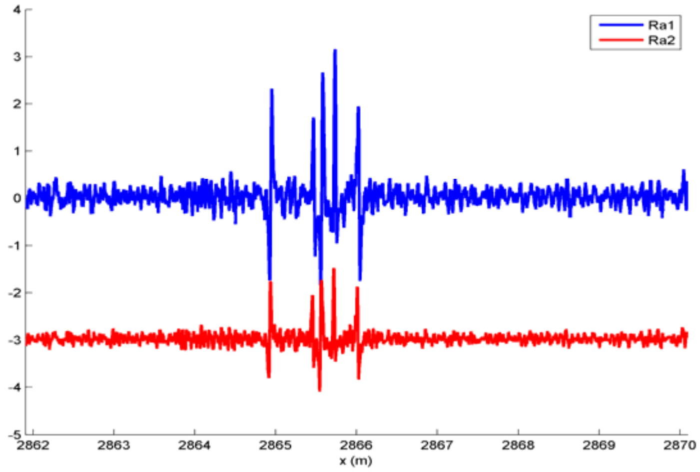
Scalogram: wire-break cluster

WB signals:
LF 1 / LF2



Q: multiple WB('s) ?

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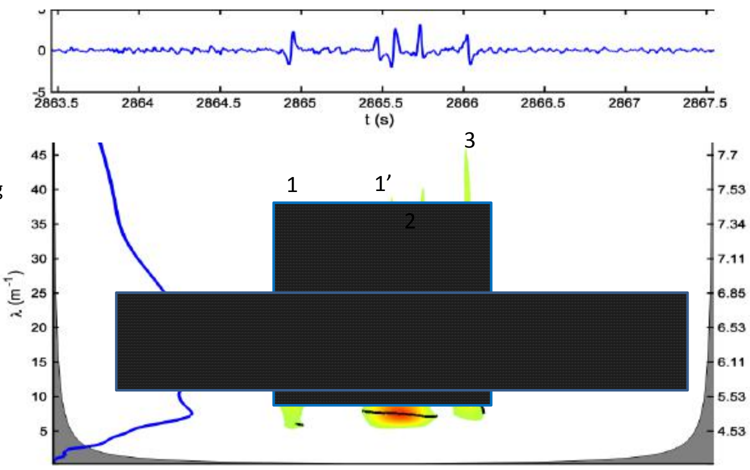
Scalogram: wire-break cluster

WB signals:
LF 1

Puy St Vincent
carrying-hauling
rope

Scalogram



A: • 1: missing wire → 1': recovered wire
• 2: 1 large WB and 3: 1 small WB

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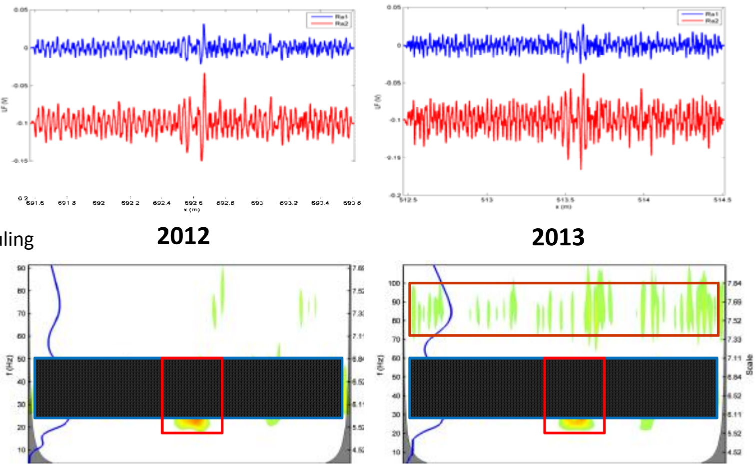
Scalogram: wear / corrosion

WB signals:
LF 1 / LF2

Montjoie carrying-hauling rope

2012 **2013**



Scalogram

1 large WB
rope ground signal

wear / corrosion ↑

developping wear / corrosion may be followed…

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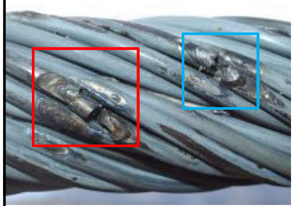
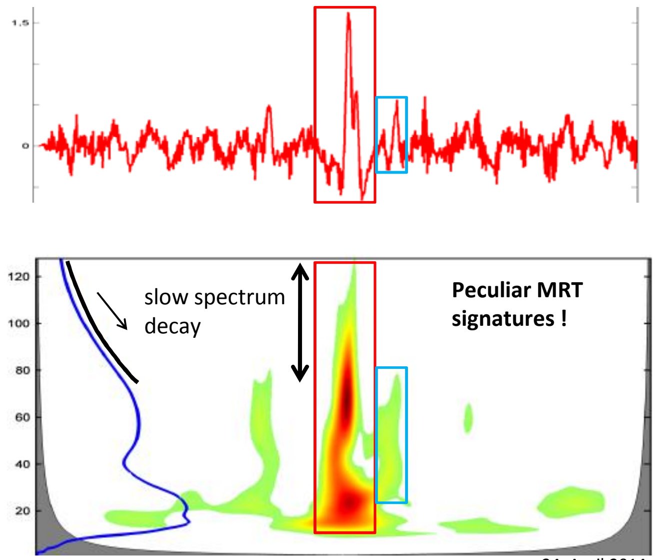
Scalogram: ligthning discharge

WB signals:
LF2

6x7 stranded trackrope:
broken melted wires





Scalogram

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7. Conclusions and prospects

1. MRT summarized
2. MRT + Visual : a complementary approach
3. Advanced : towards supervised WB analysis

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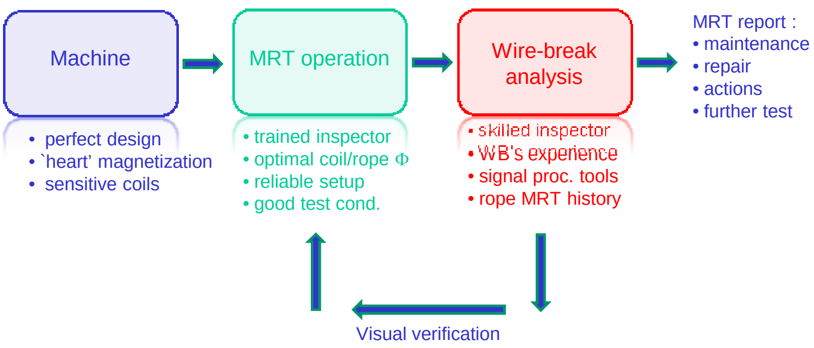
MRT summarized

Prerequisites for efficient MRT



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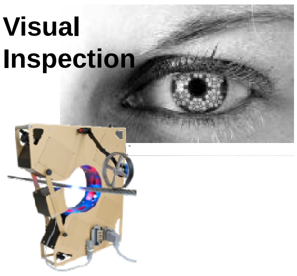
Visual + MRT: a complementary approach

Visual Inspection



Dislocation of wires

Diagram of Diameter and Laylength

Scratches, Notches

Touching Strands

Beginning corrosion

Heavy corrosion

Heavy wire damage

Outer wire breaks

Former clamping areas

Lightning strokes

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Visual + MRT: a complementary approach

MRT

Heavy corrosion

Heavy wire damage

Outer wire breaks

Former clamping areas

Lightning strokes

inner wire breaks

Wire breaks in strand touching zone

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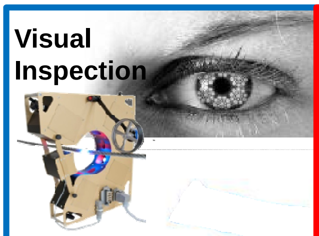
Visual + MRT: a complementary approach

Visual Inspection



MRT

Visual Inspection		MRT
Dislocation of wires	Heavy corrosion	inner wire breaks
Diagram of Diameter and Laylength	Heavy wire damage	Wire breaks in strand touching zone
Scratches, Notches	Outer wire breaks	
Touching Strands	Former clamping areas	
Beginning corrosion	Lightning strokes	

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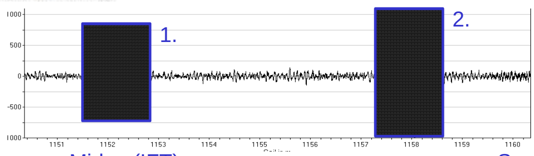
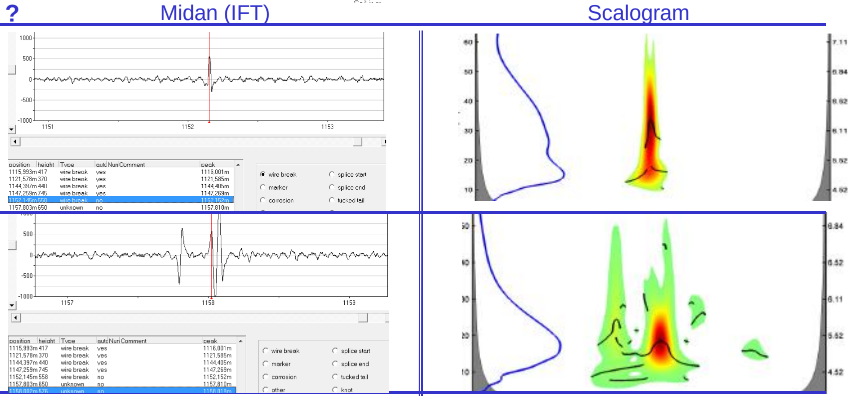
Supervised WB analysis ?

WB signal:



Id ? Midan (IFT) Scalogram



Result: 1. WB ? yes 2. WB ? unknown | 1. WB ? yes 2. WB ? 1 missing wire + 1 WB

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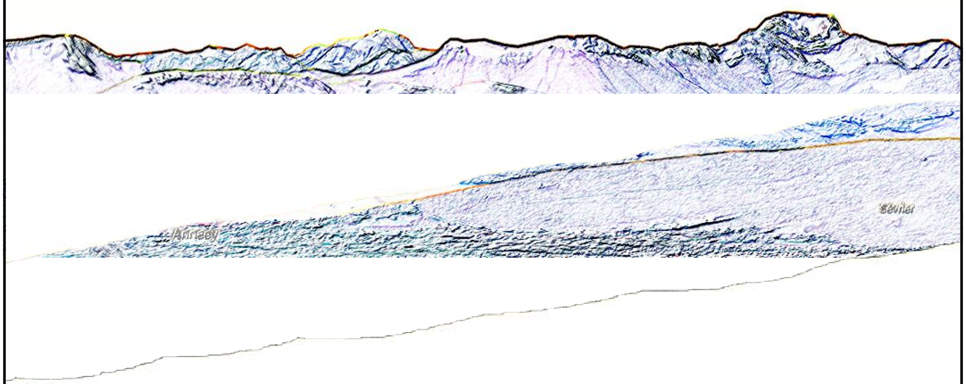
Thank you



for your attention !

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Gains and Limits of Magnetic Rope Testing

University of Stuttgart
Institute of Mechanical Handling and Logistics
Stuttgart, Germany

Dipl.-Ing. **Konstantin Kuehner /** Dipl.-Ing. **K. Kuehner**
sven.winter@ift.uni-stuttgart.de

STRMTG / French authority
Saint Martin d'Hères, France

Dr.-Ing. **Stephane PERNOT**
stephane.pernot@developpement-durable.gouv.fr