Dynamic Structural Health Monitoring of a Overhead Power Line using Interferometric Radar

Author: Fábio Paiva (IST)
Supervisors: Prof. Luís Guerreiro (IST) and Prof. Carneiro Barros (FEUP)

Outline

- RADAR equipment and the main techniques;
- Overhead Line System - Case study description;
  - Overhead Power Line Layout;
  - System under study by RADAR (Power Line and Lattice Tower);
- Comparison Experimental results vs Numerical modelling (Modal analysis)
  - An Overhead Power Line monitored by RADAR;
  - Transmission Line System = Overhead Power line + Lattice tower (monitored by RADAR)
- Conclusions and future developments

IBIS-FS RADAR

Pulse Radar working principle

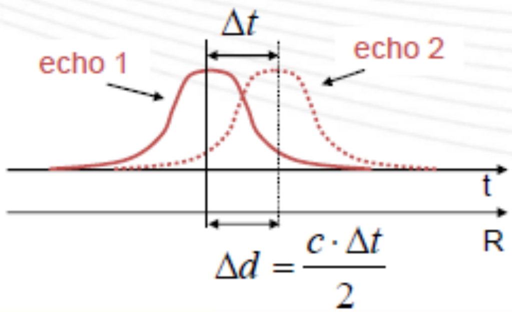
Time space equivalence for range determination:

Echo delay

$$T_0 \quad \Rightarrow \quad R_0 = \frac{c \cdot T_0}{2}$$

Range resolution concept:

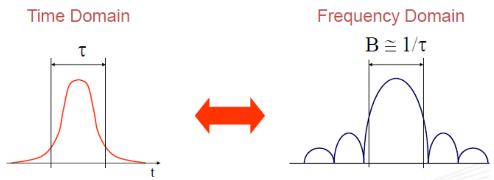
$$\Delta R = \frac{c \cdot \tau}{2}$$



The radar is able to resolve two targets if:

$$\Delta t > \tau \Leftrightarrow \Delta d > \Delta R$$

The range resolution can be expressed either in term of **pulse duration** or **pulse bandwidth**:



$$\Delta R = \frac{c\tau}{2} = \frac{c}{2B}$$

Brief description of the IBIS-FS RADAR Equipment

IBIS-FS (Image by Interferometric survey) Microwave interferometry based system
It can **measure remotely** the displacement of several points along the structure in Line of Sight (LOS)

IBIS – FS System Specifications	
Displacement accuracy	**0.01 mm ± 0.1** (depending on range)
Maximum range	**Up to 1000 m**
Spatial Resolution in LOS	**0.75 m**
Acquisition Frequency	Up to **200 HZ**
Frequency Band (ku)	17.1-17.3 GHZ (**B=200 MHz**) Pulse duration $=5 * 10^{-9} s$

Overall weight=30kg

Remote static and dynamic monitoring of structures.

Other IBIS- FS Features:

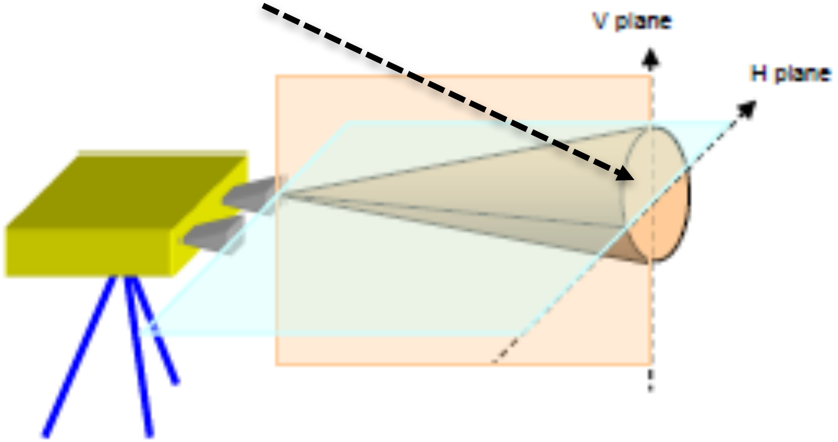
- **Remote sensing** on the area of investigation, by identifying “virtual” displacement sensors accordingly with the **spatial resolution** (several points simultaneously);
- **Fast installation** (10~15 minutes);
- Allows **monitoring of damaged structures** with direct real time measurement of displacements;
- Always operative (day/night in all weather conditions)
- Autonomy of 8 hours with batteries (or indefinitely if a power source exists)

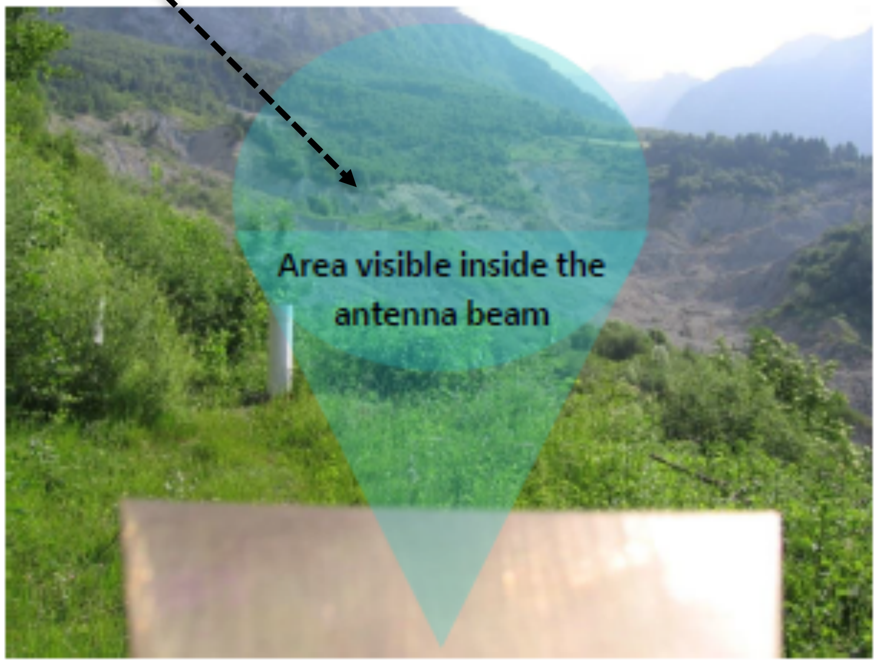
IBIS-FS RADAR Techniques

IBIS system uses interferometry to measure the structure displacements that are **illuminated by the electromagnetic beam emitted by the antennas.**

Majority of power focused in the center by the antenna :

Antenna beams:

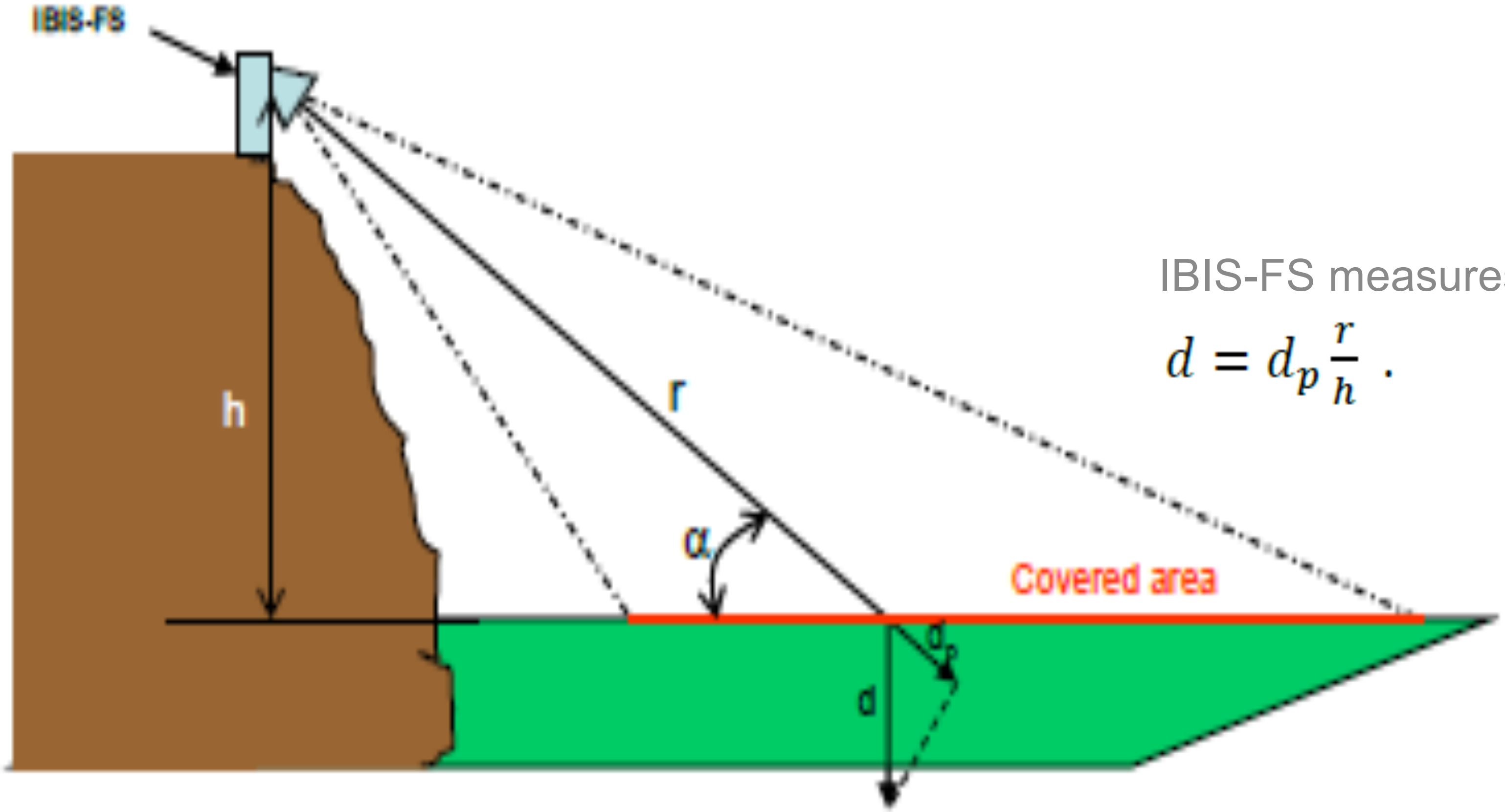




The angular amplitudes of the cone in the elevation (V) and azimuth (H) plane depends of the **type of antenna** used.

IBIS-FS RADAR Techniques

It is important to outline that the IBIS-FS system **can measure displacements only in the system <u>viewing direction</u>** (radial direction or Line of sight)



IBIS-FS measures **d_p**

$$d = d_p \frac{r}{h} \; .$$

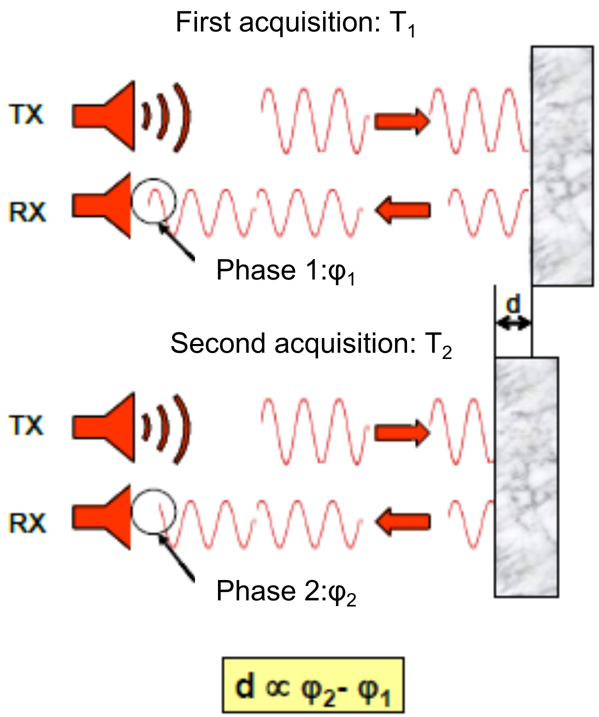
IBIS-FS RADAR Techniques

IBIS-FS is based on the following two RADAR techniques:

- **Interferometry**;
- Frequency modulated-continuous wave (FM-CW)

Interferometry is a radar technique that consents object displacement measurement by comparing the **phase information** of the electromagnetic waves reflected by the object in **different moments in time**.

Principle of the interferometric technique



Displacement measurement (d) of the object under investigation:

$$d = -\frac{\lambda}{4\pi} \cdot \Delta\varphi$$

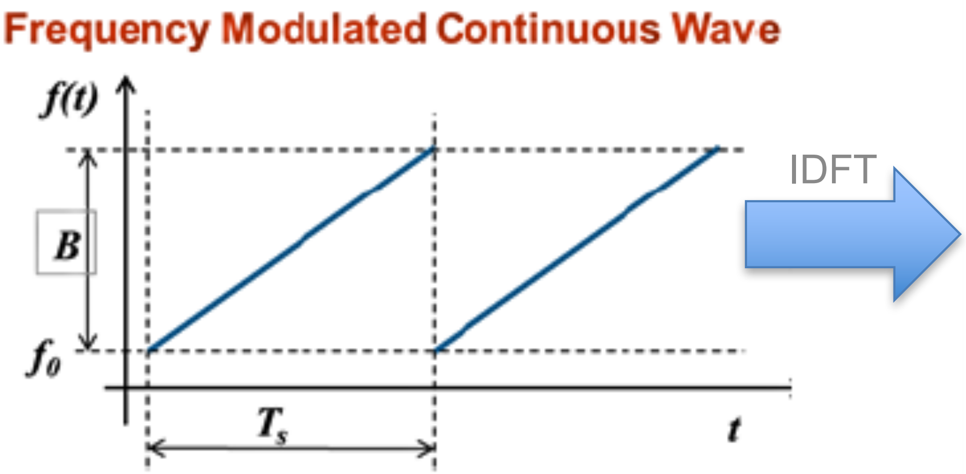
$\lambda - electromagnetic\ wave\ velocity$

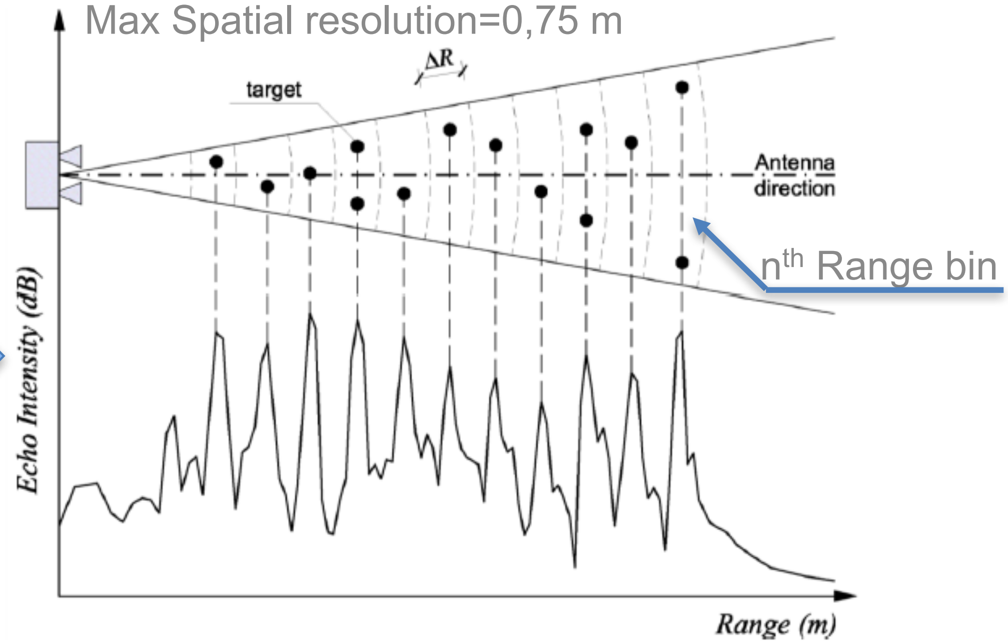
IBIS-FS RADAR Techniques

IBIS-FS is based on the following radar techniques:

- Interferometry;
- **Frequency modulated-continuous wave** (FM-CW)

This technique allows the IBIS-FS system to obtain **a one-dimensional image of the scenario of interest with high distance resolution** (range resolution) thanks to the transmission of a **series of long duration electromagnetic waves** (Continuous Wave) at increasing frequencies (Frequency Modulate)





Range profile -1D image of illuminated scenario

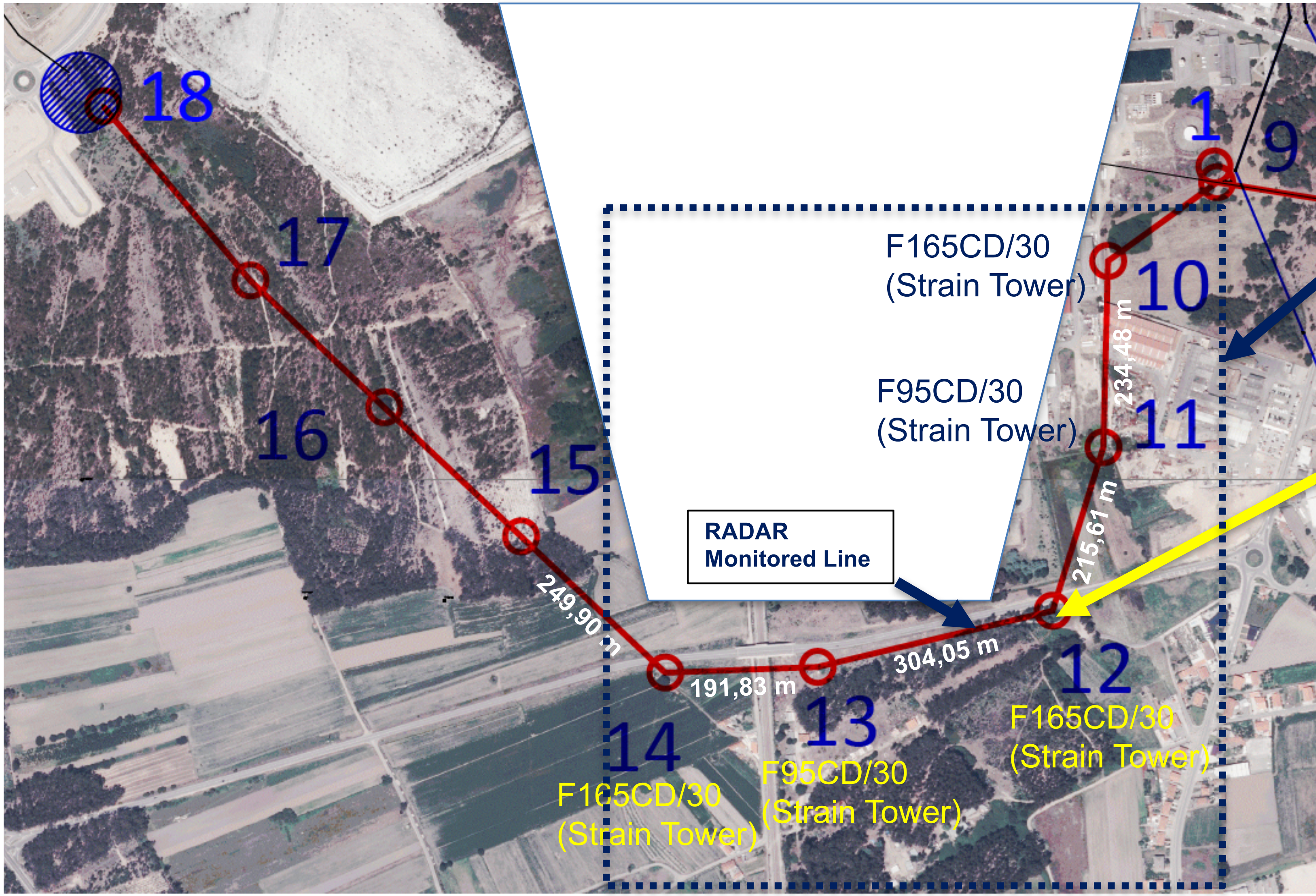
IBIS-FS RADAR PROS/CONS

PROS/CONS of IBIS-FS with other traditional monitoring system (e.g. GPS, accelerometers):

PROS	CONS
Remote sensing instrument (ideal for structures with difficult access to the site or when investigations must be performed quickly)	High dependence on atmospheric effects;
Simultaneous monitoring of all targets within the beam (within the beam antenna) with an acquisition frequency up to 200 HZ	Relative displacements in line of sight (LOS) only;
Fast installation, high accuracy (0,01 mm) and spatial resolution (0,75 m)	Difficult point localization (geo-referencing of target points); it can be reduced by installing artificial reflectors but removes one its main advantages (remote sensing)
Directly measure the displacements in real time (suitable from damaged structures or in risk of collapse)	Cost of equipment
Functioning conditions suitable for long term monitoring (as long there exists a power source);	Scenario around the monitored structure can influence its results (vegetation, other structures closed by)
Independence of daylight and weather;	Necessity of suitable installation point for the IBIS-FS in terms of scenario visibility and stability of the surface the equipment will sit on.

Case Study Presentation – Line Layout

Overhead High Voltage Line - Sub-transmission **60 kV Line** from EDP,DISTRIBUIÇÃO located in the North of Portugal

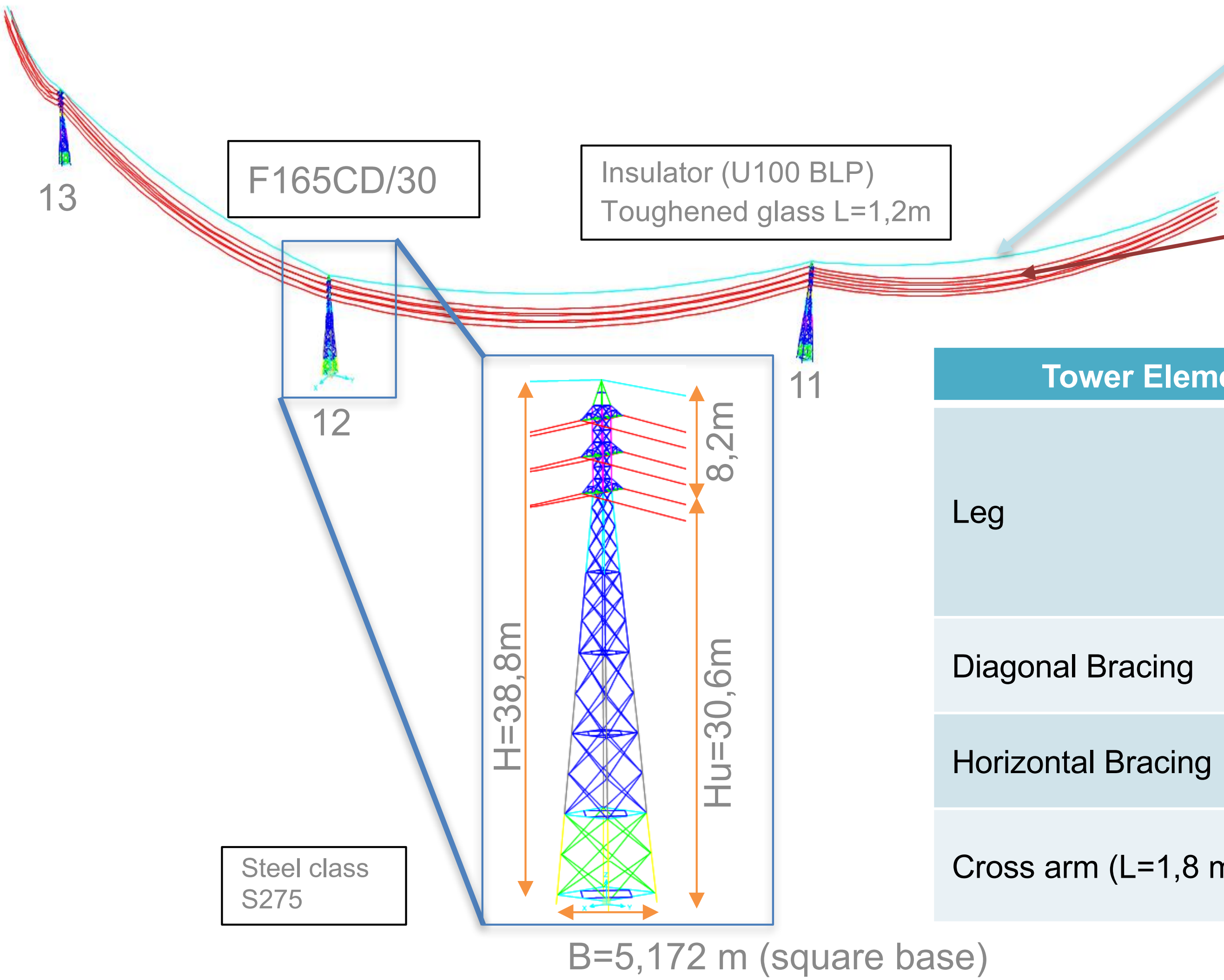


Area under study for the dynamic monitoring of the Line System

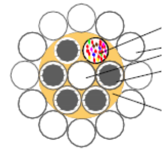
RADAR Monitored Tower

Case Study Presentation – 3D View

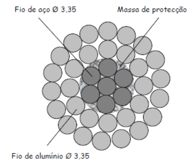
Overhead High Voltage Line - Sub-transmission **60 kV Line** from EDP,DISTRIBUIÇÃO located in the North of Portugal



Wire Shield OPGW
AA/ACS/ST 157/60



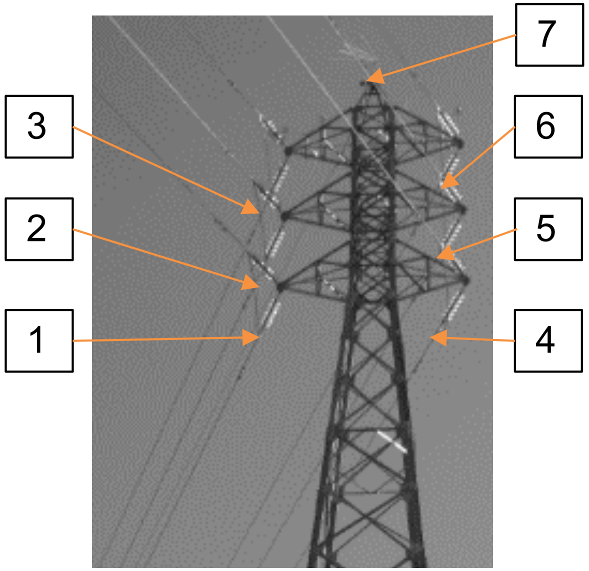
Conductor
ACSR 325 (Bear)

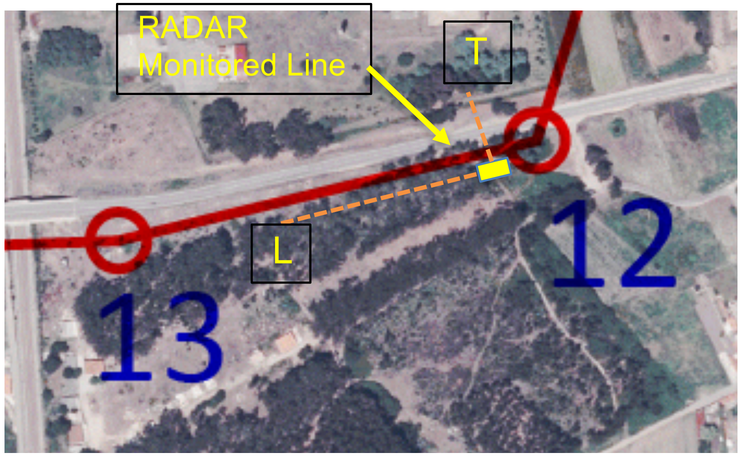


Tower Element	Sections (angle)
Leg	L180x16 (yellow) L180x15 (grey) L160x15 (blue) L140x13 (cyan) L100x10 (magenta)
Diagonal Bracing	L60x6 (green) L50x5 (blue)
Horizontal Bracing	L70x7 (cyan) L50x5 (blue)
Cross arm (L=1,8 m)	L50x5 (blue) sup. chord L60x6 (green) inf. chord

RADAR Results vs Numerical Modelling

Overhead High Voltage Line – RADAR Monitored **Span 12-13**





RADAR - **Longitudinal** direction to the Line

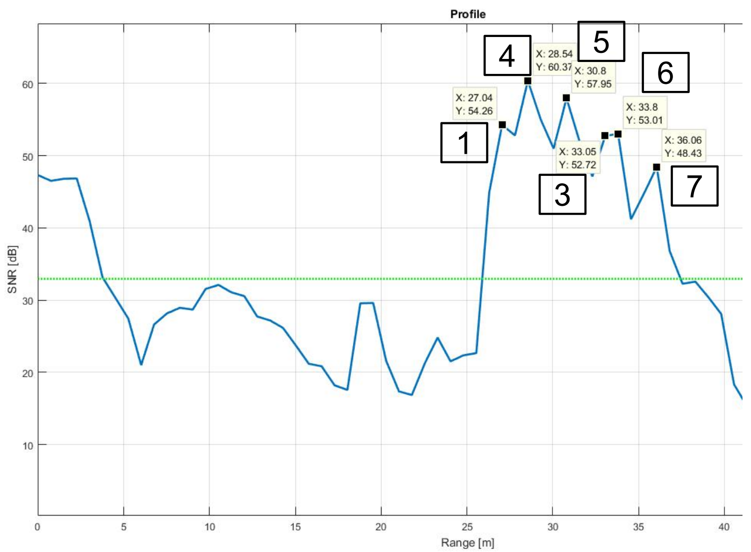
Survey Parameters	RADAR
Vertical tilt (º)	45
Survey duration (minutes)	14,6
Distance (to tower 12)	30,60 m

RADAR - **Transverse** direction to the Line

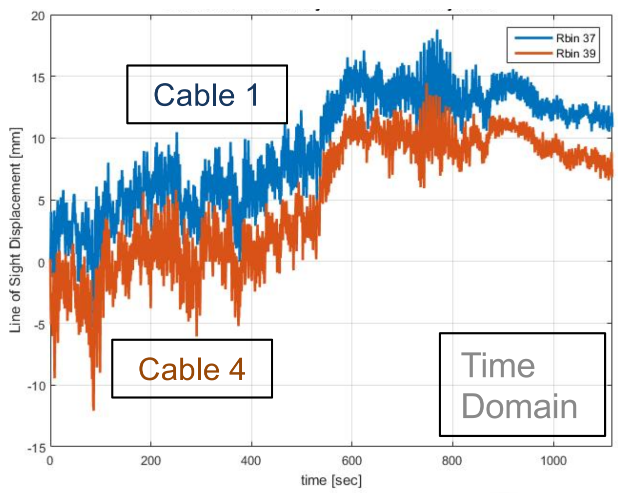
Survey Parameters	RADAR
Vertical tilt (º)	70
Survey duration (minutes)	18,5
Distance (to tower 12)	14,82 m

RADAR Results vs Numerical Modelling

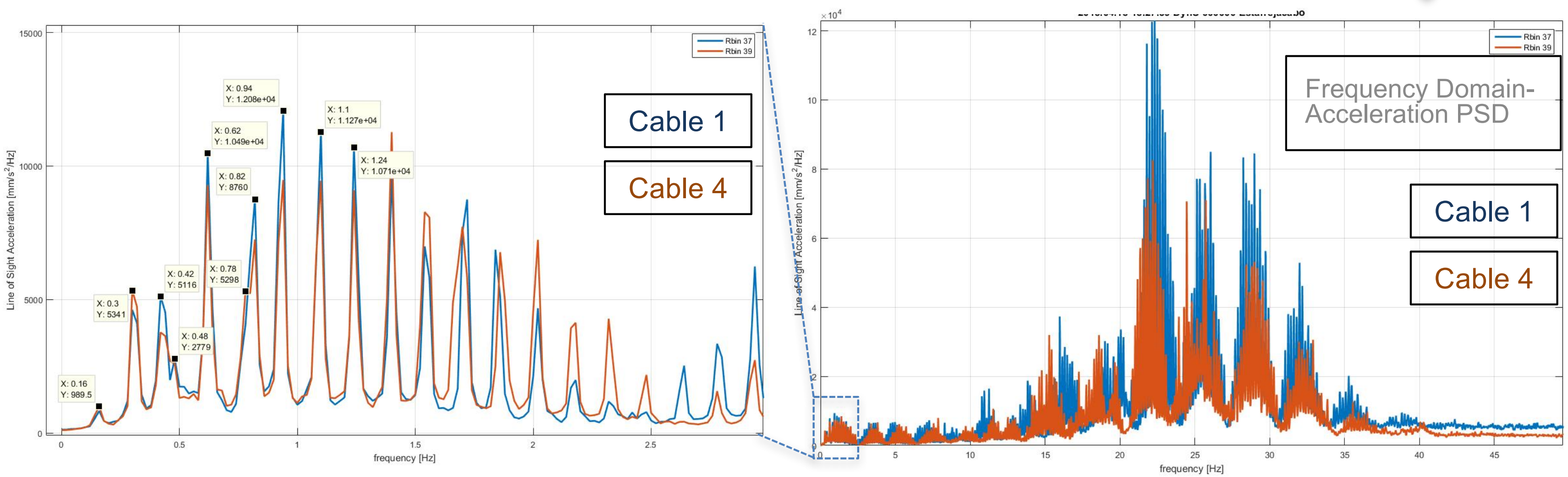
Overhead High Voltage Line – RADAR Monitored **Span 12-13** TRANVERSE



Cable	Range (m)
1	**27,04**
2	-
3	33,05
4	**28,54**
5	**30,8**
6	33,80
7	36,06

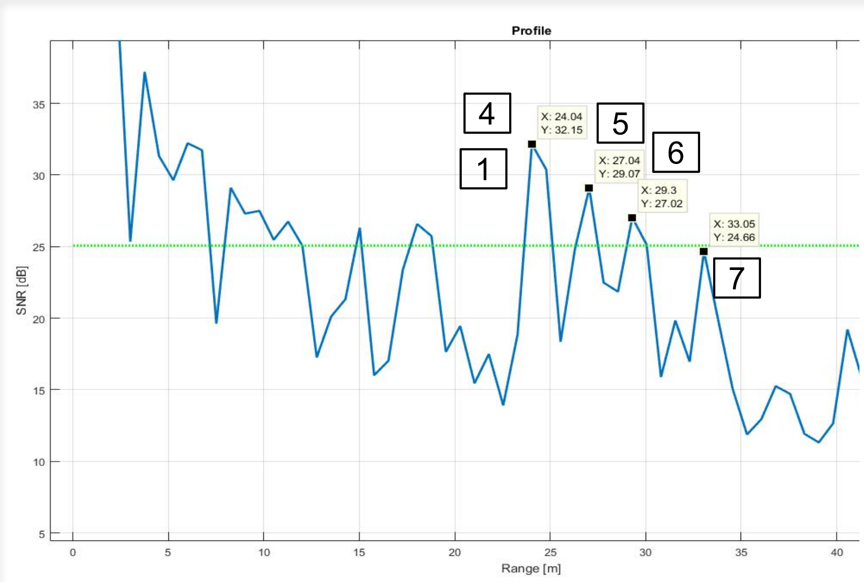


f_i	Cable 1_4 (Hz)
1	0,16
2	0,30
3	0,42
4	0,48
5	0,62
6	0,78
7	0,82
8	0,94
9	1,10
10	1,24

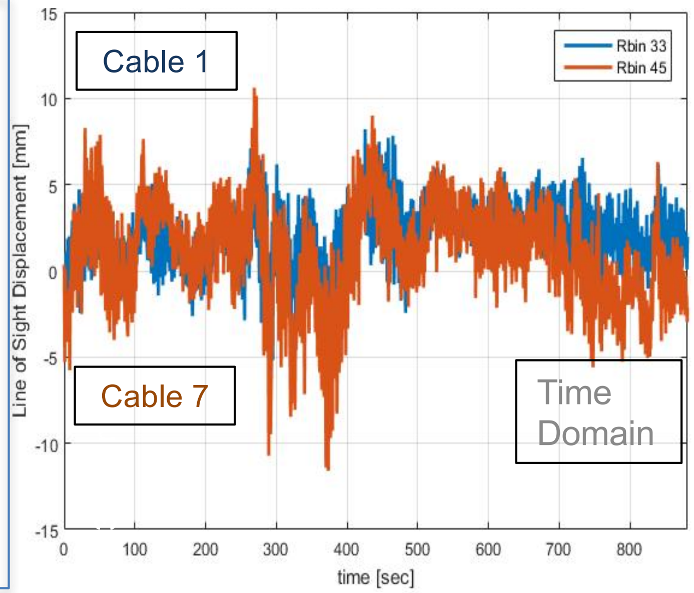


RADAR Results vs Numerical Modelling

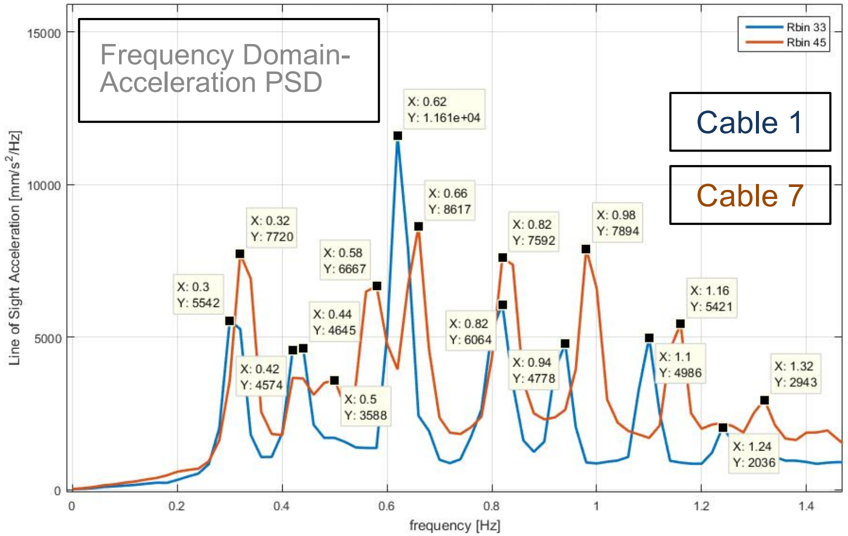
Overhead High Voltage Line – RADAR Monitored **Span 12-13-** LONG.



Cable	Range (m)
1/4	**24,04**
5	27,04
6	29,3
7	**33,05**



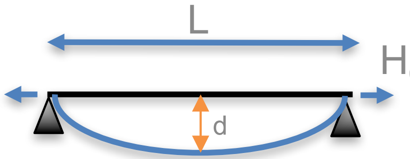
f_i	Cable 1 (Hz)	Cable 7 (Hz)
1	-	-
2	0,30	0,32
3	0,42	0,42
4	-	0,58
5	0,62	0,66
6	-	-
7	0,82	0,82/0,84
8	0,94	0,98
9	1,10	1,16
10	1,24	1,32



RADAR Results vs Numerical Modelling

Overhead High Voltage Line – Theoretical/Numerical results Vs Experimental

Cable 1- Conductor



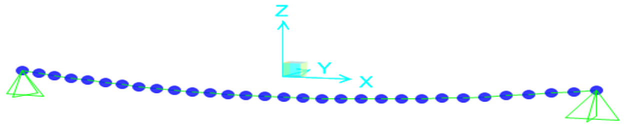
A=3,25 cm²
m=1,226 kg/m
E=79,5 GPa

H_0=11132 N (10% F_{max})
L=305,389 m
d=12,77 m (4,18%*L)

$$f_{i,o-p} = \frac{i}{2L}\sqrt{\frac{H_0}{m_c}} \qquad f_{i,i-a} = \frac{i}{L}\sqrt{\frac{H_0}{m_c}} \qquad f_{i,i-s} = \frac{\lambda_i}{L}\sqrt{\frac{H_0}{m_c}}$$

λi - Solution of transcendental equation in terms of stiffness

From Irvine and Caughey, 1974

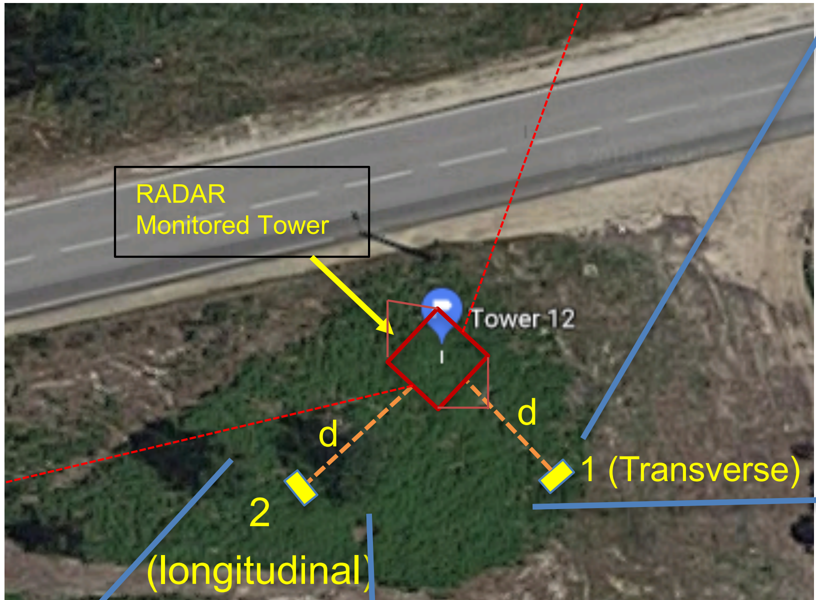


Numerical model
(fixed cable element)

Mode	Out-plane Theoret. (Hz)	Out-plane Numerical (Hz)	Error Exp. RADAR (%) T	Error Exp. RADAR (%) N	In-plane anti-symmetric (Hz) T	In-plane anti-symmetric (Hz) N	Error Exp. RADAR (%) T	Error Exp. RADAR (%) N	In-plane symmetric (Hz) T	In-plane symmetric (Hz) N	Error Exp. RADAR (%) T	Error Exp. RADAR (%) N
1	0,16	0,15	-2,49	-3,75	0,31	0,31	4,01	2,00	0,44	0,43	3,99	2,62
2	0,31	0,31	4,01	3,00	0,62	0,61	0,65	-1,13	0,72	0,71	2,40	0,71
3	0,47	0,46	-2,49	-3,75	0,94	0,91	-0,42	-2,87	0,85	0,83	3,54	1,46
4	0,62	0,61	0,65	-0,97	1,25	1,20	0,65	-3,15				
5	0,78	0,77	0,01	-1,92								
6	0,94	0,91	-0,42	-2,87								
7	1,09	1,06	-0,72	-3,73								
8	1,25	1,20	0,65	-3,06								

RADAR Results vs Numerical Modelling (Preliminary results)

Overhead High Voltage Line – RADAR Survey – **Tower 12**



RADAR – **Direction 1 (Transverse)**

Survey Parameters	Survey 1	Survey 3
Radar Vertical tilt (º)	52,5	65,0
Survey duration (minutes)	22,4	37,5
Distance (to tower 12 base)	18,90 (50%H)	10,15 (26%H)
Radar height to the ground (m)	1,00	1,05

RADAR – **Direction 2 (Longitudinal)**

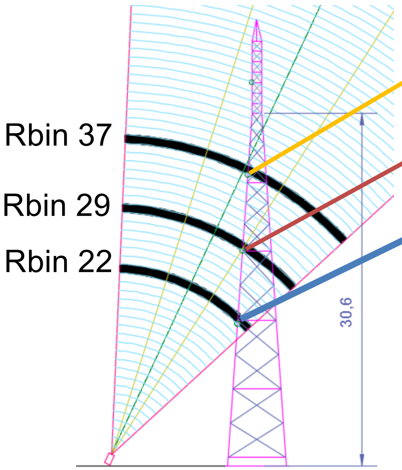
Survey Parameters	Survey 5	Survey 6
Radar Vertical tilt (º)	70	60
Survey duration (minutes)	26,4	22,0
Distance (to tower 12 base)	5,60 (14%H)	14,82 (38%H)
Radar height to the ground (m)	1,20	1,10

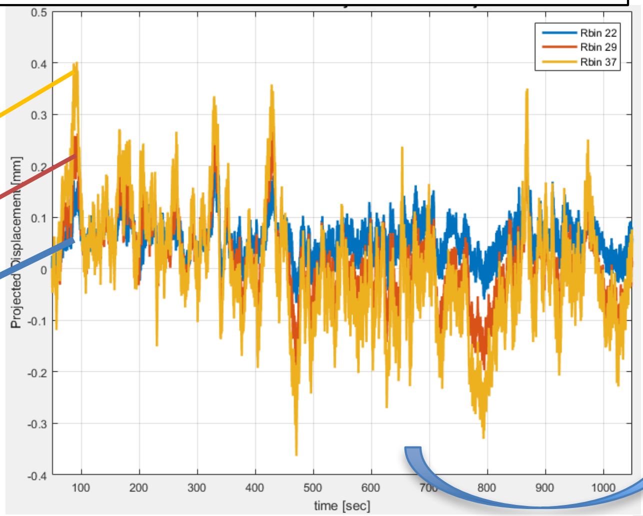
Range resolution = 0,75 m
Sampling frequency = 100 Hz

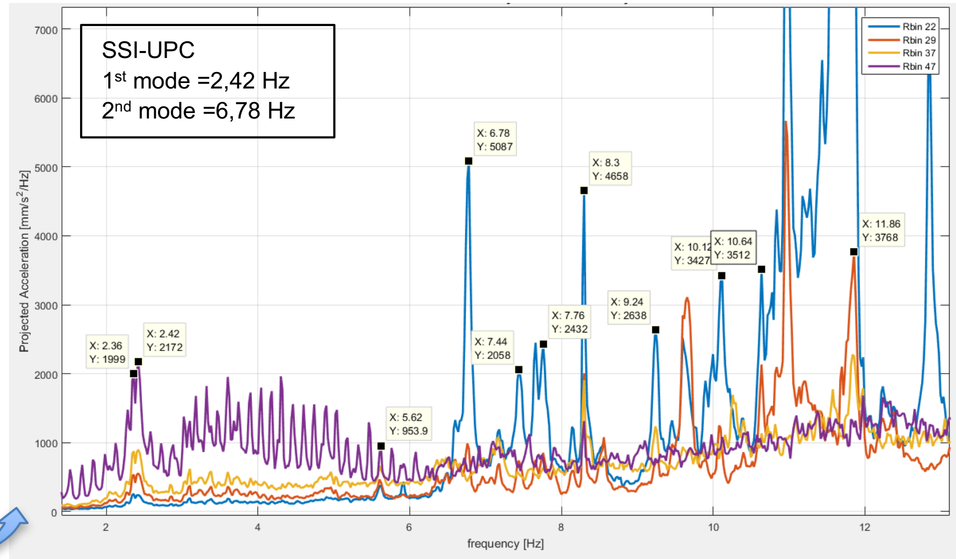
RADAR Results vs Numerical Modelling (Preliminary results)

Overhead High Voltage Line – RADAR Survey –Transmission Tower 12

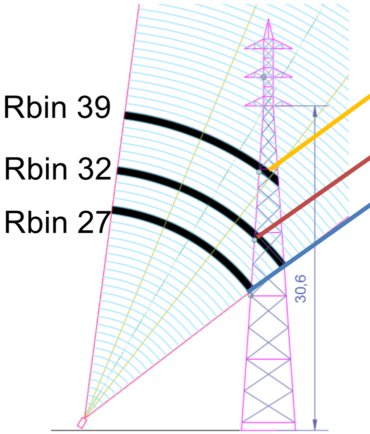
RADAR – **Direction 1(Transverse) – Survey 3**

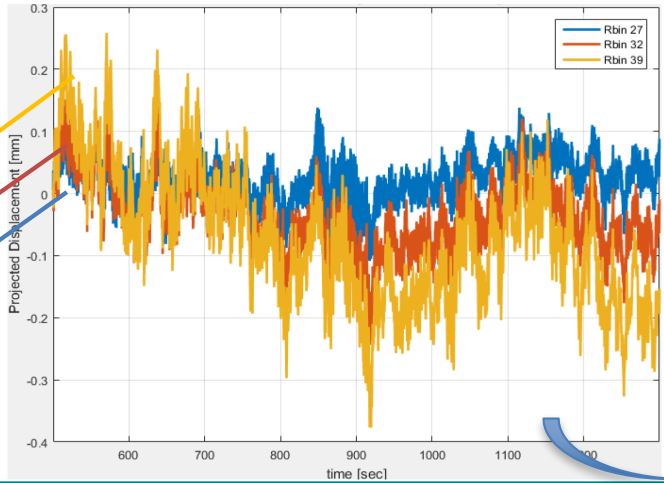


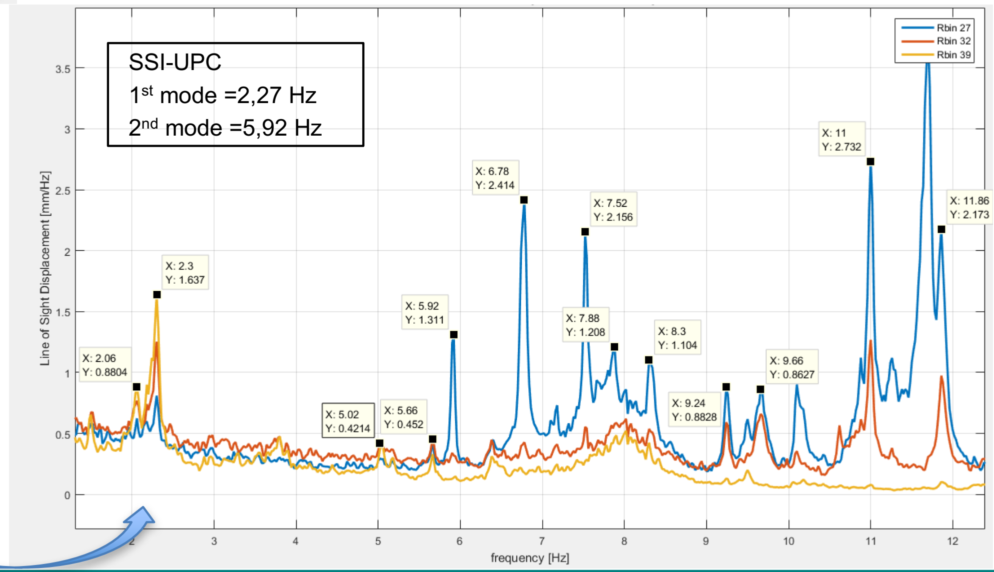




RADAR – **Direction 2 (Longitudinal) – Survey 6**



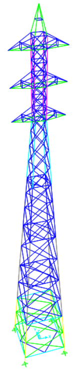




RADAR Results vs Numerical Modelling

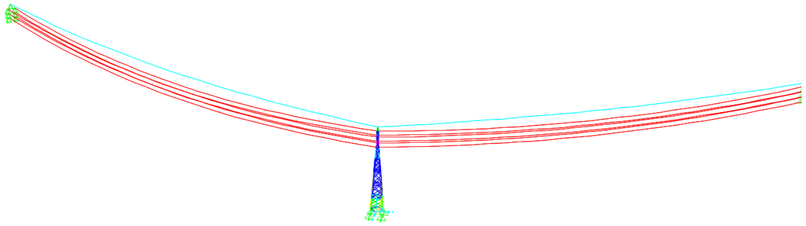
Overhead High Voltage Line – Parametric case studies

Case A – "Tower"



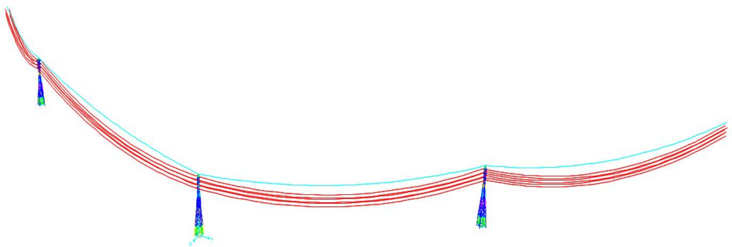
Joint Model	Model
"Rigid"	A1
"Pinned"	A2
"Semi-rigid"	A3

Case B – "Tower + 2 adjacent spans"



Joint Model	Remote span stiffness	Model
"Rigid"	Fixed	B1.1
	"Elastic Spring"	B1.2
"Semi-rigid"	Fixed	B2.1
	"Elastic Spring"	B2.2

Case C – "3 Tower + 4 spans"



Joint Model	Remote span stiffness	Model
"Rigid"	Fixed	C1.1
	"Elastic spring"	C1.2
"Semi-rigid"	Fixed	C2.1
	"Elastic spring"	C2.2

Eccentricities (in-plane and out-plane) considered in all models (through member offsets)

RADAR Results vs Numerical Modelling

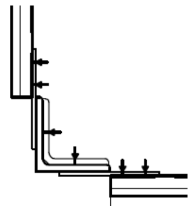
Overhead High Voltage Line – Parametric study - Case A

Case A – "Tower"

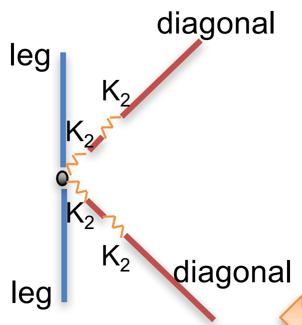
"Joint Model"	Legs (2 or more bolts)	Diagonal (2 bolts)	Horizontal (2 bolts)	Horizontal (1 bolt)
"Rigid"	rigid	**rigid**	**rigid**	pinned
"Pinned"	rigid	**pinned**	**pinned**	pinned
"Semi-rigid"	**Kx - elastic** (axial-direction)	**Kx - elastic** (axial-direction)	**Kx - elastic** (axial-direction)	pinned

Effects considered in the model:

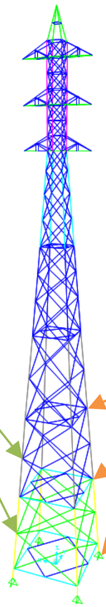
- Eccentricities (in-plane/out-plane
- Section rotation;
- Joint Masses (bolts and gusset plates represent around 19% of total weight);



Bolted joint – Slippage model



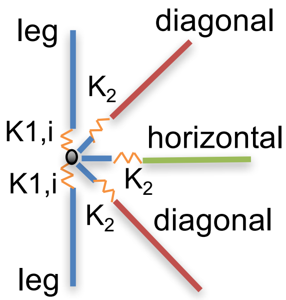
Type C
Single diagonal
-gusset



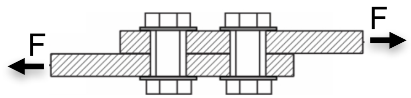
Type C- joint

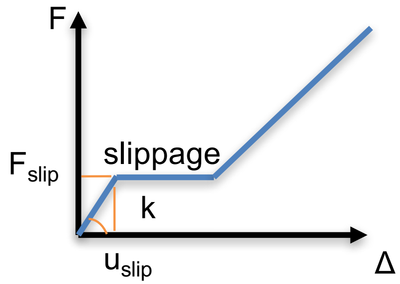
Type A- joint

Bolted joint – Slippage model



Type A
Lap-splice





$F_{slip} = \sum F_p * m * u$
u_{slip} (from literature)

Eccentricities (in-plane and out-plane) considered in all models (through offsets)
Supports assumed as pinned.

RADAR Results vs Numerical Modelling

Overhead High Voltage Line – Parametric study - Case A

Case A – “Tower”

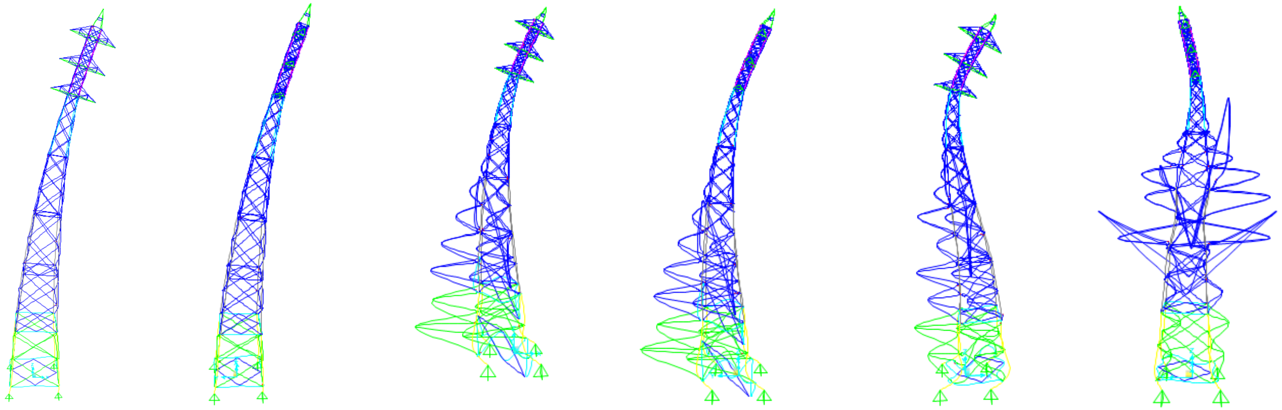
Model	f_1 (Hz)		f_2 (Hz)		f_3 (Hz)	
	T	L	T	L	T	L
A1 (rigid)	3,23 m_T=46% m_L=3%	3,23 m_T=3% m_L=46%	7,35 m_T=31% m_L=0%	7,36 m_T=0% m_L=31%	13,28 m_T=8% m_L=0%	13,34 m_T=0% m_L=6%
A2 (pinned)	3,13 m_T=44% m_L=17%	3,13 m_T=17% m_L=44%	4,80 m_T=4,8% m_L=2,4%	4,80 m_T=2,5% m_L=4,2%	9,54 m_T=3% m_L=2,5%	9,51 m_T=2,3% m_L=3,0%
A3 (semi-rigid)	3,03 m_T=44% m_L=1,2%	3,03 m_T=1,2% m_L=44%	6,39 m_T=26% m_L=0%	6,41 m_T=0% m_L=26%	11,63 m_T=3% m_L=0%	11,68 m_T=0% m_L=3,2%

m_T and m_L represent Modal participating mass ratios in the transverse and longitudinal direction

Other effects considered:

- Eccentricities (in-plane/out-plane);
- Section rotation
- Joint Masses (represent around 19% of total weight);

Mode Shapes for model A1



RADAR Results vs Numerical Modelling

Overhead High Voltage Line – Parametric study - Case B

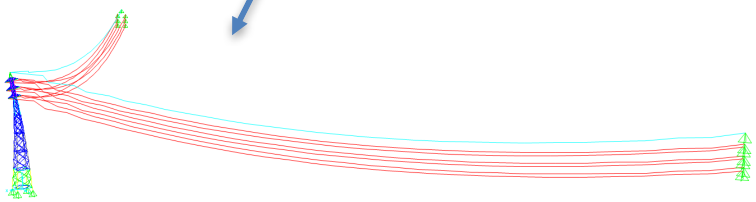
Case B – "Tower + 2 adjacent spans"

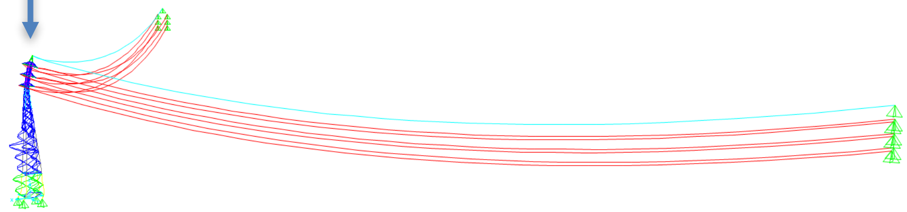
Model	f_1 (Hz)		f_2 (Hz)		f_3 (Hz)	
	T	L	T	L	T	L
B1.1 (R-F)	3,39	3,88	7,19	6,53	12,94	12,95
B1.2 (R-E)	2,59 (error=7%)	1,99 (error=12%)	7,35 (error=8%)	6,38 (error=8%)	12,95	12,95
B2.1 (S-F)	3,24	3,74	6,31	5,95	11,55	11,39
B2.2 (S-E)	2,45 (error=1%)	1,89 (error=17%)	6,49 (error=4%)	5,95 (error=1%)	11,69	10,15

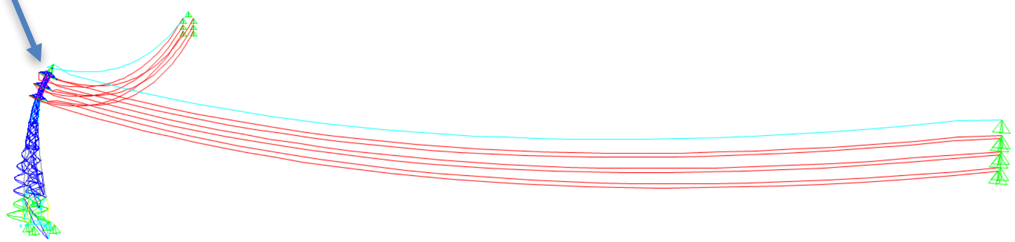
Other effects considered:

- Eccentricities (in-plane/out-plane);
- Section rotation
- Joint Masses (represent around 19% of total weight);
- P-Δ effect

Mode Shapes for model B1.1







RADAR Results vs Numerical Modelling

Overhead High Voltage Line – Parametric study - Case C

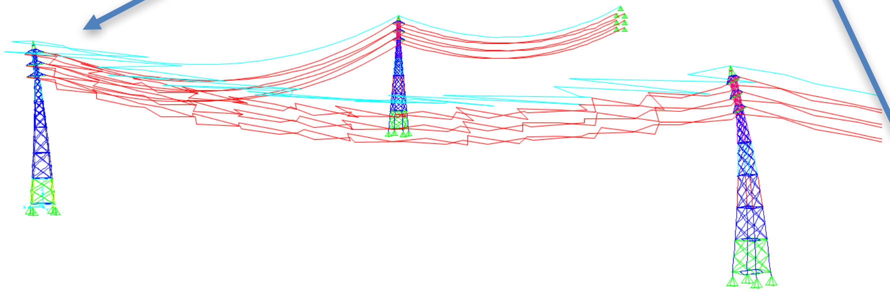
Case C – “3 Towers + 4 spans”

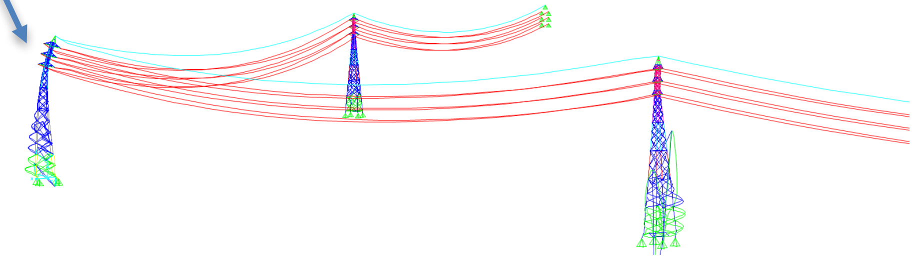
Model	f_1 (Hz)		f_2 (Hz)		f_3 (Hz)	
	T	L	T	L	T	L
C1.1 (R-F)	3,24	2,82	6,57	6,16	12,96	12,80
C1.2 (R-E)	2,33 (error=4%)	2,11 (error=7%)	6,98 (error=3%)	6,43 (error=9%)	13,15	13,15
C2.1 (S-F)	2,99	2,63	5,74	5,51	11,56	11,07
C2.2 (S-E)	2,22 (error=8%)	1,98 (error=12%)	6,2 (error=9%)	5,86 (error=1%)	11,69	11,47

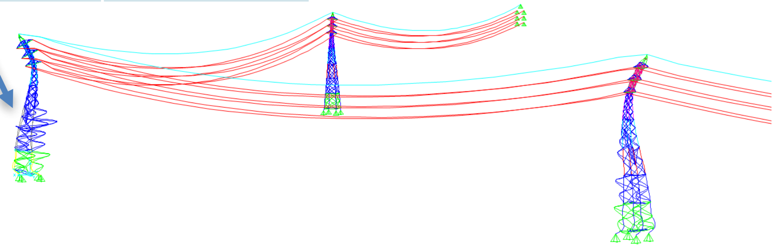
Other effects considered:

- Eccentricities (in-plane/out-plane);
- Section rotation
- Joint Masses (represent around 19% of total weight);
- P-Δ effect

Mode Shapes for model C1.1







Conclusion and Future Developments

Main Conclusions

IBIS- FS RADAR proved to be an **efficient and reliable monitoring equipment** for the **dynamic characterization of the Overhead Power Line case study**

- *Fast measurement of the displacements on power lines by remote sensing (detection of frequencies, which can be indirectly used for the line sag control)*
- *Excellent agreement with theoretical expressions for determining fundamental frequencies.*

In general the Model C1.2 *(Rigid joints / Remote span with elastic springs)* ***provided*** *the* ***best accuracy*** *(errors of 3-9%) when comparing only the fundamental frequencies. Parameters like the size of the model (nº of Towers/spans), remote span boundary conditions and joint slippage effects have demonstrated a strong impact on the dynamic behavior of the tower system under study.*

Future Developments

Further investigation of the dynamic behavior *with accelerometers and impact hammers (validation purposes and for the simultaneous comparison with both sensing approaches)*

Estimation *of the* ***system modal parameter*** *(frequency, modal shape and damping) by different* ***Operational Modal Analysis (OMA) techniques***

Experimental characterization *of typical* ***joint slippage behavior in lattice towers through laboratory testing***

Thank you!