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REAL WORLD CONDITIONS **REAL WORLD SOLUTIONS**

STRUCTURAL HEALTH MONITORING OF LANDMARK CIVIL INFRASTRUCTURE IN THE UK

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VIBRATION ENGINEERING SECTION

OUTLINE

About VES/FSDL

Structural health/performance monitoring in other industries

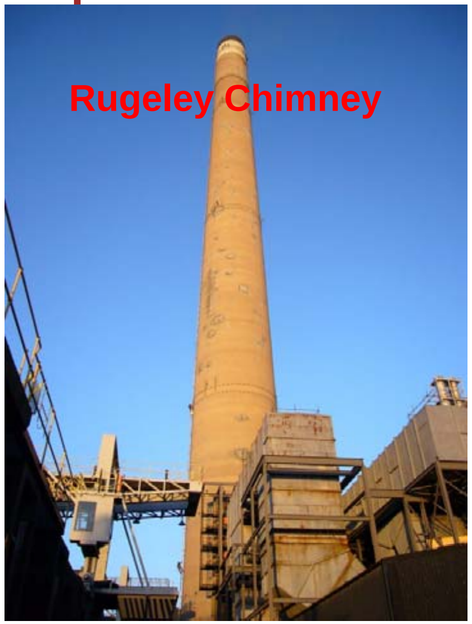
Purposes and definitions

JMWB UK examples:

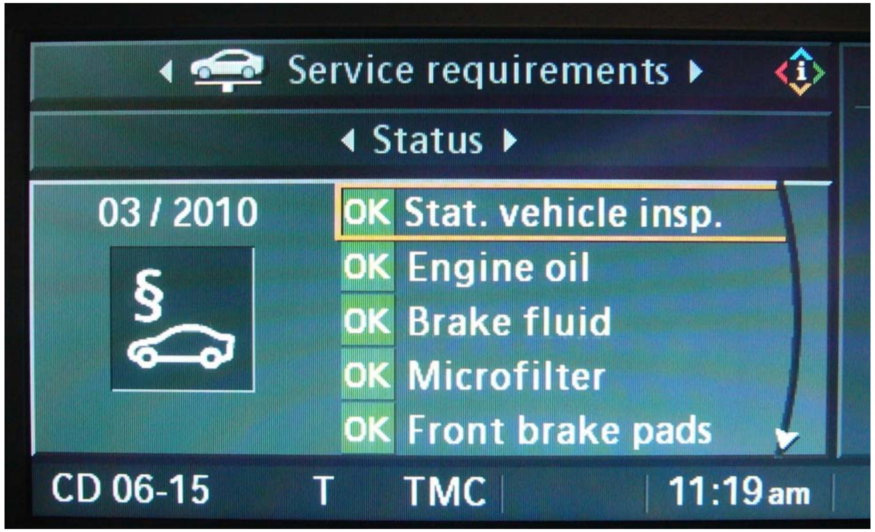
- Humber Bridge,
- **Tamar Bridge –example 1,**
- **Rugeley Chimney –example 2,**
- Sheffield University Arts tower

Conclusions

VES/FSDL deals with actual or potential operational performance issues with structures like these:



SHM in other industries: Health/performance monitoring with real-time alerting and condition-based maintenance are the norm for cars

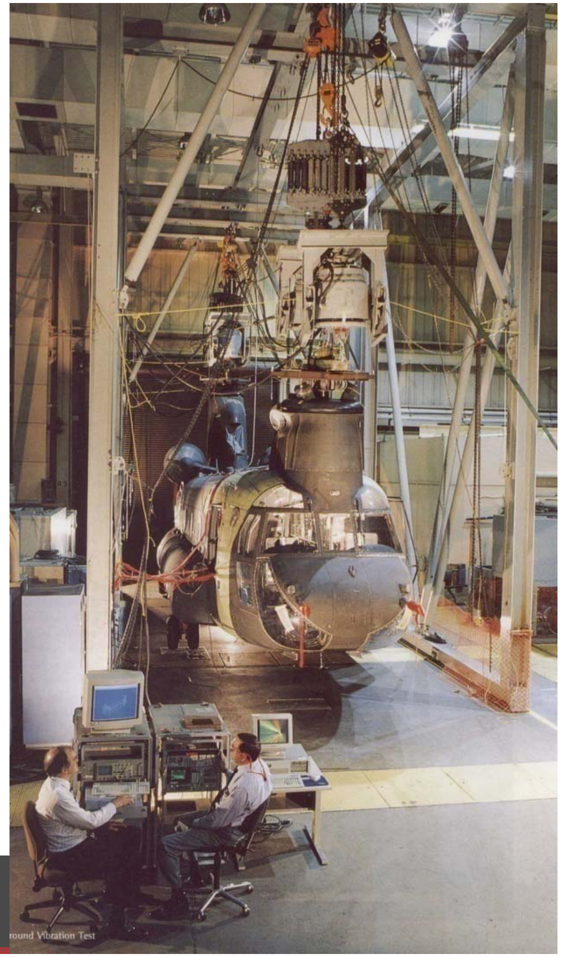


… whose prototypes are extensively tested before entering service,

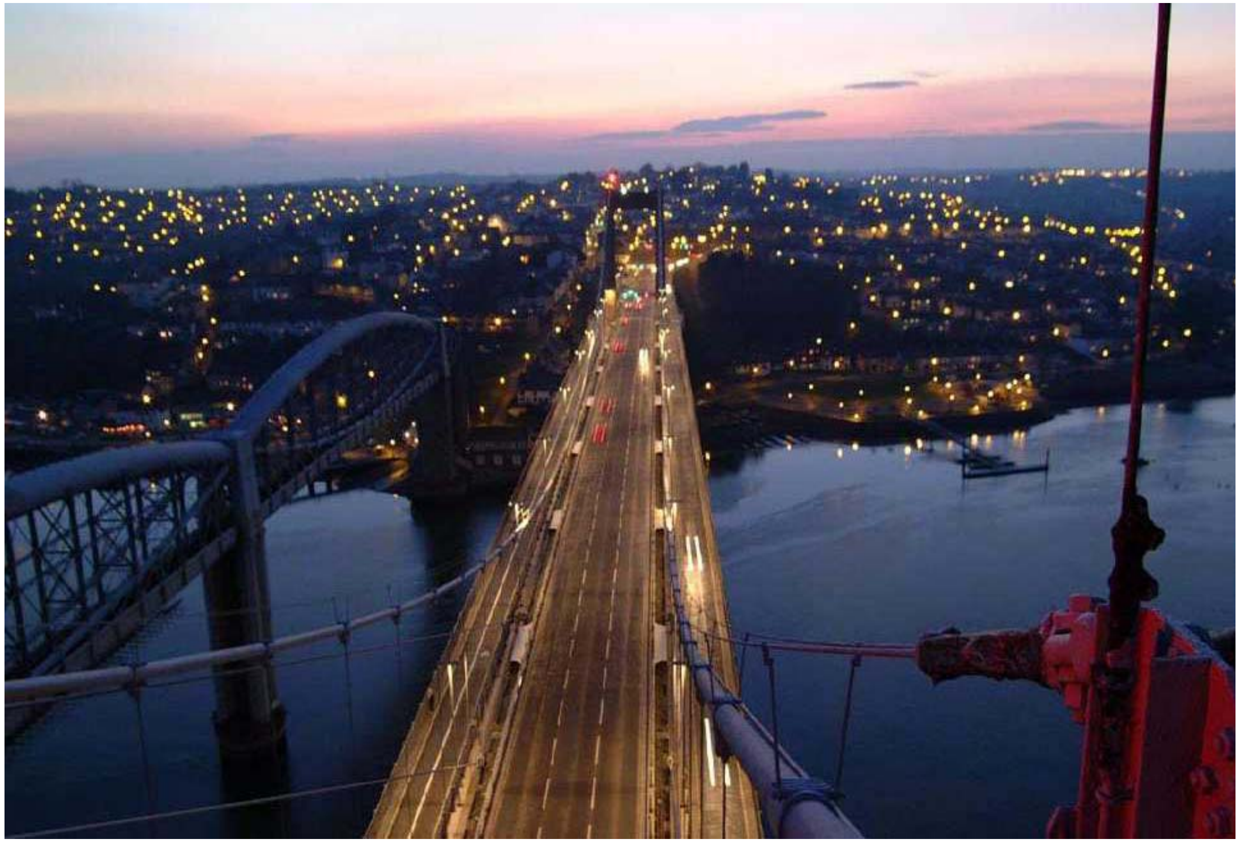
ULS (collapse)

SLS (serviceability)

…as are aircraft which undergo thorough ground vibration test before entering service to evaluate fitness for purpose.



Each civil structure is a prototype, incorporating large safety factors. We can only study the structure in operational condition to establish performance profile.



WHY DO WE NEED SHM FOR CIVIL STRUCTURES?

Track structural loads/overloads/extreme responses

Provide warning of impending failure (who dares to declare successes?)

Check novel systems of construction/structural forms

Validate structural modifications

Assess structural safety/performance after trauma (e.g. earthquake/impact)

Provide a feedback loop to design and loading codes

Evaluate 'servicability' –e.g. User comfort/safety

Track long term movement or degradation to aid maintenance decisions

'Damage' detection? Not for structures in the real world, in my experience

Elements of civil infrastructure SHM system

Automated continuous/long term monitoring

- Sensors (static/dynamic)
- Local data storage
- Local processing
- Data transmission
- System identification
- Data reduction/mining
- Performance/ load evaluation

→ **Data-driven model**

↓

Using data-driven/physics-based model:

- Anomaly detection
- Reporting/alerting/decisions

One-off/offline assessment

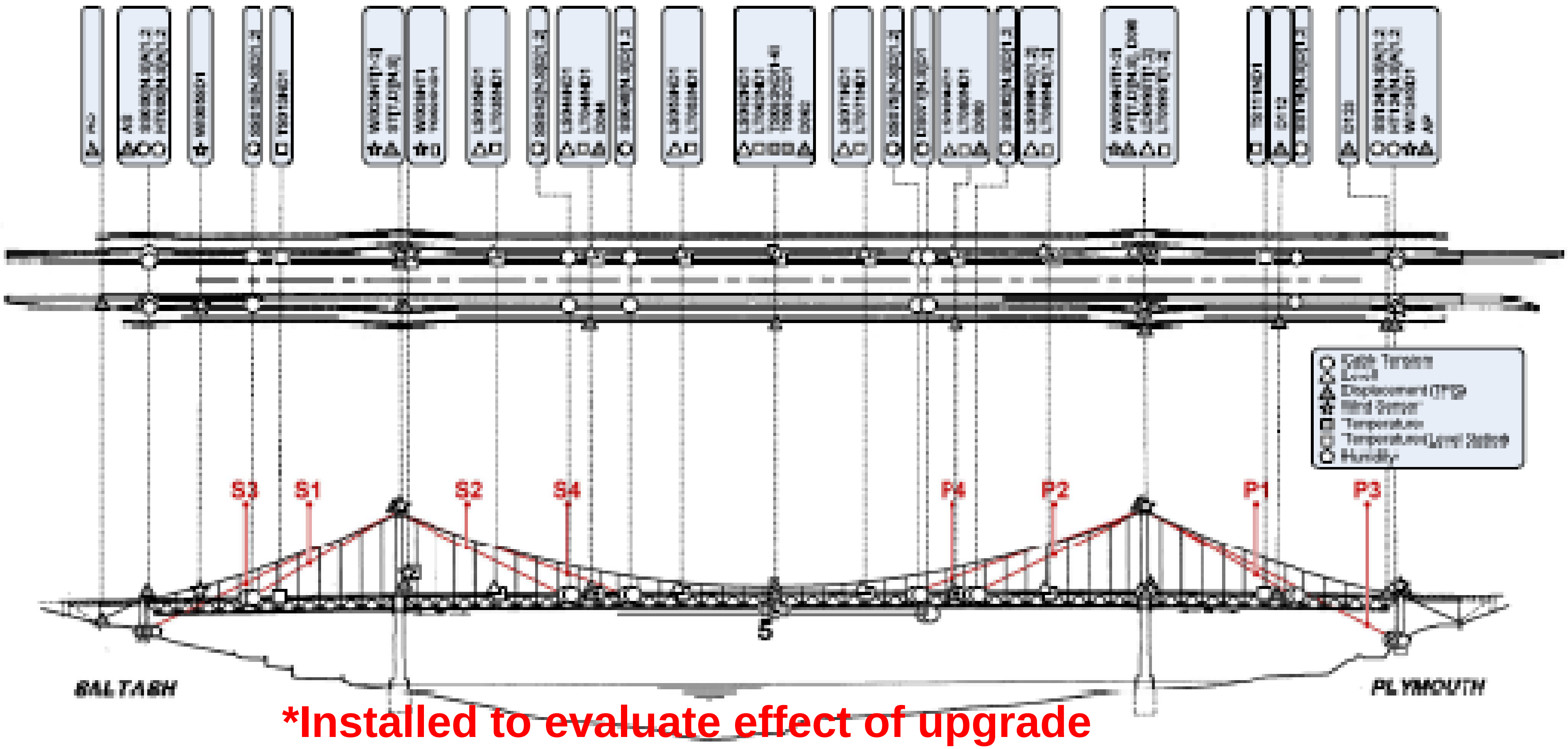
- (FE) modeling
- (Dynamic) testing
- Model validation/updating

→P**hysics –based/FE model**

Example 1: Tamar Bridge: opened 1961, upgraded 2000, static monitoring system installed by Fugro to check effects of upgrade

SHM configuration with three sub-systems:

Fugro system* (2000, upgraded 2007),
Sheffield dynamic system (2006),
Sheffield TPS system (2009)
(Data fusion managed via MATLAB/MySQL database)



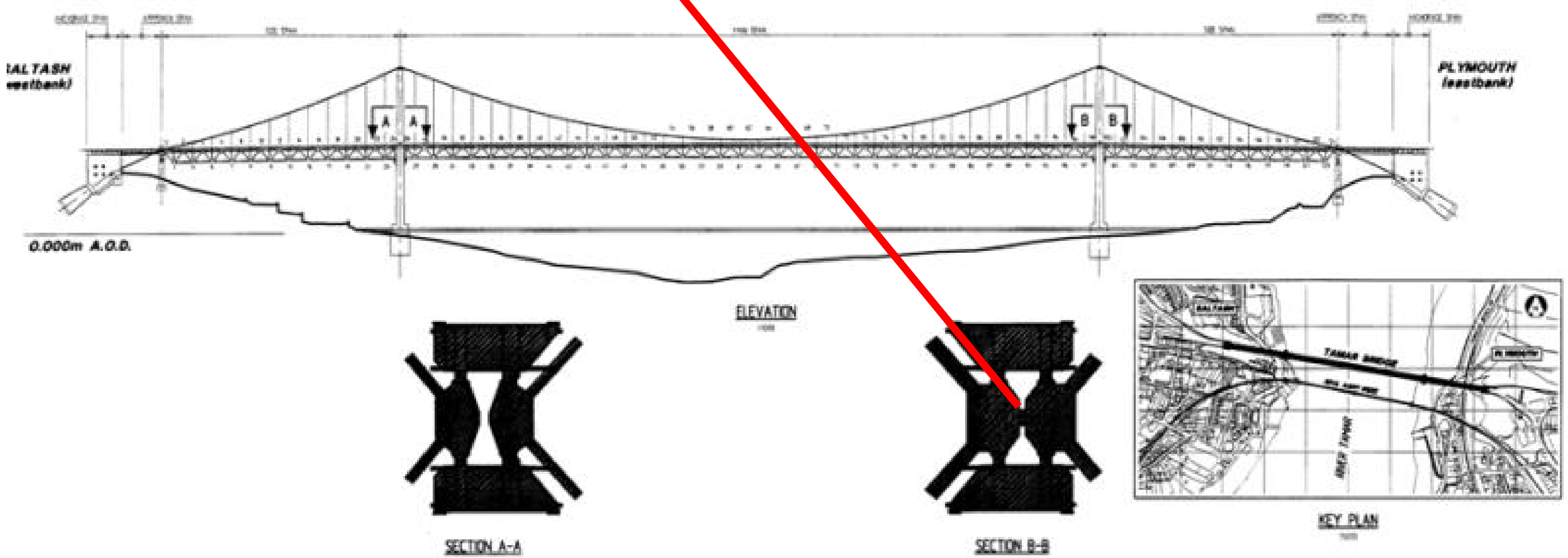
*Installed to evaluate effect of upgrade

Results of 2000 strengthening and widening (upgrade):

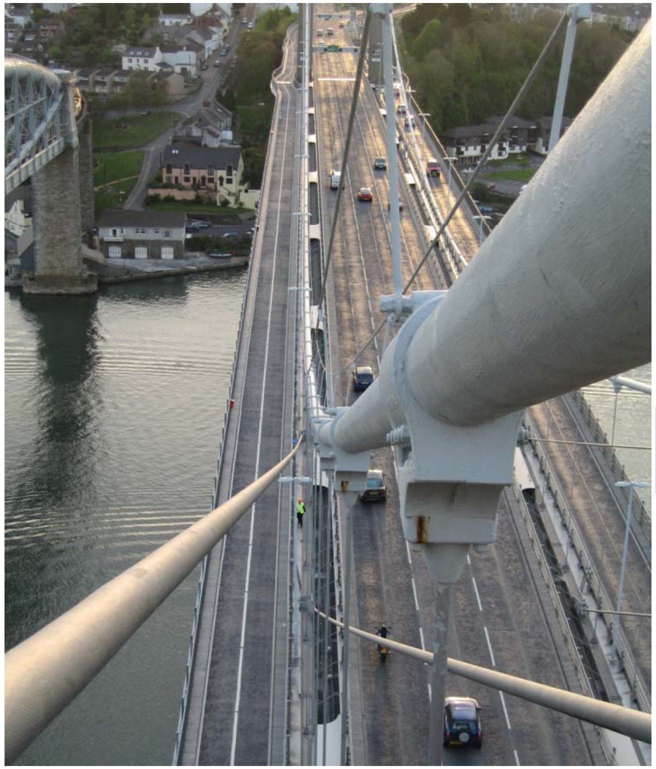
Lateral restraint ←

Vertical restraint →

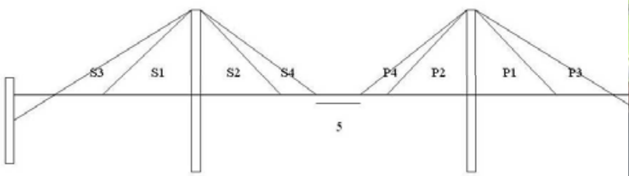
1) Deck bearing system rearranged w.r.t. longitudinal restraint



2) Cantilevers added (retaining continuity at Plymouth)



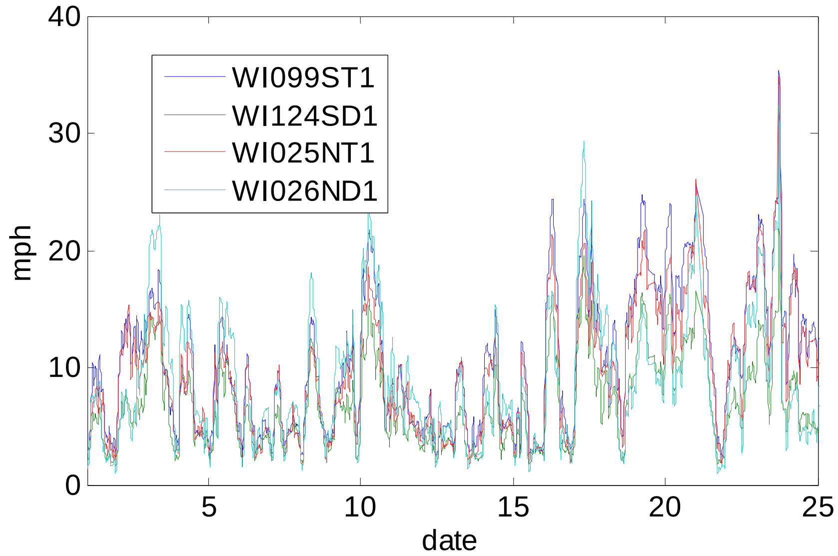
3) Additional stays (ϕ~100mm) added to carry extra load



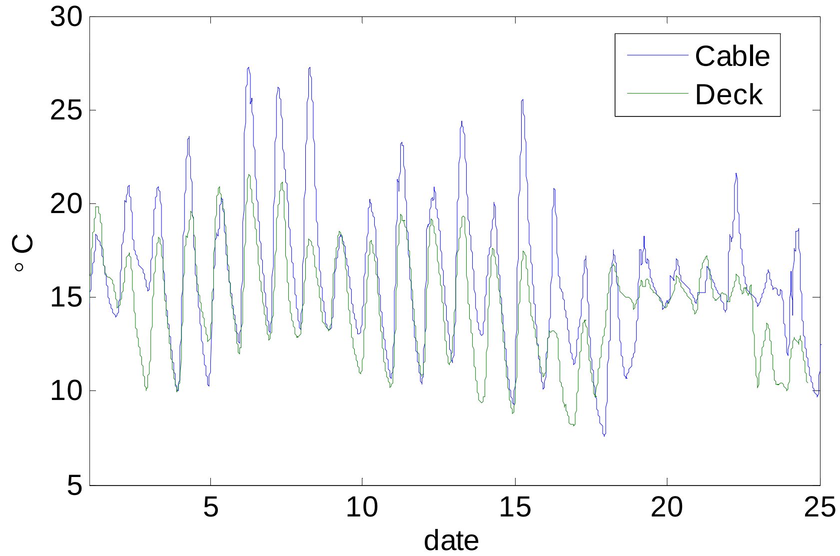
Cable vibrations controlled by 'interesting' design of damper

Loads are wind, temperature and traffic;

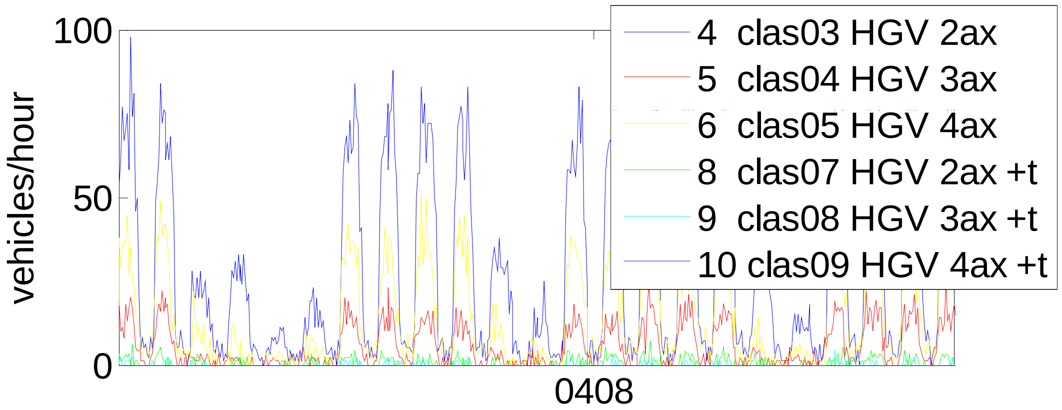
These have complex effect on ‘normal performance’, to be filtered out to reveal abnormal performance



Wind speeds at Tamar Bridge



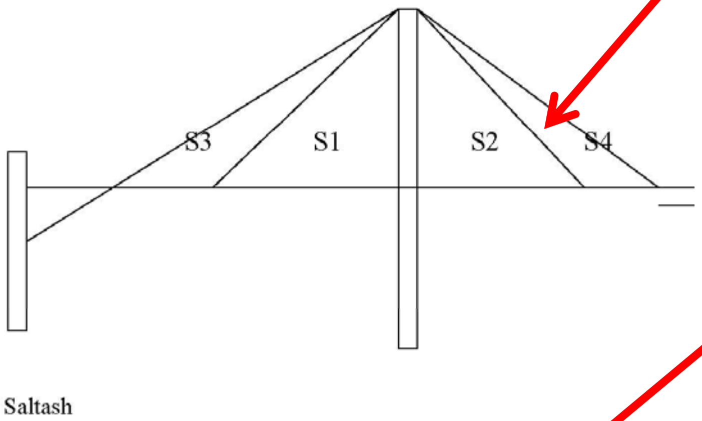
Deck and main cable temperatures

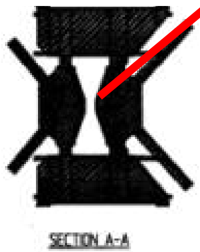


Temperature: major effect
Wind: secondary effect
Traffic: minor effect

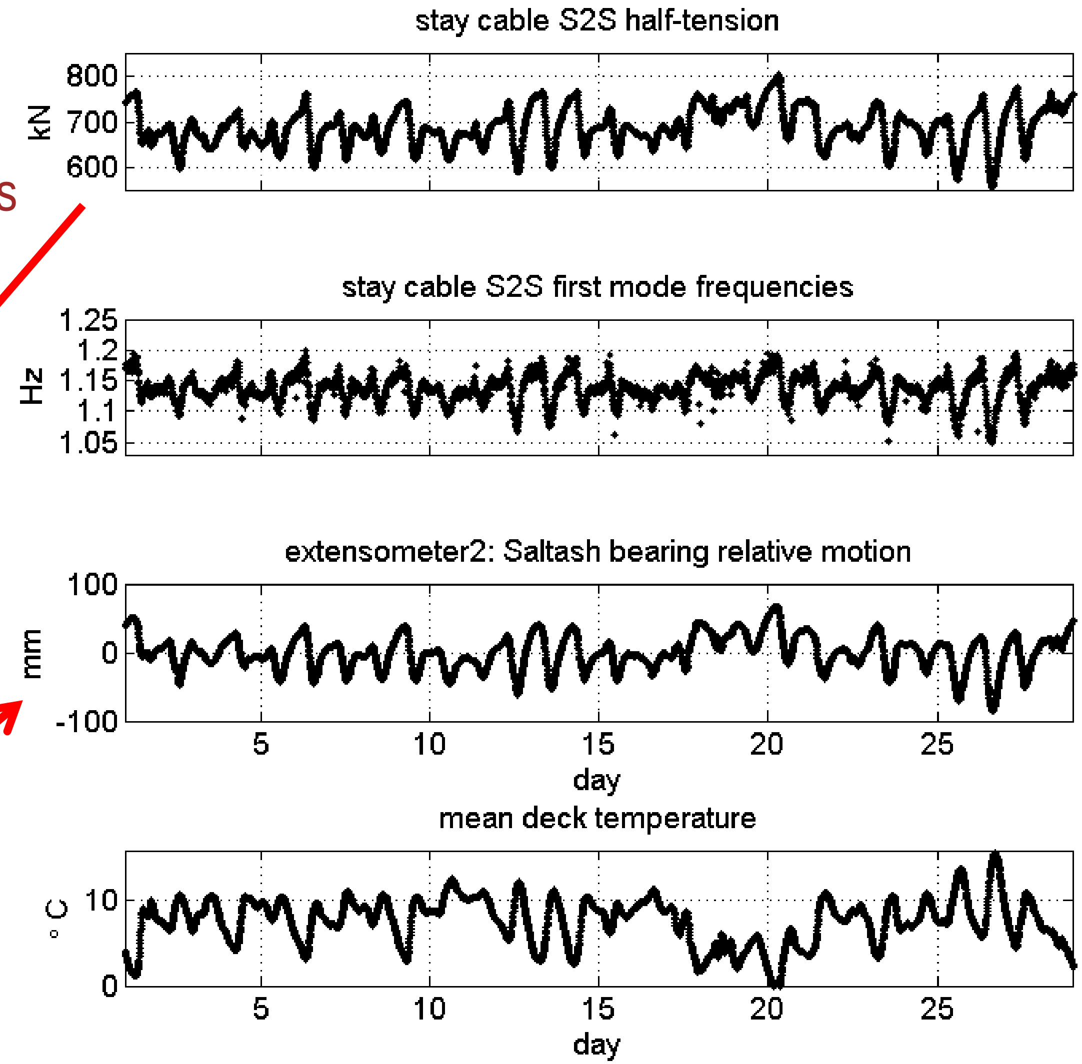
Temperature loads, drive global deformations

We expected strong temperature influence so we looked for effects of thermal expansion on bearing movement and cable tensions





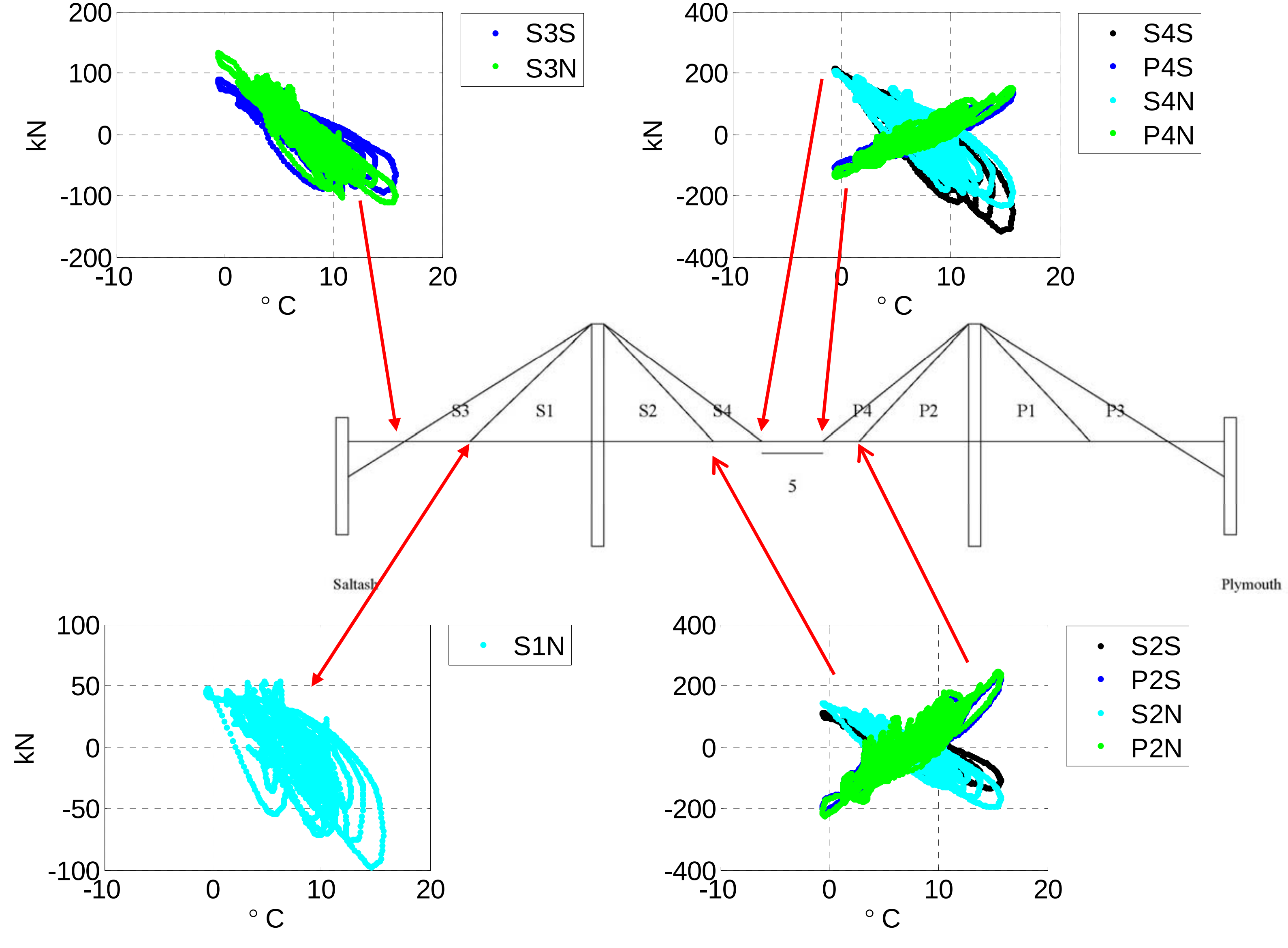
Saltash tower expansion joint



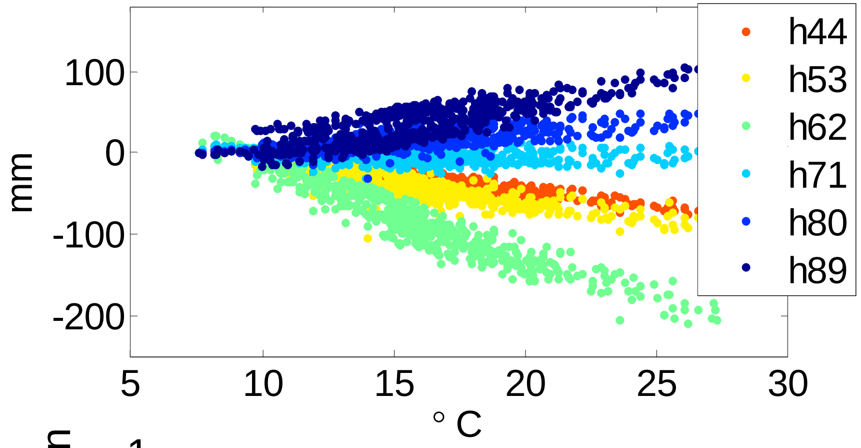
(March 2007 data)

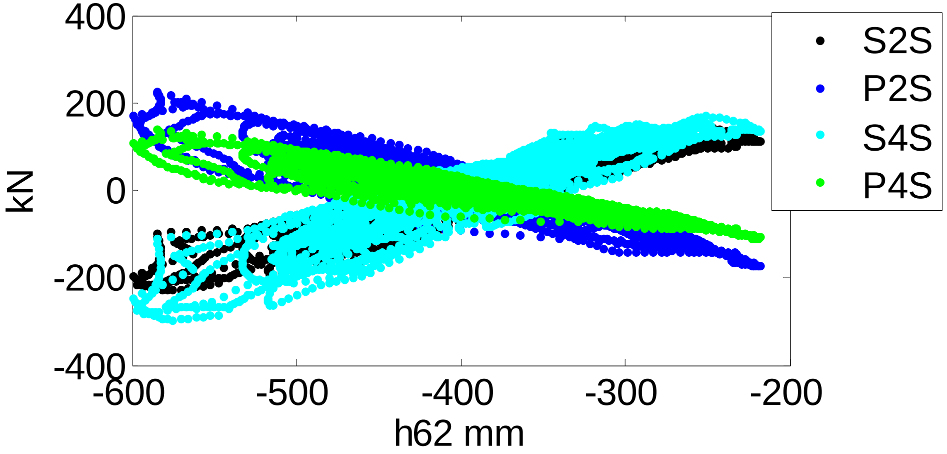
Relationship of stay cable tensions &deck temperature:

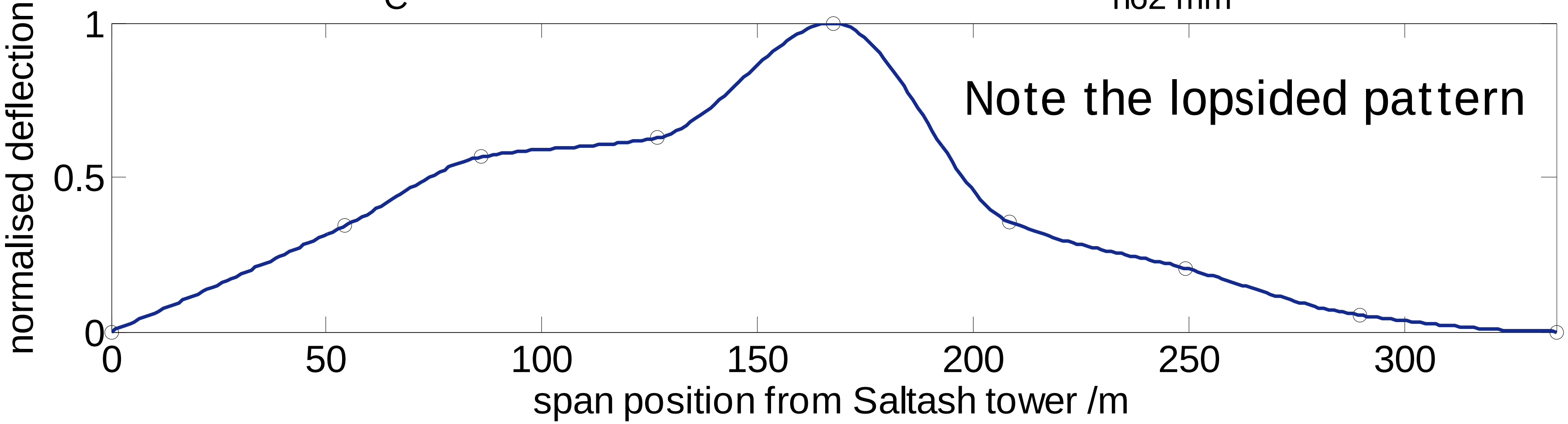
This is hysteretic, nonlinear and seasonal, not as simple to interpret as first seems

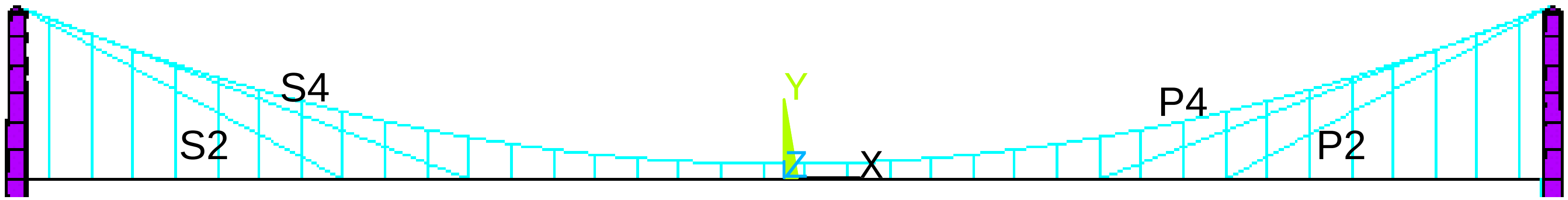


Deck level and stay cable tension are linked
(and of course strongly correlated with temperature)

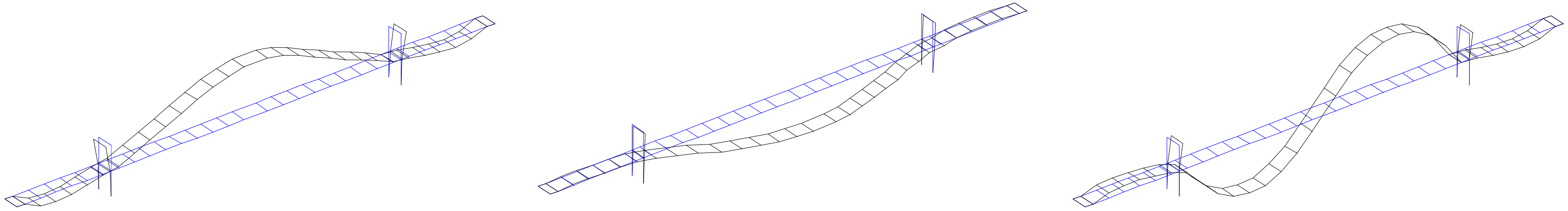






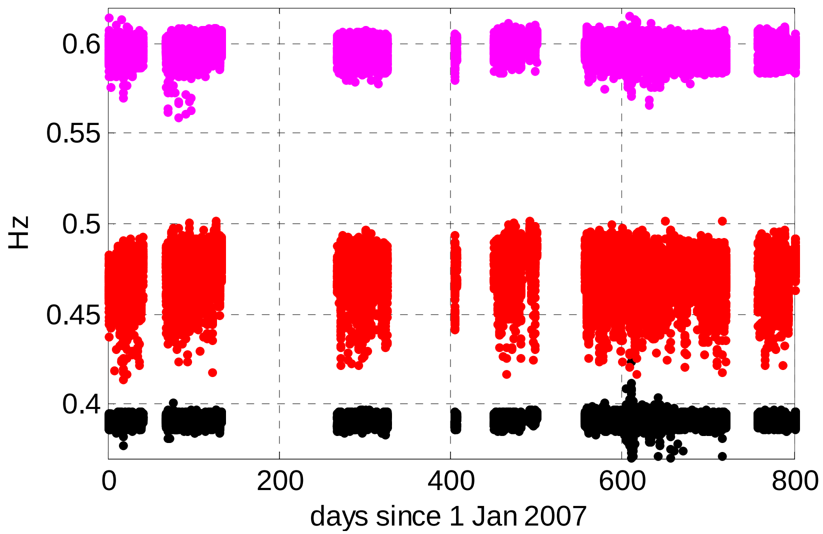


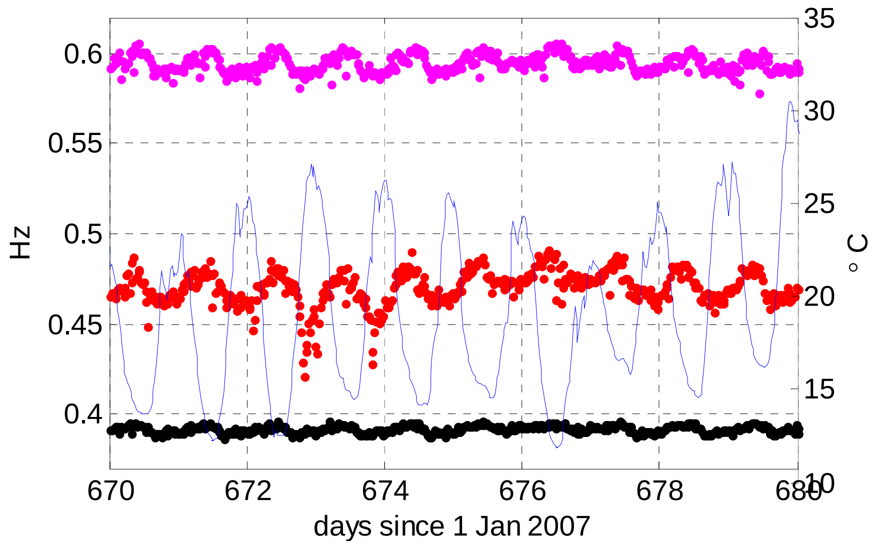
Deck mode frequencies have large ranges with obvious diurnal variations but not obvious correlations with loads:



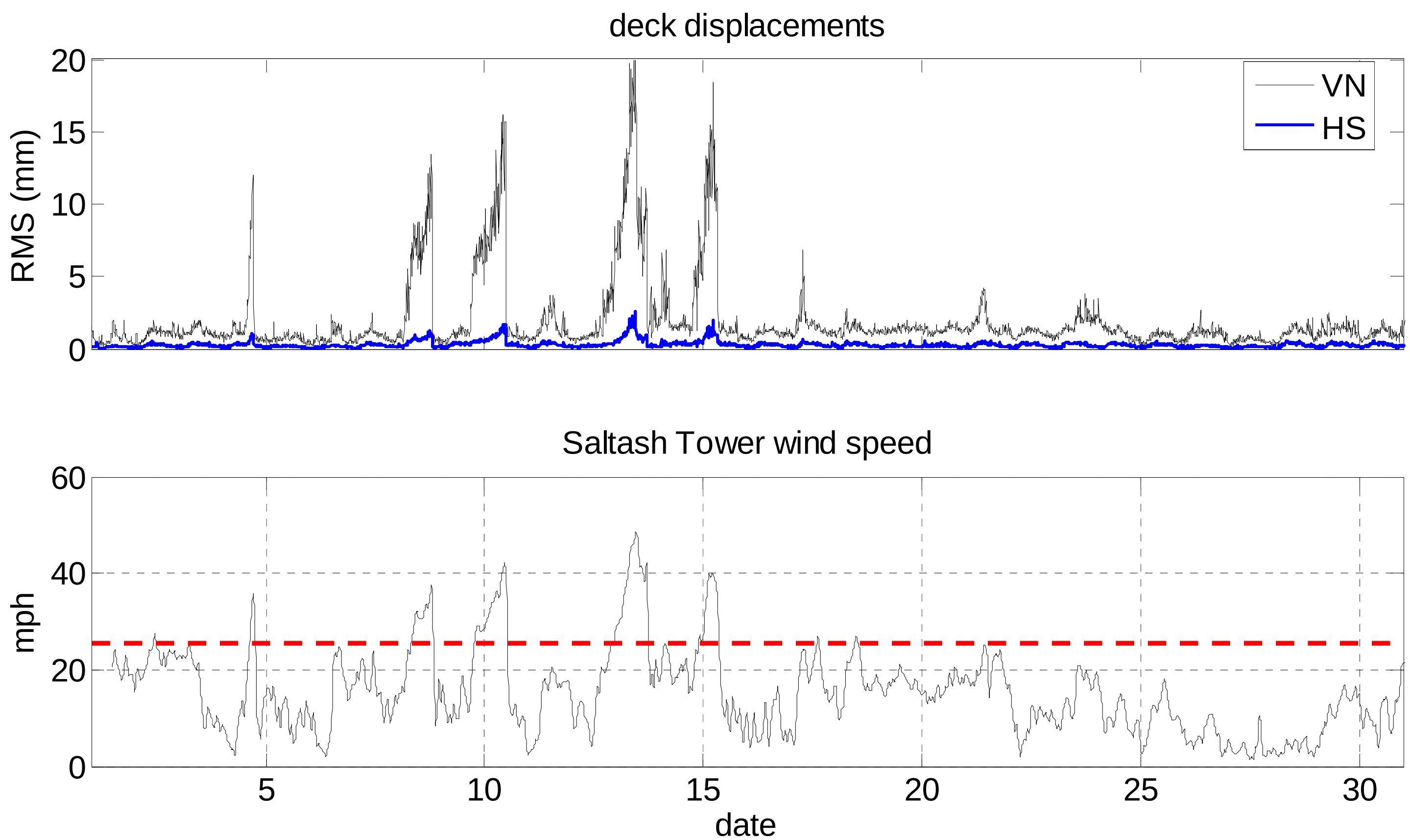
Deck vibration modes identified by full scale ambient vibration survey, April 2006

VS1 0.393Hz LS1 0.457Hz VA1 0.595Hz





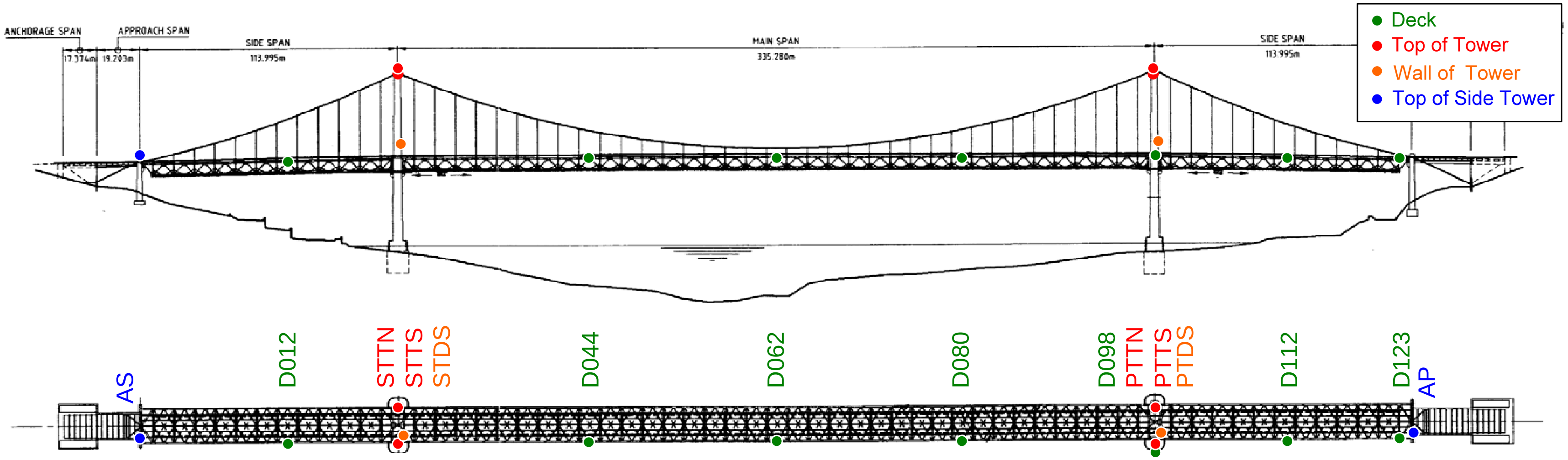
Wind and effects on dynamic displacements for band 0.1Hz-1.0Hz, only noticeable for strongest winds



Mechanisms not clear, due to incomplete picture of deck movement. So we explore with Total Positioning System

Definition of Local Coordinates for (Leica) TPS

Reflector Locations along south side of deck and on towers



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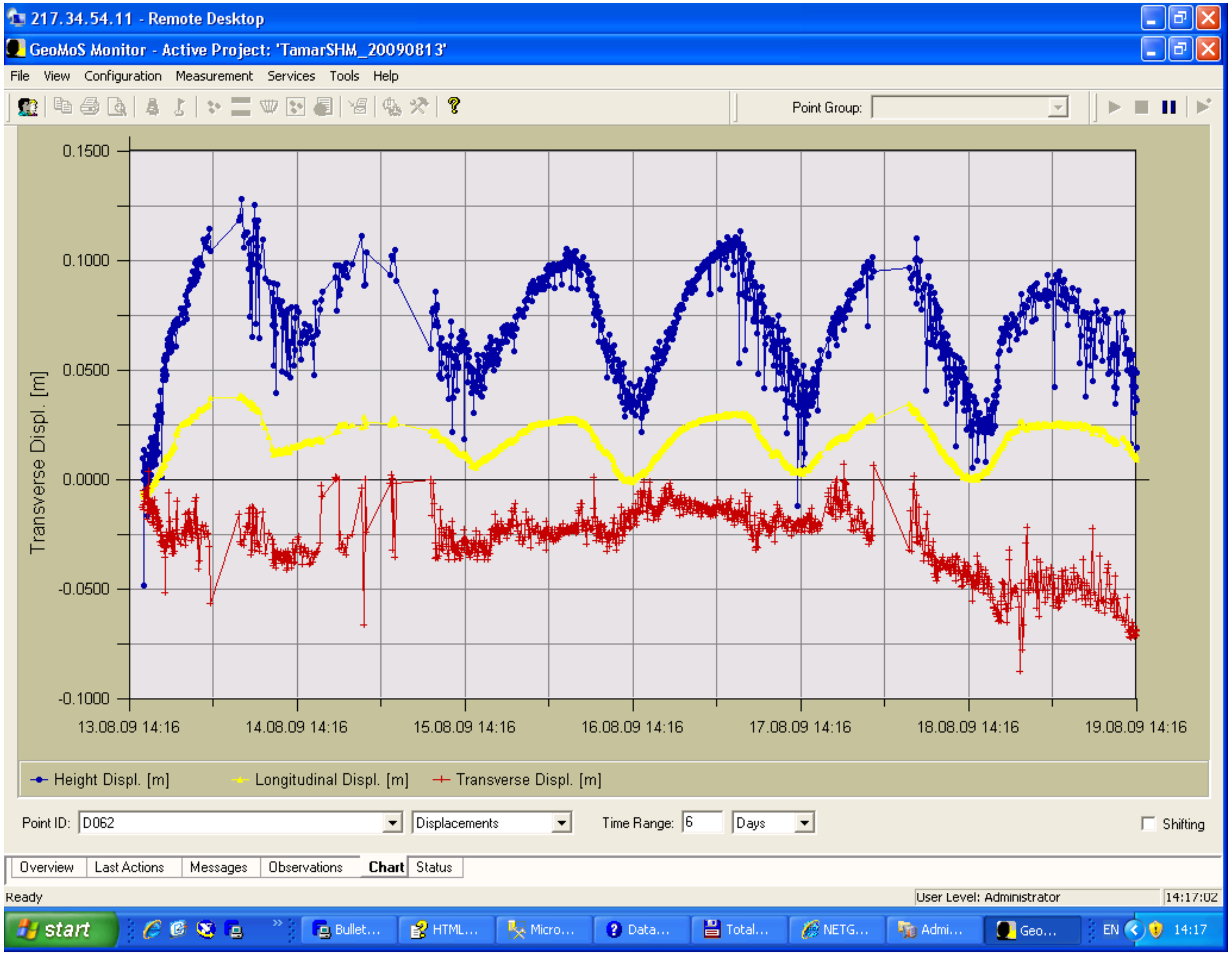
Remote desktop access to laptop running GeoMoS

Vertical

Longitudinal (E)

Lateral (S)



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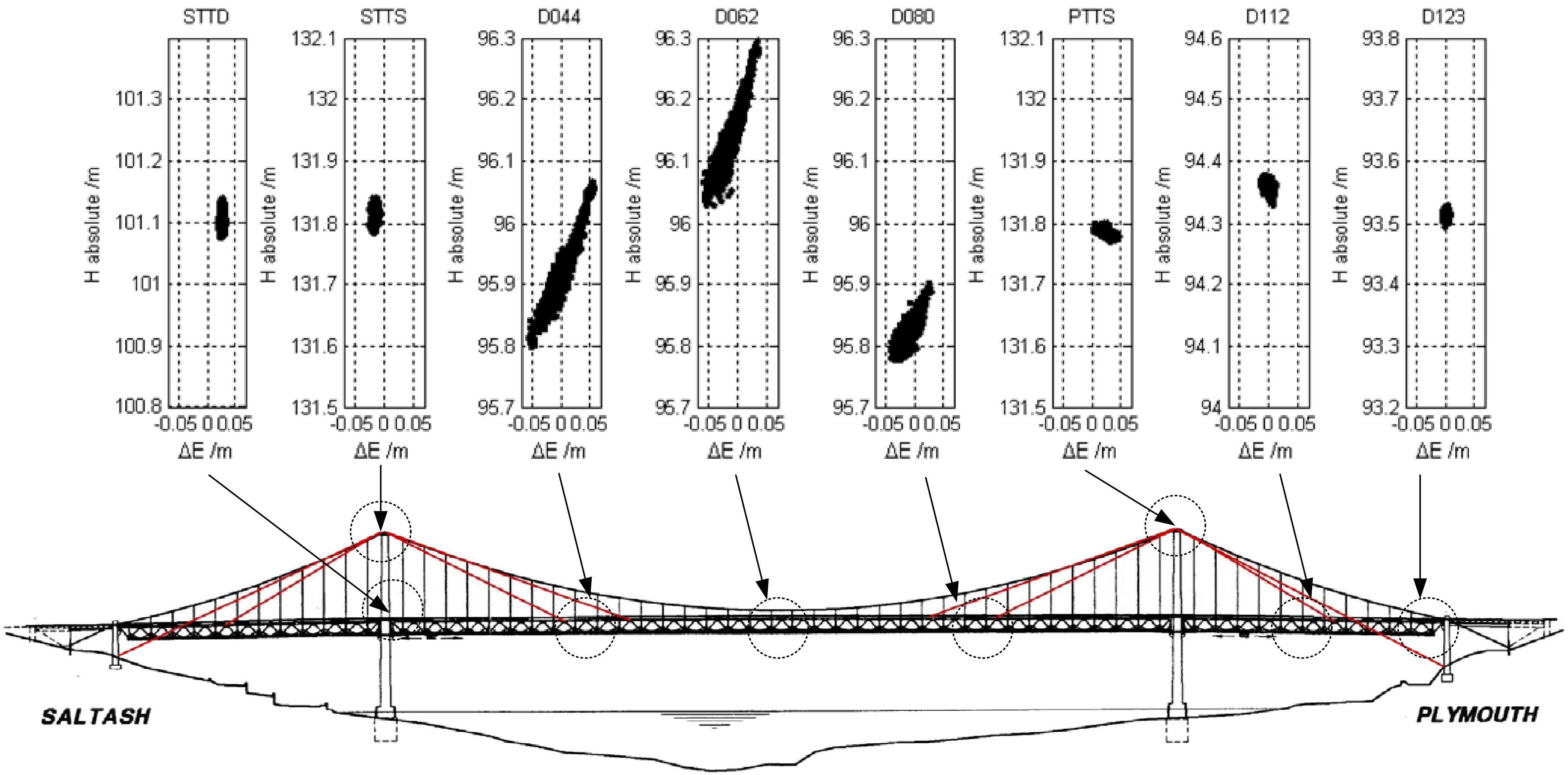
Measured east/vertical displacement bBehavior (no clear pattern in other planes so far)



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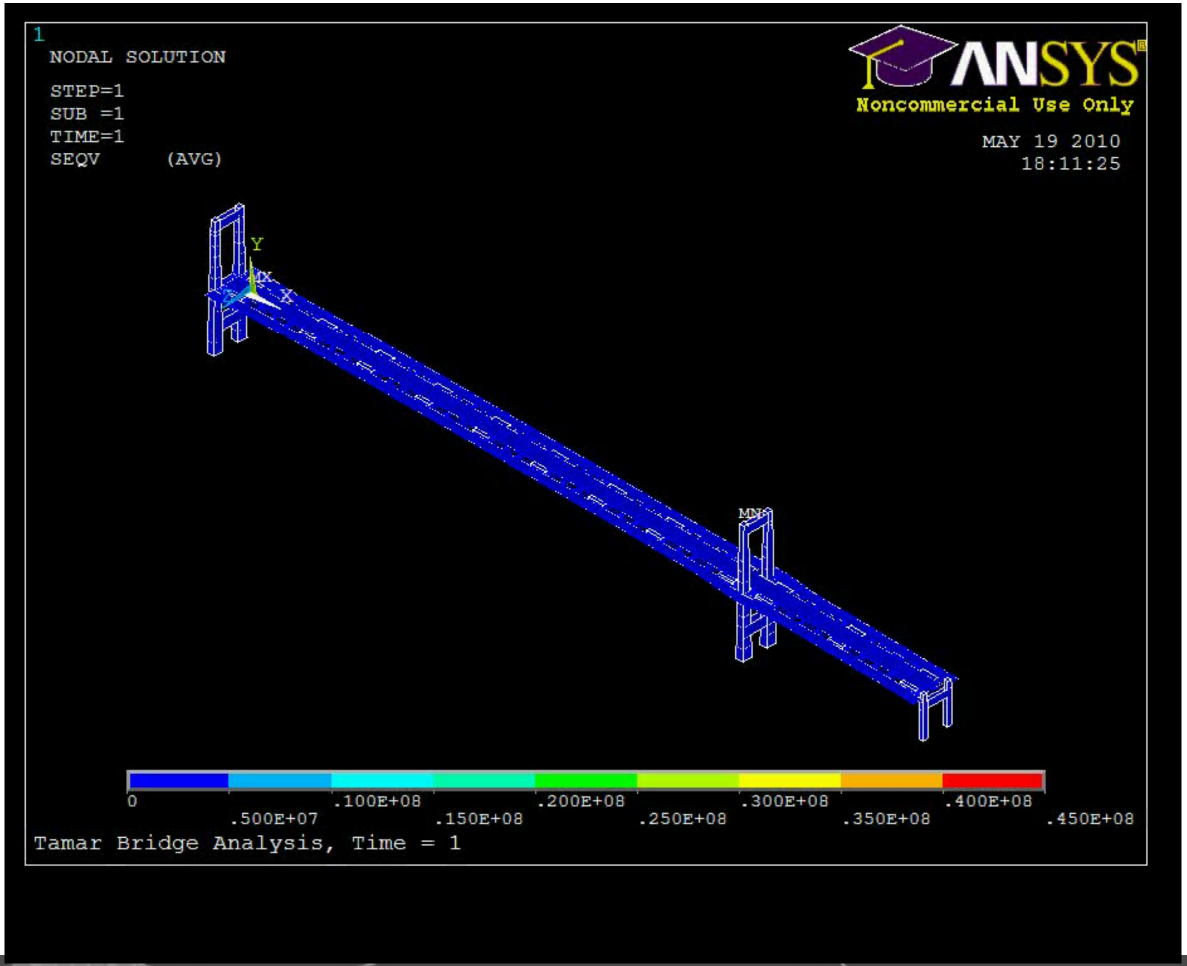
So this is how the continuous section of deck (from Plymouth abutment to Saltash tower) moves



Result of SHM study so far for Tamar Bridge

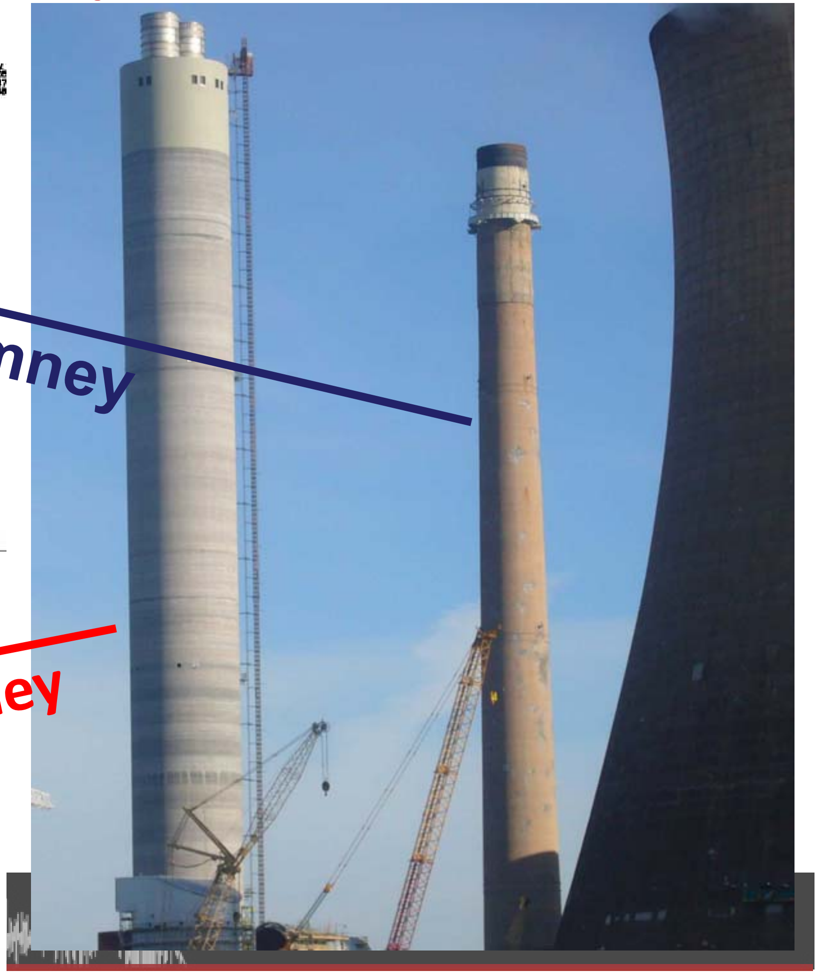
- Temperature is the dominant driver of structural configuration
- Majority of dynamic loads derive from traffic (heavy vehicles)
- Wind effects on configuration and dynamic response are minimal
- Structural configuration variation leads to major effects on dynamic properties making their use as sole measure for SHM a major challenge
- We believe boundary conditions (bearings) are primary influence on bridge global dynamic performance (i.e. mode frequencies)
- Stay cable vibrations are well controlled by damper system
- Establishing a performance ‘baseline’ is critical but complex aspect of SHM: we need to know what’s OK before we can see what’s wrong
- Ongoing study with validated model not reported here

Example 2: Rugeley chimney

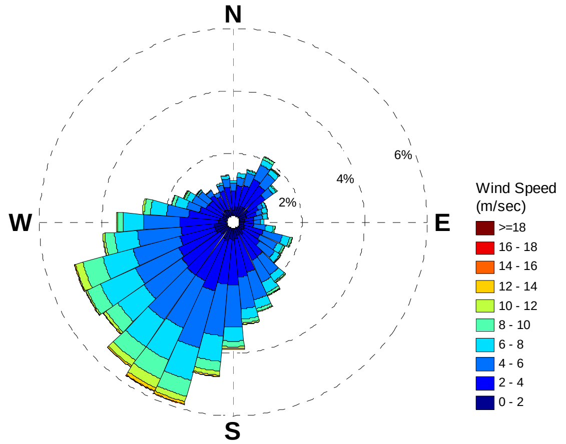
- Reinforced concrete flue gas chimney at Rugeley coal-fired power station (Staffordshire, U.K.)
- Built in 1968
- 183m high

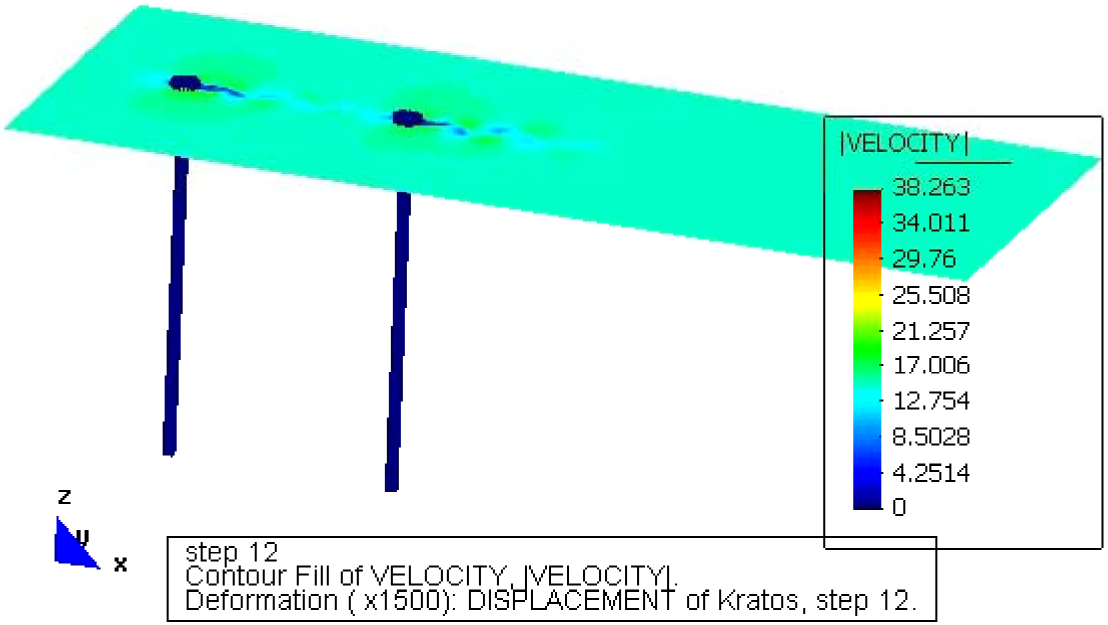


- 2006: construction of new chimney for flue-gas desulphurisation (FGD) system.
- 183m high reinforced concrete chimney (same height as old one).
- Approx. 100m in SSW direction from old chimney



- Problem of wind-structure interaction identified during construction of new chimney.
- Enhanced vortex shedding from new chimney caused excessive vibration of old chimney (in SSW winds).
- Structural capacity can be exceeded for 1% damping!
- Consultant recommended response monitoring





FSI animation by Dr Antolin Lorenzana (CFD + structure interaction)

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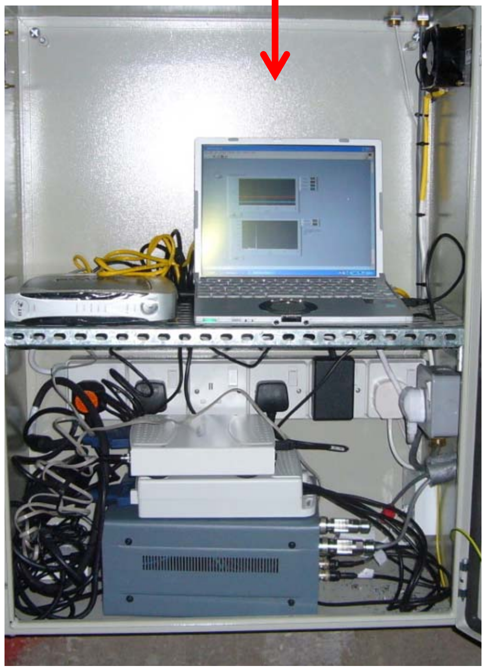
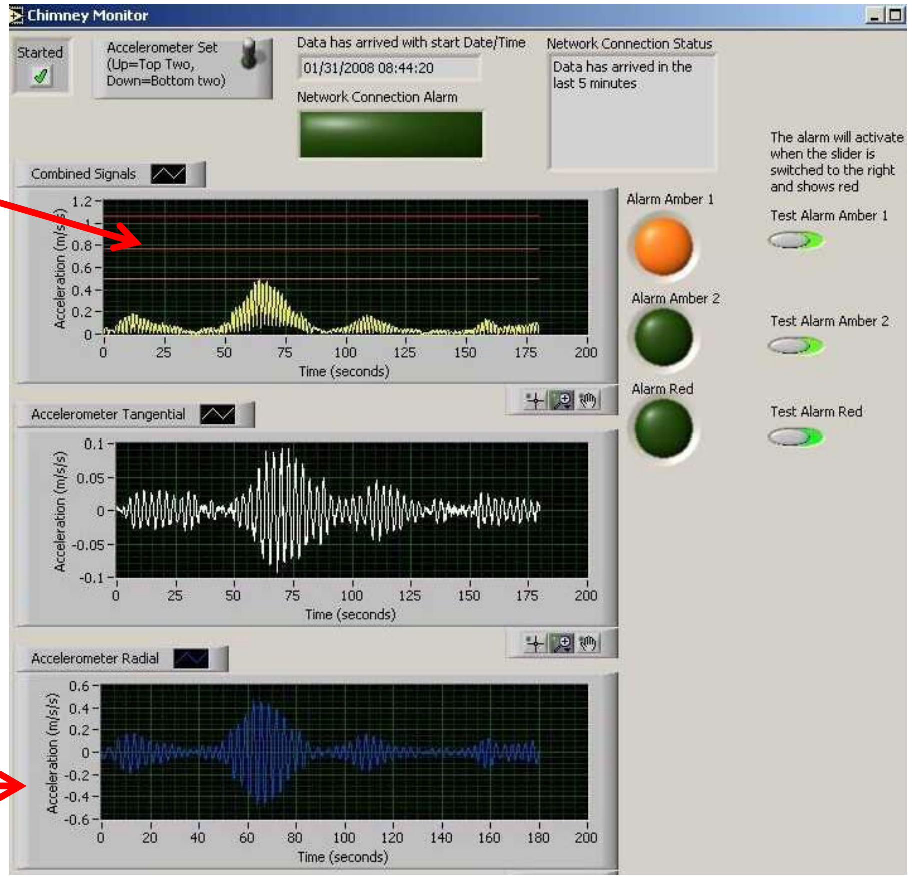
Live performance monitoring:

4-channel monitoring system online from March 2007 -designed to give alarm for high response and provide response data

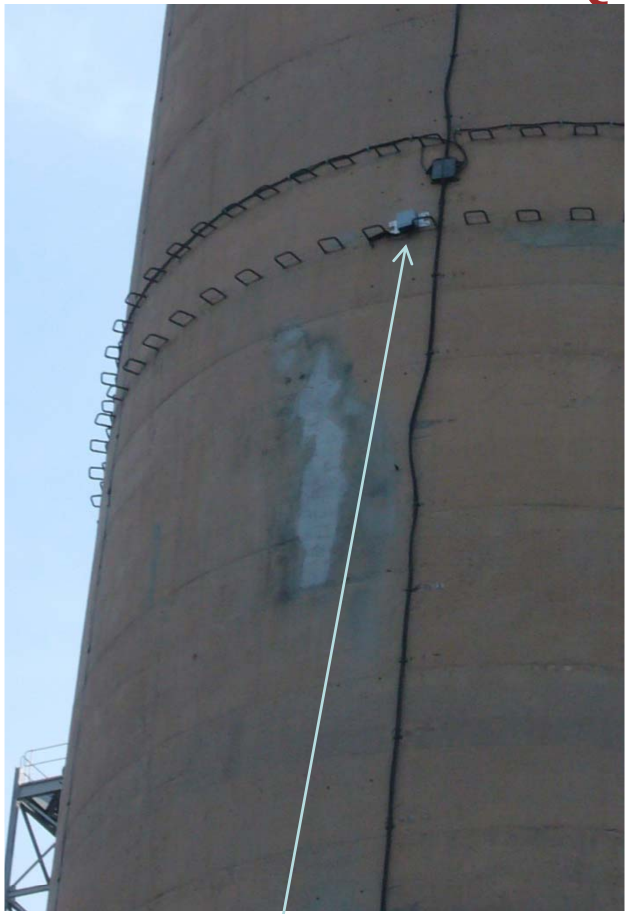


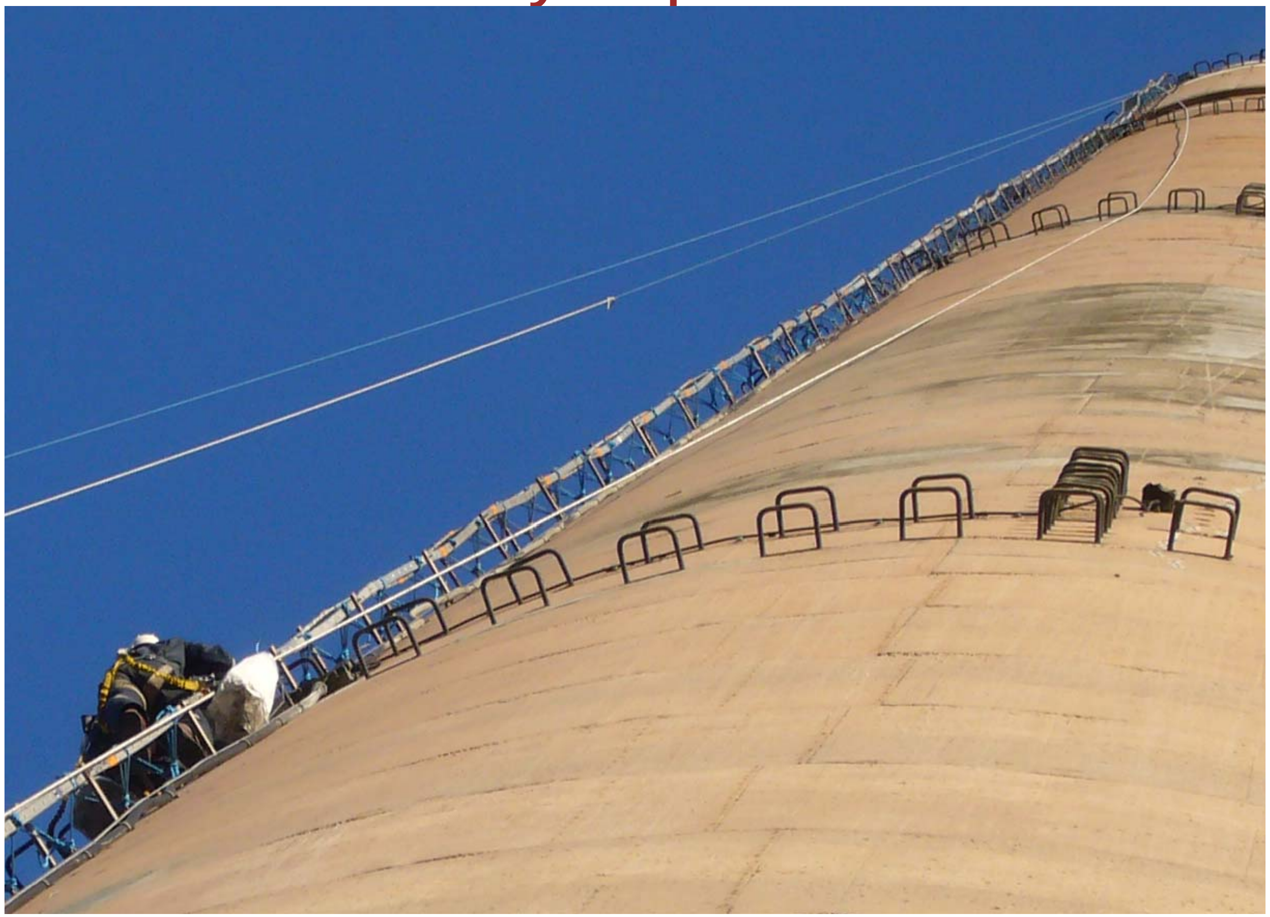
High alert level

Panasonic Toughbook+
NI USB-6251 or
NI USB-9239



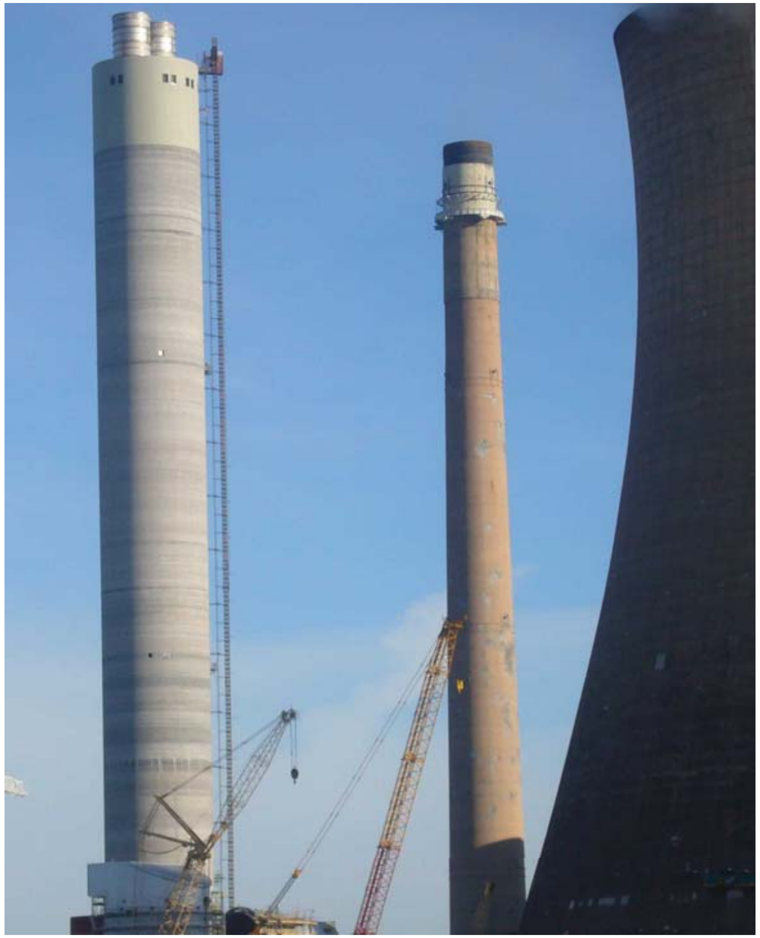
NO existing access for accelerometer installation: Hence QA750s installed by experts ….





40m box is cherry-picker accessible backup

…followed quickly by installation of tuned mass damper (TMD, by Multitech), from March 2007



Tuned mass damper:

42 tonne mass
(~3% mass ratio)
180kNs/m damping
450mm travel

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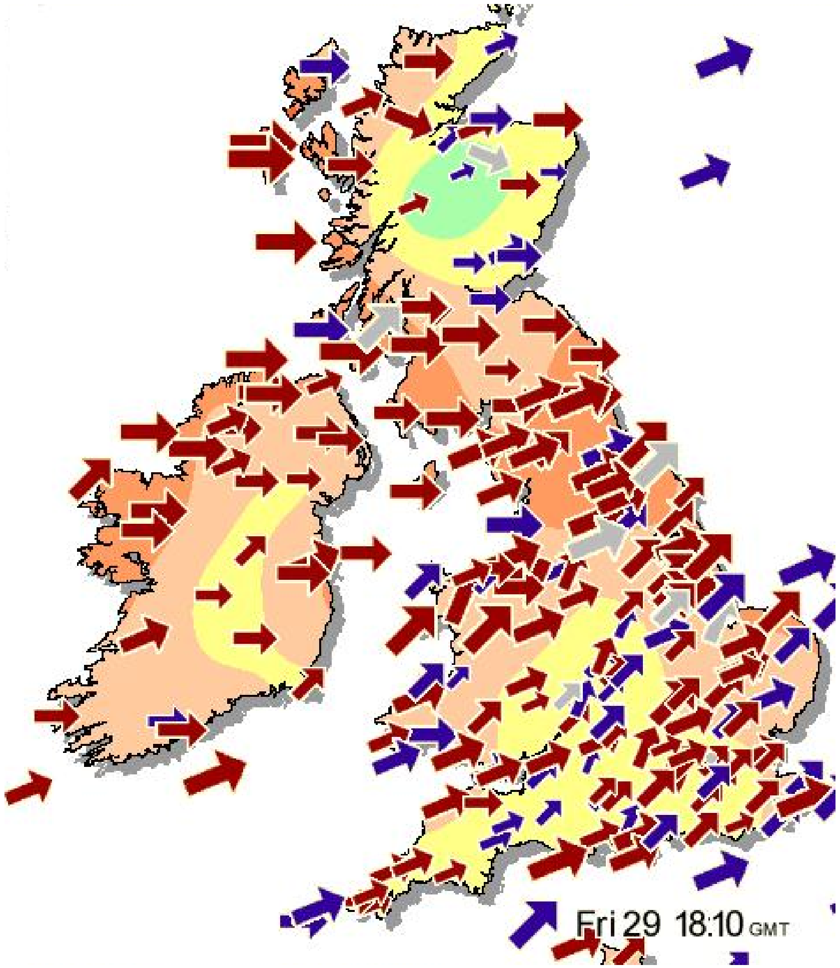
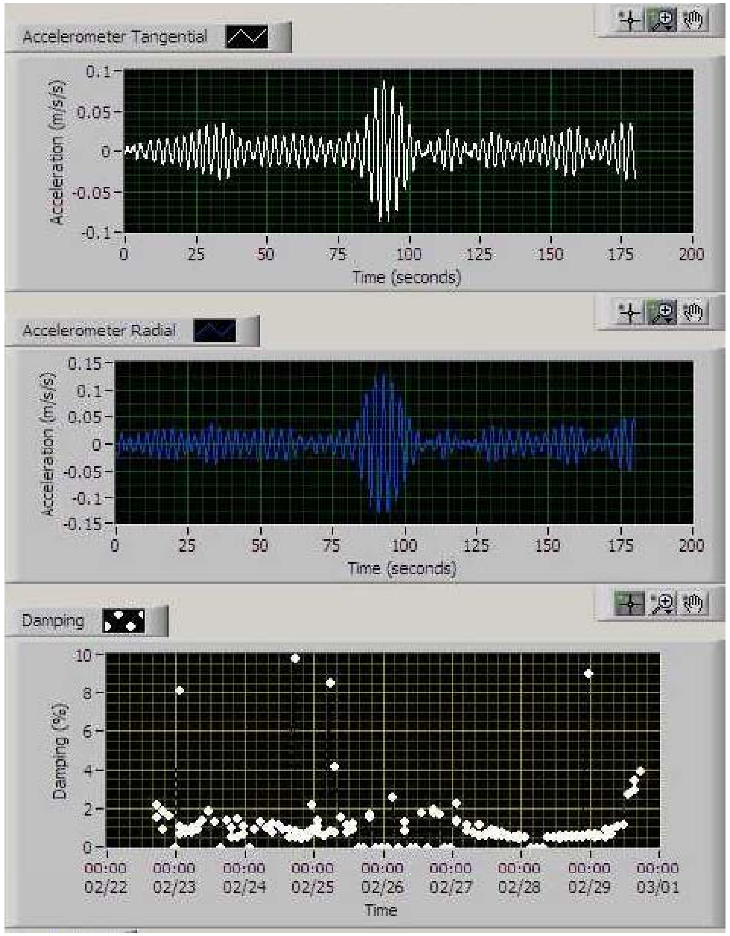
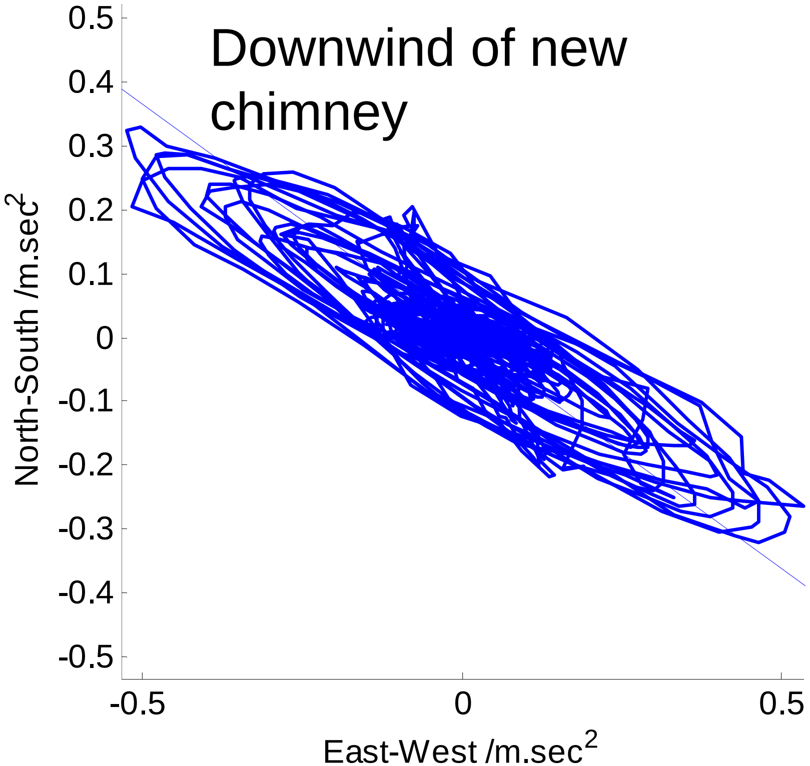
Real time frequency and damping estimation shows max performance of TMD around 4% (29 February 2008)





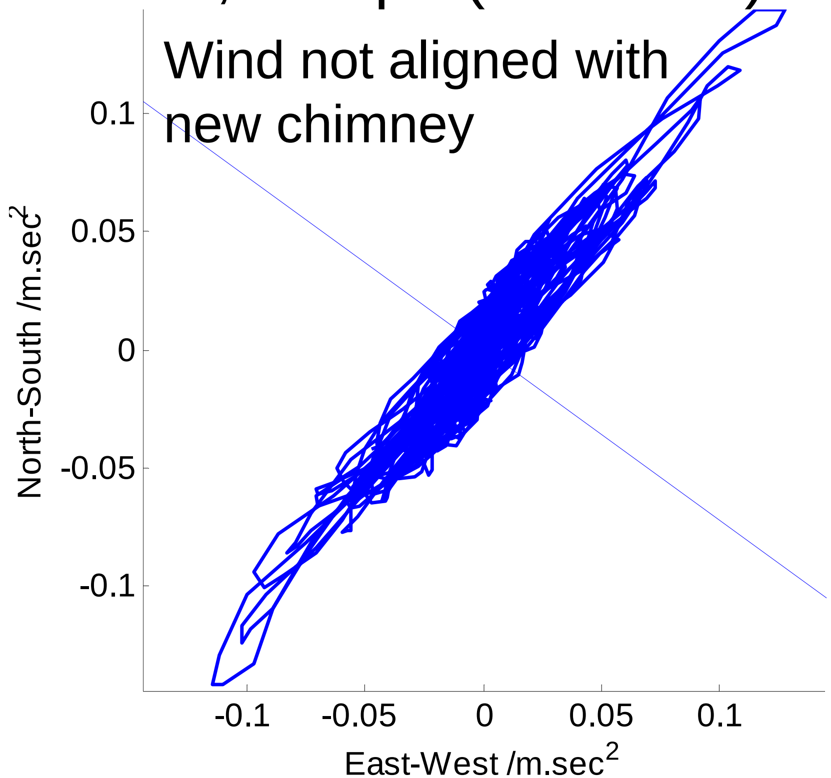
Crosswind response shows clear evidence of enhanced vortex shedding

SSW, 39 mph (17.4m/sec)

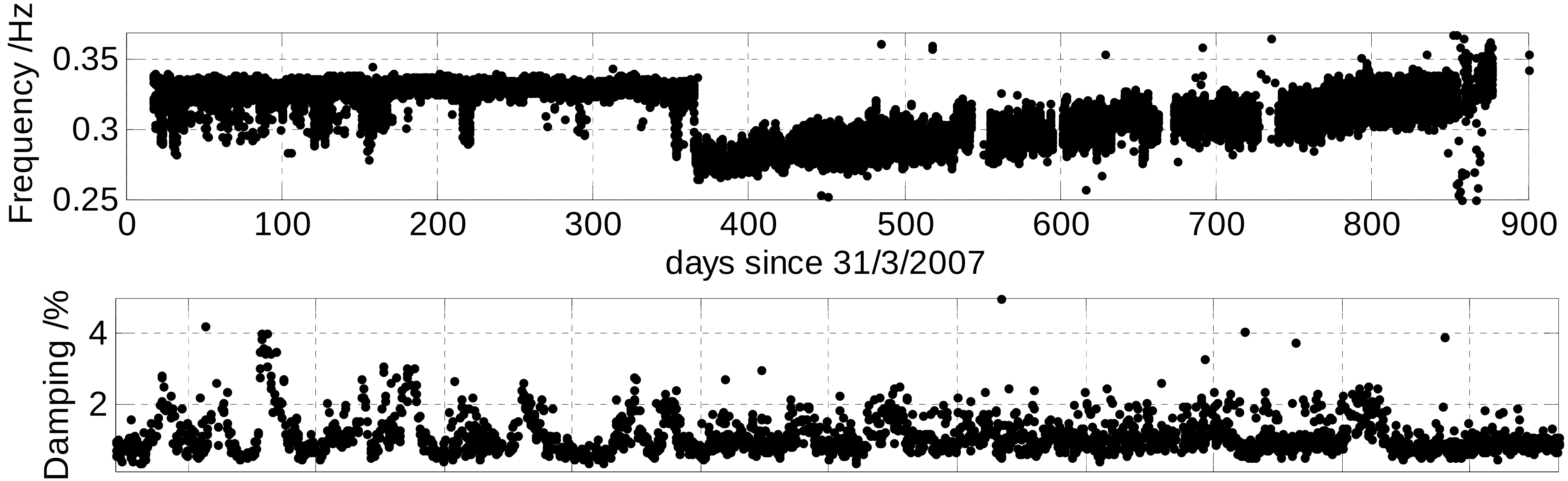


North

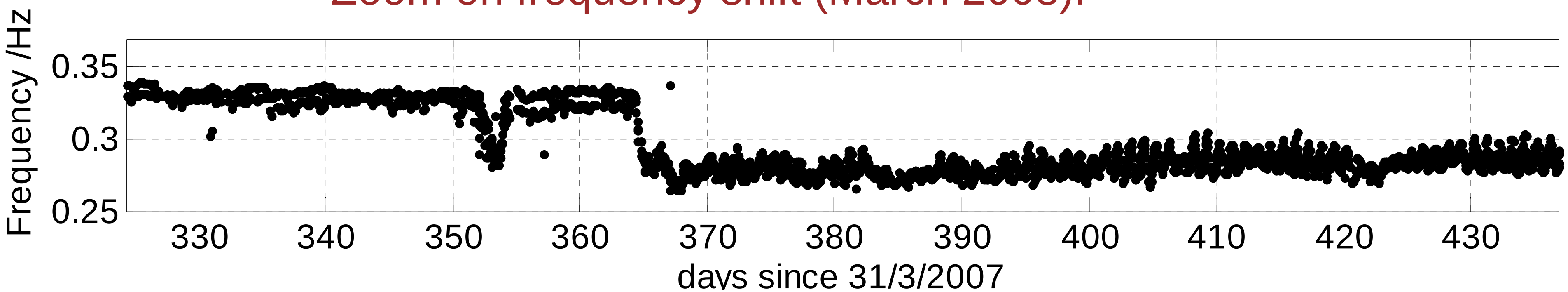
WNW, 22mph (9.8m/sec)



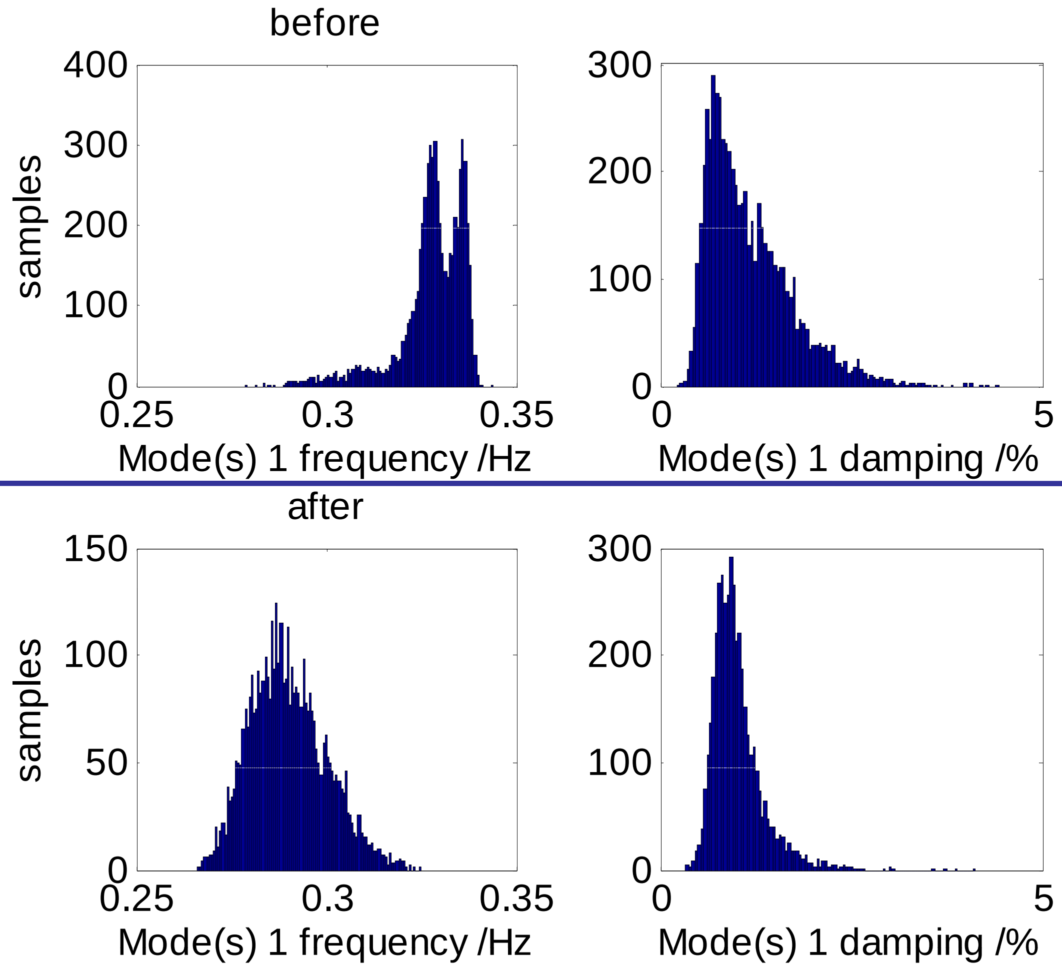
This is bizarre: modal parameter variation over time



Zoom on frequency shift (March 2008):



Changes in frequency & damping distribution:



Mode of damping distribution has increased, extreme values reduced

Mode pairing blurred

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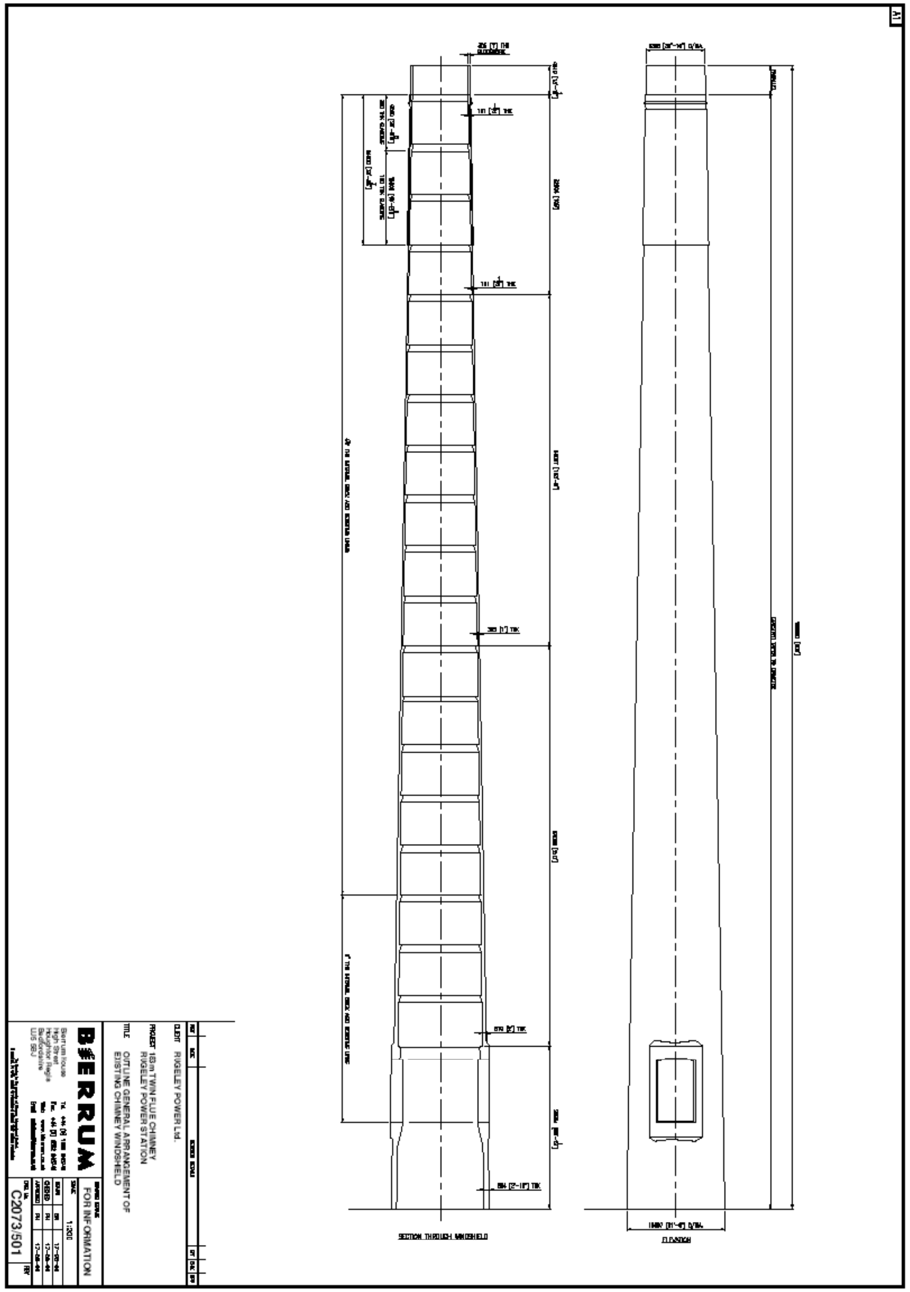
The mechanism is a mystery but constructions joints are believed to play a part.

The mode shape is also changed: $\phi_{40m}=0.07\rightarrow 0.06$



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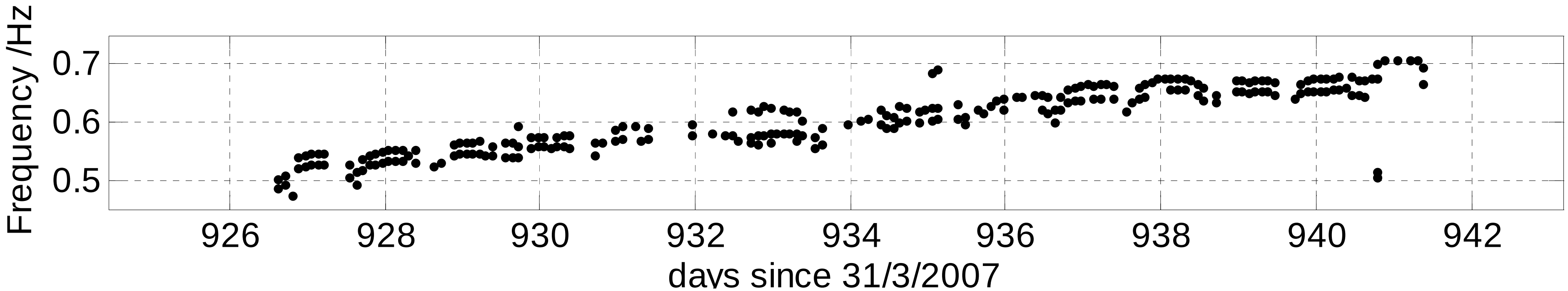
Chimney has now been demolished



Result of SHM study on Rugeley Chimney

- This is a very rare example where pure vibration-based monitoring and frequency changes have had direct value for structural assessment
- Safe-range performance of the chimney was proven at all times during tandem operation
- TMD effectiveness was demonstrated in real time
- Bizarre form ‘structural mechanism’ observed due to gross temperature changes
- Damping, frequency and response level evaluation are critical for super-tall buildings (e.g. Burj Kahlifa)
- Real-time evaluation is crucial for effective SHM; results are needed soon enough to make informed decision on operation and intervention

Other structures -in UK- include:

City of Manchester stadium
(vibration monitoring
for serviceability assessment
during rock concerts)

Sheffield University Arts Tower
(vibration monitoring for
serviceability during retrofit)

Humber Bridge
(static and dynamic response monitoring
to study aero-elastic & thermal effects)

Acknowledgements:

•EPSRC (support for Tamar Bridge SHM project)

•Keith Worden, Elizabeth Cross, collaborators in EPSRC project

•Bierrum (allowing publication of Rugeley Chimney study)

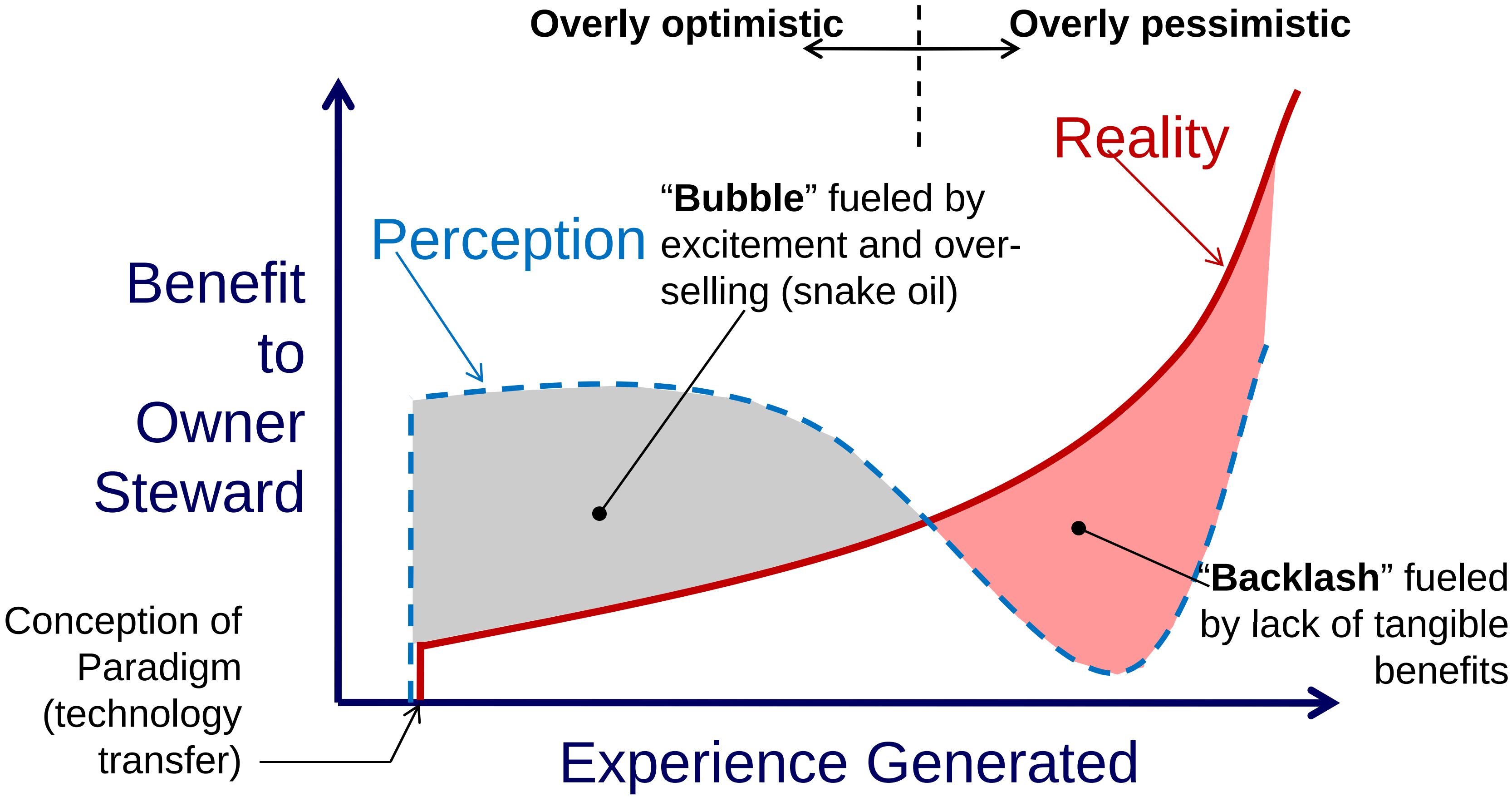
•Peter Carden, Rob Westgate and others for crucial help in both projects

•David List and Richard Cole of Tamar Bridge and Torpoint Ferry Committee

•Antolin Lorenzana for Chimney response simulation

The University Of Sheffield.
Department of Civil and Structural Engineering
VIBRATION ENGINEERING SECTION

A final thought: The snake-oil* effect in civil SHM
*quack medicine



By courtesy of Dr Franklin Moon, Drexel University, Philadelphia, PA