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Measuring the Monument

The Rt. Hon. Professor Michael Mainelli

Lord Mayor of London

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The Monument - construction

The Monument was built, between **1671 and 1677**, to **celebrate** London's **rebuilding and recovery** after the **Great Fire of London** of September **1666**.

But **Christopher Wren** and **Robert Hooke** had a **second purpose** in mind.

The two **Royal Society Fellows** decided to make it **a site for scientific experiments**.

The Monument, 1750

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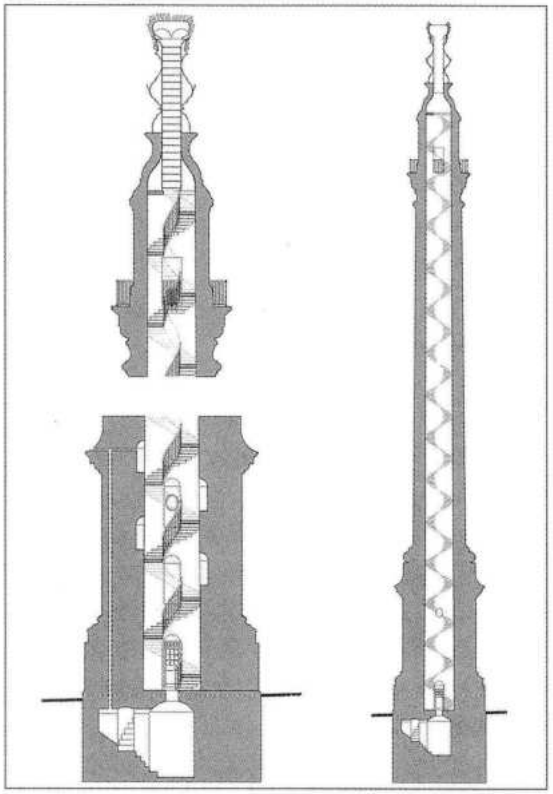
The Monument as a giant telescope



"Vertical sections through the Monument revealing its intended use as a **zenith telescope**. When the two hinged semi-circular iron doors at the top were opened, an **observer** in the **underground observation chamber** at the base of the column could measure with a **micrometer eyepiece** the changes in position of an overhead star throughout the year."

Lisa Jardine

Figure 27 of 'A more beautiful City': Robert Hooke and the rebuilding of London after the Great Fire, Michael Cooper, Sutton Publishing, Stroud, Gloucestershire, 2003.

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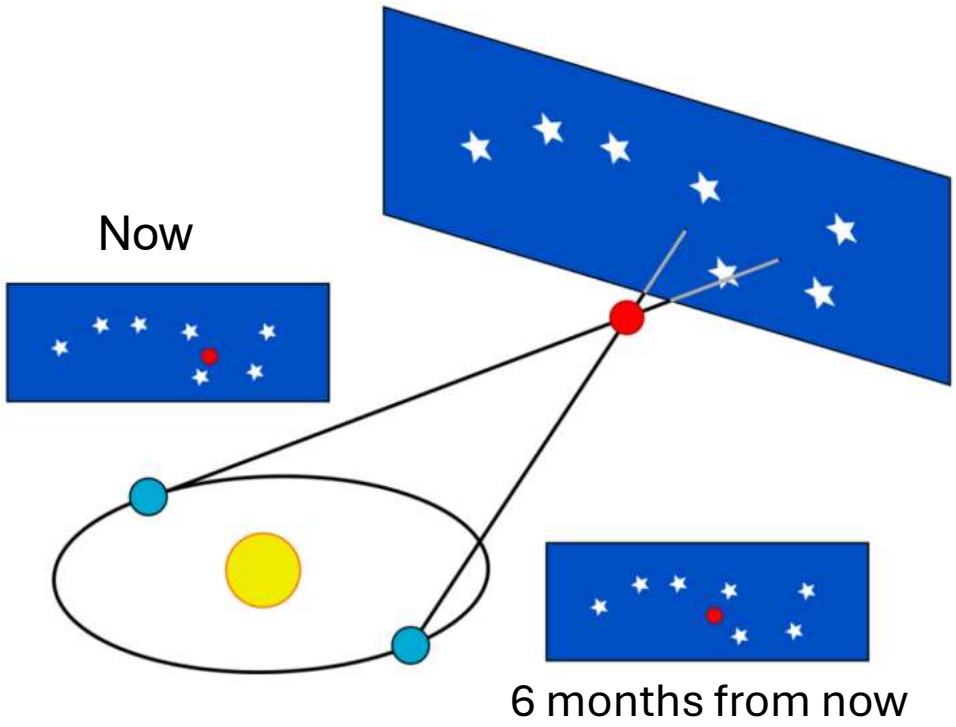
Stellar Parallax

The **principle of stellar parallax:**

An imagined near star, ●, pictured against the background of *The Plough,* observed from the earth now **and in 6 month's time**.

For us on earth, the near star, ●, will seem to have moved.



By KES47 / Original version from German Wikipedia. By user: WikiStefan. 28 Oct 2004 - Own work based on: ParallaxeV2.png:, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=40217603

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Bad Vibrations

Hooke failed to measure parallax as he had hoped.

He chose Gamma Draconis as his overhead star, but Gamma Draconis, while very bright, is also very far away: **900 million million miles** away. Hooke was trying to measure a **very small difference in position**.

James Hodgson, Christopher Wren's nephew, said **vibrations from traffic on Fish Street** prevented Hooke being able to discriminate the small positional change. The BBC and Wikipedia repeat the claim.

Questions: How big were the vibrations?

How big are they now?

Was road traffic the root cause?

Can modern technology solve a 350-year-old mystery?

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Robert Hooke: Britain's neglected genius

Professor Philip Thomas

Past Master, The Worshipful Company of Scientific Instrument Makers

Chairman, Measuring the Monument Steering Group

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Newton or Hooke: whose first law of motion?

Newton's first law of motion (**1687**):

"A body will remain at rest or in uniform motion in a straight line unless acted upon by a force."

(modern translation from Latin).

Hooke's first law of motion (**1674**):

"All bodies that are put in a direct and simple motion, will so continue to move forward in a streight line, till they are by some other effectual powers deflected and bent."

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Principle of Universal Gravity: apples falling or pennies dropping?

Newton (1675):

"Yet by some secret principle of unsociableness they [the planets] keep asunder, & some that are Sociable may become unsociable by adding a third thing to one of them, as water to Spirit of Wine by dissolving Salt of Tartar in it"

Hooke (1674):

"all Coelestial Bodies whatsoever, have an attraction or gravitating power towards their own Centers, whereby they attract not only their own parts, and keep them from flying from them, as we may observe the Earth to do, but that they do also attract all the other Coelestial Bodies that are within the sphere of their activity"

Hooke (1680) :

"the Attraction always is in a duplication proportion to the Distance from the Center Reciprocal"

Newton (**1687**): *Philosophiæ Naturalis Principia Mathematica*

Newton (**1726**): He tells the falling apples story, supposedly set in Lincolnshire in 1666.

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Who was the genius?

Hooke (1664): White light is made up of a multitude of colours, *Micrographia*.

Newton (1684): ditto.

Boyle's Law for gases **(1662)**, or the **Hooke-Boyle-Towneley Law**?

Hooke's field of scientific exploration and discovery was vast.

Robert Hooke, **Christopher Wren**, **Edmond Halley** and **Isaac Newton collaborated** (and **competed**) under the auspices of the newly formed Royal Society.

They were all brilliant men. Which, if any, was the genius?

How do we define genius?

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Why the interest in space?

- **Challenge**: stars could be seen from every country, but still presented a mystery.
- **Science**: stars were free from human interference, which meant that objective observations could be made.
- **Commercial motive**: stars were vital for maritime navigation and understanding them better would mean less risky and and more profitable trade.
- **The Monument as a giant telescope**: Hooke was motivated by all the above. He saw **validating the basic science**, showing that **the earth orbited the sun rather than vice-versa**, as an **essential part** of the process : ***Nullius in verba*.**

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Non-contact measurement systems – Digital Image Correlation (DIC) and pattern recognition algorithms

Elisabeth Jarvis

Imetrum Ltd

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Imetrum – a UK SME

- Imetrum is a globally recognised leader in the field of non-contact measurement systems, based on patented Digital Image Correlation (DIC) and pattern recognition algorithms
- Imetrum can measure sub-micron movements in structures at a distance without the need for any marking on a structure
- Usually we measure material samples, but we can also measure Monuments

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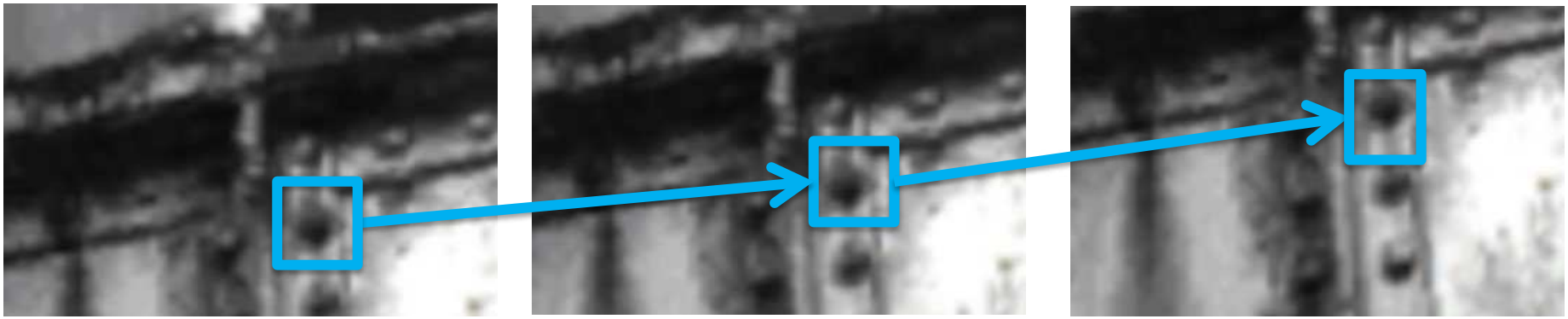
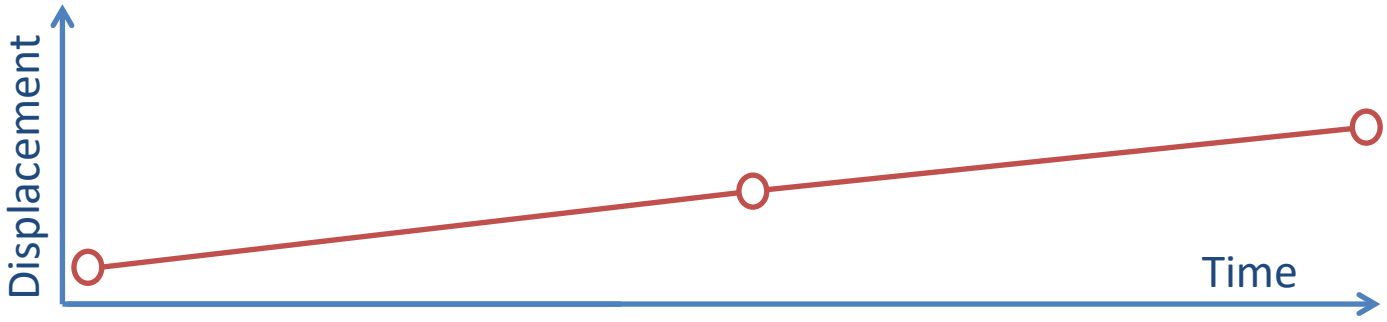
How does it work?





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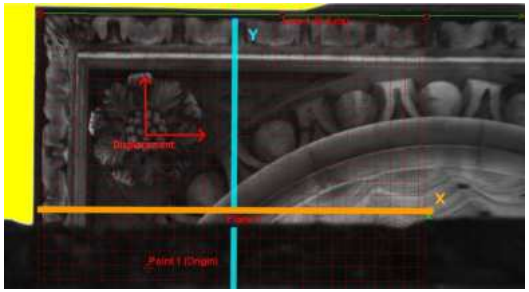
The set-up at the Monument



- Measured up to 100m away from the Tower
- At the base of the Tower
- From inside the Tower
- Measured for intervals of around 15 minutes

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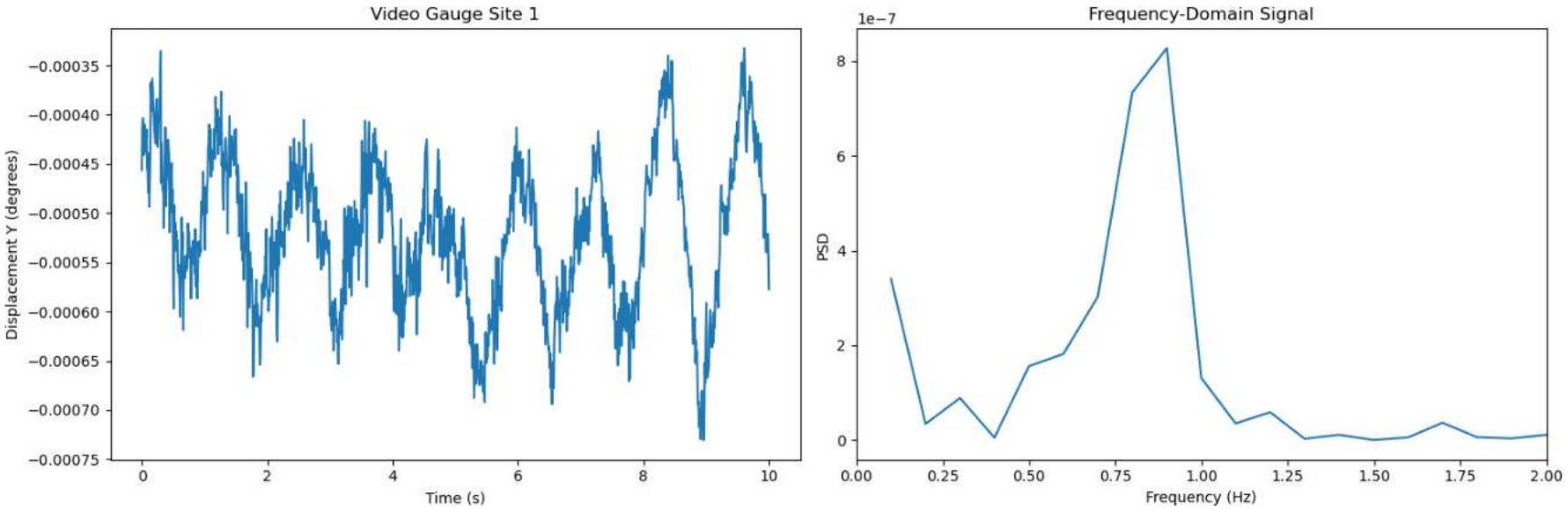
Results of the measurements



- Detected tilt in the tower of 0.0002 degrees (sub arc seconds) – with a frequency peak at ~0.85 Hz

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Imetrum's measurements - conclusions

- We have validated that there is an underlying movement of the Monument – this is a common characteristic of stone buildings
- This movement would have created noise to interfere with Hooke's plans to measure parallax
- Measurements made without touching the Tower or putting any marks on it – and approach which is ideal for a heritage building

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Fibre optic sensor-based measurements solve Robert Hooke's problem

Professor Kenneth TV Grattan OBE FREng

City St George's, University of London *and*

City Optotech Ltd

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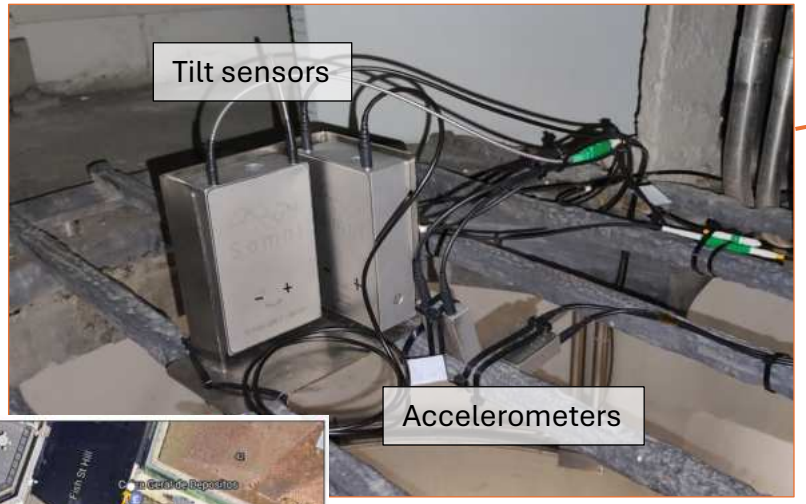
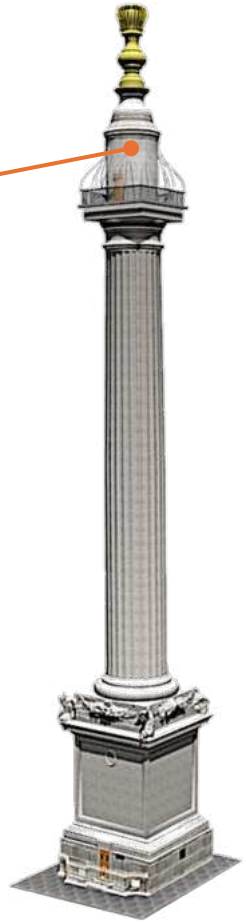
Fibre optic sensor data solve Robert Hooke's problem

- Fibre optic-based sensors developed and installed to measure the tilt and acceleration on the Monument
- Optical sensors - non-electrical, accurate and safe



Sensors fixed to the reinforcing bars at the top of the Monument and aligned with likely strongest wind direction – no damage to the historic walls done



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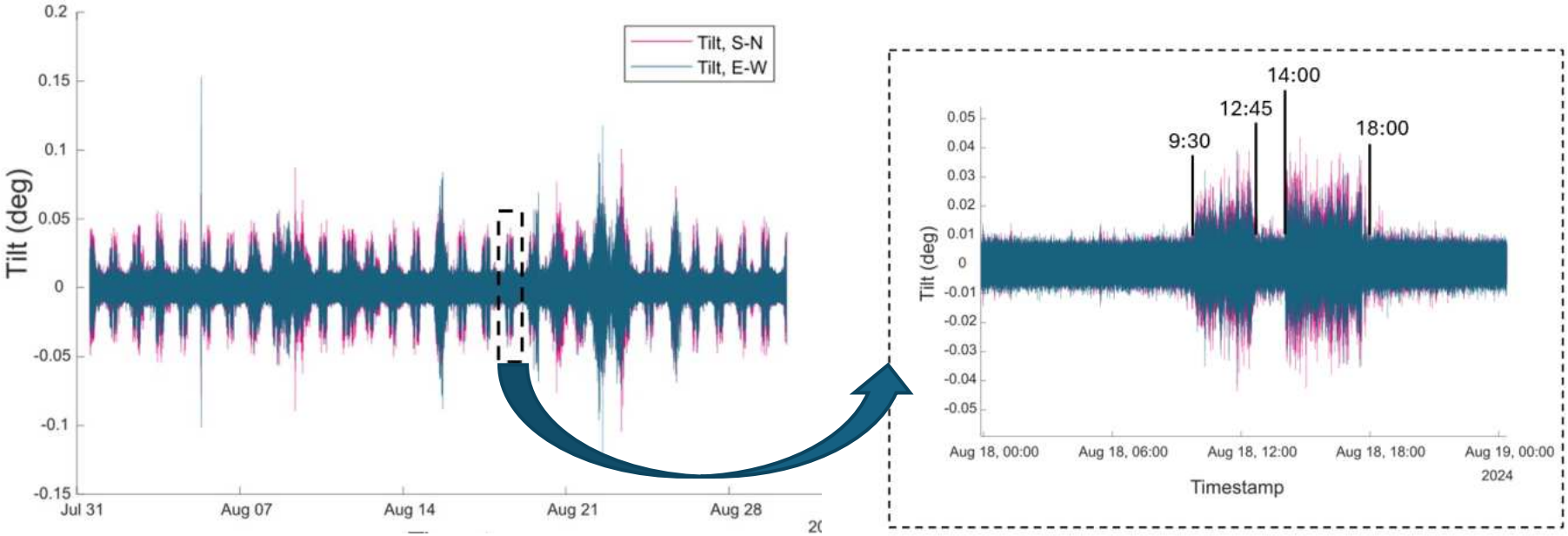
Monument tilt data captured during August

- Sensor data show that the Monument is tilting during the day
- Tilt angle vs time monitored using both tilt sensors
- Consistent pattern of effect due to the opening/closing times of The Monument



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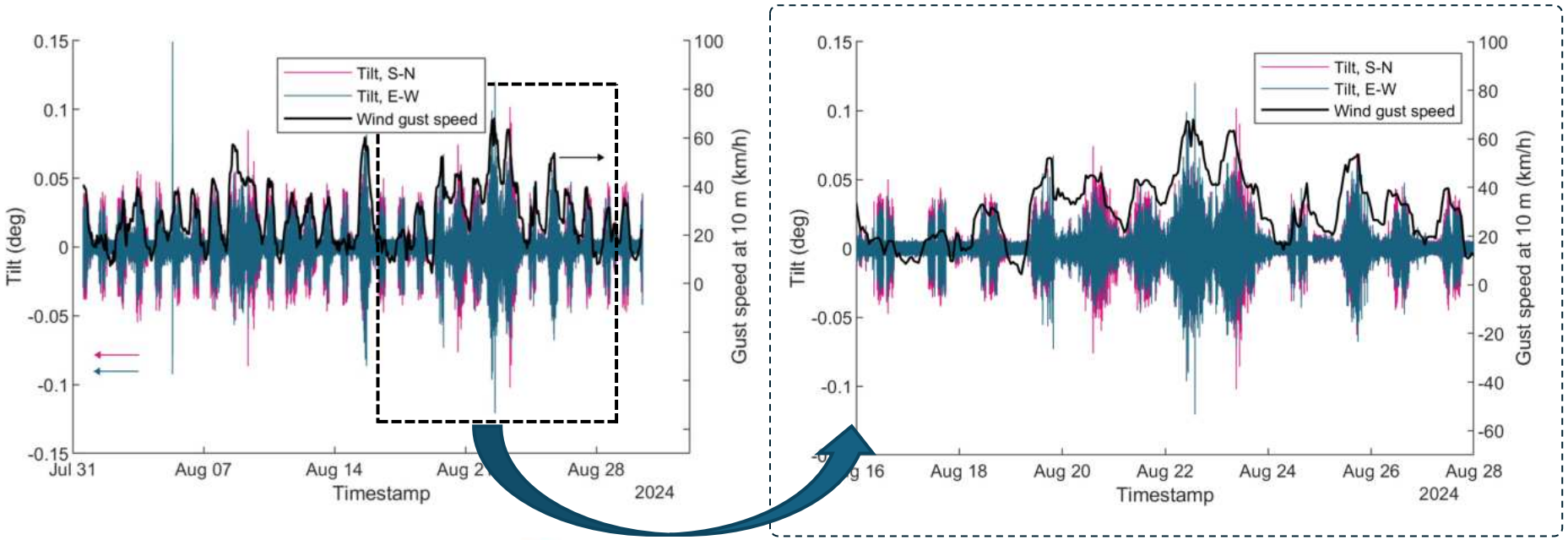
Correlation with meteorological data on wind speed

- Tilt angle and wind gust speed vs time monitored by fibre optic sensors
- Strong correlation seen between wind and sensor data
- On ‘windy’ days the regular pattern caused by visitors is overshadowed suggesting that strong winds outweigh any other cause of vibration



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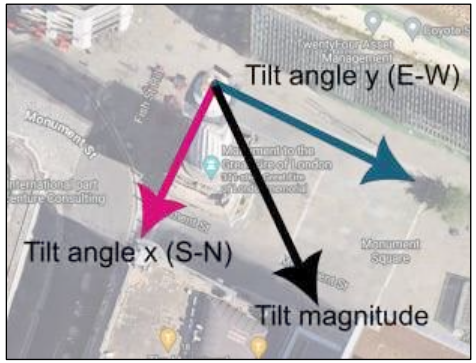
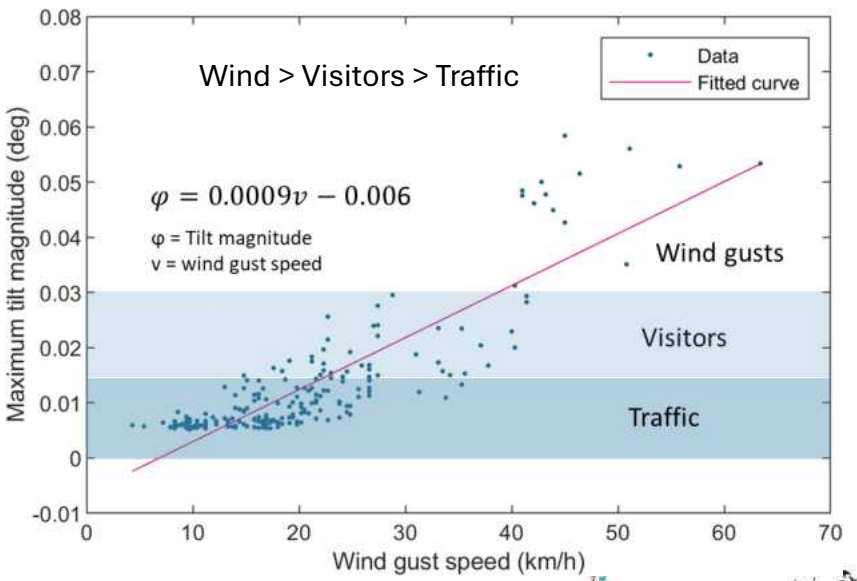
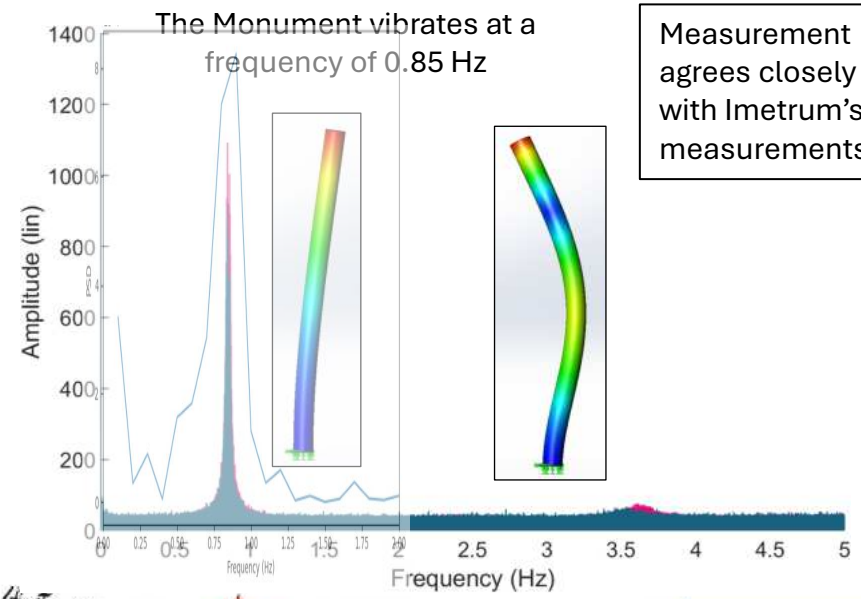
Wind gusts case major tilt

- Wind gusts cause the most significant tilt effect
- Tilt of the Monument is most affected by the wind – with wind gusts up to ~15 km/h having the same effect as traffic, and over ~35 km/h exceeding the effect of visitors







Measurement agrees closely with Imetrum's measurements

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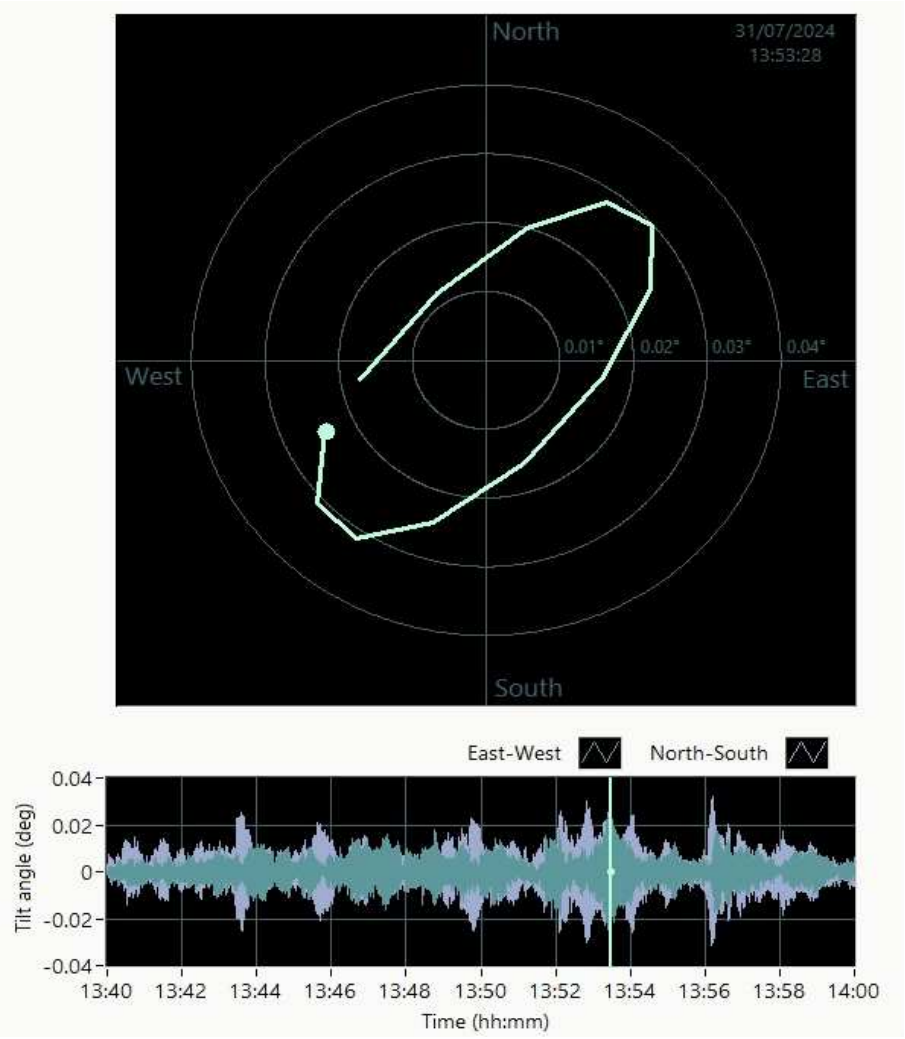
2D Motion visualization



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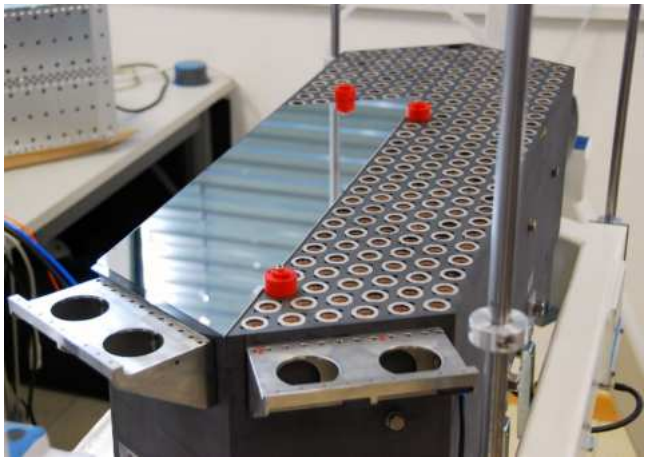
Solving Robert Hooke's problem with today's technology?

- **The fibre optic sensors used can provide real time data on the vibration of the Monument**
- Hooke's telescope used the best long focal length lenses available at the time – an attempt to make longer focal lengths a practical proposition
- **Newton's approach – from 1668 – was to use *reflecting telescope*, using mirrors rather than lenses.**
- **Active Optics** – developed in the 1980s – is a technique which can be used to create a stable mirror for a telescope
- This allows actively shaping a telescope's mirrors to prevent deformation due to external influences - **signals from the fibre optic tilt sensors could be used to computer-control the shape of the mirror to compensate for the vibration detected**
- A stable telescope possible after 350 years?



Active Optics mirrors being developed for the Extremely Large Telescope (ELT) under construction

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$$23'' \simeq \pm 25'' \simeq -20''$$

The Dawn of Gravity

Prof. Enrique Gaztanaga
Institute of Cosmology and Gravitation
University of Portsmouth
Institute of Space Studies, CSIC/IEEC

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An Attempt to Prove the Motion of the Earth from Observations

Robert Hooke (1674 Gresham Lecture)

Hooke presented the following key points:

1. Aesthetic, philosophical, or practical arguments alone cannot determine whether the heliocentric or geocentric model is correct—evidence is required: ***Nullius in Verba* –Take no one's word for it.**
2. A new zenith telescope and a new instrument (the Mesurator) to observe the parallax of Gamma Draconis, a magnitude 2 star passing near London's zenith
3. On October 21, 1669, Hooke achieved the first successful **daytime** observation of a star recording Gamma Draconis at 15:17.
4. Hooke **recorded a 23" (arc seconds) southward** shift in Gamma Draconis from July to October 1669. He **mistakenly** attributed this shift to parallax, but he was correct to identify it as **evidence of Earth's motion**.
5. He explored the forces driving this motion, and his ideas on **gravity and inertia** were important and correct**.**

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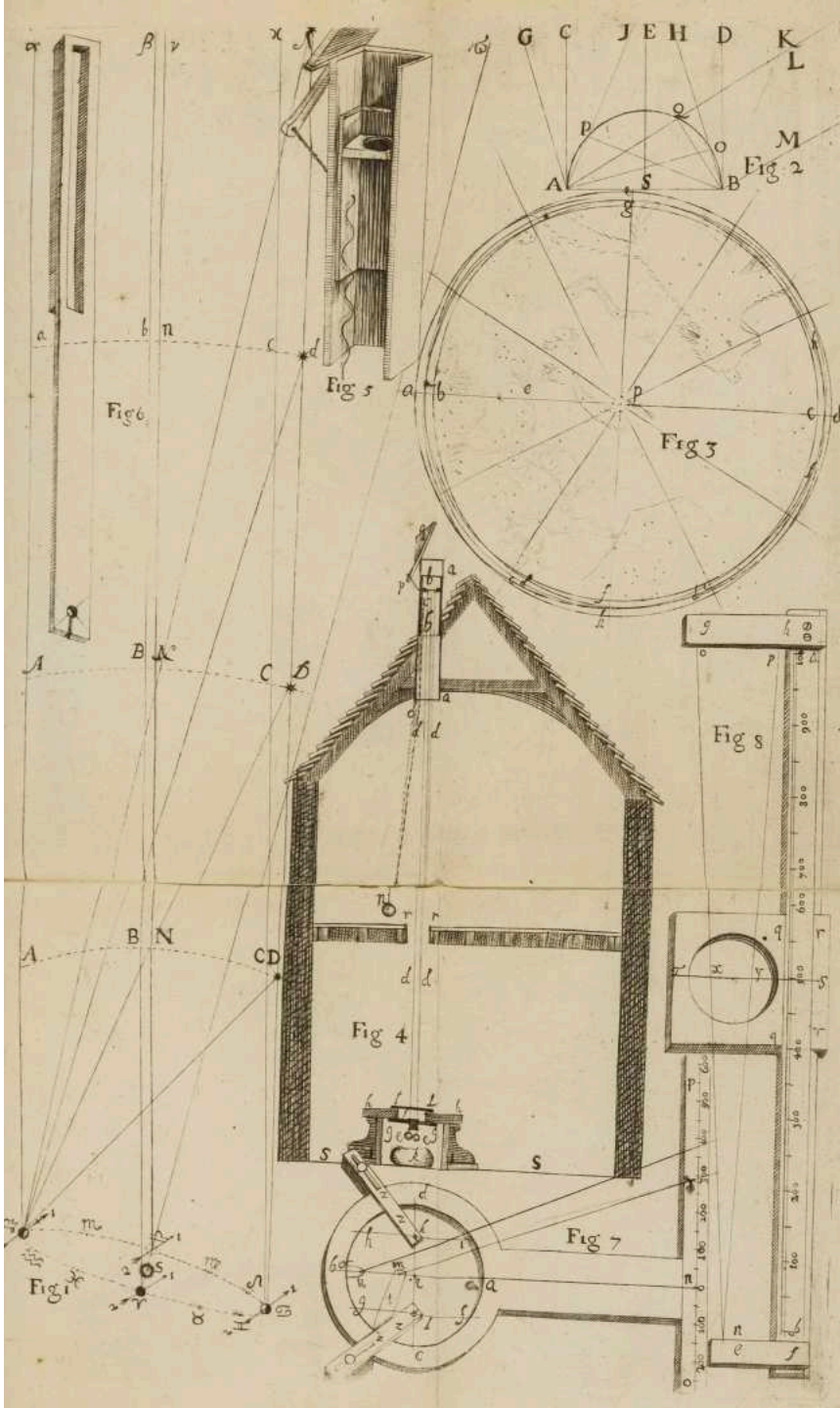

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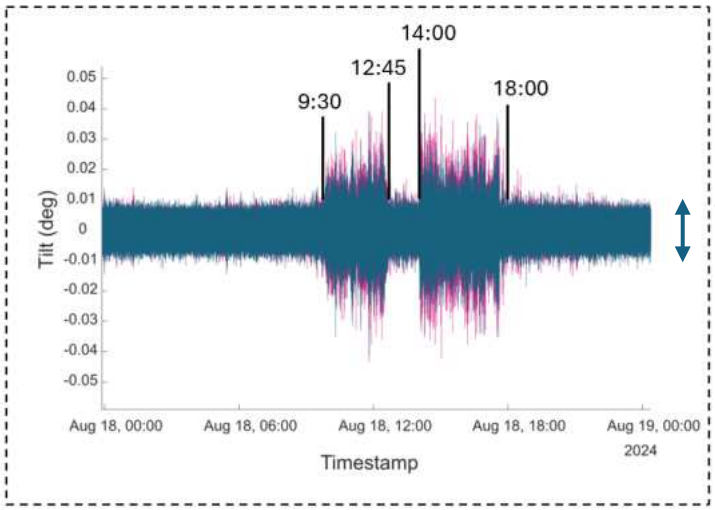
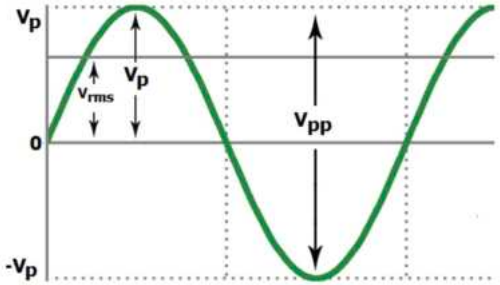
How to correct for the tilt we measured on The Monument?

Knowing what we now know, simple averaging would have helped a lot



72 arcseconds



$$V_{rms} = \frac{1}{\sqrt{2}} * V_p = 0.7071 * V_p$$

- The standard deviation (rms value) is 25 arc seconds.
- If Hooke had known this, he could have been 99 per cent confident of detecting that the Earth was moving through space if he had taken averages of **nine observations** for each data point.

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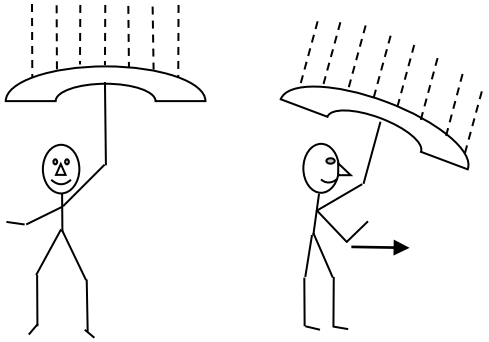
Aberration effects

James Bradley repeated Hooke's experiment in 1725 and found roughly 20 arcseconds of angular shift in the star's position.
Very similar to Hooke's figure but Hooke got his sign wrong – not as unusual as you might think in astronomy!
The shift is caused not by parallax but by **aberration**.

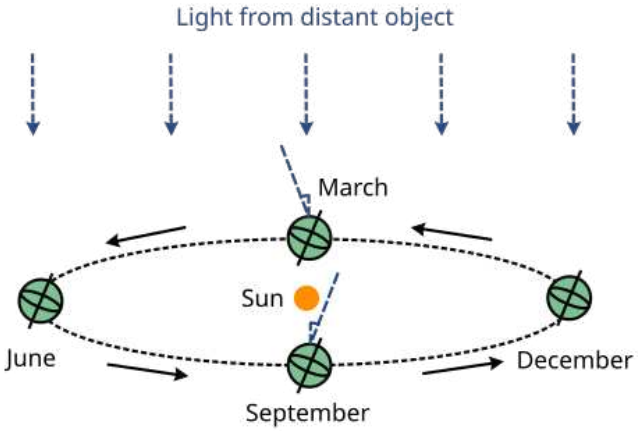
Aberration and rain drops on a still day



Keeping dry when standing

Keeping dry when walking

Aberration in astronomy



We still use aberration today to understand how the Earth is moving.

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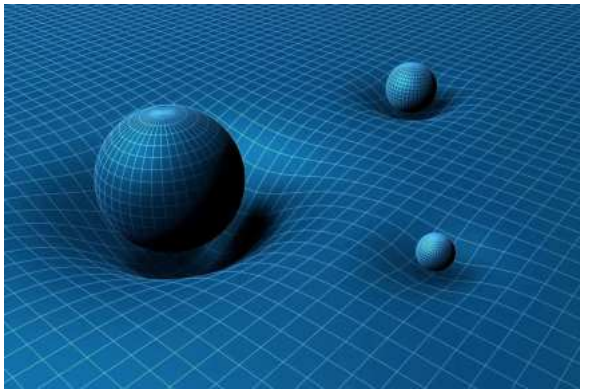
The line connecting Hooke, Bradley and Einstein



Hooke's ideas not only guided **Newton** towards the laws of gravity and **Bradley** towards aberration, but, through Bradley, they also laid the ground for **Einstein**'s understanding of **gravity**.

The finite speed of light (regardless of relative motion) measured by **Bradley** is key to understanding **gravity as geometry**.

On the Electrodynamics of moving bodies, *A. Einstein* (1905).

=> **space-time (3D-1D = 4D)**: $c = \frac{r}{t} \Rightarrow x^2 + y^2 + z^2 - c^2 t^2 = 0$ *Minkowski* (1908)

This idea later (in 1915) led Einstein into 4D Riemann geometry where 3D real space (x,y,z) combines with 1D imaginary time in the 4D complex plane: $x^2 + y^2 + z^2 + (ict)^2 = \text{constant}$

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Scientific Instrument Makers clear up the 350-year old mystery of why Robert Hooke gave up trying to prove the Earth moved round the Sun

- The team, led by Past Master Philip Thomas, found that even a moderate breeze can sway the top of The Monument enough to stop it being used as the giant, astronomical telescope that Hooke intended.
- It was thought, up to now, that traffic caused the vibrations at the top of the column, **but advanced, modern instrumentation has shown that wind, even a light wind, has a much bigger influence.**
- Hooke, genius though he might be, was up against not only man-made interference, but the forces of Nature herself!

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End of Presentation

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