IMEKO International Measurement Confederation
Technical Committee TC10 Testing, Diagnostics & Inspection
Conference on Testing, Diagnostics & Inspection as a comprehensive value chain for Quality & Safety
Berlin, Germany - September 3-4th 2019

LABORATÓRIO NACIONAL DE ENGENHARIA CIVIL

MEASUREMENT UNCERTAINTY ADDED VALUE FOR EXPERIMENTAL RESEARCH AND TESTING IN CIVIL ENGINEERING

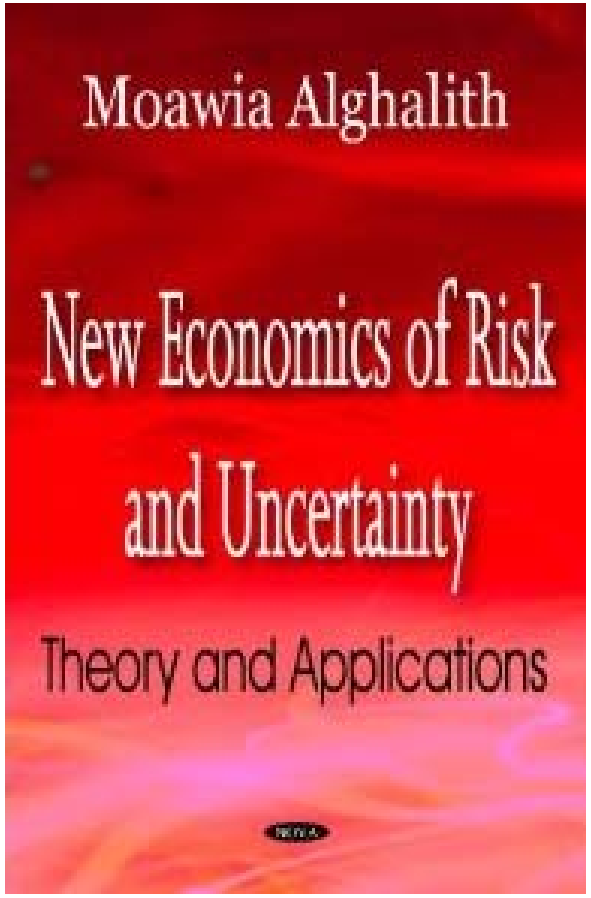
A. S. Ribeiro

National Laboratory for Civil Engineering, Lisbon, Portugal

Overview

- Uncertainty everywhere?
- Historical notes
- Road to the GUM
- New ISO/IEC 17025: 2017
- Providing safety and security to large infrastructures
- 3 examples in Civil Engineering domain
  - Seismic research infrastructure
  - Bridge displacement monitoring
  - Dams long term inspection
- Final remarks

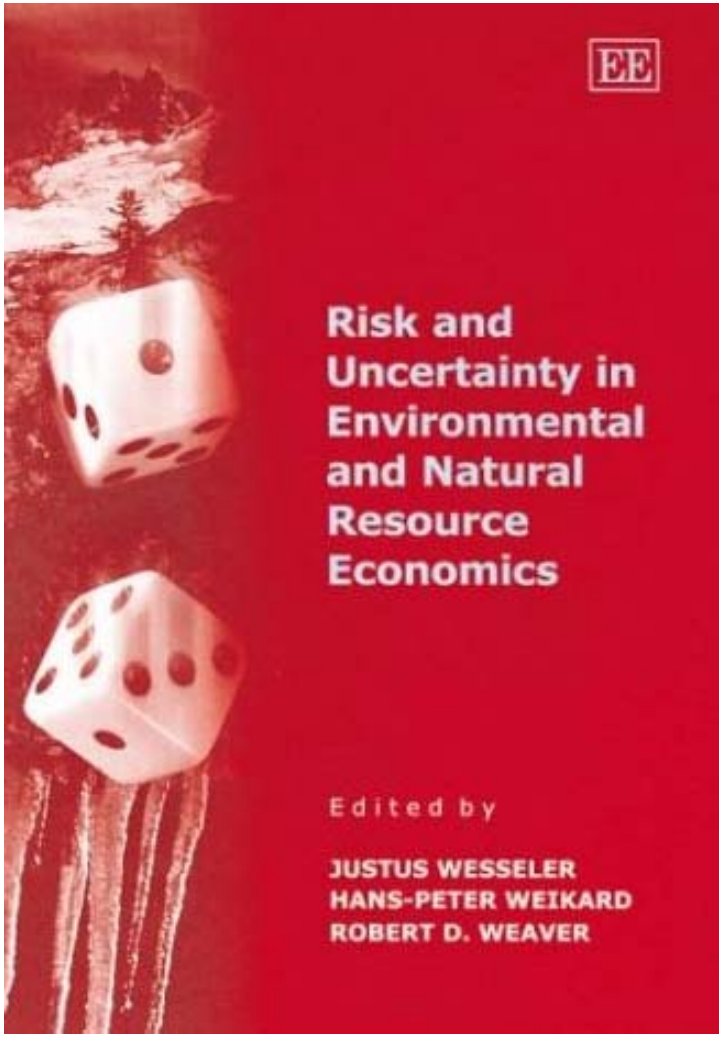
Uncertainty everywhere?



Economy

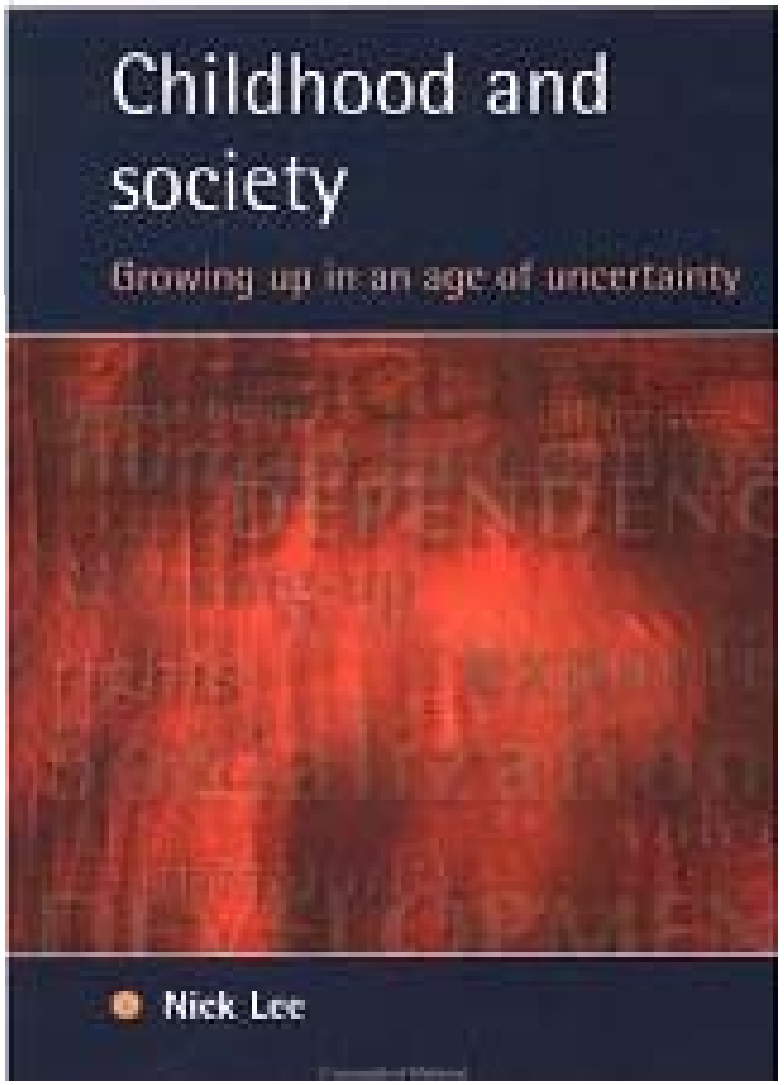
Uncertainty everywhere?

Environment



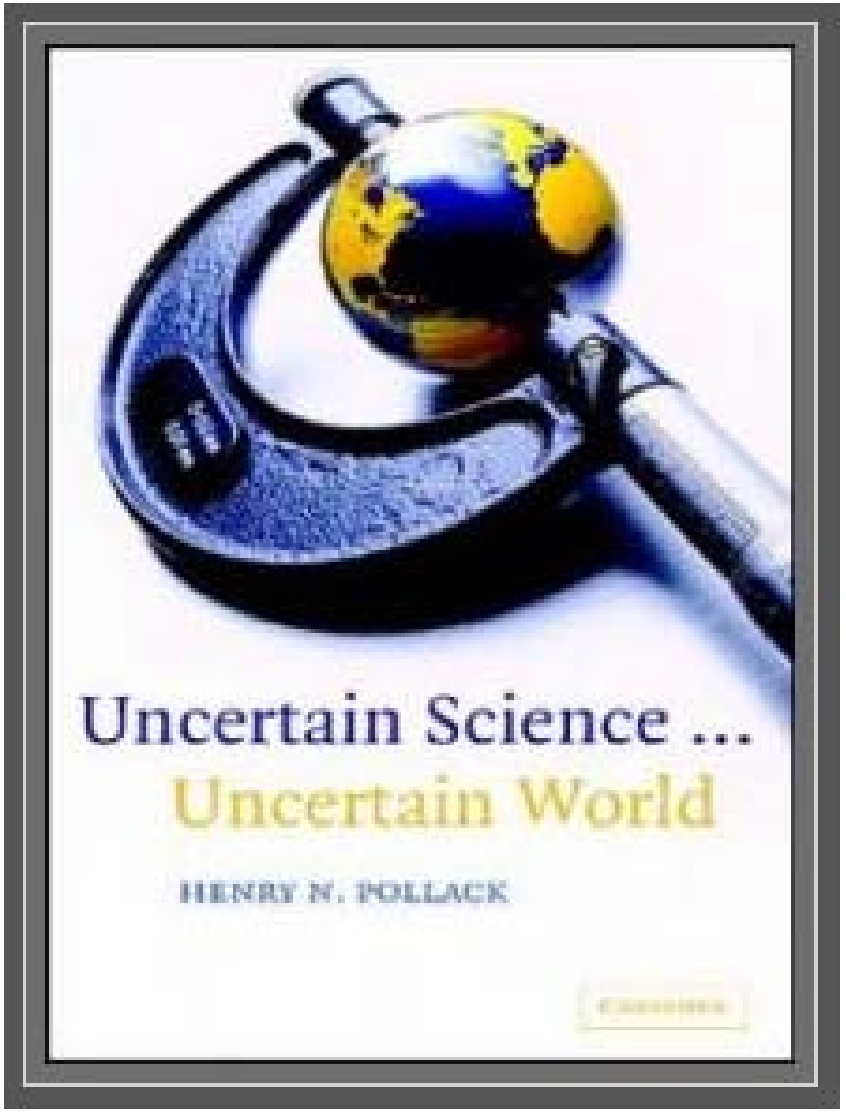
Uncertainty everywhere?

Society & Social Sciences



Uncertainty everywhere?

and also … in Science !



Determinism vs. Stochastic process

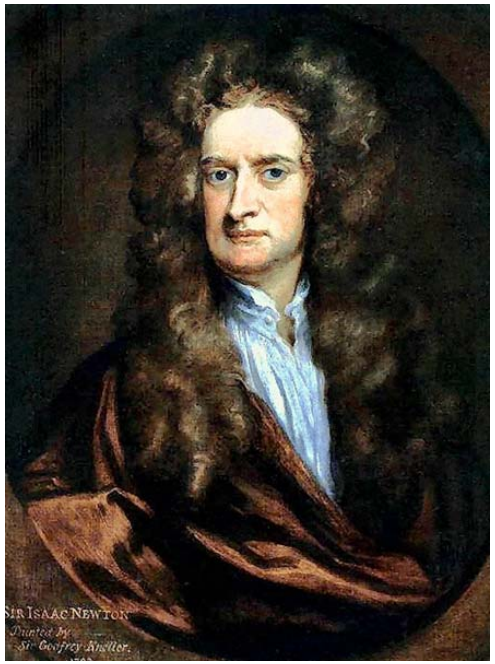
Historical notes

> Determinism: The *world* is *governed by* (or is *under the way of*) determinism if and only if, given a specified *way things are at a time t*, the way things go *thereafter* is *fixed* as a matter of *natural law*.

The roots of the notion of determinism surely lie in a very common philosophical idea: the idea that *everything can, in principle, be explained*, or that *everything that is, has a sufficient reason for being and being as it is, and not otherwise*. In other words, the roots of determinism lie in what Leibniz named the Principle of Sufficient Reason. But since precise physical theories began to be formulated with apparently deterministic character, the notion has become separable from these roots. Philosophers of science are frequently interested in the determinism or indeterminism of various theories, without necessarily starting from a view about Leibniz' Principle.

Stanford Encyclopedia of Philosophy

Historical notes



Sir Isaac Newton
(1643 – 1727)

Classical mechanics & Determinism

three laws of determinism:

The first law of determinism: In the absence of external influences, the separate natural formation retains its condition or continues motion, function, behaviour, development under the influence of its own internal determination.

The second law of determinism: the more strongly (of higher power) its own internal determining origin is expressed (developed), the greater the external effort that must be applied to its movement (life, behaviour, development) to induce change.

The third law of determinism: any external influence on a separate natural formation causes a corresponding reaction, as long as it keeps its structural and functional integrity. Clearly, this action is organized, carried out and directed by its own internal determination.

Historical notes

Maxwell electromagnetic theory – new approach

In 1873, James C. Maxwell develop the fundamental equations of the electromagnetic theory considering both microscopic and macroscopic frameworks divergent from Newtonian mechanics

James Clerk Maxwell
(1831 – 1879)

Table of 'microscopic' equations

Formulation in terms of *total* charge and current[note 2]

Name	Differential form	Integral form
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$	$\oiint_{\partial V} \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \frac{Q(V)}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\oiint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0\mathbf{J} + \mu_0\varepsilon_0\frac{\partial \mathbf{E}}{\partial t}$	$\oint_{\partial S} \mathbf{B} \cdot \mathrm{d}\mathbf{l} = \mu_0 I_S + \mu_0\varepsilon_0\frac{\partial \Phi_{E,S}}{\partial t}$

Table of 'macroscopic' equations

Formulation in terms of *free* charge and current

Name	Differential form	Integral form
Gauss's law	$\nabla \cdot \mathbf{D} = \rho_f$	$\oiint_{\partial V} \mathbf{D} \cdot \mathrm{d}\mathbf{A} = Q_f(V)$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\oiint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t}$	$\oint \mathbf{H} \cdot \mathrm{d}\mathbf{l} = I_{f,S} + \frac{\partial \Phi_{D,S}}{\partial t}$

Historical notes

Statistical Mechanics

• 1850, Rudolph Clausius (measurement of Entropy in an isolated system, at thermodynamic equilibrium)

•1870, Ludwig Boltzmann (statistical definition of Entropy related with the statistical behaviour of microscopic components of a system).

Historical notes

Statistical Mechanics

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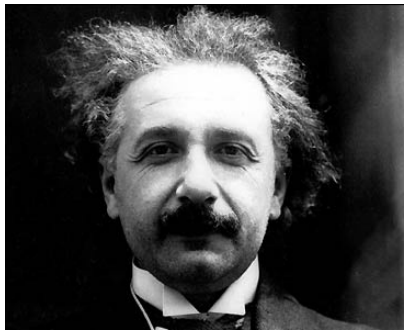
Concept of Entropy: $$S = -k_{\mathrm{B}} \sum_{i} P_i \ln P_i$$

Being the Boltzmann Constant k_B=1,38065×10^{-23} JK^{-1}

Historical notes

Causal Determinism vs. Quantum Mechanics



A. Einstein.

Causal determinism is "the idea that every event is necessitated by antecedent events and conditions together with the laws of nature".

W. Heisenberg, N. Bohr & Others

Heisenberg uncertainty principle or **indeterminacy principle** **(1927):** the position and the velocity of an object cannot both be measured exactly, at the same time, even in theory. The very concepts of exact position and exact velocity together, in fact, have no meaning in nature.

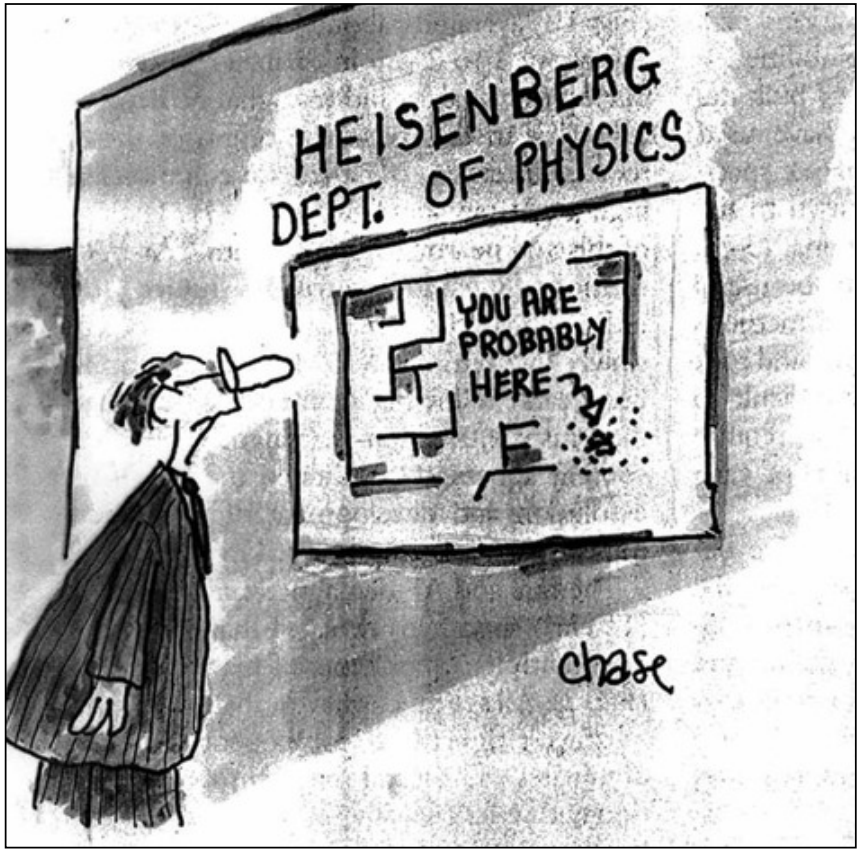
Historical notes

“I will never believe that God plays dice with the universe.”

Albert Einstein

“The conception of chance enters in the very first steps of scientific activity in virtue of the fact that no observation is absolutely correct. I think chance is a more fundamental conception that causality; for whether in a concrete case, a cause-effect relation holds or not can only be judged by applying the laws of chance to the observation.”

Max Born



Historical notes

Information Theory

1948: Bell Labs' Claude Shannon introduces Information Theory. Shannon quantified "information" and gave engineers a math-based theoretical maximum information carrying capacity for any communications system.

The concepts of ***uncertainty*** and ***information*** are tightly interconnected. Uncertainty is viewed as a manifestation of some information deficiency, while information is viewed as the capacity to reduce uncertainty.


Measurement uncertainty

Uncertainty gives a level of confidence … but don't exagerate!

In the 1930's, P. H. Myers at NBS and his colleagues were studying the specific heat of ammonia. After several years of hard work, they finally arrived at a value and reported the result in a paper. Toward the end of the paper, Myers declared: "We think our reported value is good to one part in 10,000; we are willing to bet our own money at even odds that it is correct to two parts in 10,000; furthermore, if by any chance our value is shown to be in error by more than one part in 1000, we are prepared to eat our apparatus and drink the ammonia!"

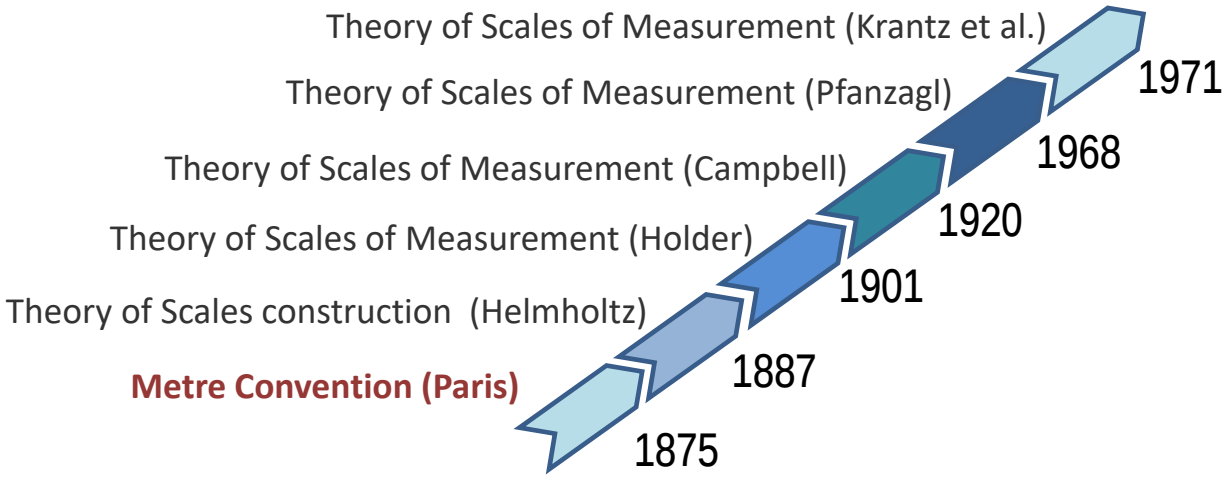
In Experimentation, validation and Uncertainty Analysis for Engineers
H. W. Coleman and W. G. Steele

Road to the GUM
A Timeline

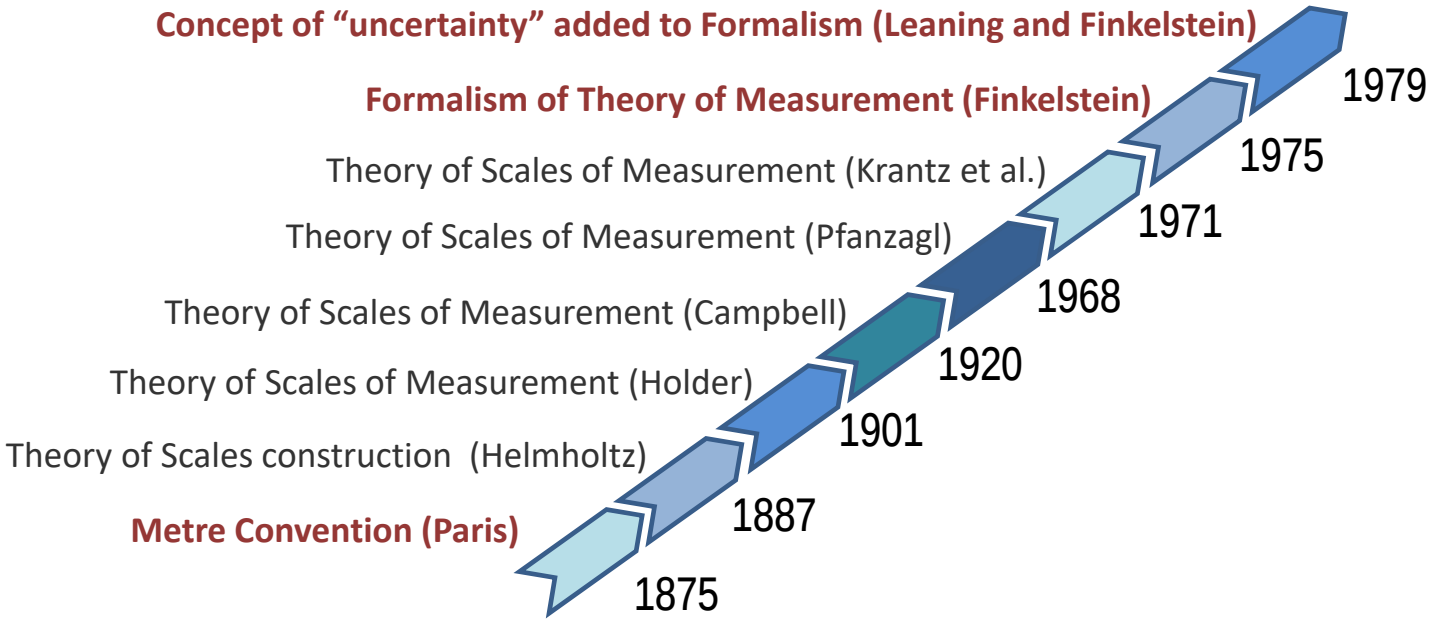
Metre Convention (Paris)

1875

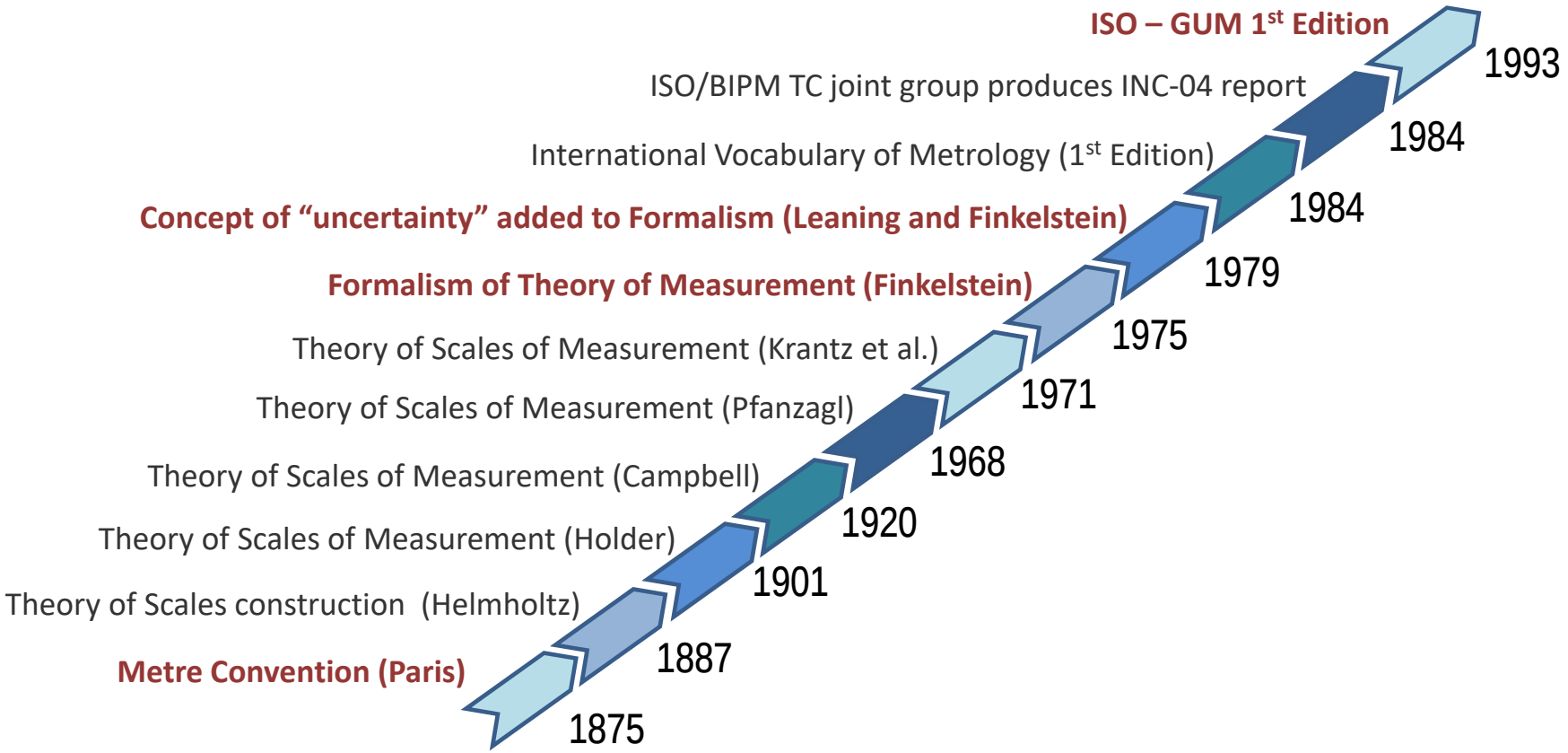
Road to the GUM
A Timeline



Road to the GUM
A Timeline



Road to the GUM
A Timeline



Road to the GUM
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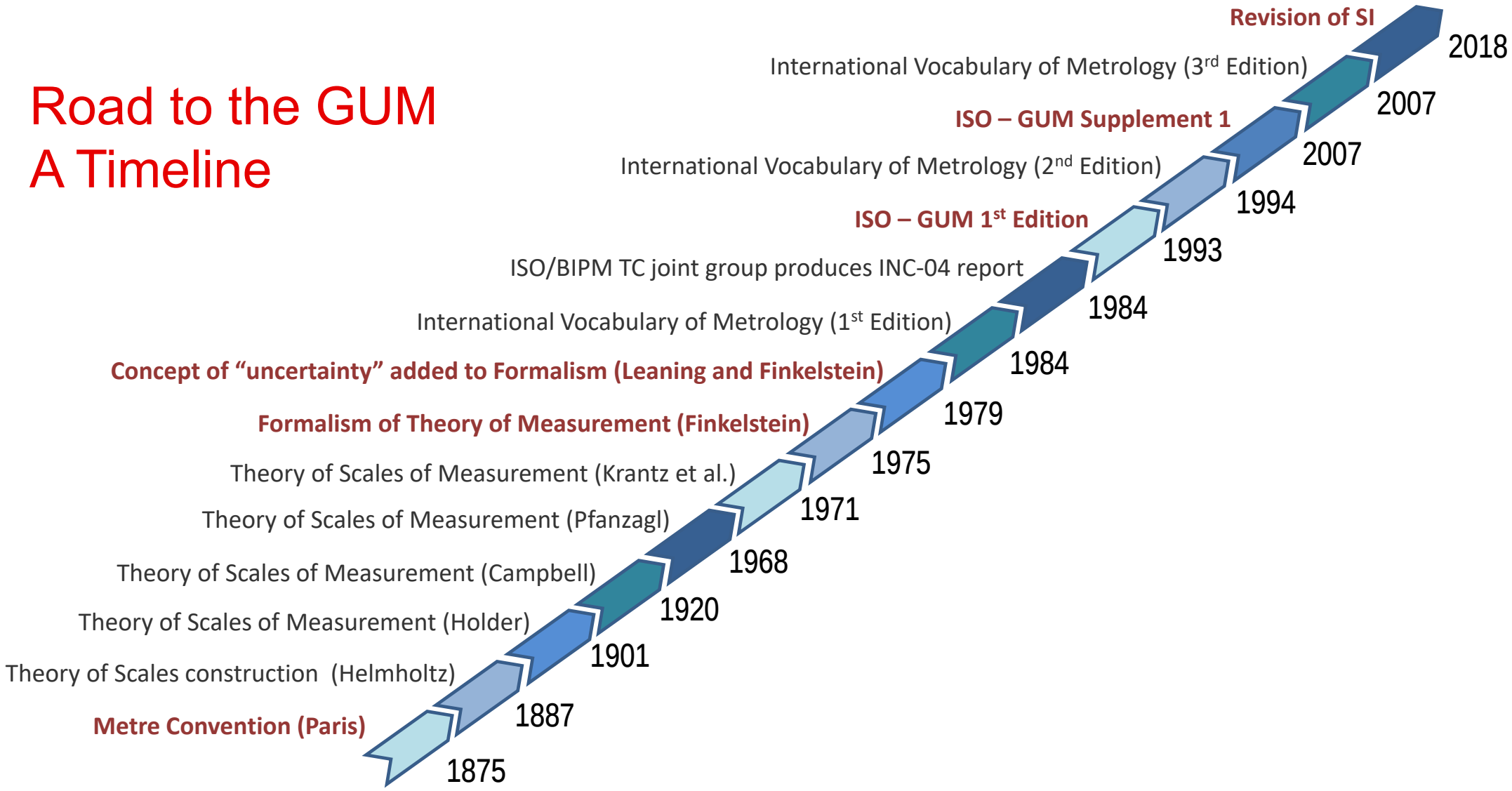

Road to the GUM – Representational Theory

Measurement is here defined, in the wide sense, as any process of empirical, objective assignment of symbols to attributes of objects and events of the real world, in such a way as to represent them, or to describe them.

L. Finkelstein, 2008

Road to the GUM – Representational Theory

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L. Finkelstein, 2008

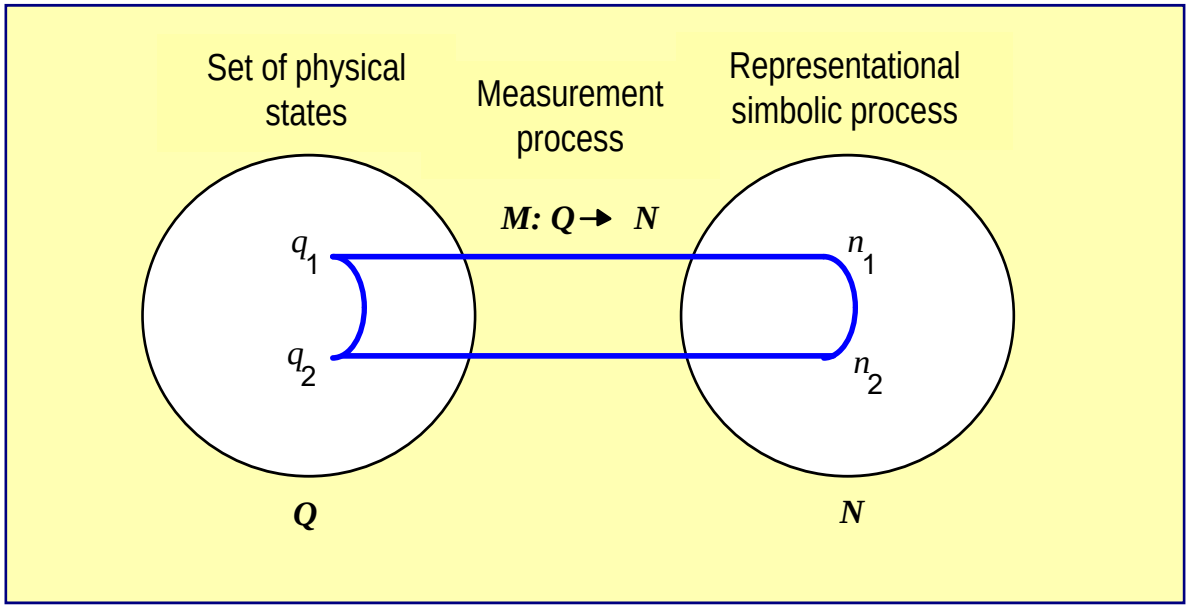
4 conditions of the formalism:

a) Empirical relational system $D = \langle Q, R \rangle$

b) Numerical relational system $N = \langle N, P \rangle$

c) Representational condition $M : Q \rightarrow N$

d) Uniqueness condition



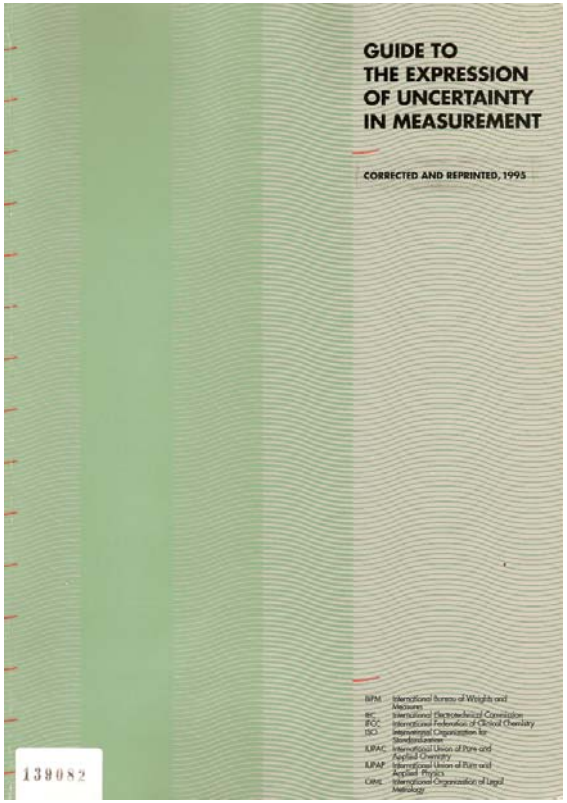
Road to the GUM

"… The BIPM convened a meeting for the purpose of arriving at a uniform and generally acceptable procedure for the specification of uncertainty; It was attended by experts from 11 national standards laboratories."

WG Recommendation INC-1 (1980) – Expression of Experimental Uncertainties

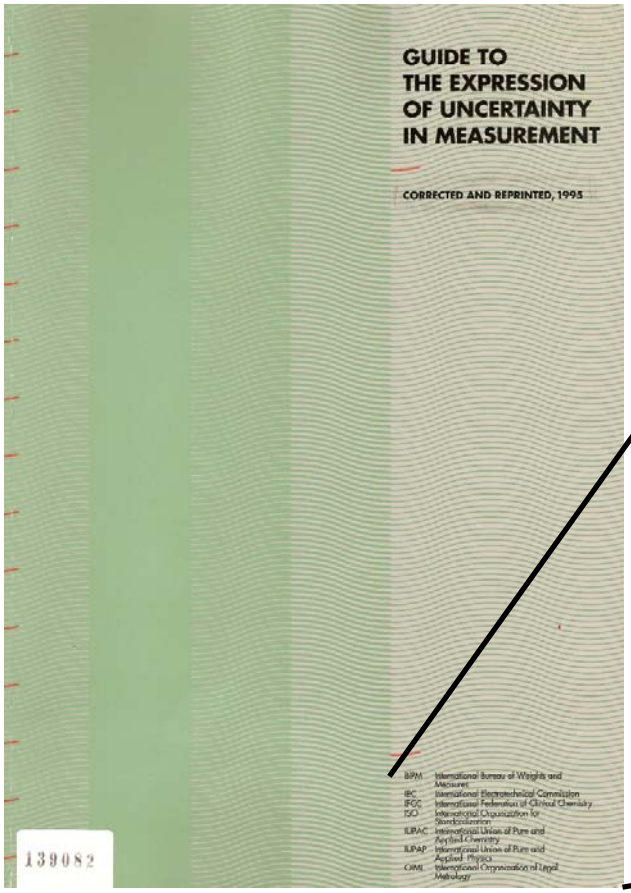
CIPM approval (1981)

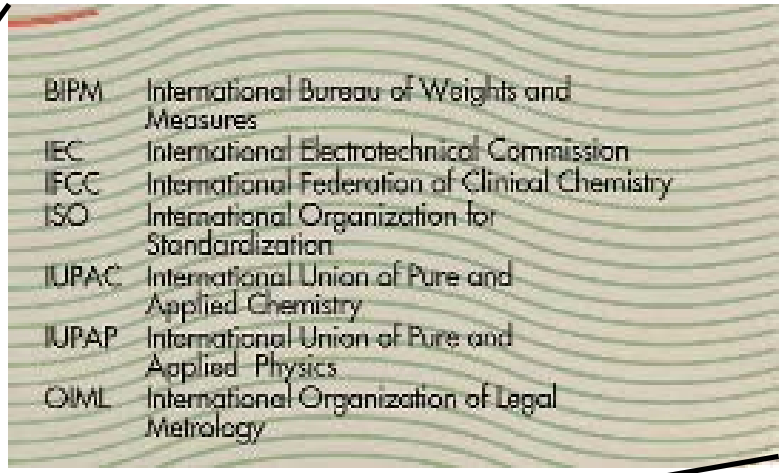
ISO /TAG 4 / WG3 (Technical Advisory Group) joint work of ISO, IEC, CIPM, OIML, IUPAC, IUPAP e IFCC, developed the Guide to the Expression of Uncertainty in Measurement 1993, revised in 1995)



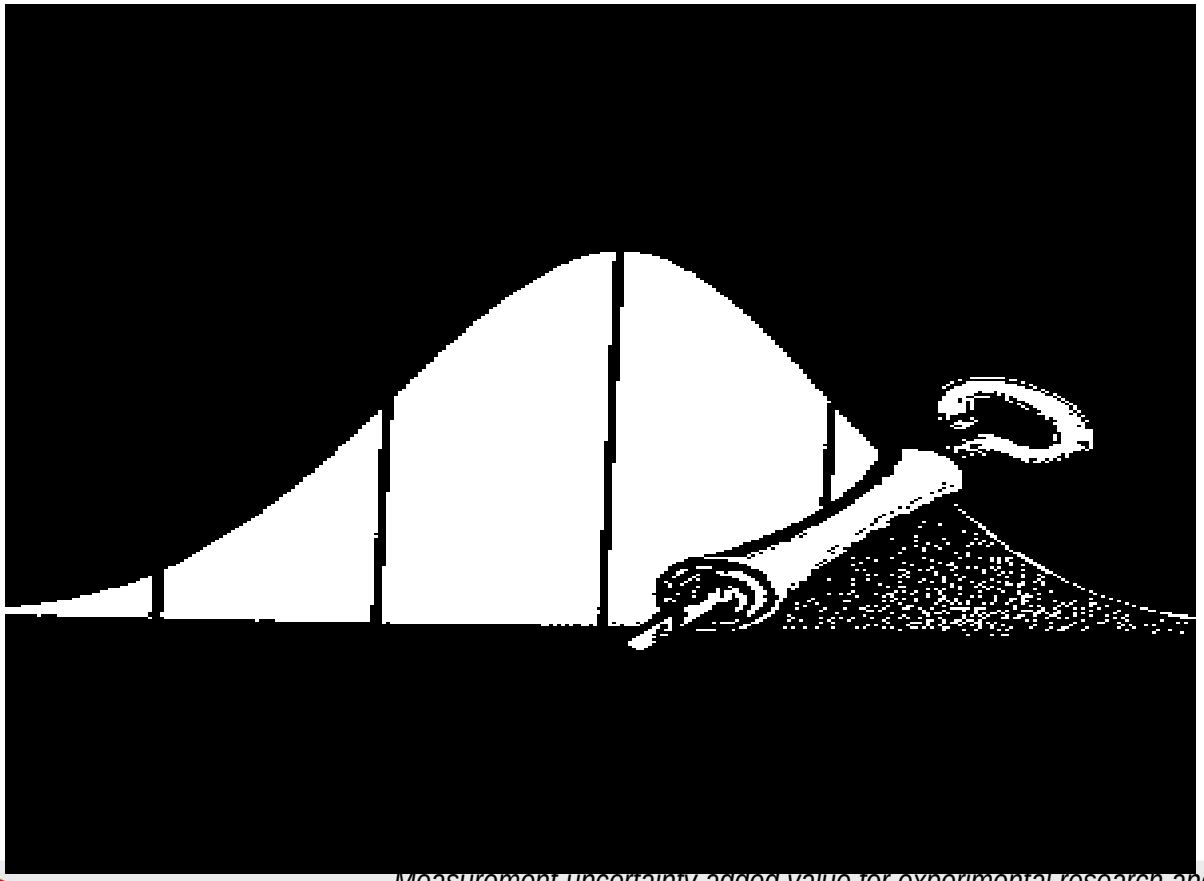
Road to the GUM

1993 – publicação do GUM





Road to the GUM
Probability Distribution Function as key to measurement information



Extended information

Data

Estimates of the measurands

Dispersion

Symmetry

Confidence intervals

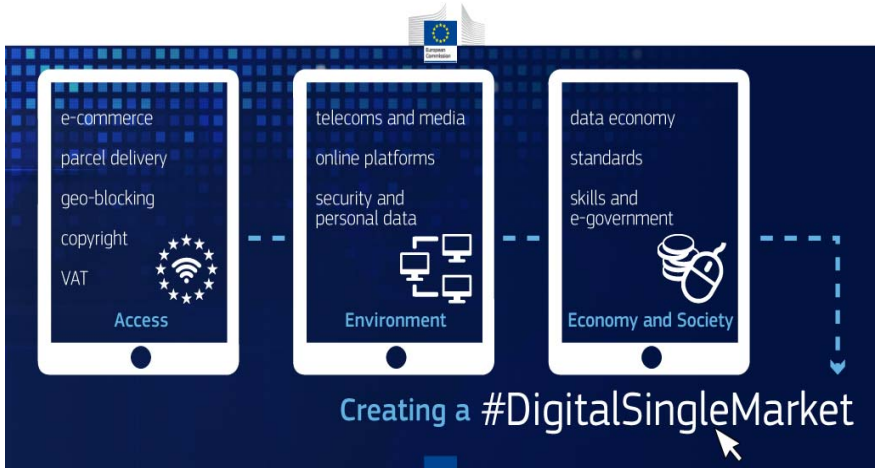
Probability of outcomes


Uncertainty added value in infrastructures safety

Providing safety and security to large infrastructures

In modern societies, safety and security of large-scale infrastructures (such as bridges, dams, tunnels, buildings, highways, airports, maritime and fluvial hydraulics) are major concerns, raising the need to establish many legal and technical requirements that must be assured through accredited testing and conformity assessment.

New ISO/IEC 17025: 2017 & Digital Transition



- Risk-based thinking
- Conformity and decision rules
- Process structure
- Digital framework
- Sampling analysis

Providing safety and security to large infrastructures

Is it needed?

Providing safety and security to large infrastructures

Is it needed?

Providing safety and security to large infrastructures

Is it needed?

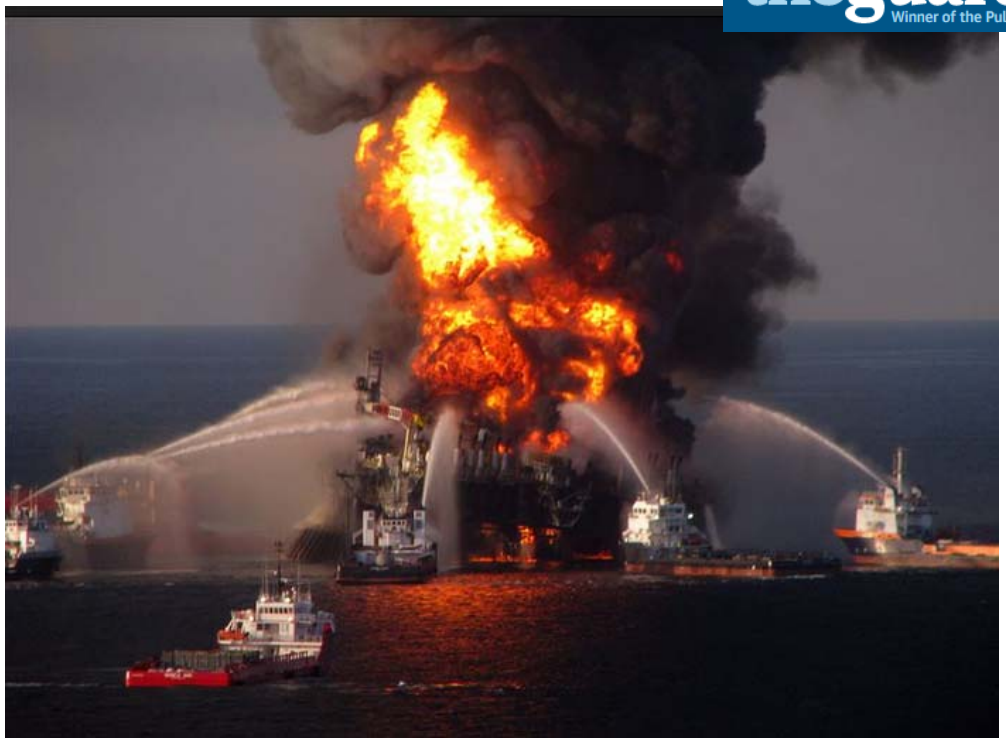
NASA lost a $125 million Mars orbiter because a Lockheed Martin engineering team used English units of measurement while the agency's team used the more conventional metric system for a key spacecraft operation, according to a review finding released Thursday.

The units mismatch prevented navigation information from transferring between the Mars Climate Orbiter spacecraft team in at Lockheed Martin in Denver and the flight team at NASA's Jet Propulsion Laboratory in Pasadena, California.

Lockheed Martin helped build, develop and operate the spacecraft for NASA. Its engineers provided navigation commands for Climate Orbiter's thrusters in English units although NASA has been using the metric system predominantly since at least 1990.

Providing safety and security to large infrastructures

Is it needed?



Deepwater oil spill: BP steps up PR effort to insist all is well in the Gulf
April, 2010

theguardian
Winner of the Pulitzer prize

In the run-up to the five-year anniversary of the Deepwater Horizon spill this April, BP is ramping up its effort to convince consumers that life is returning to normal on the Gulf coast.

Over the last month, the company has released PR materials that highlight the Gulf's resilience, as well as a report compiling scientific studies that suggest the area is making a rapid recovery.

But evidence is mounting that five years after millions of gallons of oil spilled into the Gulf of Mexico, wildlife is still struggling to rebound. A new report, released on Monday by the National Wildlife Federation (NWF), suggests that at least 20 species are still being affected by the spill.

"This report, more so than any, shows that science is certain that this is a long-term problem," said Ryan Fikes, a scientist with NWF. "But it's going to take even more time to understand the true magnitude of this."

The NWF report is the organization's fifth survey highlighting scientific research into the environmental impact of the spill. This year, the NWF found that higher-than-normal rates of death for many species continued, and are likely linked to the disaster: dolphins along Louisiana's coastline were found dead at four times historic rates last year, and research has shown the deaths of 12% of brown pelicans and 32% of a species of gull can be linked to the spill.

The NWF report also says the eggs of many animals - from trout in the Gulf to pelicans nesting as far away as Minnesota - have been found to contain oil and the dispersant used by BP in the wake of the spill.

A representative from BP sent a statement, attributed to senior vice-president Geoff Morrell, that read in part: "The National Wildlife Federation report is a work of political advocacy ... the dire predictions made in 2010 have fortunately not come to pass."

Providing safety and security to large infrastructures

Is it needed?

Deepwater oil spill: BP steps up PR effort to insist all is well in the Gulf

Impact:

- Environment;
- Economy;
- Financial.

Providing safety and security to large infrastructures

Is it needed?

Deepwater oil spill: BP steps up PR effort to insist all is well in the Gulf

The New York Times

Panel Says Firms Knew of Cement Flaws Before Spill

By JOHN M. BRODER OCT. 28, 2010

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WASHINGTON — Halliburton officials knew weeks before the fatal explosion of the BP well in the Gulf of Mexico that the cement mixture they planned to use to seal the bottom of the well was unstable but still went ahead with the job, the presidential commission investigating the accident said on Thursday.

In the first official finding of responsibility for the blowout, which killed 11 workers and led to the biggest offshore oil spill in American history, the commission staff determined that Halliburton had conducted three laboratory tests that indicated that the cement mixture did not meet industry standards.

The result of at least one of those tests was given on March 8 to BP, which failed to act upon it, the panel's lead investigator, Fred H. Bartlit Jr., said in a letter delivered to the commissioners on Thursday. "There is no indication that Halliburton highlighted to BP the significance of the foam stability data or that BP personnel raised any questions about it," Mr. Bartlit said in his report.

Providing safety and security to large infrastructures

Is it needed?

THE WALL STREET JOURNAL.

BP Agrees to Pay $18.7 Billion to Settle Deepwater Horizon Oil Spill Claims

Settlement of all federal and state claims brings total costs to nearly $54 billion

Providing safety and security to large infrastructures

Is it needed?

Flooded area after a dam collapsed in Attapeu province, Laos, July 25, 2018 (photo: Reuters)

Morandi bridge Collapse in Genoa, Italy, Aug. 14, 2018 (photo: Reuters)

Providing safety and security to large infrastructures

Management of infrastructures rely on testing and measurement to obtain information for decision making, being expected that measurement data has robustness and confidence due to:

- traceability;
- the use of Quality Management Systems (QMS); and
- the use of Qualified Resources (Human, Technical and others)

able to satisfy the requirements of competence (accuracy, proficiency and others).

Providing safety and security to large infrastructures

The Portuguese National Laboratory for Civil Engineering was created in 19 of November of 1946, in Lisbon.

It was born by merging the National Laboratory for “Testing and Study of Materials”, established in 1898 and the “Centre for Studies in Civil Engineering”, created in 1942.

Providing safety and security to large infrastructures

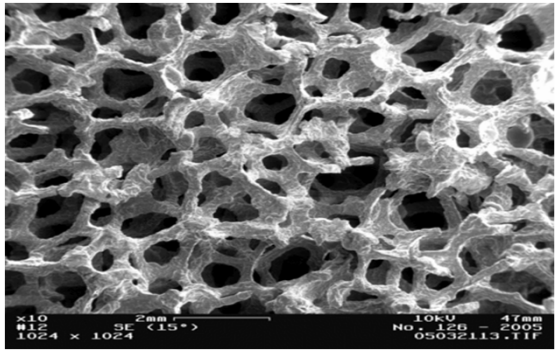
Dams

Buildings

Structures

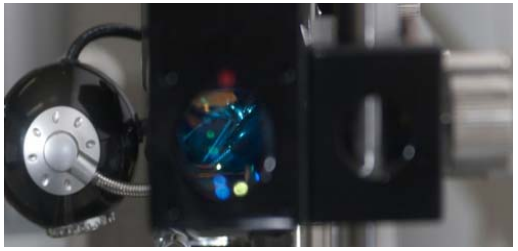
Geotechics

Hydraulics & Environment



Materials

Transportation



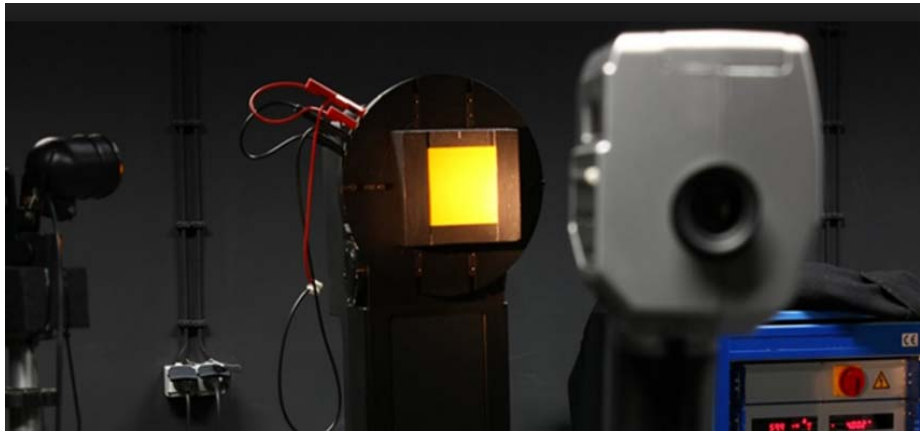
Instrumentation

Providing safety and security to large infrastructures

LABORATÓRIO NACIONAL DE ENGENHARIA CIVIL

ENSAIOS e METROLOGIA

- 32 laboratories (Testing & Metrology)
- 12 labs accredited (ISO 17025)



- 196 technical skilled persons

- ~ 1 100 testing methods

- ~19 000 tests / year

Providing safety and security to large infrastructures

Conformity assessment and decision rules – the role of uncertainty

Quality of measurement

ISO general definition of Quality as: *"The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs".*

Providing safety and security to large infrastructures

Conformity assessment and decision rules – the role of uncertainty

Quality of measurement

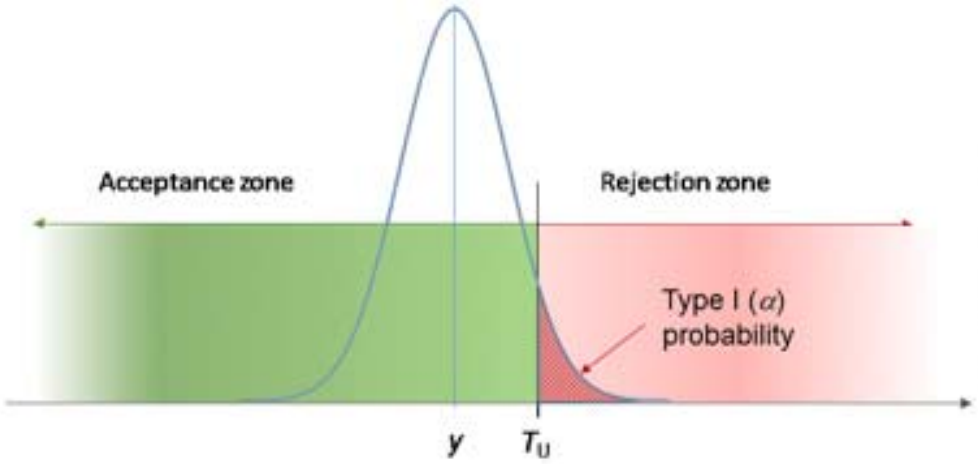
ISO general definition of Quality as: *"The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs".*

In measurement, one can interpret as the aim of measurement to achieve a certain level of accuracy that should be obtained considering the metrological conditions of the experimental performance. To have an evidence of this "compliance", a comparison between the result (estimate of a quantity and its uncertainty) and a parameter that express the requirements of the intended use is needed.

Conformity assessment (formal or informal) should validate this approach. defined as *the demonstration that specified requirements relating to a product, process, service, person, system or body are fulfilled*.

Providing safety and security to large infrastructures

Conformity assessment and decision rules – the role of uncertainty



Decision rule

Acceptance if the hypothesis H_0: $P(Y \leq T_U) \geq (1-\alpha)$ is true;

Rejection if the hypothesis H_0 is false, $P(Y \leq T_U) < (1-\alpha)$.

Expression to test: $P_c = P(\eta \leq T_U) = \Phi\left(\frac{T_U - y}{u(y)}\right)$

Figure 5. Example of diagram and decision rule based on a test of hypothesis

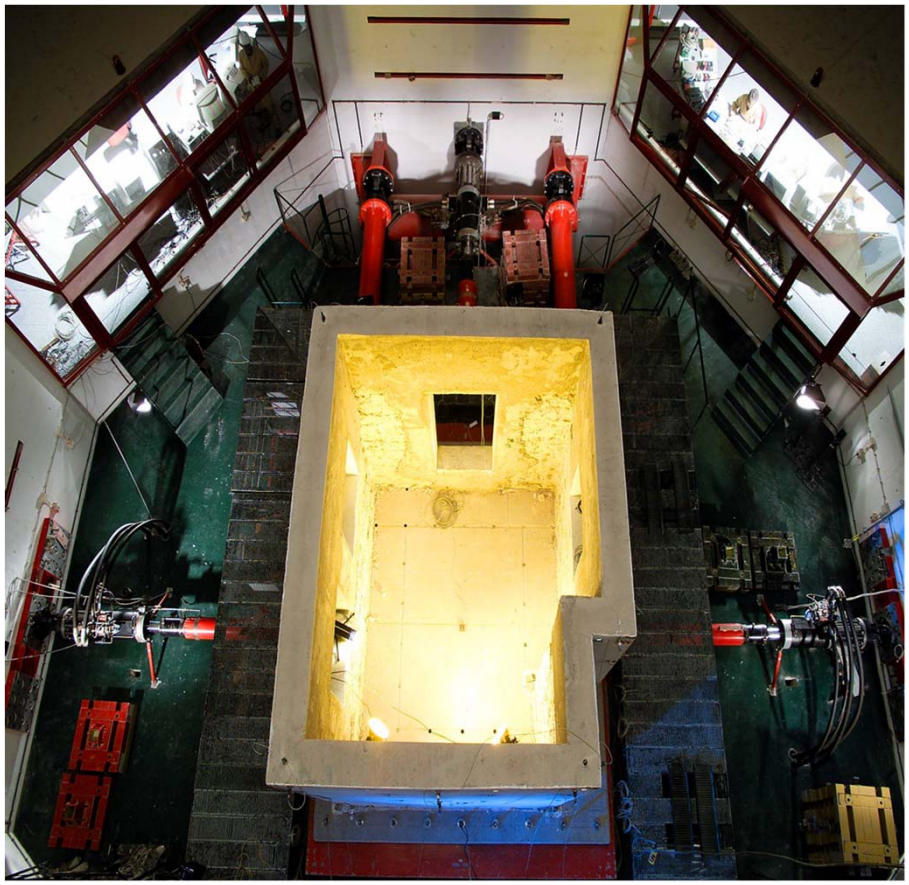
An experiment is a question which science poses to Nature,
and measurement is a recording of Nature’s answer.

Max Planck

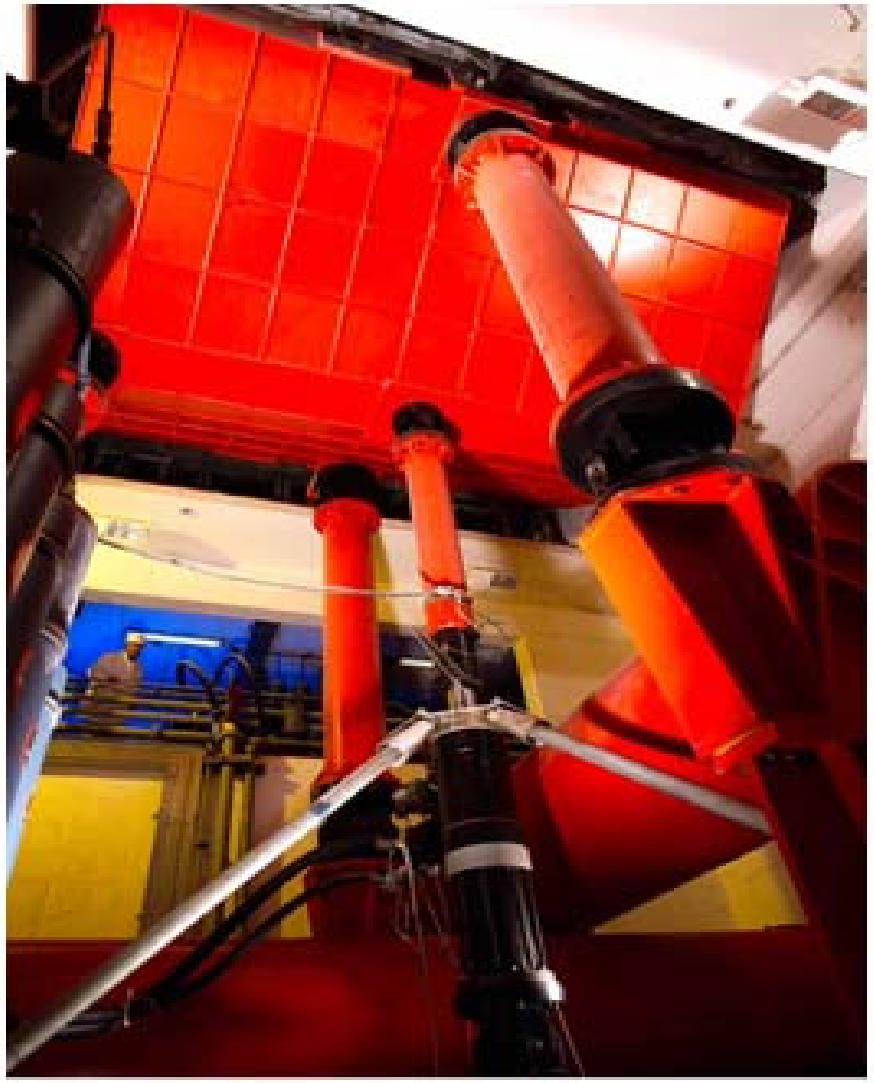
Seismic research infrastructure

The main infrastructure include:

- Large payload capacity (able to support weights up to 400 kN) at extreme testing conditions (near collapse);
- Steel testing platform with size of (4,6x5,6) m^2;
- Weight of 392 kN;
- 3 axis hydraulic actuators;
- Acquisition system with 8 A/D channels and 96 configurable digital input channels;
- operation and control uses in-house based software.



Seismic research infrastructure



Seismic research infrastructure

The conformity assessment is the basis for the validation of testing specifications, namely, performed by seismic shaking tables.

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The procedure compares the
target measurement uncertainty
Measurement uncertainty as specified as an upper limit and decided on the basis of the intended use of measurement results,

Seismic research infrastructure

The conformity assessment is the basis for the validation of testing specifications, namely, performed by seismic shaking tables.

The procedure compares the
target measurement uncertainty
Measurement uncertainty as specified as an upper limit and decided on the basis of the intended use of measurement results,

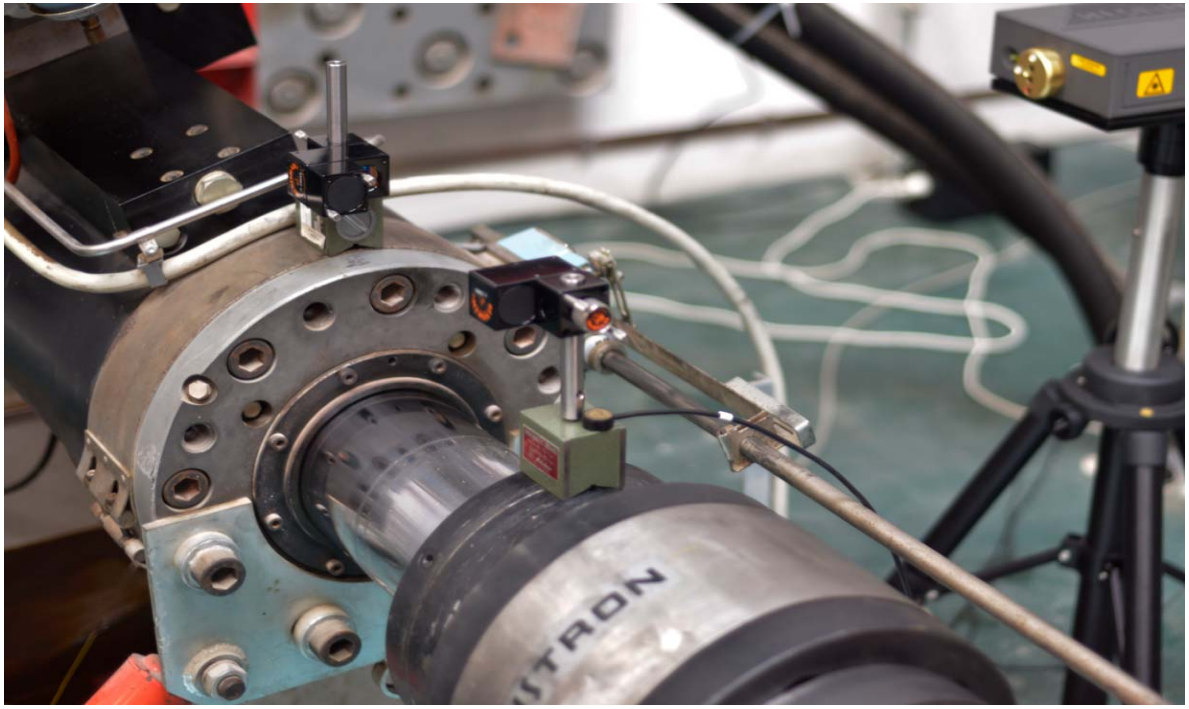
with the instrumental measurement uncertainty
component of measurement uncertainty arising from a measuring instrument or measuring system in use.

Seismic research infrastructure

To evaluate dimensional cross-axis motion and rotational motion across axis performances of the LNEC shaking table a laser interferometer was used (λ = 633 nm) as reference.

The experimental requirements for error minimization:

- ✓ misalignment of optical elements with the axis of the actuators (vertical/horizontal);
- ✓ signal synchronization;
- ✓ compensation of temperature;
- ✓ compensation of pressure.



Seismic research infrastructure

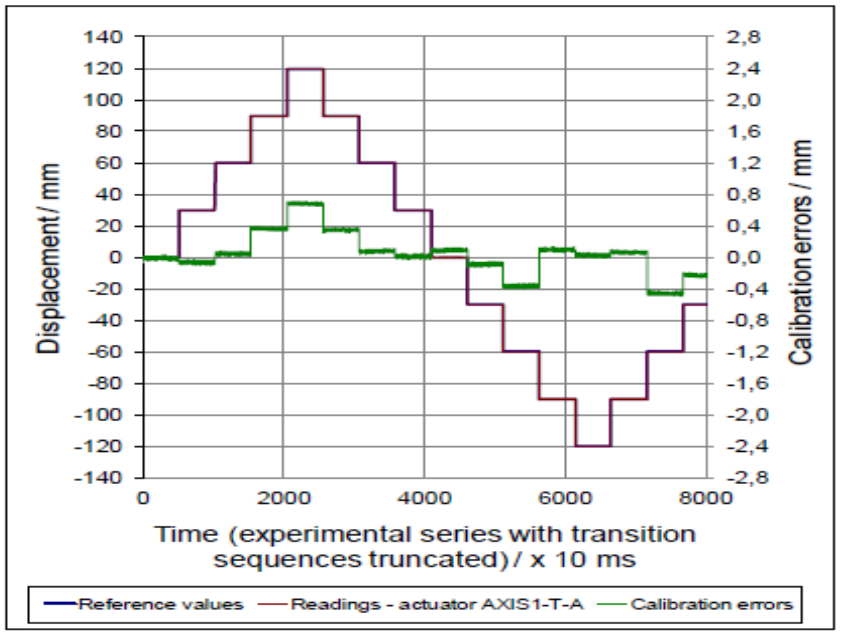


Figure 7. Cross-axis motion: static position testing axis 1-T-A calibration errors [12]

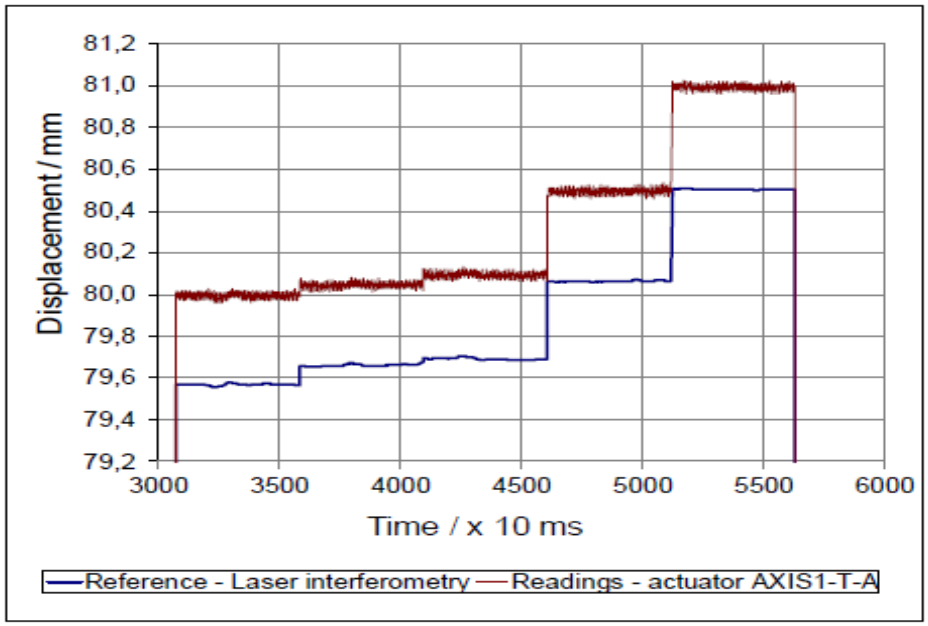
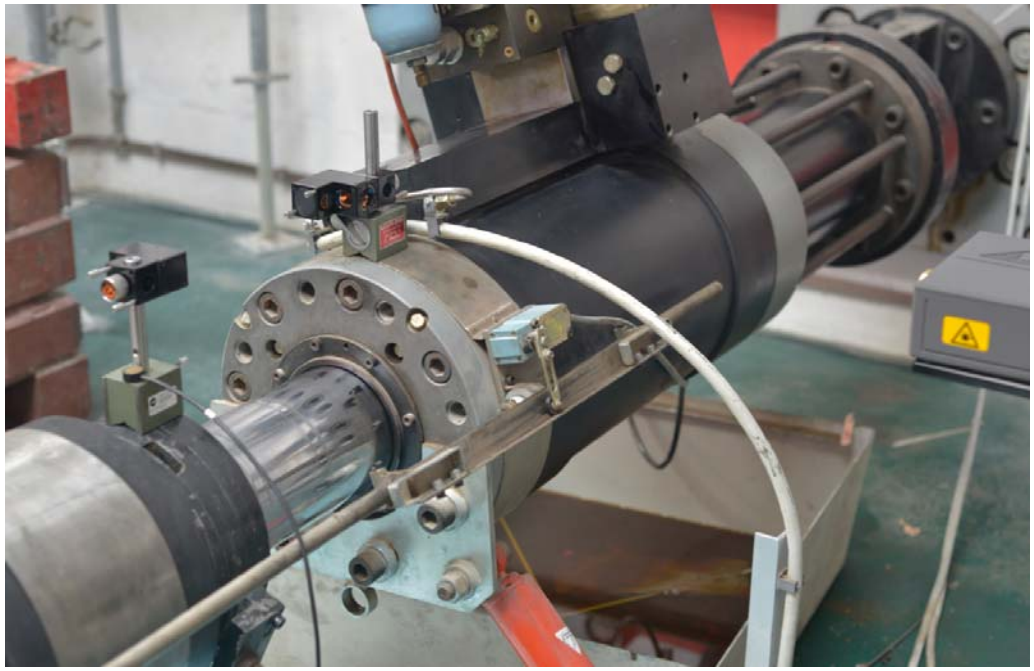


Figure 8. Cross-axis motion: discrimination testing for axis 1-T-A at a reference displacement of 80 mm [12]

Seismic research infrastructure

1/3 octave Fourier spectra ordinates computed from the laser interferometer and measuring instrument as well as the difference between them which is the error seen in spectral ordinates.



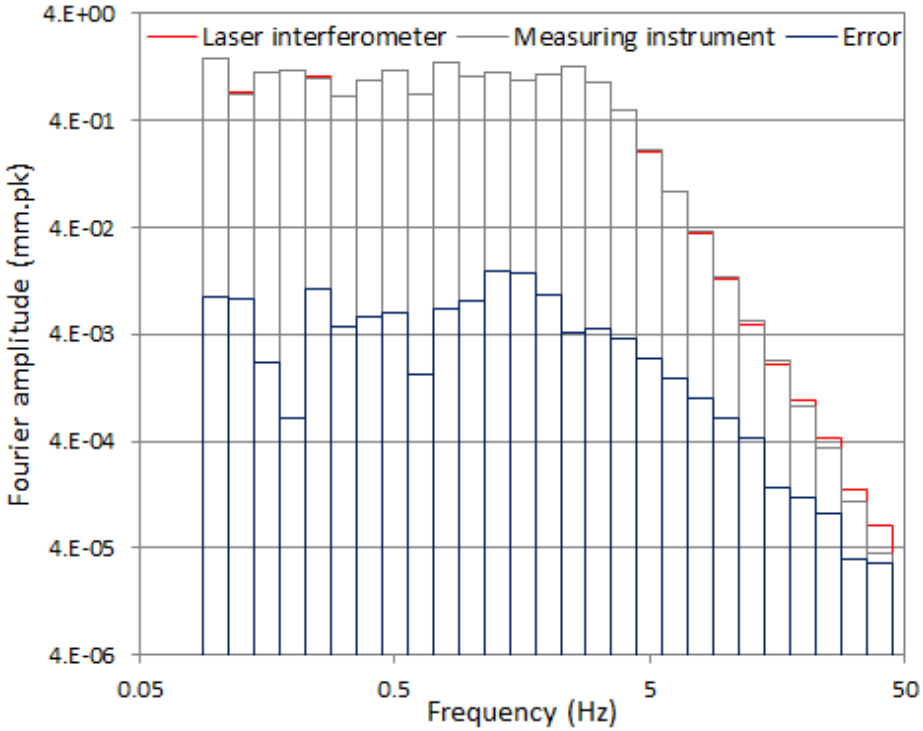


Figure 8 – 1/3 octave Fourier spectra

Bridge displacement monitoring

Displacement measurement of the main span central section of the P25A suspension bridge

- Opening date*: August 6, 1966
- Structural reinforcement: 1999
- Six road lanes (upper deck)
- Two railway tracks (lower deck)
- Suspension lenght: 2278 m
- Main span: 1012 m
- Daily traffic: 150 000 cars, 157 trains

The *Bridge 25 de Abril* (P25A) in Lisbon (Portugal)

* Constructed by the American Bridge Company, the same builder of the San Francisco – Oakland Bay Bridge

Bridge displacement monitoring

Measurement referential with LED targets in the south tower foundation

Bridge displacement monitoring

Camera (300 mm lens + converter)
installed in the main span central section

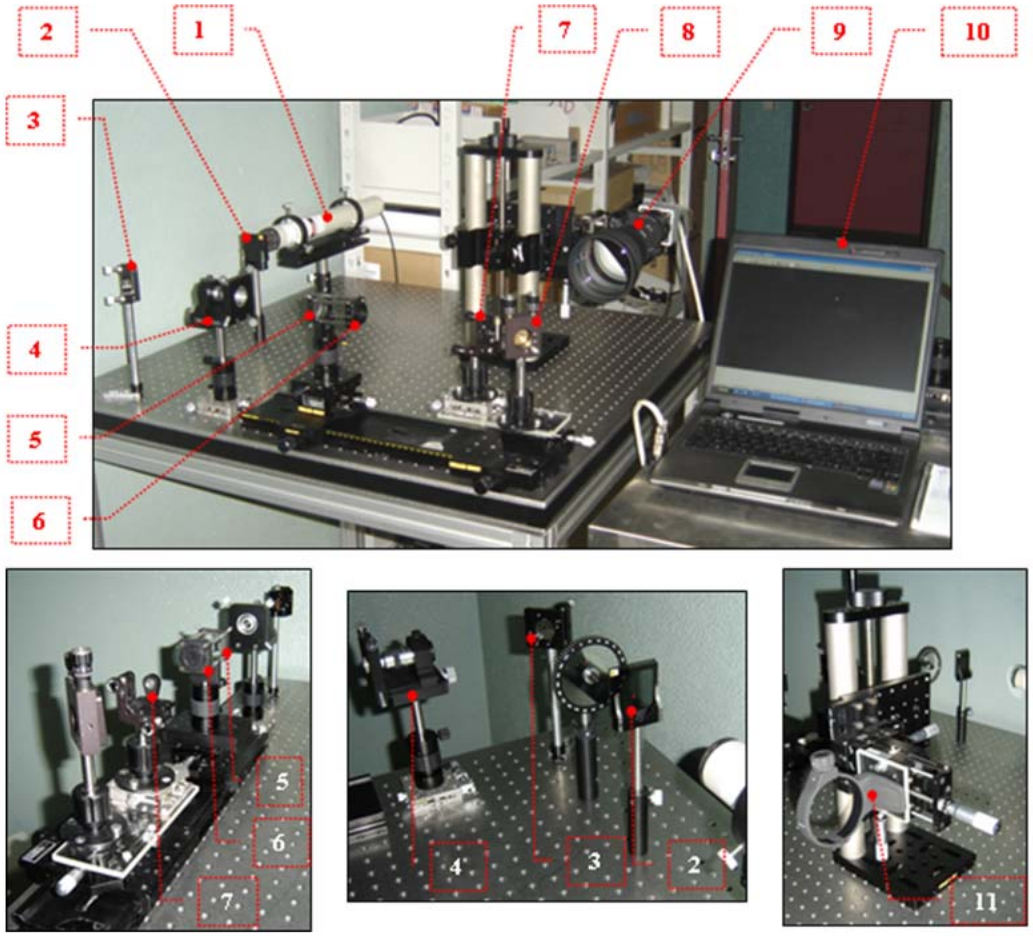
Measurement referential with LED
targets in the south tower foundation

Bridge displacement monitoring

Relevant achievements

Traceability using DOE in lab
– Diffractive Optical Element

1 – Laser ($\lambda = 633$ nm)
2 – Neutral filter
3 – Mirror
4 – Spatial filter
5 – Reference lens
6 – Aperture
7 – Diffraction grating
8 – Mirror
9 – Tested camera
10 – Computer
11 – Camera support



Bridge displacement monitoring

Iterative procedure adopted for the measurement uncertainty evaluation by a Monte Carlo Method

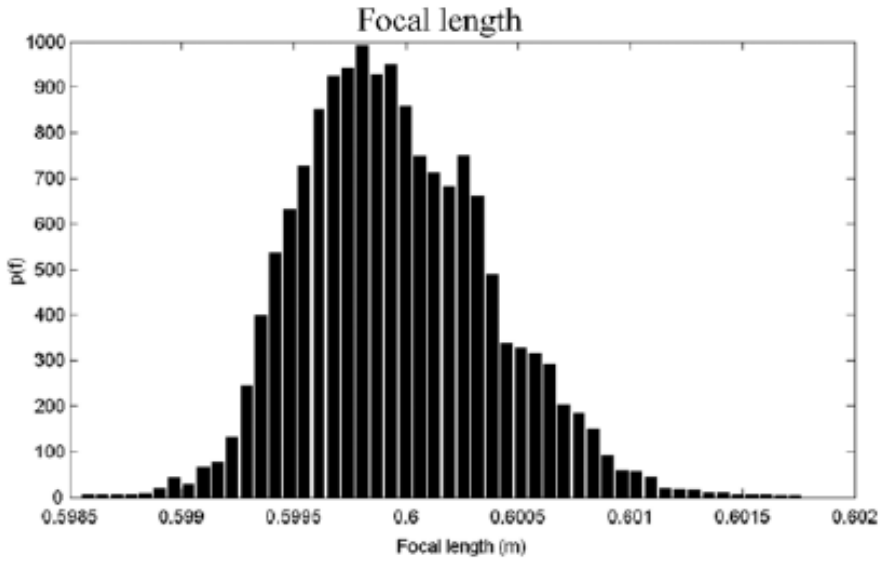


Figure 15. Probability density function of the camera focal length

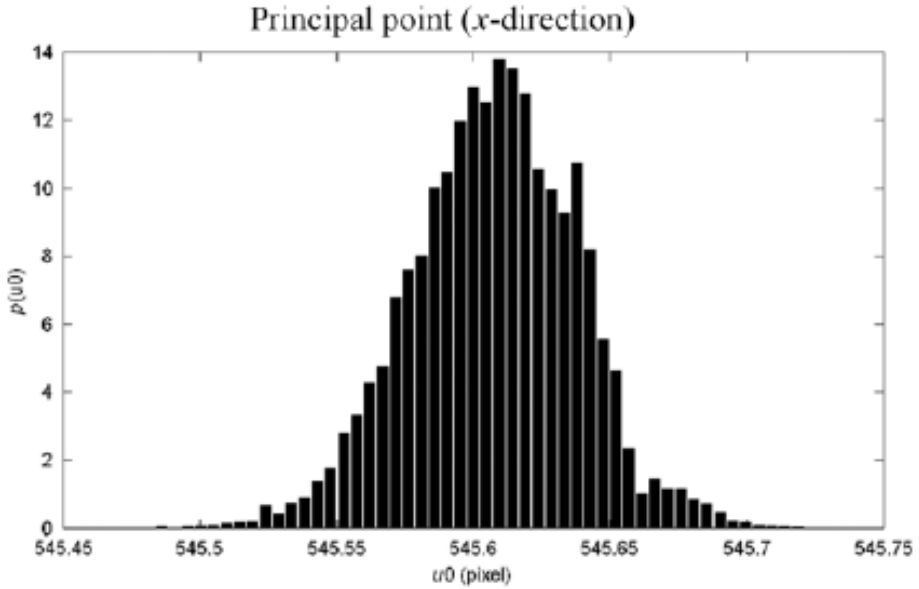
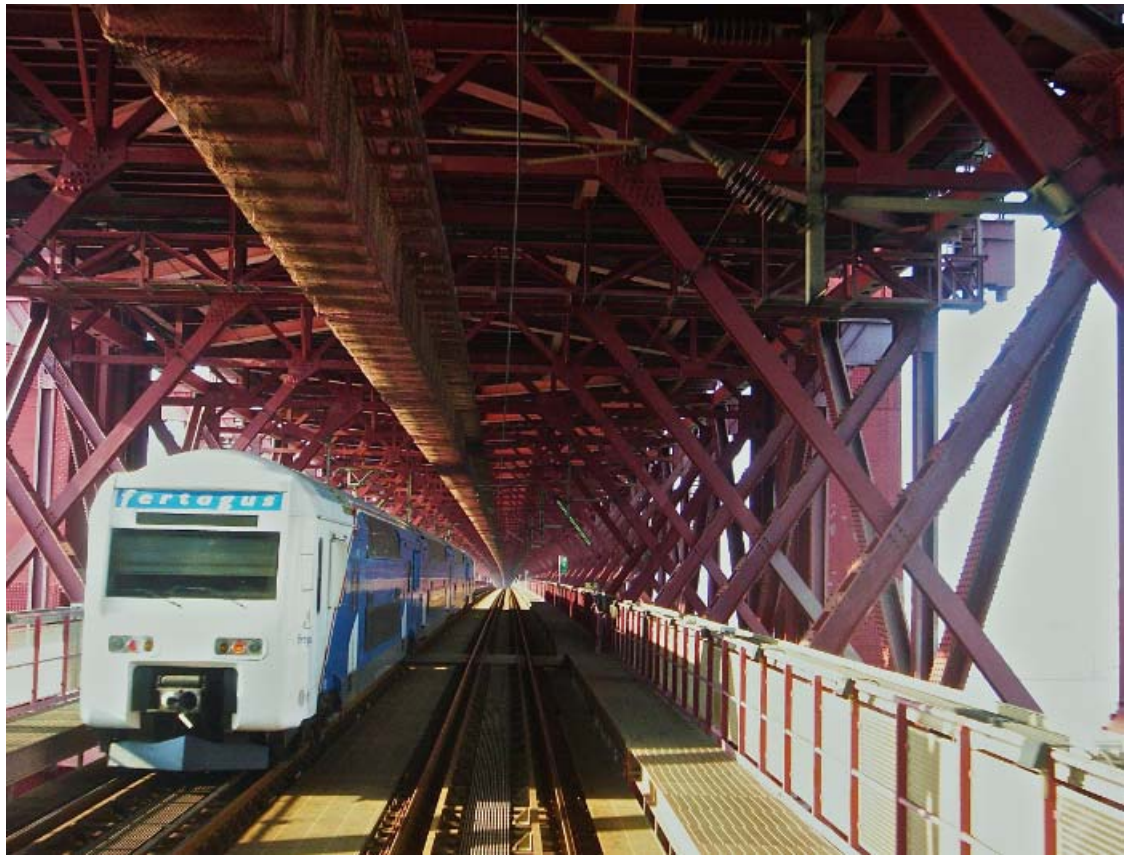


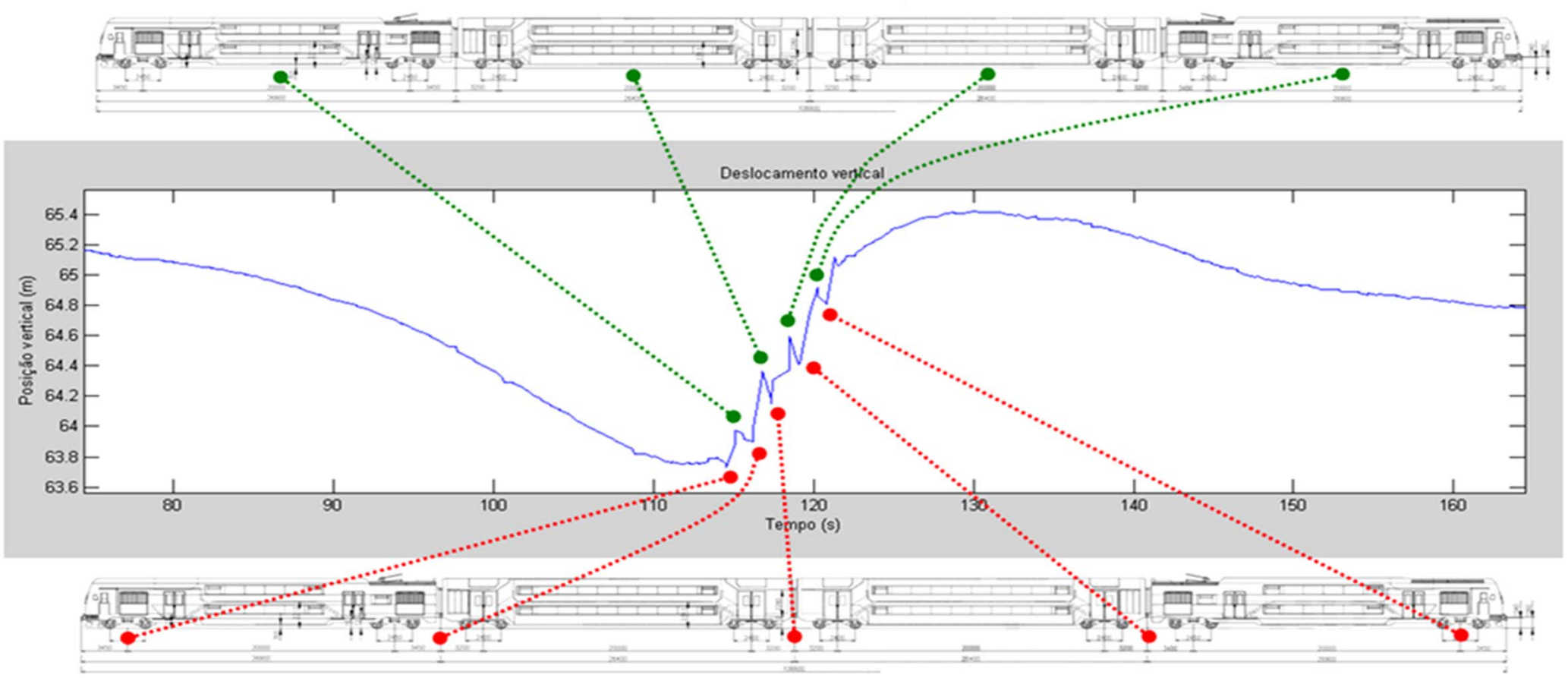
Figure 16. PDF of the principal point coordinate (x-direction)

Bridge displacement monitoring



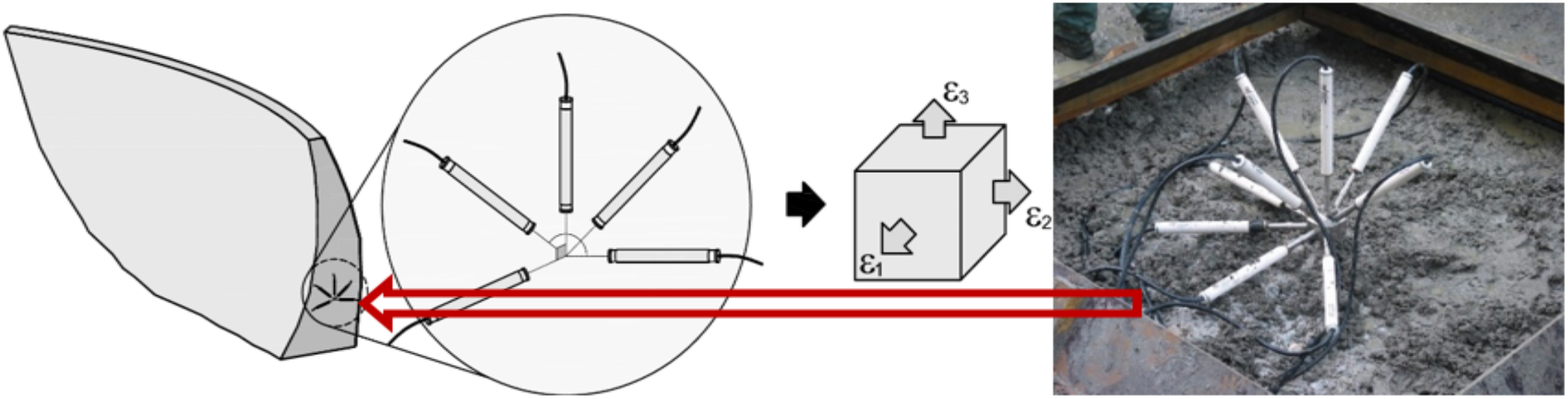
Increase the accuracy of the measurement of 3D displacements of the bridge, including during the train crossing.

Bridge displacement monitoring



Dams long term inspection

The activity related with long term monitoring of concrete dams rely on several measurement systems, some of them embedded in the concrete structure (see fig. 17), aiming to provide data during the life-time of the infrastructure. This is the case of Carlson electrical devices (strain meters) used by LNEC's Concrete Dam Department to study and characterize dam structural behaviour



3D set of Carlson strain gauges application inside a concrete wall of dam

Dams long term inspection

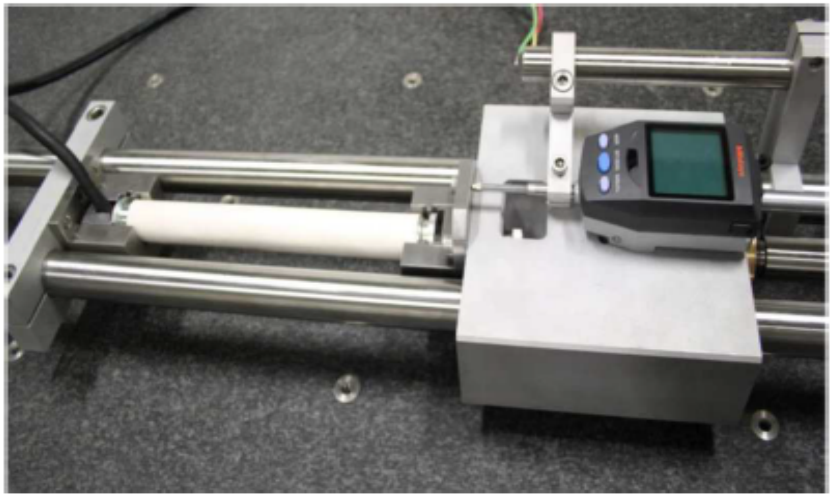


Figure 18. Calibration device for Carlson measuring instruments

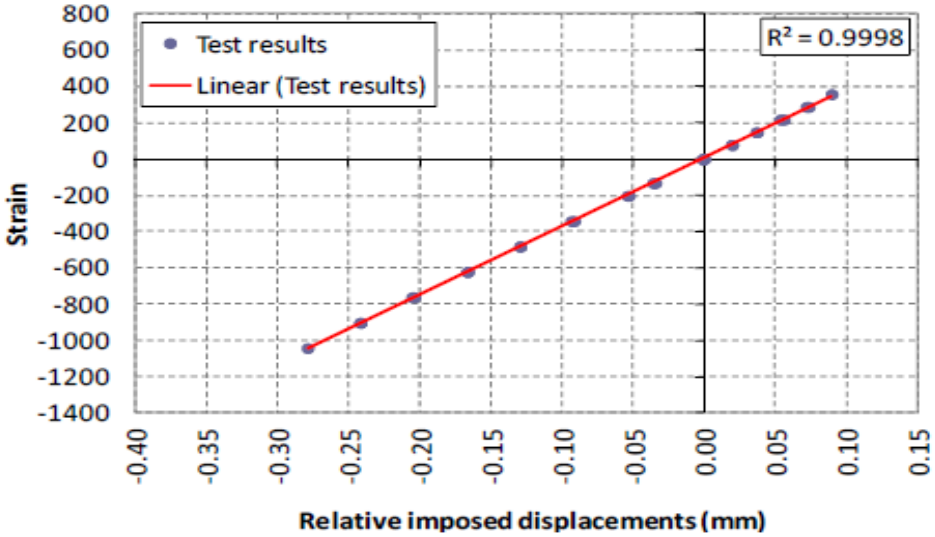


Figure 19. Linear mathematical relation between displacement and strain

The need to provide traceability to the Carlson strain meters *in situ* (before being inserted in the concrete wall of the dam), requires the use of a transfer standard traceable to LNEC reference standards (3D coordinate measuring machine).

Final remarks

Safety and Security are key issues for modern Society.

Governance relies in conformity assessment as tool to provide confidence and information needed to decision-making processes.

Since the development of a new probabilistic perspective of measurement, the concept of measurement including measurement uncertainty became key to the interpretation of phenomena and to scientific activities and applications.

Today, the Science of Measurement (Metrology) is a discipline with a large contribution to understand and develop other branches for Science supported by experimental activity.

Acknowledgements

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Thank you for your kind attention!

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