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Current and future challenges in modelling and simulation of measuring systems

T J Esward, National Physical Laboratory (UK)

7 December 2012

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Aim of talk

- Provide a metrologist's perspective on some of the current challenges in modelling and uncertainty analysis
- Informed by experiences with two research projects supported by the European Metrology Research Programme (EMRP)
  - Traceable dynamic measurement of mechanical quantities
  - Novel mathematical and statistical approaches to uncertainty evaluation
- Model uncertainty and its role in these projects

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Introducing NPL


NPL
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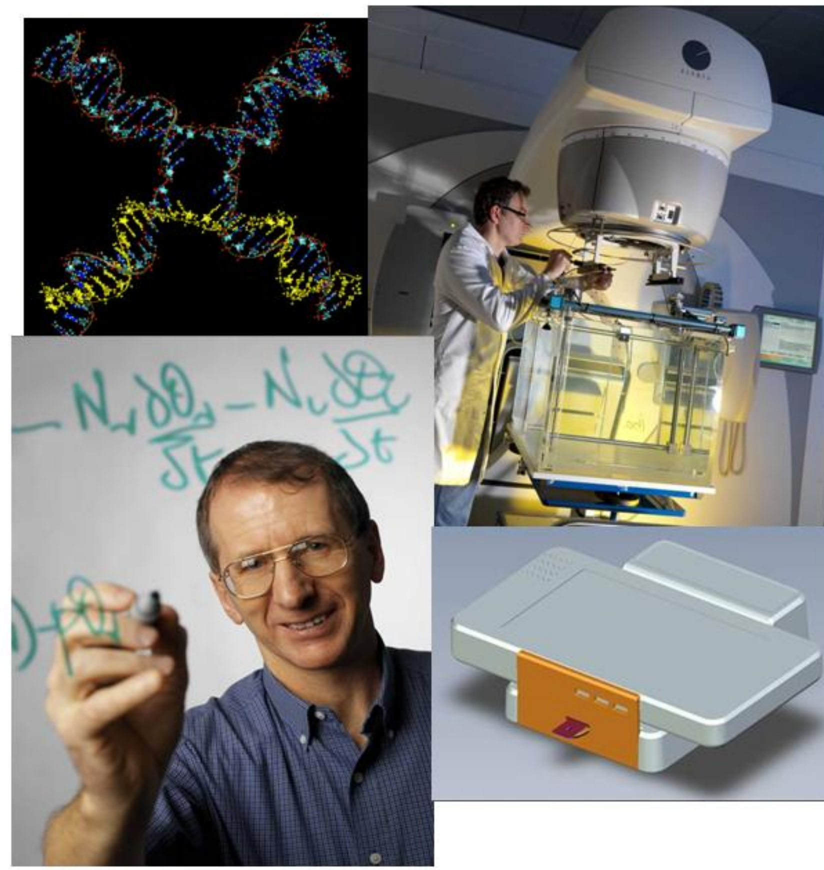
About NPL …

- UK’s national standards laboratory
- Founded in 1900
- 600+ specialists in measurement science
- State-of-the-art standards facilities; new building dates from early 2000s



NPL’s building 1

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NPL has five science divisions

Science Divisions

- Materials
- Engineering measurement (Mass, length, temperature & humidity)
- Time, Quantum and Electromagnetic
- Acoustics and Ionising Radiation
- Analytical Science (including environmental & biological measurement)

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Introducing the EMRP

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What is the EMRP?

- Supports the collaboration of European Metrology Institutes, industrial organisations and academia through Joint Research Projects (JRPs)
- Implemented by EURAMET (European Association of National Metrology Institutes)
- Based on Article 185 of the Lisbon Treaty
- Jointly funded by the EMRP participating countries and the European Union (50:50) and has a budget of approximately 400 M€ over seven years

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Aims of EMRP

- Structured around European Grand Challenges in: Health, Energy, the Environment & New Technologies, while also addressing challenges in fundamental metrology and industry
- Improve measurement to drive innovation and competitiveness in Europe
- Ensure collaboration between National Measurement Institutes, reducing duplication and increasing impact

Participating countries

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How does EMRP fund science?

- Multi-partner Joint Research Projects (JRPs)
- JRPs are primarily undertaken by the National Metrology Institutes (NMIs) and Designated Institutes (DIs) of the countries participating in the EMRP
- However, other organisations are able to participate in the JRPs with their own resources - they can participate as:
  - unfunded JRP Partners – part of the JRP Consortium
  - JRP Collaborators

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EMRP calls

Energy - Calls in 2009 & 2013

SI Units - Calls in 2011 & 2012

Environment - Calls in 2010 & 2013

Health - Call in 2010

Industry - Calls in 2010 & 2012

New Technologies - Call in 2011

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EURAMET web site: http://www.euramet.org/

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EMRP project IND09: Traceable dynamic measurement of mechanical quantities September 2011 - August 2014

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What is a dynamic measurement? A practical definition

- Measurement where physical quantity being measured varies with time and where this variation may have significant effect on measurement result and its associated uncertainty
- Nature of physical quantity (measurand) depends on application
  - often difficult to measure irregular and rapidly varying details of signal, maxima, minima etc
  - but it is frequently these features that are of interest

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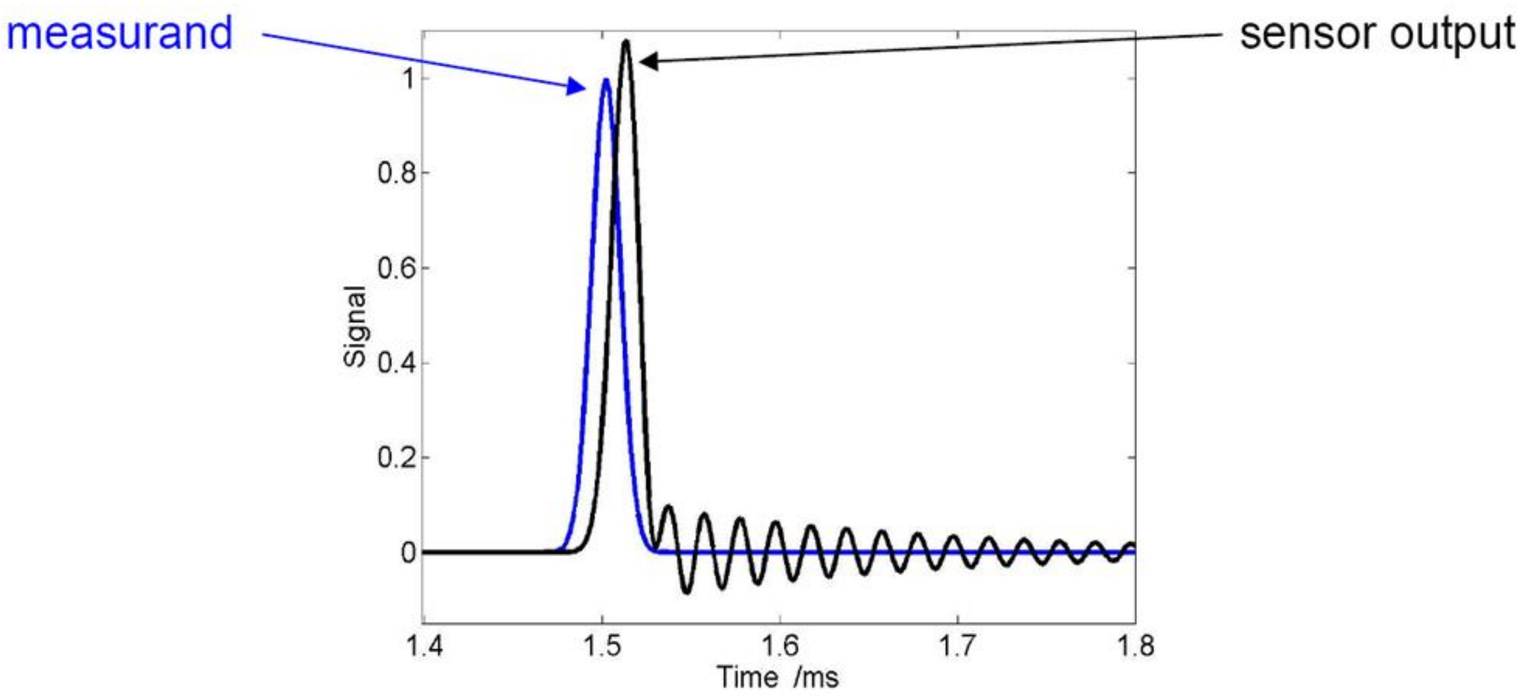
Time domain response of sensor to pulse



Interpreting the sensor output

- Sensor response includes a delay
- Overestimates and underestimates the measurand at various times
- Ringing after end of pulse
- Error signal (difference between measurand and sensor output) varies with time and persists after measurand is zero
- Need to correct sensor output for these effects and then evaluate appropriate uncertainties
  - methods for these tasks are subject of EMRP project IND09

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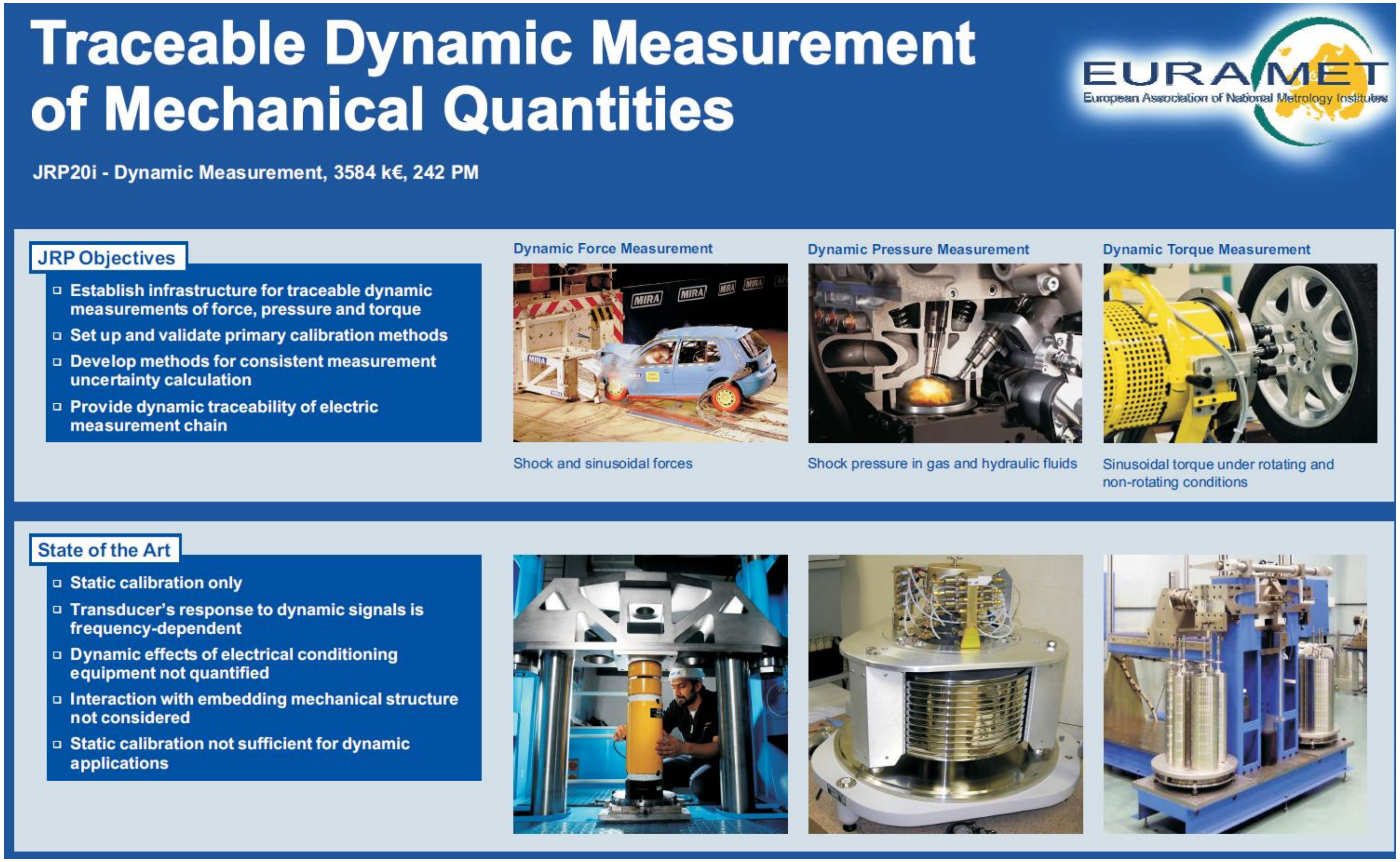
Dynamic metrology concept

- Methods for transferring results of dynamic calibrations to measurements of interest
- Dynamic calibration methods for various quantities and measuring systems
- System analysis of complex measurements
- Optimisation of measuring systems
- Dynamic correction of time-dependent measurements
- Evaluation of time-dependent measurement uncertainty

IND09 project poster



Project team

JRP Participants

PTB
Germany

NPL
United Kingdom

LNE
France

MIKES
Finland

CEM
Spain

SP
Sweden

INRIM
Italy

CMI
Czech Republic

TÜBITAK-UME
Turkey

Collaborators

Traceable dynamic measurement of mechanical quantities: objectives

- Establish infrastructure for traceable dynamic measurement of force, torque and pressure
  - including electrical measurement chain
- Set up and validate primary standards
- Develop methods for consistent uncertainty evaluation
- Learn more at:
  - http://www.euramet.org/fileadmin/docs/EMRP/JRP/JRP_Summaries_2010/IND09_Publishable_JRP_Summary.pdf & http://www.ptb.de/emrp/ind09-home.html

Traceable dynamic measurement of mechanical quantities: current state of the art

- Mainly static calibration methods but transducer’s response to dynamic signals is frequency dependent
- Dynamic effects of electrical conditioning equipment often not quantified
- Interaction between sensors and mechanical structure in which they are embedded not evaluated

Our approach to modelling and uncertainty analysis

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Basic assumption for modelling and uncertainty analysis

- Linear Time Invariant (LTI) systems
  - In reality almost all systems are non-linear but may often be approximated by linear models
  - Example: to describe distortion in an amplifier non-linear models will be needed, but to describe its transfer characteristics a linear model may be sufficient
- Use system identification methods to develop models and estimate parameters

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Useful textbooks

- J. Schoukens and R. Pintelon, *Identification of Linear Systems: A Practical Guide to Accurate Modelling*, Pergamon Press, 1991
- A. V. Oppenheim and R. W. Schafer, *Discrete-time signal processing*, Prentice Hall Signal Processing Series, 1999
- L. Ljung, *System identification: Theory for the user*, Prentice Hall Information and System Science Series, 1999
  - Matlab® system identification toolbox based on his work

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Identifying LTI systems: the process (1)

- Class of models is developed to describe the dynamic system
  - models may be parametric (white or black box) or non-parametric
- Parametric model: the system is described by a (typically small) number of characteristic quantities called parameters of the model, e.g., the coefficients of the transfer function of a filter
- Non-parametric model: the system is characterised by the measured data obtained from the measurement of a system function at a certain number of points, e.g., the time domain measurement of the impulse response of a filter

Identifying LTI systems: the process (2)

- White or grey box model is a parametric model given by physical laws and where the parameters of the model have physical interpretation (e.g., damping or resonance frequency)
- Black box model is a parametric model that provides a description of the relationship between observed inputs and outputs that is empirical

Identifying LTI systems: the process (3)

- After a class of models has been developed, mathematical and statistical methods are applied to estimate the parameters of the model and evaluate their associated uncertainty using the available calibration data
- Finally, validation of the model and a check of model-data consistency are carried out

LTI systems: parameter estimation

- Having specified a model linking the measured data with parameters describing the system characteristics, a number of statistical techniques may be employed for estimation of the parameters of interest
- Among these techniques at least two distinct groups can be identified: frequentist (or so-called classical) methods and Bayesian procedures
  - Frequentist: point estimates of the parameters and uncertainties associated with their estimation
  - Bayesian: results in a posterior probability distribution for the parameters that summarises the current state of knowledge about them and estimates and associated uncertainties can then be calculated from this distribution

LTI systems and calibration

- How to use the outputs of system identification and calibration processes practically?
- Convolution and deconvolution
- To analyse a dynamic measurement the available information is the sensor output signal and the characterisation of the system transfer function in terms of a calibrated model

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Convolution

$$x(t) * h(t) + \epsilon(t) = y(t)$$

- where "$*$" denotes convolution
- $y(t)$ is the output signal from a measuring system,
- $x(t)$ is the input signal of interest
- $h(t)$ represents the impulse response of the measuring system or sensor
- $\epsilon(t)$ is noise that is present in the output signal $y(t)$

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Convolution and deconvolution

- Convolution is a straightforward process that is well defined mathematically
- Inverse or deconvolution process, in which one attempts to reverse the effects of convolution, can only be defined algorithmically and is ill-posed
- The deconvolution problem is to estimate x given h and y (or at least some knowledge about the form that h takes)
  - Owing to the ill-posedness of this task, some prior knowledge about the measurand must be taken into account

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Deconvolution tutorial

- *Deconvolution filters for the analysis of dynamic measurement processes: a tutorial*, Eichstädt, Elster, Esward, Hessling, Metrologia 47, 522, 2010

Advice from Metrologia paper

- Taking into account numerical complexity and underlying assumptions of the methods, when a continuous model of the LTI system is available, or when starting point is a set of measurements of the frequency response of a system, application of least squares in the frequency domain for construction of an approximate inverse filter is preferred
- Asynchronous time reversal filtering using exact inverse filter appears superior when a discrete model of the LTI system is available and when causality of the deconvolution filter is not an issue

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Deconvolution in action

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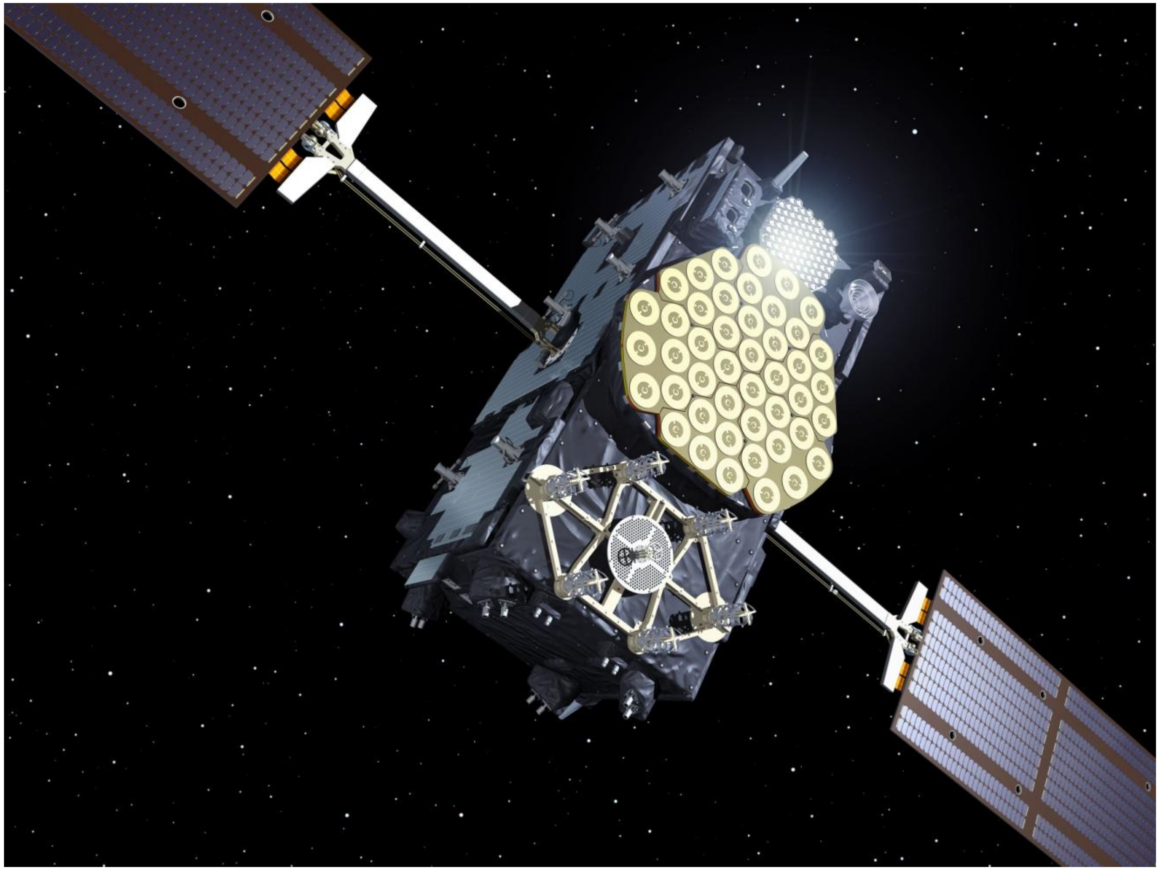
21 October 2011: Soyuz lifts off for first time from Europe's Spaceport in French Guiana carrying first two Galileo In-Orbit Validation (IOV) satellites

Image credit: ESA/CNES/ARIANESPACE - S. Corvaja, 2011



Artist's impression of the Galileo IOV satellite

Image credit: ESA/P. Carril

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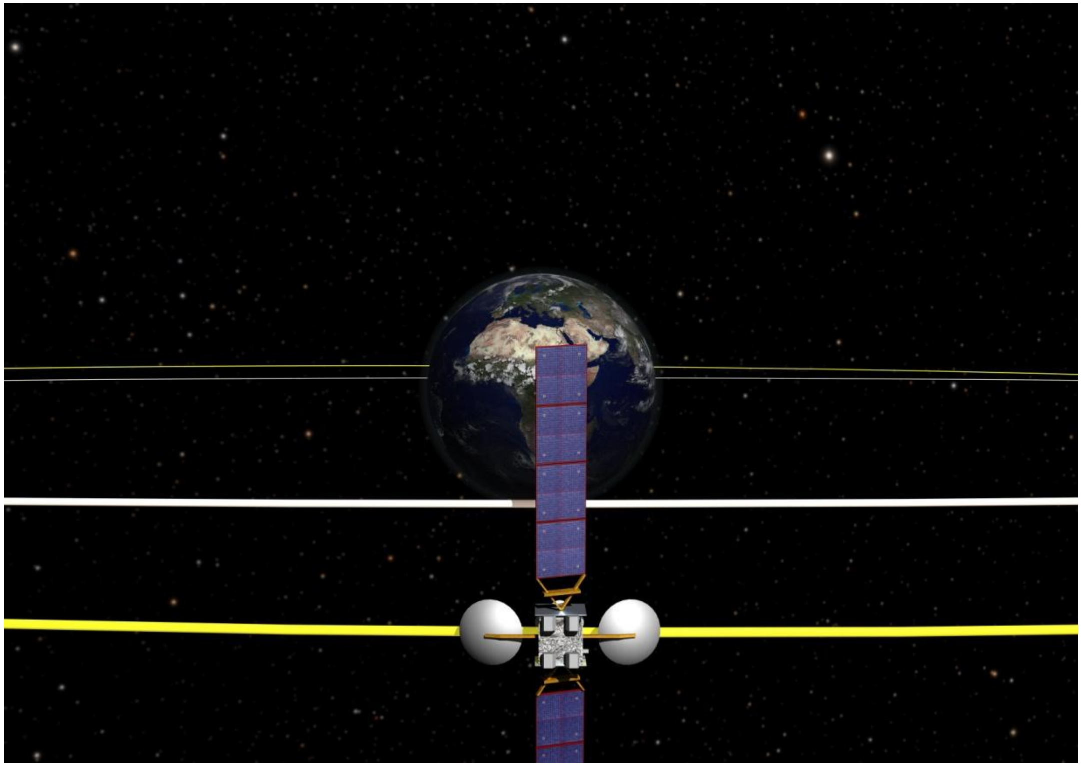
Station keeping

To compensate for perturbations of orbit due to gravitational and other forces, satellites must operate their thrusters and perform manoeuvres at regular time intervals.

Whenever a satellite diverges too much from its nominal position thrusters are fired. Here a so-called North-South station keeping manoeuvre is shown, where the orbit inclination is put back to zero degrees. (Image: ESA)



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Thruster calibration facility at European Space Agency labs (ESTEC), Noordwijk

- Requirements
  - Calibrate in vacuum in purpose-built laboratory
  - Frequency range from mHz to 10 Hz and beyond
  - Measure forces in micronewton to millinewton range
  - Isolation from environmental disturbances, including seismic disturbances
- Solution
  - Micro-Newton thrust balance (µNTB) designed by NPL

Thrust balance method of operation: 1

- System is composed of two identical null-displacement balances, the Measurement Balance Assembly (MBA) and the Tilt Compensation Assembly (TCA)
- Both balances built in the form of a monolithic folded pendulum
- A capacitive displacement sensor measures the thrust-induced displacement of the pendulum
- A force actuator integrated in a feedback servo system applies a force to the pendulum so that its displacement is held at zero (null displacement)

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Thrust balance method of operation: 2

- Force actuators were designed and manufactured by NPL for the μNTB
- The actuators are voice coil actuators including a Maxwell pair solenoid assembly and a permanent magnet mounted in a holder
- Thruster is placed on the MBA and a dummy load is placed on the TCA
- TCA signal is subtracted from the MBA signal to eliminate tilt effects and low frequency noise

Thrust balance measurement challenges

- Both balances are exposed to the same environmental disturbances but only one balance is used for thrust measurements
- Prior to subtracting the balance outputs beneficial to correct the two outputs for system and balance effects using deconvolution
- In practice there are small differences in performance between the balances that make deconvolution and vibration compensation a challenging task

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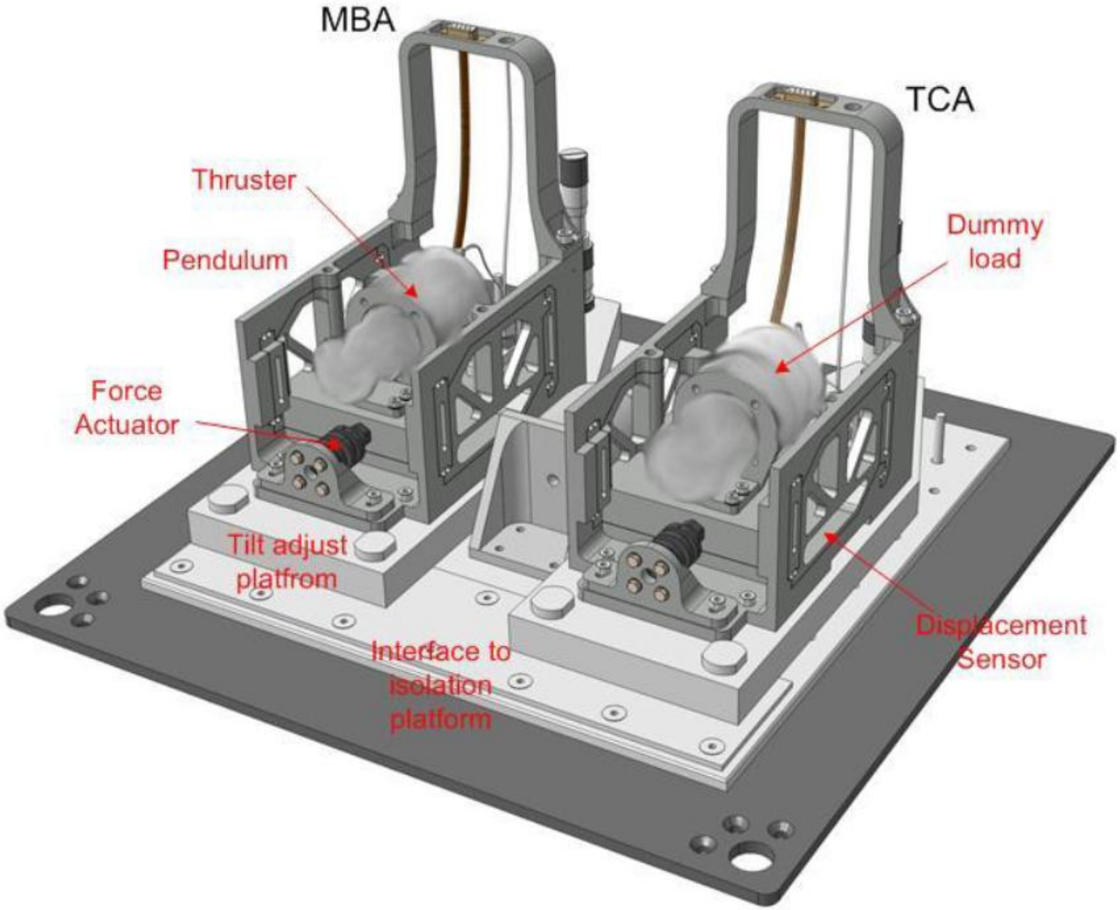
Thrust balance schematic



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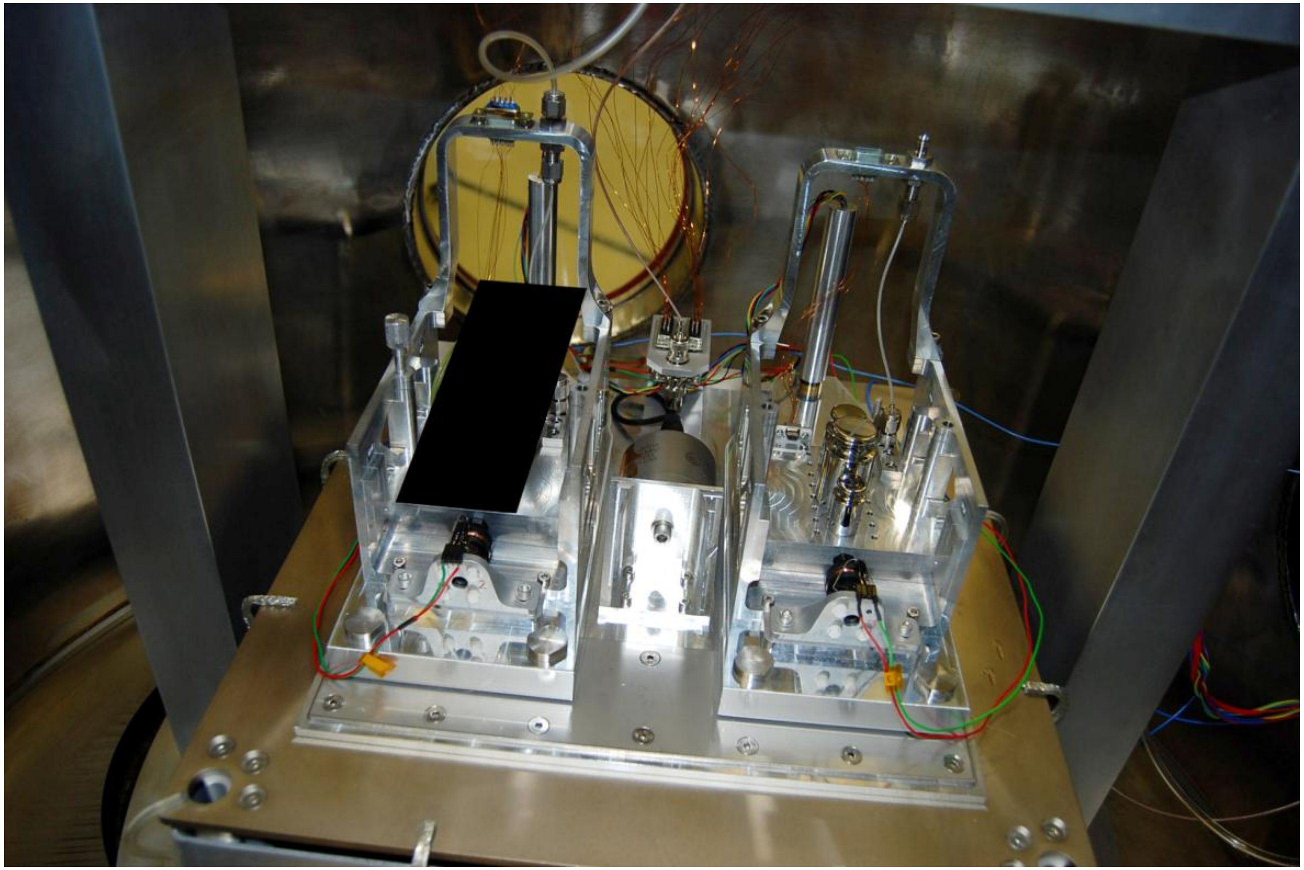
Thrust balance with load and dummy load



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Uncertainty analysis needs

- Typical input signal used to drive thruster is a series of steps
- Would like to associate an uncertainty with estimates of individual step heights
- Currently have to omit parts of measured step signal output to avoid transients at start and end of step
- Can deconvolution help to obtain improved estimates of step heights and associated uncertainties?

Continuous transfer function model of balance

$$\frac{T_m}{T} = \frac{\frac{k_a k_p k_c}{M_e}\left(1 + \frac{1}{s\tau_i} + \frac{s\tau_d}{1 + s\tau_f}\right)}{s^2 + \left(\frac{k_a k_p k_d}{M_e} + 2\xi\omega_0\right)s + \frac{k_a k_p k_c}{M_e}\left(1 + \frac{1}{s\tau_i} + \frac{s\tau_d}{1 + s\tau_f}\right)}$$

T_m	Measured thrust
T	Applied thrust
k_a	Force actuator sensitivity
k_p	Displacement sensor sensitivity
k_c	PID proportional gain
k_d	Velocity feedback gain

τ_f	PID derivative filter time constant
τ_i	PID integration time constant
τ_d	PID derivative time constant
M_e	Equivalent mass of pendulum
ξ	Damping ratio of pendulum (open loop)
ω_0	Natural frequency of pendulum (open loop)

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Nominal values

	MBA	TCA
k_a	63.192 μN/V	59.947 μN/V
k_p	0.0787 V/μm	0.0787 V/μm
k_c	35	35
k_d	3.2	3.2
τ_f	0.000035	0.000035
τ_i	0.07	0.07
τ_d	0.0035	0.0035
M_e	0.3 kg	0.3 kg
ξ	0.009048	0.01698
ω_0	14.5537 rad/s	14.4237 rad/s

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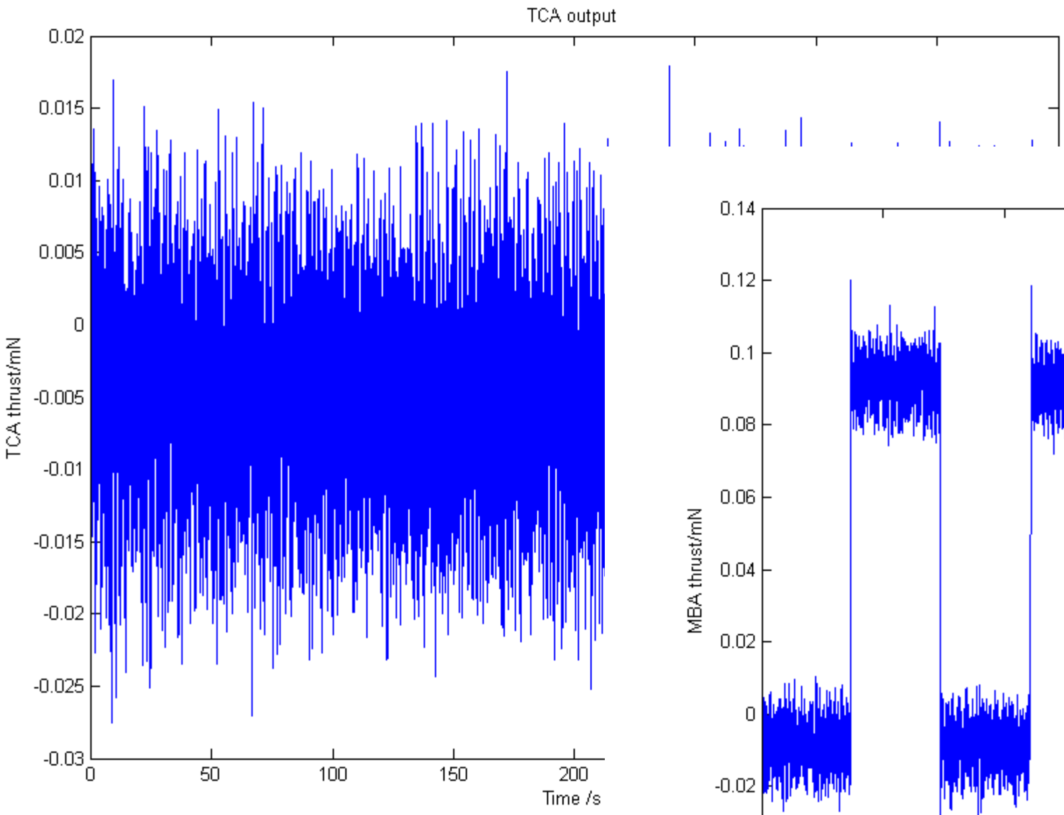
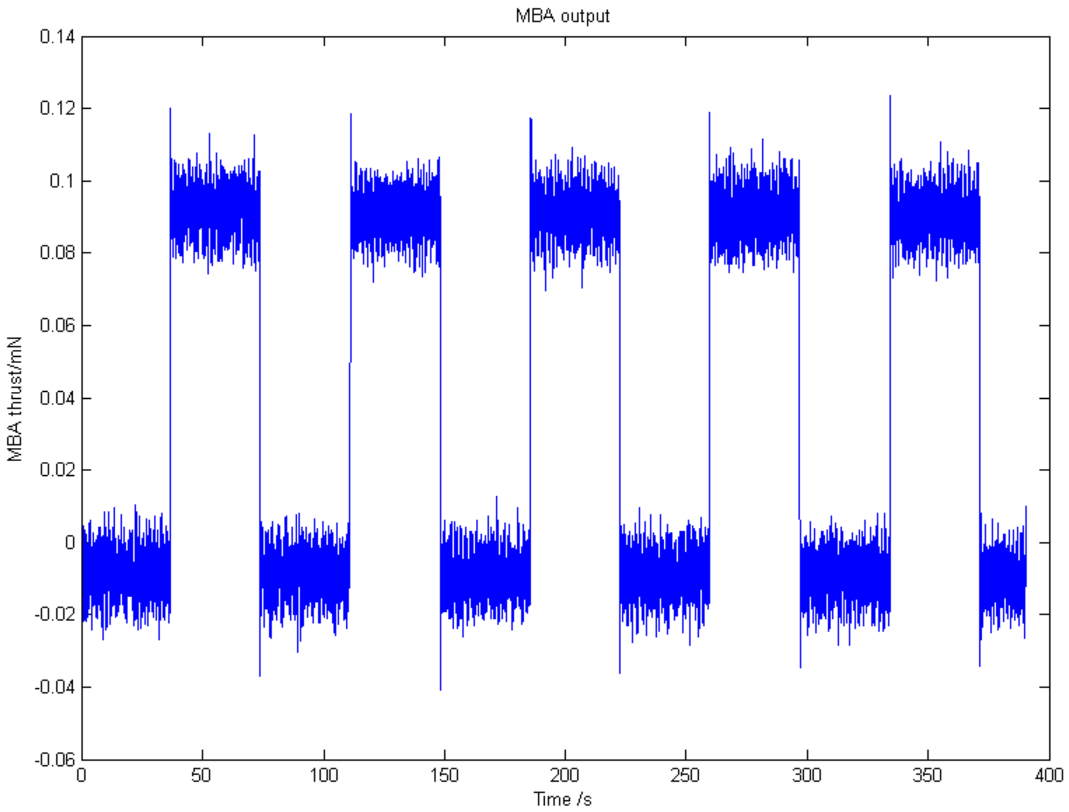
MBA and TCA outputs





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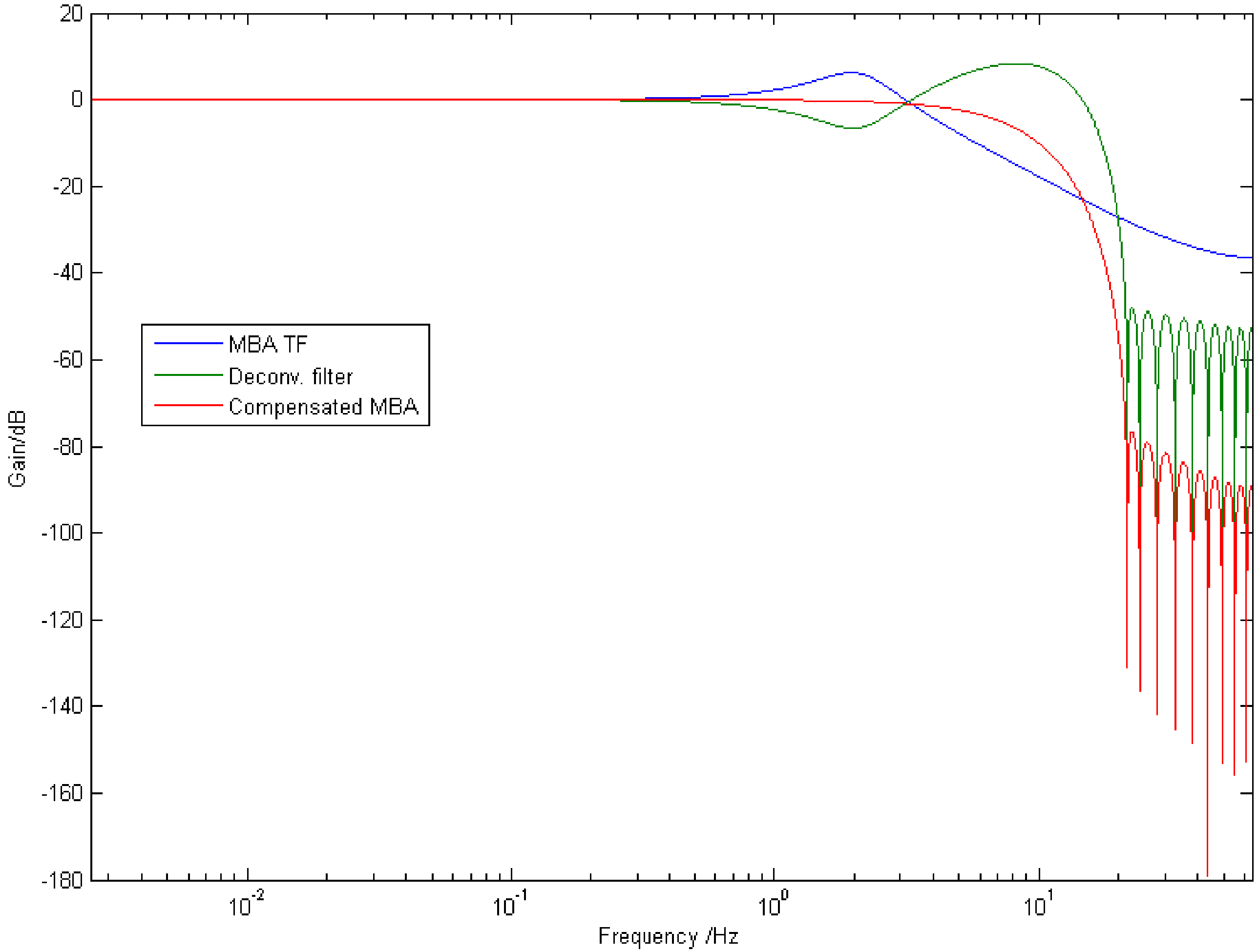
Compensation filter: MBA



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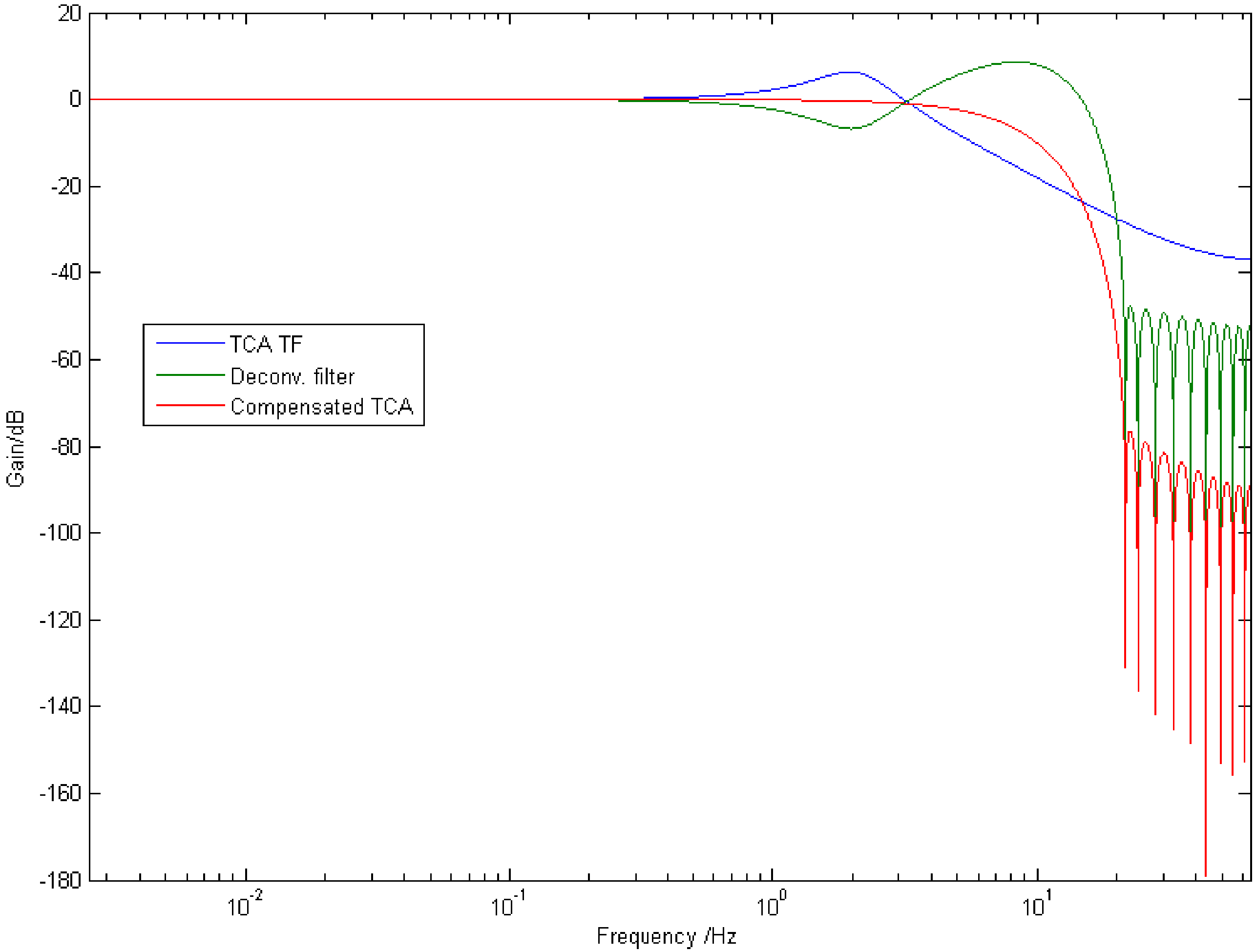
Compensation filter: TCA



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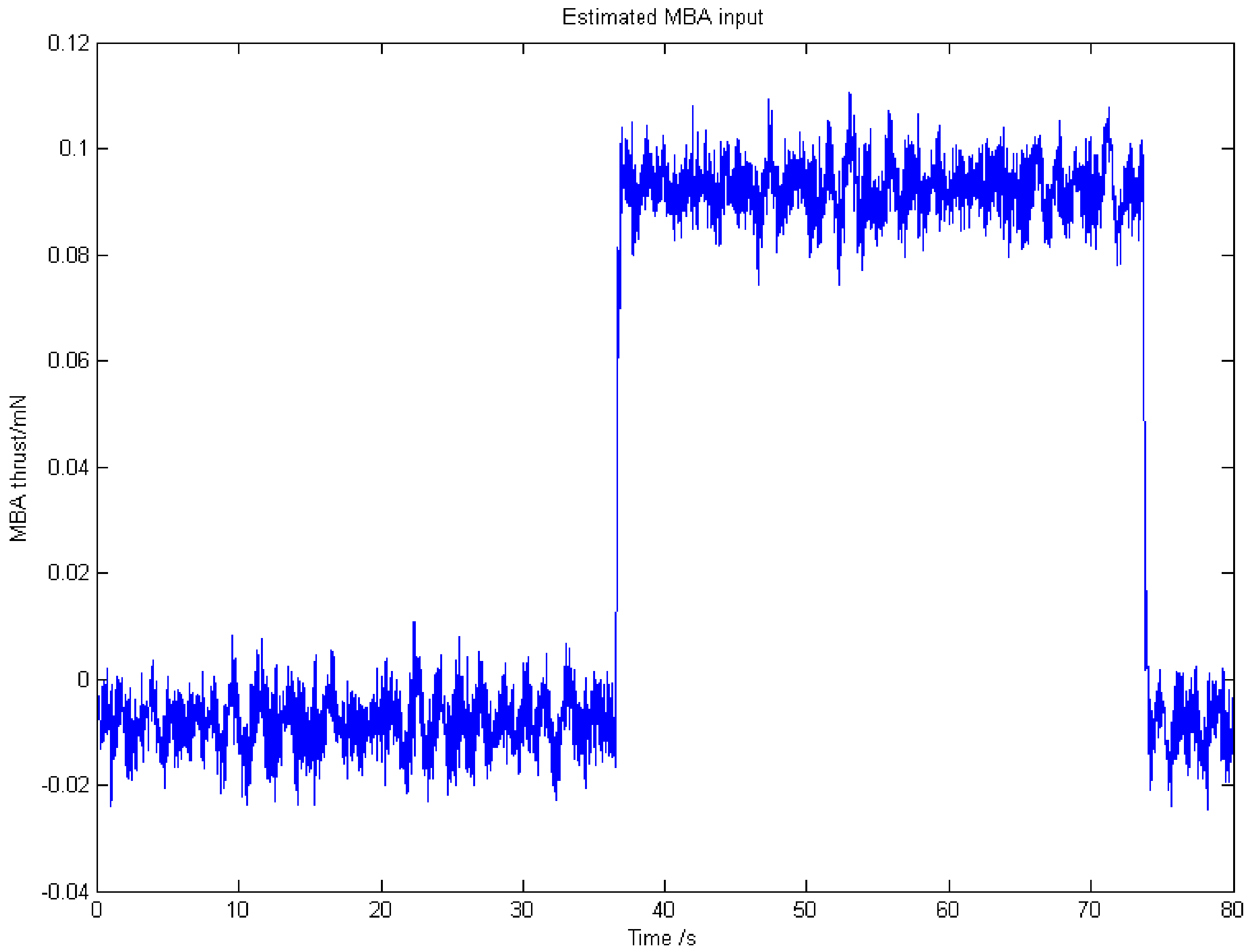
Estimated MBA input



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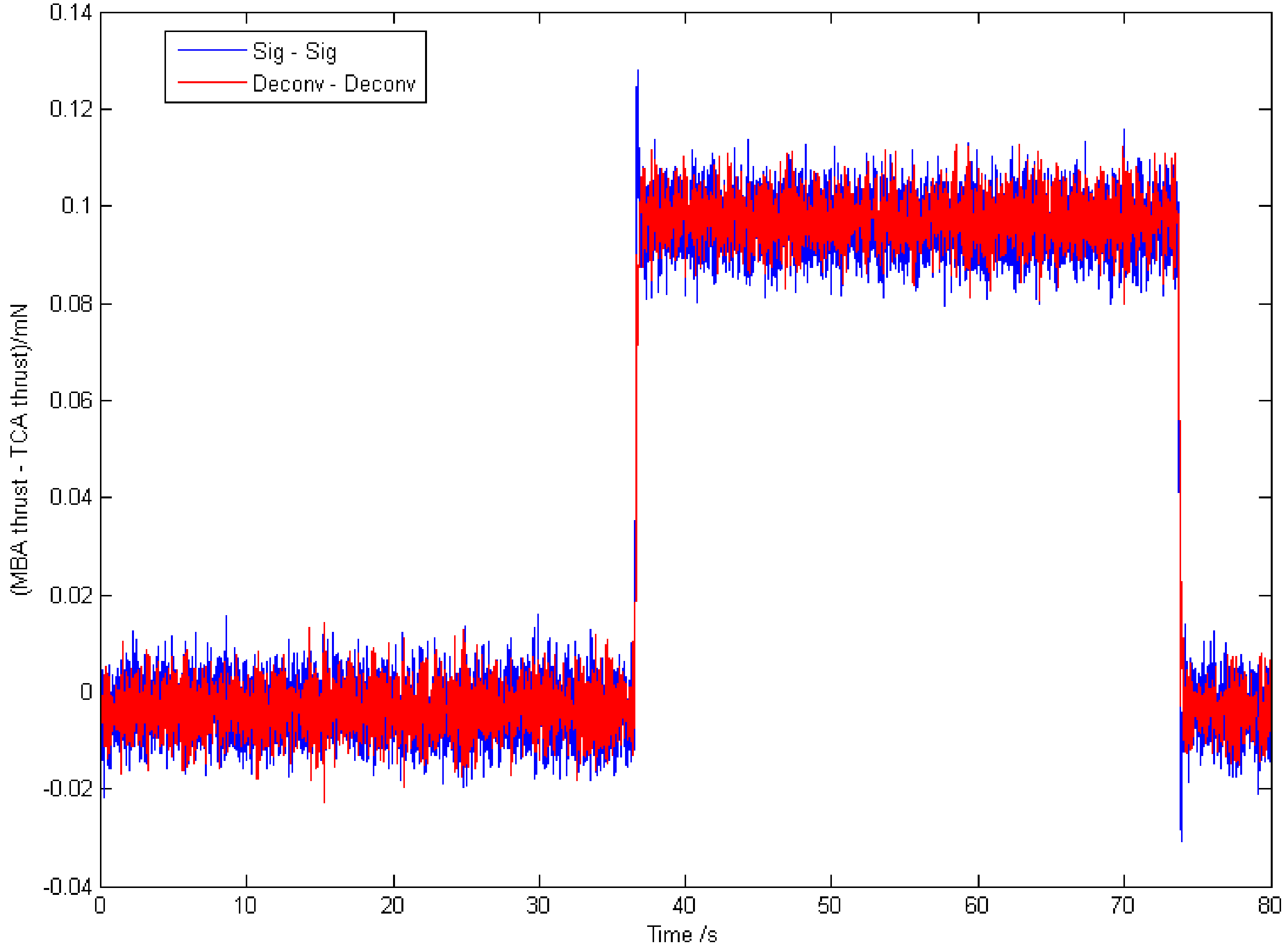
MBA – TCA after deconvolution



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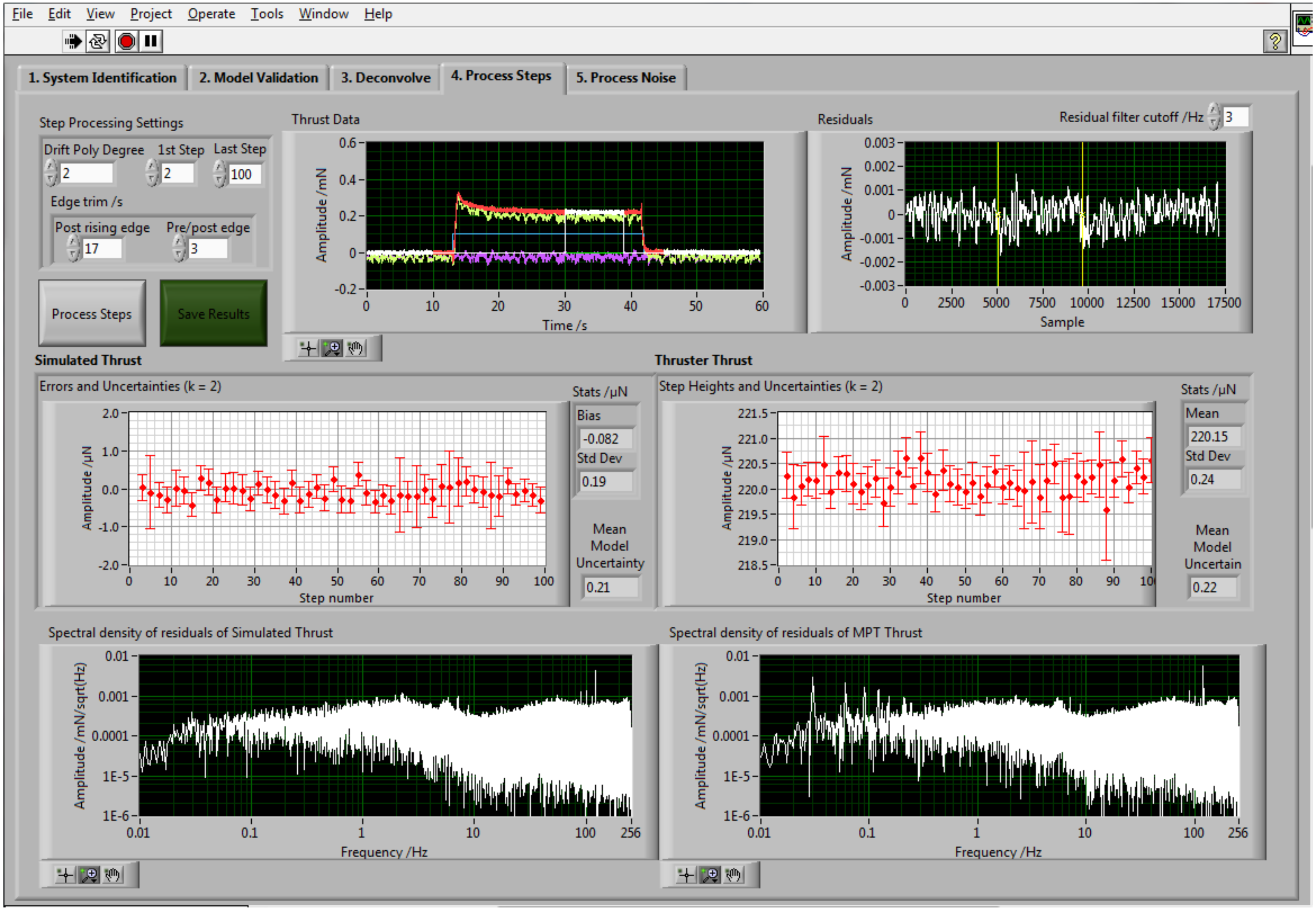
Typical step height uncertainties



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Where next with dynamic measurements?
Some questions from a BIPM workshop

System identification and calibration session: 1

- Guide to the expression of uncertainty in measurement (GUM)
  - To what extent is it currently understood and used by industry metrologists?
  - Can the GUM methodology be applied easily to industrial dynamic measurement problems?

System identification and calibration session: 2

- How are dynamic measurement tasks tackled at present?
  - Ignore the problem and use static calibration data in dynamic situation?
  - Make many repeat measurements to gain confidence in data but without reliable uncertainty analysis?

System identification and calibration session: 3

- Do we need new mathematics or new measurement/ sensing methods, or both?
  - New sensors with sufficient bandwidth, or new deconvolution and signal correction methods?
- What is the current extent of signal processing expertise in industry?

System identification and calibration session: 4

- How can NMI maths and uncertainties experts best support industry partners who have dynamic measurement problems?
- Calibration certificates of the future, what might they look like?
  - Lists of numbers on paper, or software for digital correction filters?

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EMRP project NEW04: Novel mathematical and statistical approaches to uncertainty evaluation August 2012 – July 2015

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Project topics

WP1

Inverse Problems and Regression

- Bayesian statistics
- Prior knowledge and physical constraints
- Simultaneous observation equations

WP2

Computationally Expensive Systems

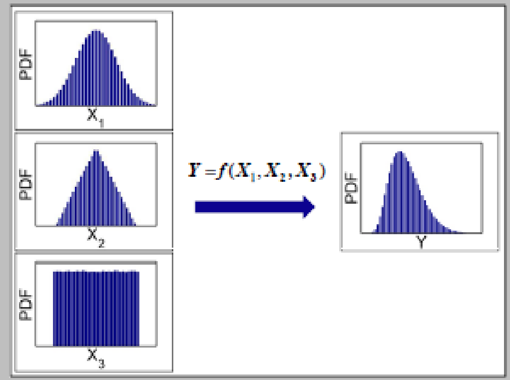
- Smart sampling methods
- Surrogate and statistical modeling

WP3

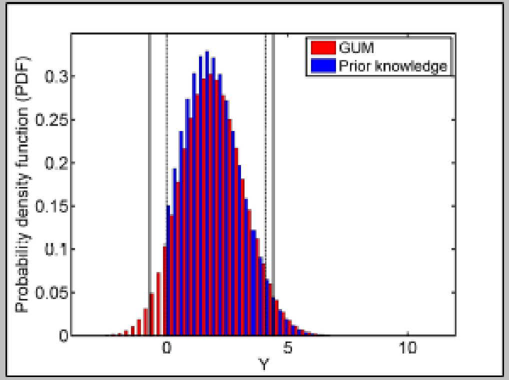
Decision-making and Conformity Assessment

- Methods for multivariate problems
- Cost function approach

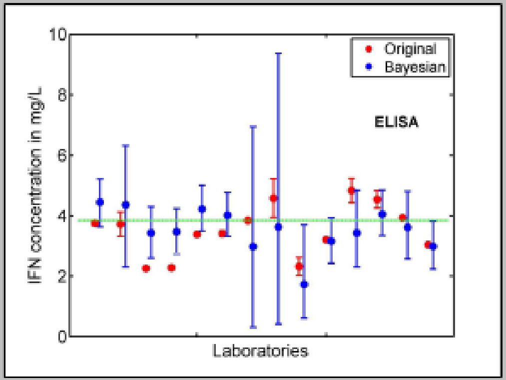
Monte Carlo Sampling



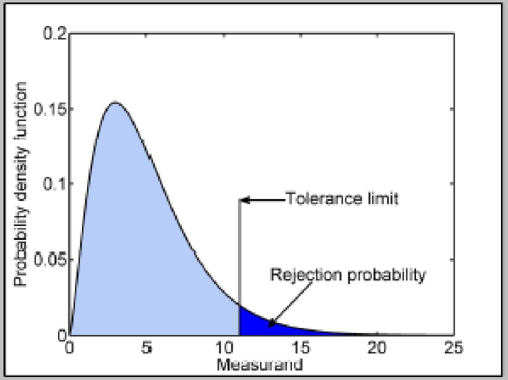
Prior Knowledge



Regression Methods



Conformity Assessment



Project team

JRP-Participants

PTB
Germany

CMI
Czech Republic

FORCE
Denmark

INRIM
Italy

JV
Norway

LGC
United Kingdom

LNE
France

NPL
United Kingdom

SP
Sweden

VSL
Netherlands

SCA (unfunded)
Sweden

Collaborators

WP1: Inverse problems and regression

- Regression and inverse problems arise when the quantity of interest cannot be measured directly, but has to be inferred from measurement data (and their uncertainties) by using a mathematical model that relates the quantity of interest and the data
- Such problems occur in many applications from everyday calibration tasks to advanced techniques in rapidly growing areas such as biochemistry and nanometrology
- Need new tools as well as guidelines and standards for uncertainty evaluation

WP1: solutions

- Bayesian statistics
- Prior knowledge and physical constraints
- Simultaneous observation equations
  - Note: observation equation defines what is being measured or observed, unlike traditional measurement model that links outputs to influence quantities

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WP2: Computationally expensive systems

- Many important applications described by model equations whose numerical solutions are computationally expensive e.g., the Navier-Stokes equations for fluid flows, and other transport equations
- Most computationally expensive systems are strongly nonlinear
- Linear approximations for uncertainty evaluation, as suggested by the GUM, can be applied, but results may be invalid

WP2: Solutions

- Simulations using a Monte Carlo method recommended by Supplement 1 to the GUM (GUM-S1)
  - Current Monte Carlo methods are based on a large number of model evaluations and consequently cannot be applied practically to computationally expensive systems
- Solutions
  - Smart sampling methods
  - Surrogate models and statistical modelling

WP3: Conformity assessment and decision-making

- Many measurements are made to provide an objective basis for decisions about a product or process.
- Inevitable presence of measurement uncertainty leads to the risk of incorrect conformity decisions for consumers and suppliers
- Need to make reliable conformity decisions given relevant measurement results
- Ensure the consistent application of decision-making techniques

WP3: Solutions

- Multivariate cases not currently addressed in guidelines and standards – need to extend current guidelines to these cases
- Cost function methods – to balance producer’s and consumer’s risk
- Note: current guidelines for univariate cases can be found in JCGM 106:2012 *Evaluation of measurement data: The role of measurement uncertainty in conformity assessment*

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Thermophysical properties of materials

- Links NEW04 work packages on regression and inverse problems (WP1) and on computationally expensive systems (WP2)
  - Laser flash thermal diffusivity technique being studied by both WPs: requires measurement of a time-varying temperature (therefore also a dynamic problem)
  - WP1: homogeneous samples
  - WP2: layered systems

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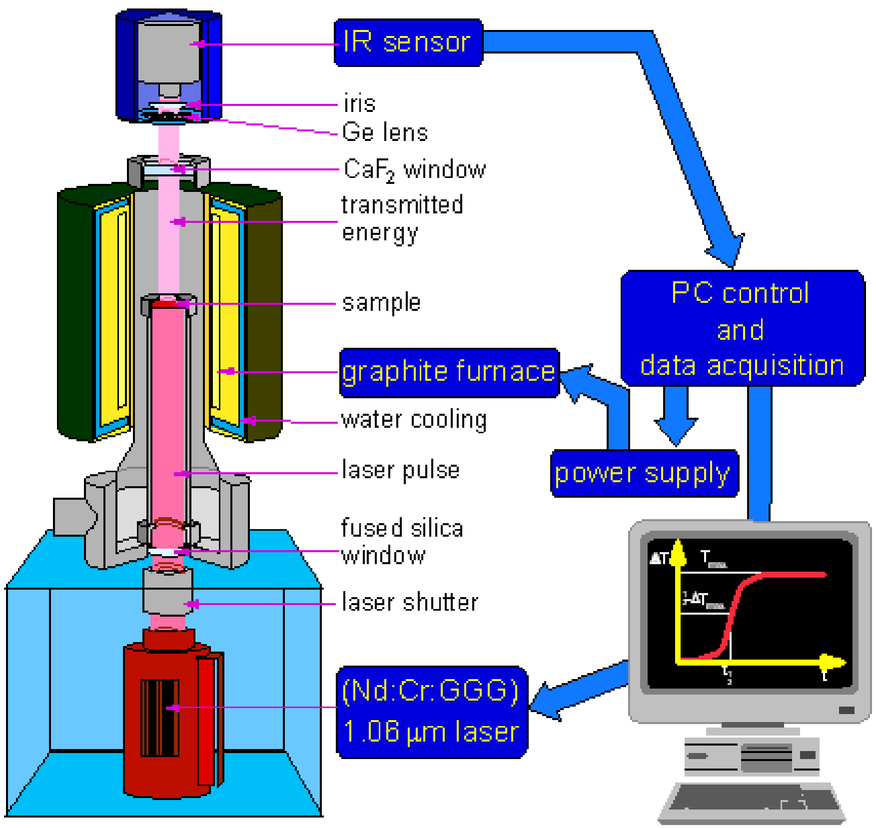
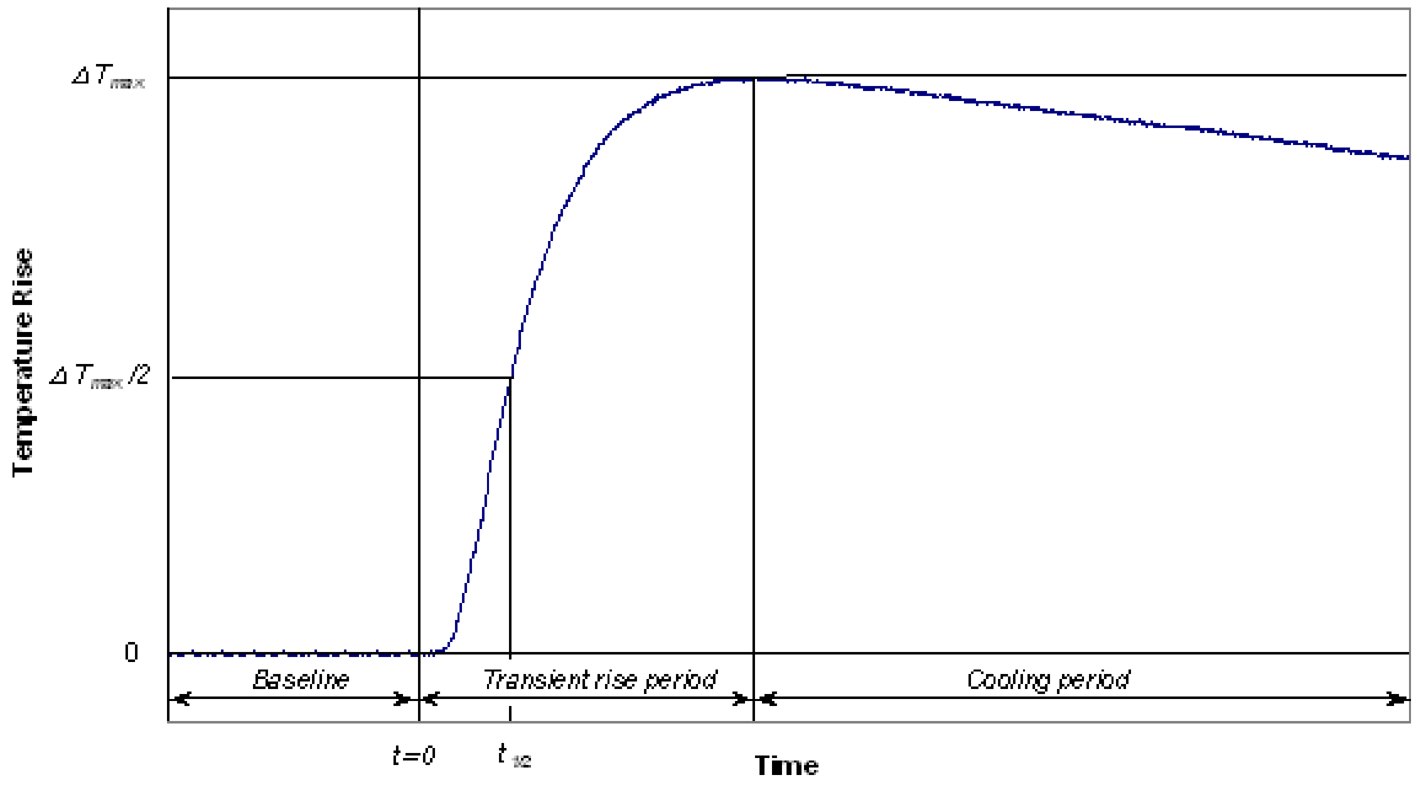
Laser flash apparatus at NPL



Measure temperature/time history



Deriving the thermal properties of interest

- Diffusivity and conductivity not measured directly
- Infer these from the temperature time history
  - for the homogeneous case various (analytical) models exist in the scientific literature
  - for the inhomogeneous case will need finite element models and optimisation methods to fit to data
    - will require surrogate models and/or smart sampling techniques for computationally expensive cases

To learn more about NEW04

- http://www.euramet.org/fileadmin/docs/EMRP/JRP/JRP_Summaries_2011/New_Tech_JRPs/NEW04_Publishable_JRP_Summary.pdf
- http://www.ptb.de/emrp/new04.html

Model uncertainty

Sources of uncertainty in models: 1

- Parameter uncertainty (available knowledge of input quantities in a model is captured by probability distributions)
- Structural uncertainty (the model approximates the physical system)
- Model-selection uncertainty (there are often several models of the physical system)
- Condition uncertainty (relating to boundary and initial conditions, and forcing functions)

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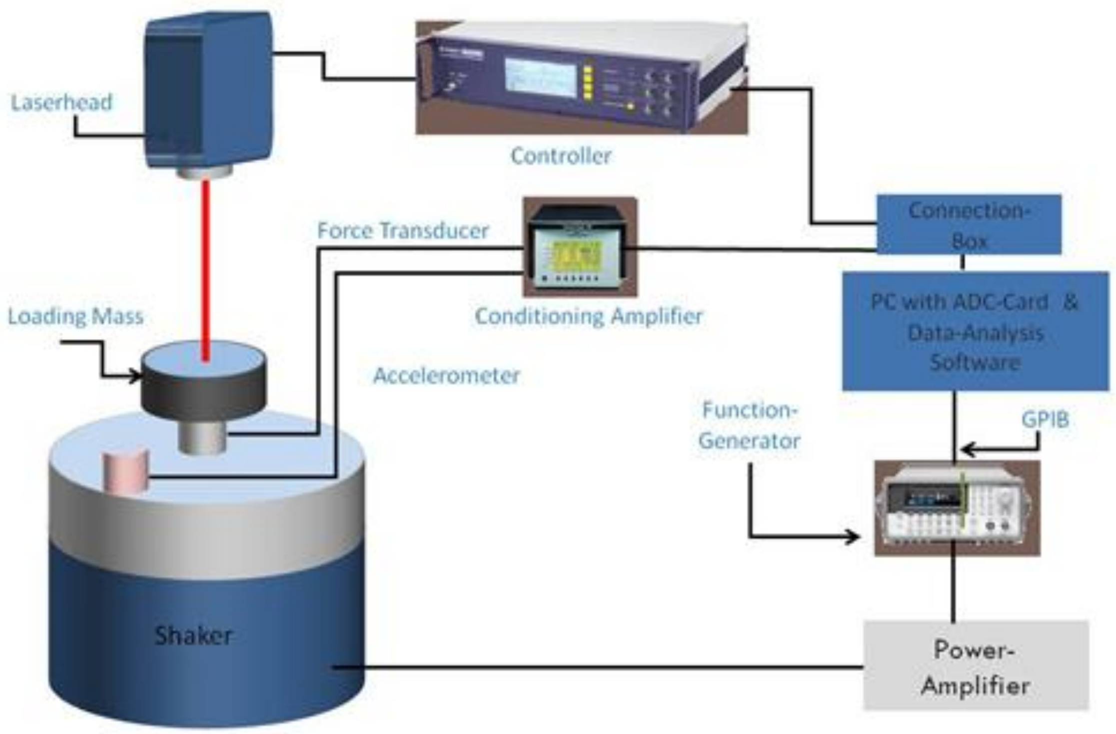
Sources of uncertainty in models: 2

- Functional uncertainty (the model function is expensive to evaluate and so unknown almost everywhere)
- Solution uncertainty (numerical methods are used to solve the model)
- Note: knowledge elicitation techniques are used to derive probability distributions that capture available knowledge of the input quantities and parameters involved in a model

Dynamic force calibration set-up: PTB Braunschweig



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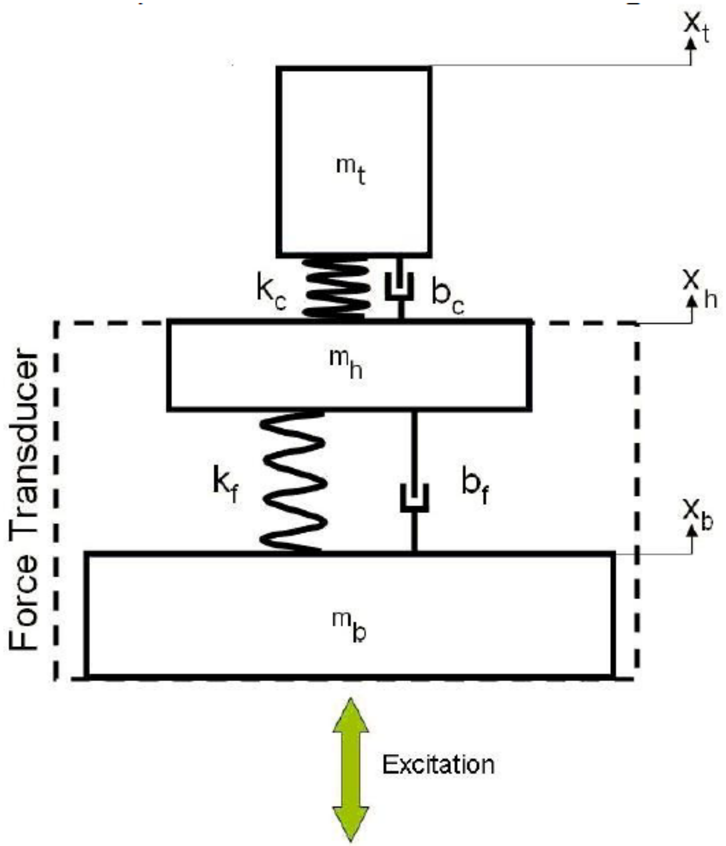
1-D model of calibration system



$$m_t a_t = -k_c(x_t - x_h) - b_c(\dot{x}_t - \dot{x}_h)$$

$$m_h a_h = k_c(x_t - x_h) + b_c(\dot{x}_t - \dot{x}_h) - k_f(x_h - x_b) - b_f(\dot{x}_h - \dot{x}_b)$$

$$m_b a_b = k_f(x_h - x_b) + b_f(\dot{x}_h - \dot{x}_b) + F$$

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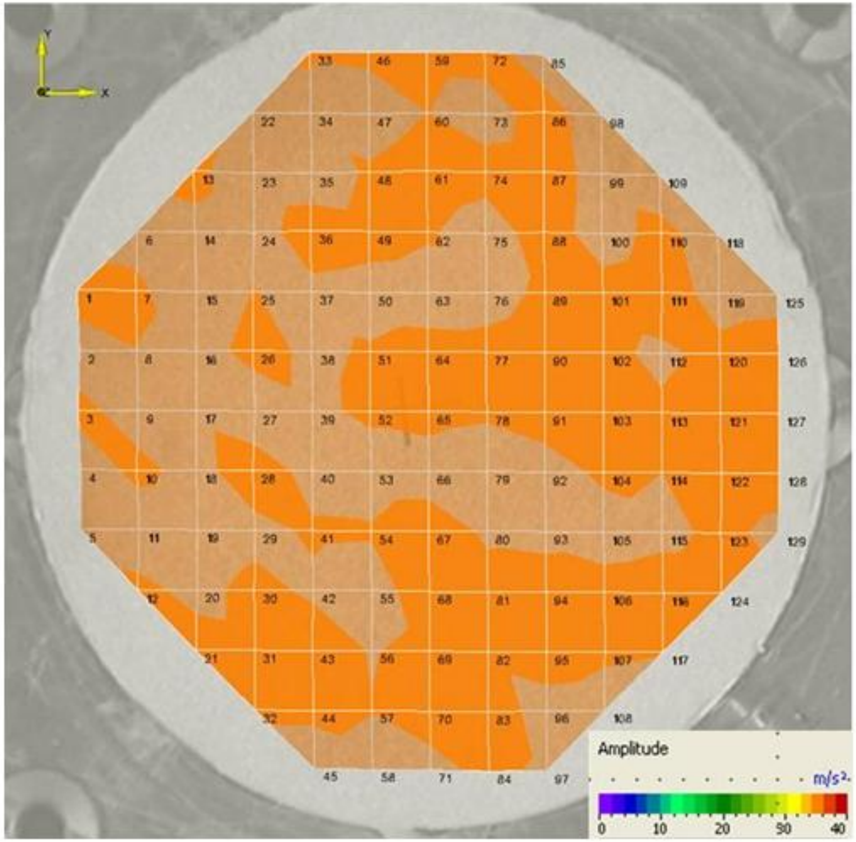
Laser detects rocking motion of top mass



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Model uncertainty or experimental uncertainty?

- Replace 1-D lumped parameter model by 3-D finite element model?
- … or treat variation in observed acceleration as measurement uncertainty?
- Would the different approaches produce the same value for the uncertainty estimate?
- How to use a finite element model within the calibration task?

Summary: 1

- Have introduced two new EMRP projects that address new challenges in modelling and uncertainty analysis
- Both projects are at an early stage – progress can be tracked on the project web sites
- New industrial and academic partners are still actively being sought for both projects

Summary: 2

- EURAMET is seeking views on future of EMRP

Support European Metrology Research!

Public Consultation now open.

Please spend 10 minutes of your time and take part in the Public Consultation of the European Commission on a "European Metrology Research Programme under Horizon 2020". The evaluation is a crucial factor for the support of the proposed EMRP-successor programme EMPIR.

Until December, 23rd 2012 individuals, companies and institutions are invited to pronounce their opinion on metrology research in Europe in this online questionnaire. Feel free to invite your network in other research institutions, local companies and policy to answer the questionnaire.

http://ec.europa.eu/research/consultations/metrology/consultation_en.htm

EMRP project approved November 2012

Large Volume Metrology in Industry

EURAMET European Association of National Metrology Institutes

END USER NEED	AEROSPACE		ADVANCED MANUFACTURING		BIG SCIENCE
					
	International traceability 100 laser trackers in 5 countries	**Clean Skies: Laminar flow wing, weight loss** Improved jig and manufacture accuracy	**Factory of the future, Energy production** Metrology networks, error map large tools	**High value engineering** Compensate thermal errors, measure fast	**LHC replacement at CERN** 25 km tunnel, 10x better beam accuracy
	Need: calibrate/verify ADM SOA: requires intrinsic interferometer	Need: 100 µm full wing accuracy SOA: 400 µm	Need: < 100 µm SOA: 200 µm	Need: 100 µm in 15 °C to 30 °C factory SOA: 200 µm, slow photogrammetry	Need: 10 µm accuracy in 200 m SOA: 100 µm to 300 µm

National Measurement System

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National Measurement System

National Measurement System

The National Measurement System delivers world-class measurement science & technology through these organisations

National Measurement Office NPL National Physical Laboratory LGC Setting standards in analytical science nel technology for life

The National Measurement System is the UK's national infrastructure of measurement Laboratories, which deliver world-class measurement science and technology through four National Measurement Institutes (NMIs): LGC, NPL the National Physical Laboratory, TUV NEL the former National Engineering Laboratory, and the National Measurement Office (NMO).