Precision interferometry for traceable sub-nanometer displacement measurements

Dirk Voigt

Dimensional Metrology

VSL R&D

Precision Fair 2011

1 December 2011

Precision Fair 2011

Dutch Metrology Institute

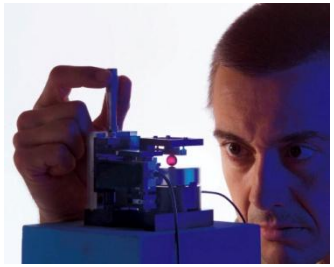
Dutch Metrology Institute

- **National Metrology Institute:**
  part of Holland Metrology Group
  private company (shareholder TNO)
- **Public task:**
  national standards
  metrology infrastructure

- **Broad scope:**
  dimensional metrology, photometry, chemistry, flow and electrical power

Holland Metrology

HOLLAND METROLOGY



VSL

- National measuring standards

NMi

- Type approval metrology & gaming
- System certification
- Calibration & verification
- Netherlands
- Belgium
- Italy

VERISPECT

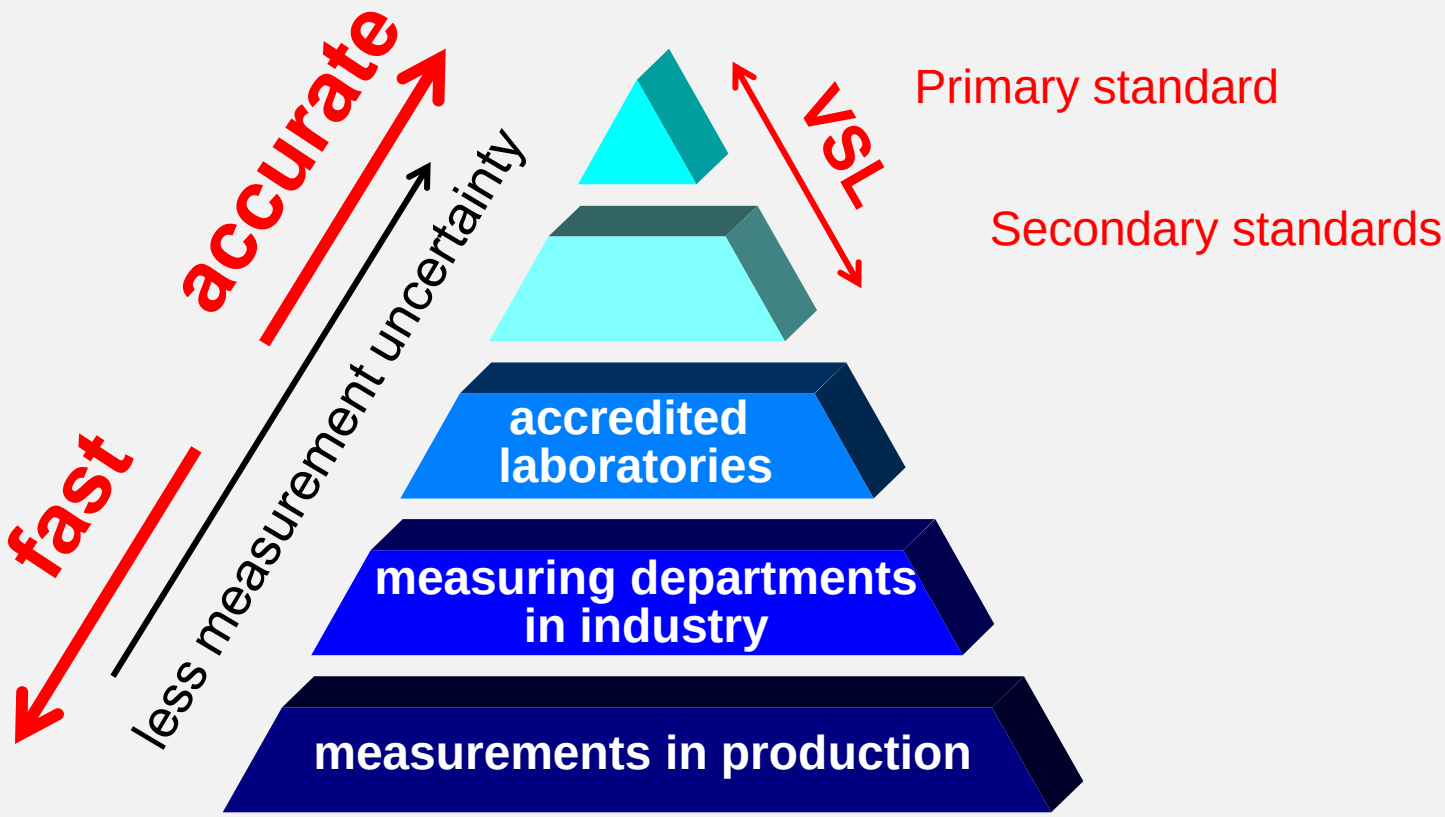
- Inspection & enforcement
- Metrology & gaming
- Independent

Services:

- Calibrations of lowest uncertainty
- Reference materials
- Instrument validation
- Consultancy, metrology support, complex calibrations
- Training

VSL is independent (before 2009: **NMi Van Swinden Laboratorium**)

“Snel en nauwkeurig”



High Tech Systems and Materials

Semiconductor industry – Wafer steppers

Metrology Needs:

- Sensors: calibration
- Materials, connections: (bolts, glue, bonds) drift stability

Metrology platforms

- “fast and accurate”
- picometer scale
- cost efficiency

Roadmaps: ITRS, EuMat, Euromet, Top Sectors (NL)

Time Scales

Scanning microscopy

Production equipment Lithograpy

Transfer standards Gauge blocks

Space Photonics Consumer products

Recalibration interval cost factor

Minute | Week | Year | Lifetime

Dimensional Calibrations

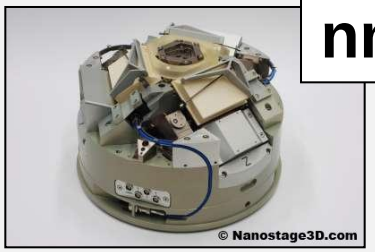
Coordinate Measuring Machines

- **F25 micro-CMM (Zeiss / VSL)**
- tactile and optical metrology (imaging)
- µm accuracy / cm range

µm

Nanometrology

- **metrological AFM (TU/e / VSL)**
- nm accuracy / mm range



nm

Picometer accuracy, µm..cm range?

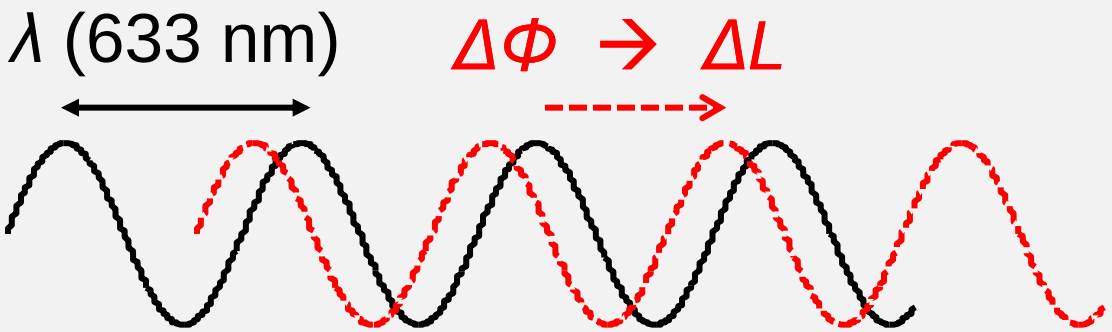
- capacitive sensors ➔ **Interferometry**

pm

Optical wavelength ruler

Count wavelength or measure phase change

Calculate displacement



Laser wavelength is directly traceable

Direct traceabilitiy to time standard

Displacement → λ [m] → frequency → time [s]

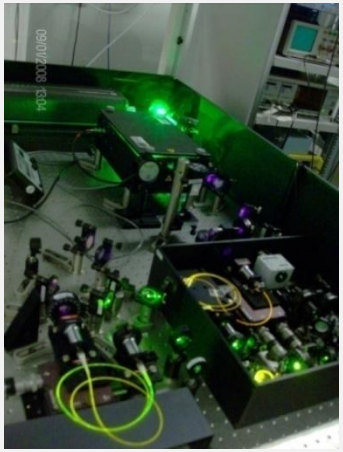
Laser frequency traceable to atomic clock

$$f = c / (n_{air}\ \lambda_{air}) = 474\ \text{THz}$$

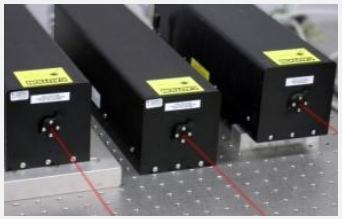
- Wavelength in air $\lambda_{air} = 632.8$ nm
- Air refractive index $n_{air} = 1.003$

Sub-nanometer uncertainty and precision

- Need to know (stable) air $\Delta n_{air} / n_{air} < 10^{-8}$
- Temperature, pressure, humidity, CO_2 concentration



optical frequency comb generator



Iodine stabilized lasers

VSL Measurement Services

Measure with sub-nanometer accuracy

- Uncertainty budget and traceability

Dimensional stability measurement

- Picodrift Interferometer

Displacement sensor calibration

- Metrological Fabry-Pérot Interferometer

You can contribute to EMRP

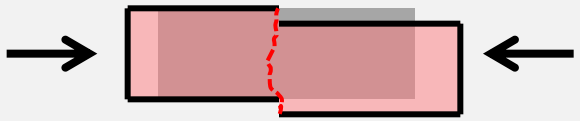
- European Metrology Research Program

Picodrift – Dimensional Stability

How measure intrinsic dimensional drift ?

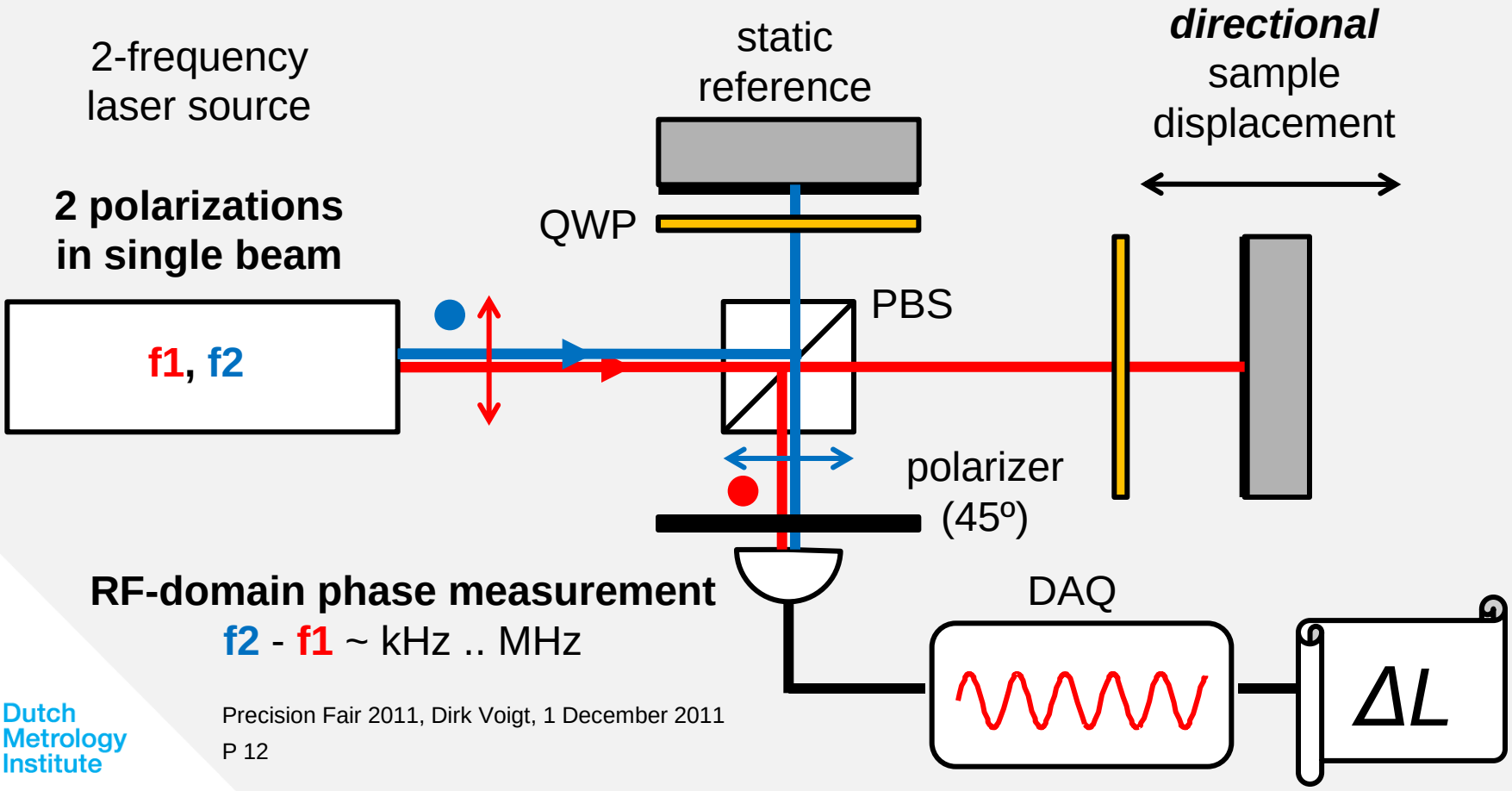
Uncertainty 10 pm (100 pm) over a minute (week)

- Instrumentation ***insensitive*** to perturbations
  …rather than (impossibly) stable
- Discriminate **instability events**
  …from thermal expansion
  …measure fast enough
- Don't touch
  …use double-ended optical interferometry

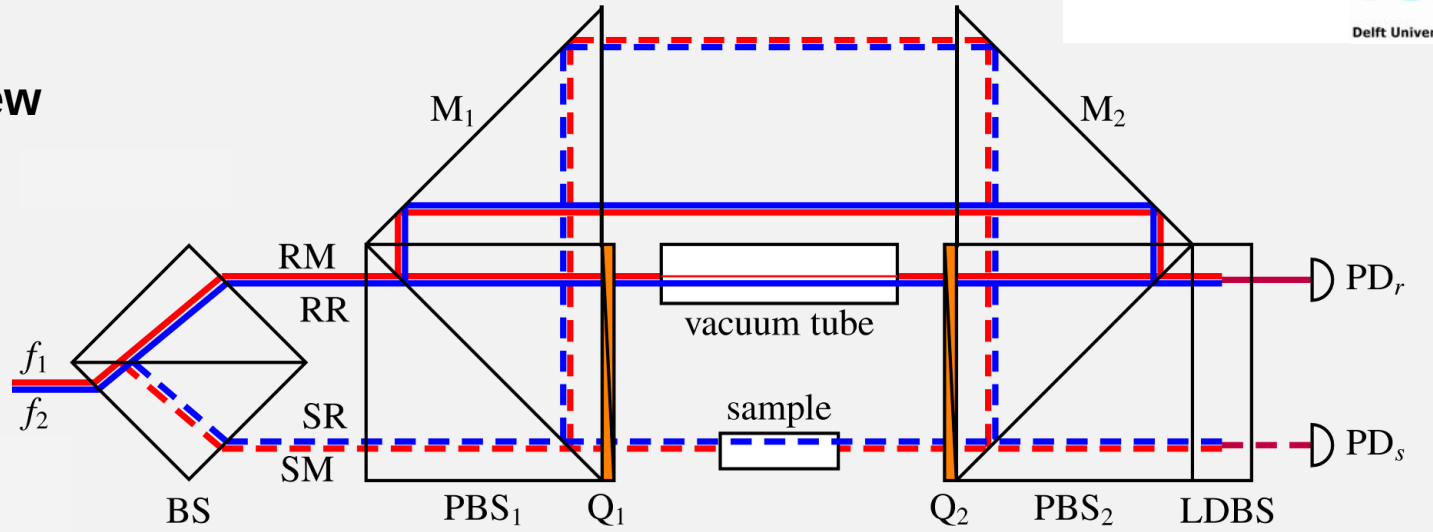


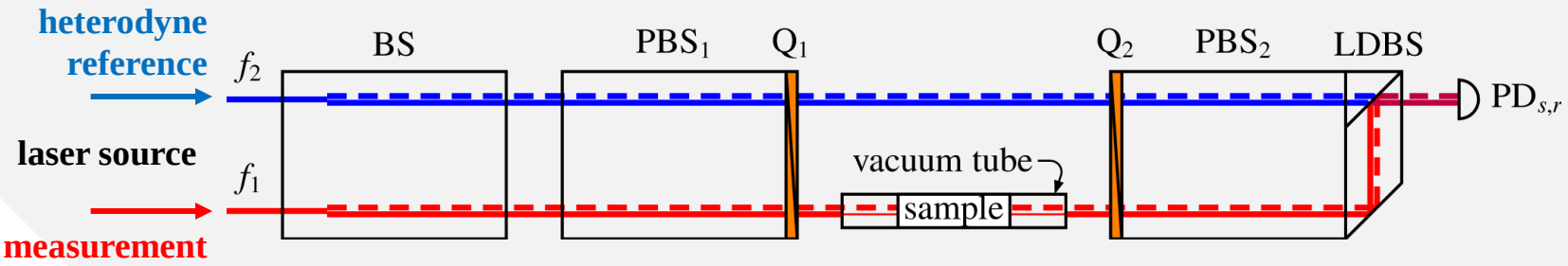
Heterodyne Interferometers

Commercial state-of-the art (~ nm uncertainty)



Insensitive Heterodyne Interferometer





Sample interferometer

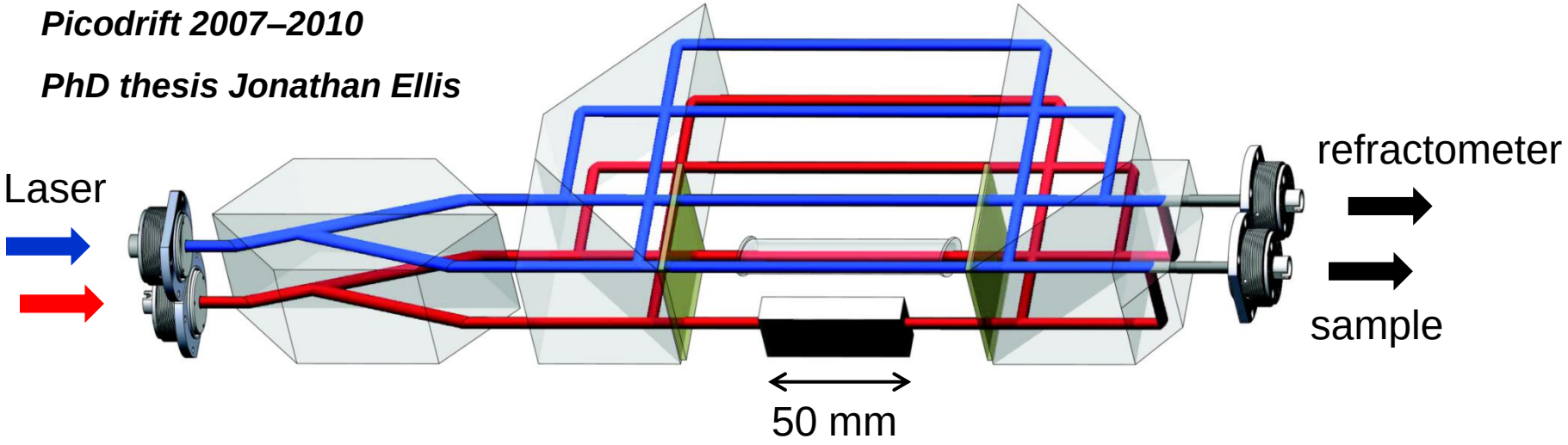
Refractometer

Picodrift Twin-Interferometer

AgentschapNL IOP Precisietechnologie

Picodrift 2007–2010

PhD thesis Jonathan Ellis



- Double-ended, balanced heterodyne interferometer
- Spatially separated frequency split source delivery
- In-situ air refractive index compensation (twin-interferometer)
- Monolithic optics (custom TNO), fiber coupled source and detection

Pressure-Sealed Test Setup

Intrinsic system drift stability?

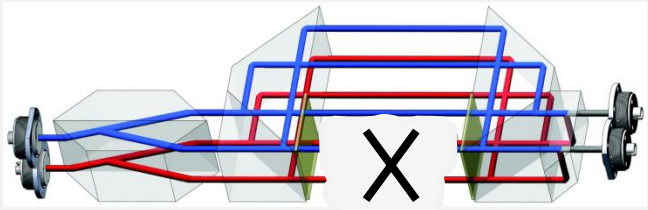
“Double dead path”:

- Empty interferometers

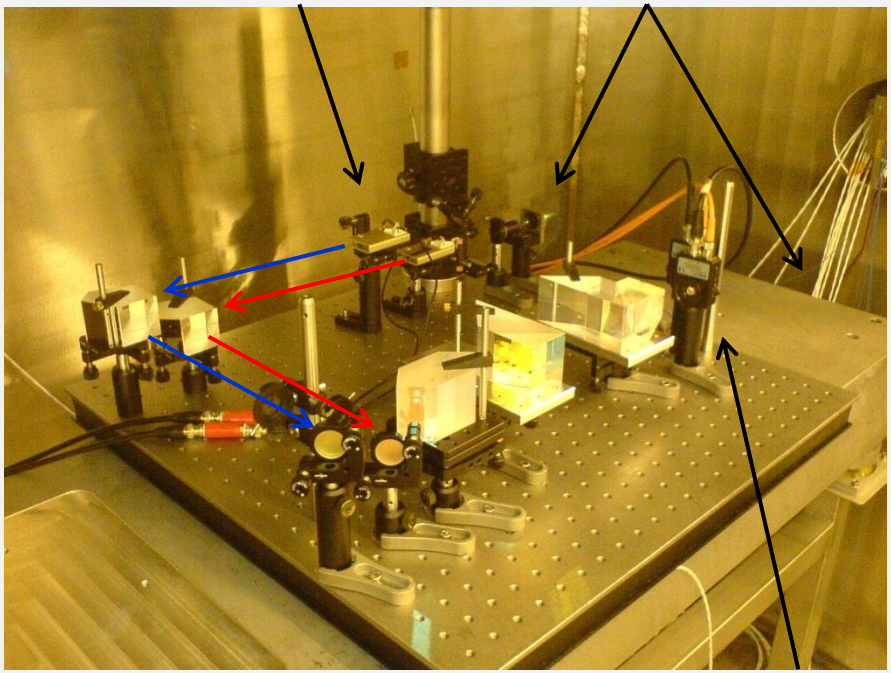
  no sample, no vacuum cell

- Differential displacement:

  Drift $= \Delta L_{\text{sample}} - \Delta L_{\text{refractometer}}$



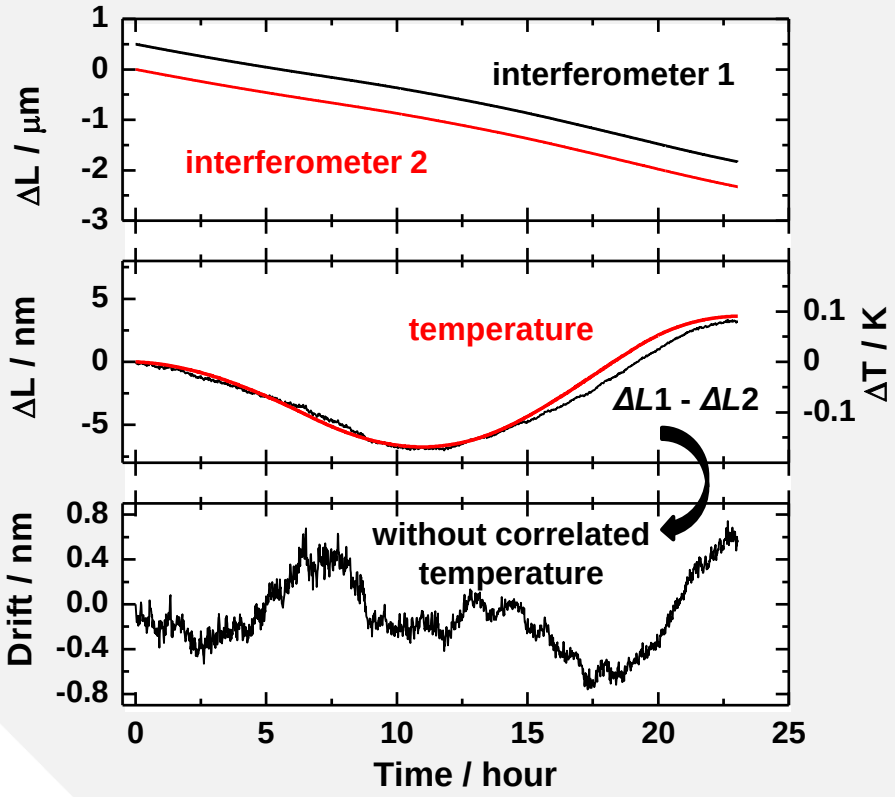
AOM’s (f_1, f_2) Laser source fiber



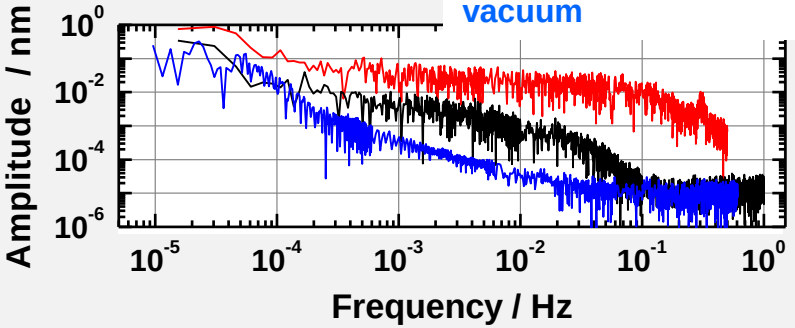
Detectors

Twin-Interferometer Stability

Drift



Noise



- Sub-nm drift over hours
- 30 pm noise level over a minute
- Need stable temperature & refractometer or vacuum

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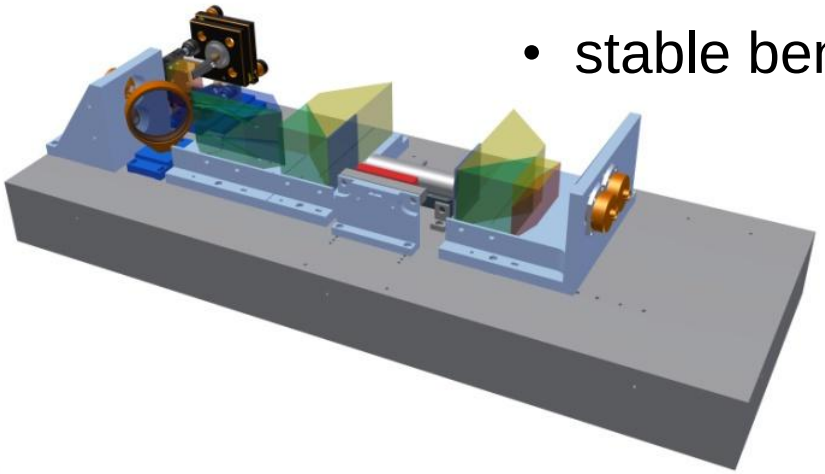
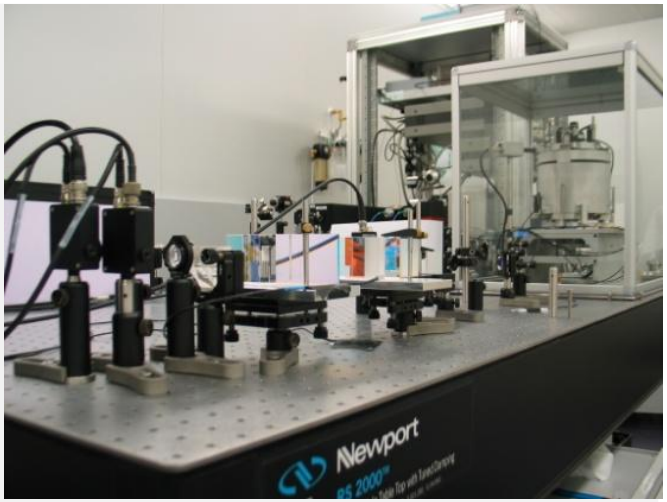
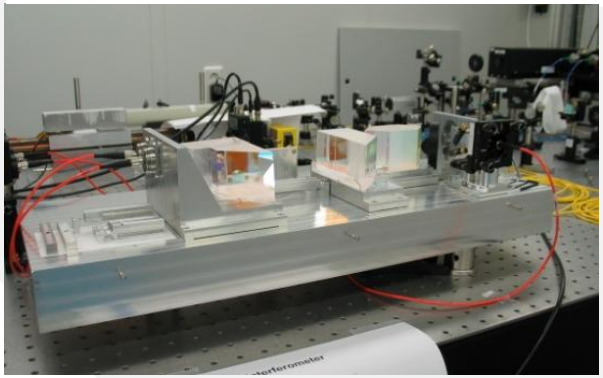
Voigt *et al.*, Meas. Sci. Technol. **22** (2011) 094029

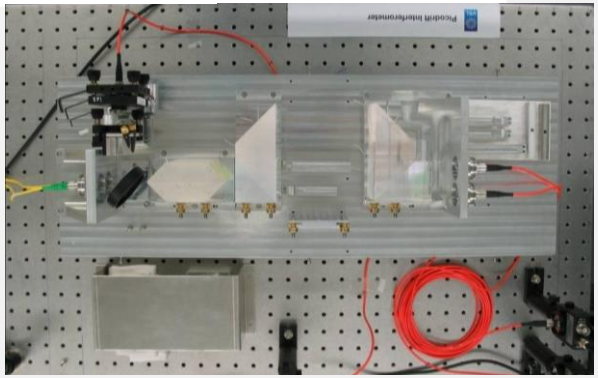
Picodrift … next steps

- stable VSL *Nanolab*
- stable bench









- Custom optics and kinematic bench by TNO
- added heterodyne optical reference pick-up

Sensor calibration

What do we need ?

- Resolution, precision, accuracy
- Displacement range
- Referencing interface, sensor alignment
- Drift stability, dynamics (fast?)

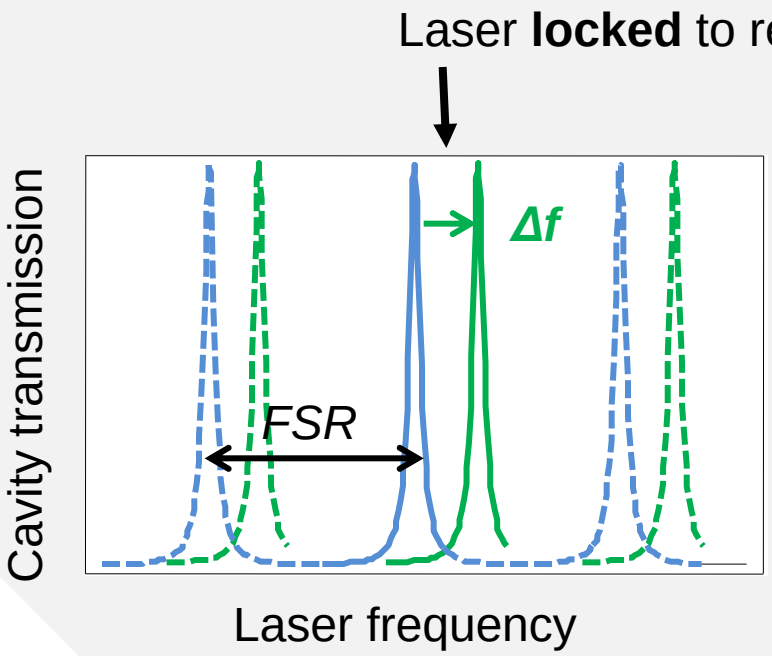
Accuracy:

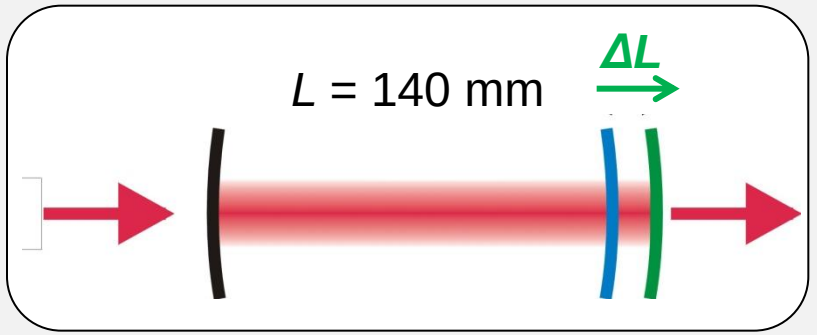
- *Systematic* uncertainty budget
- Traceability

Fabry-Pérot Interferometry

Laser frequency tracks cavity length change ΔL

➔ Sensitivity 3.4 MHz/nm, high resolution



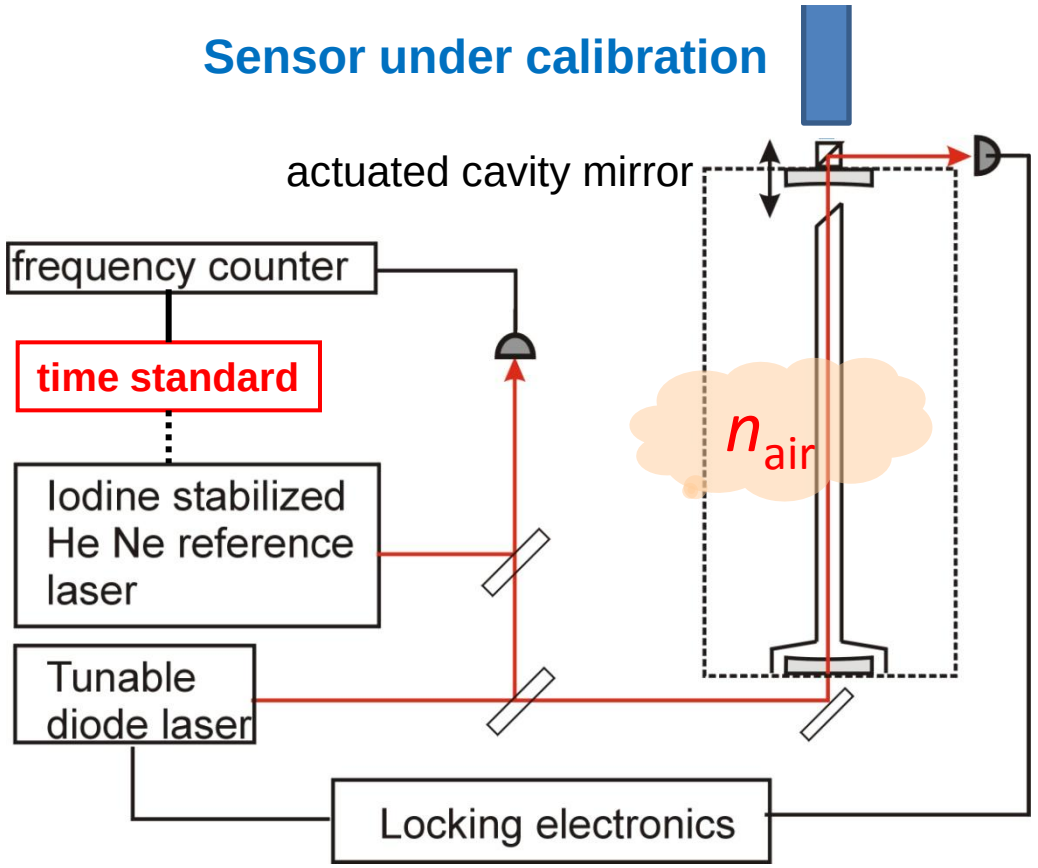


$$\Delta L = \frac{\Delta f}{FSR} \cdot \frac{\lambda}{2} \qquad FSR = \frac{c}{2nL}$$

Free Spectral Range 1070 MHz

Metrological FPI

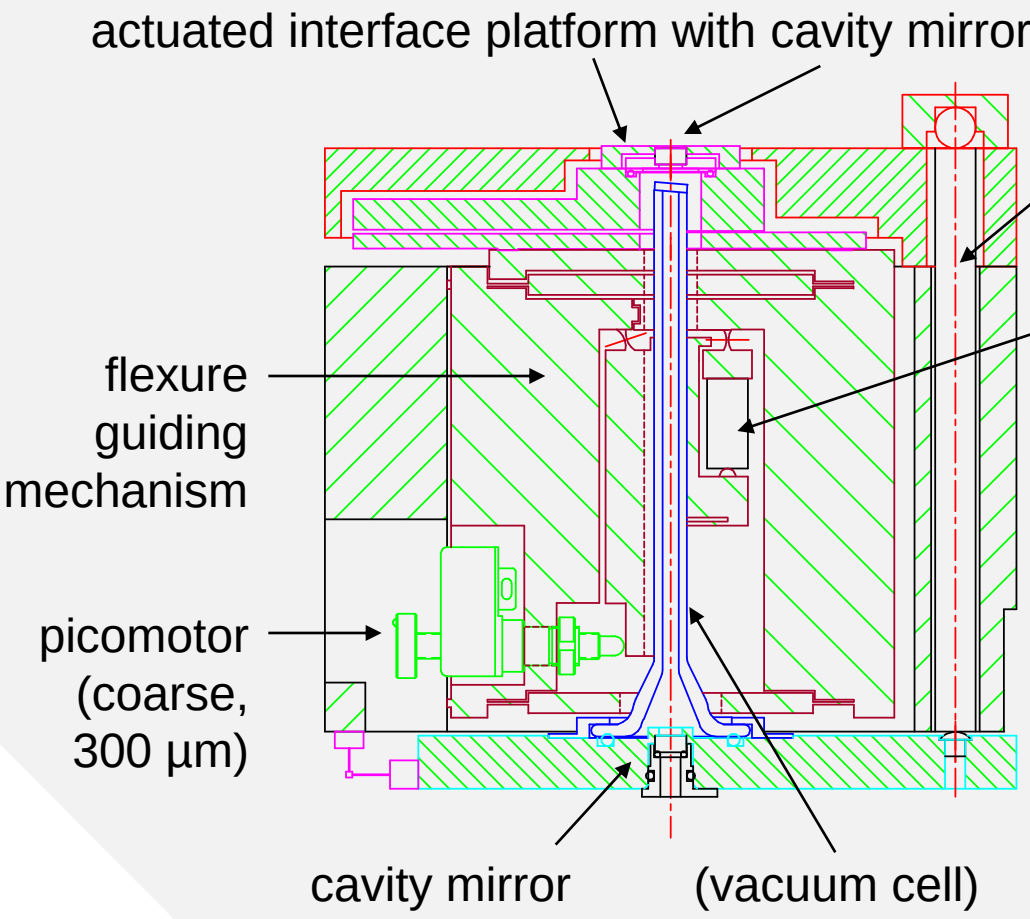
Traceable displacement calibration

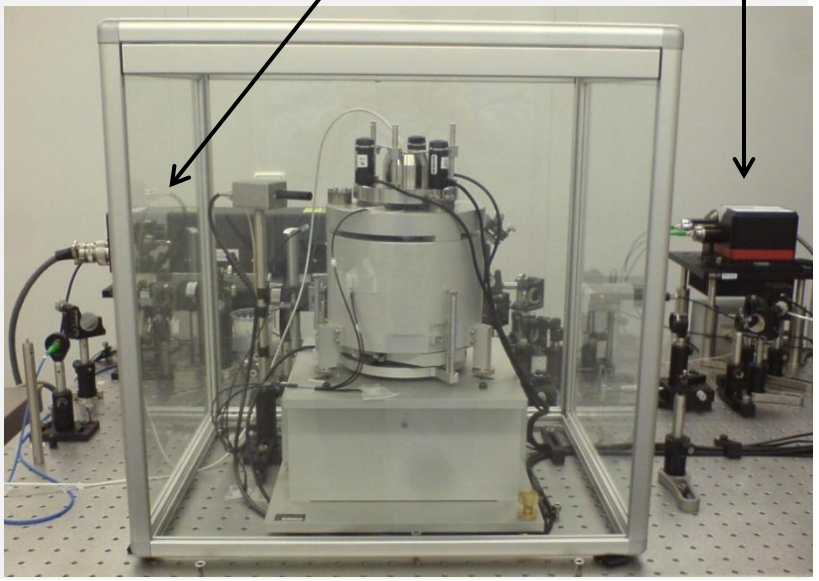


- **Versatile referencing to sensors:**
  - capactive
  - inductive
  - optical
- **Climate logging:**
  - temperature
  - pressure
  - humidity
  - CO_2
- (vacuum or Helium cell)

Metrol. FPI developed by TU/e & VSL

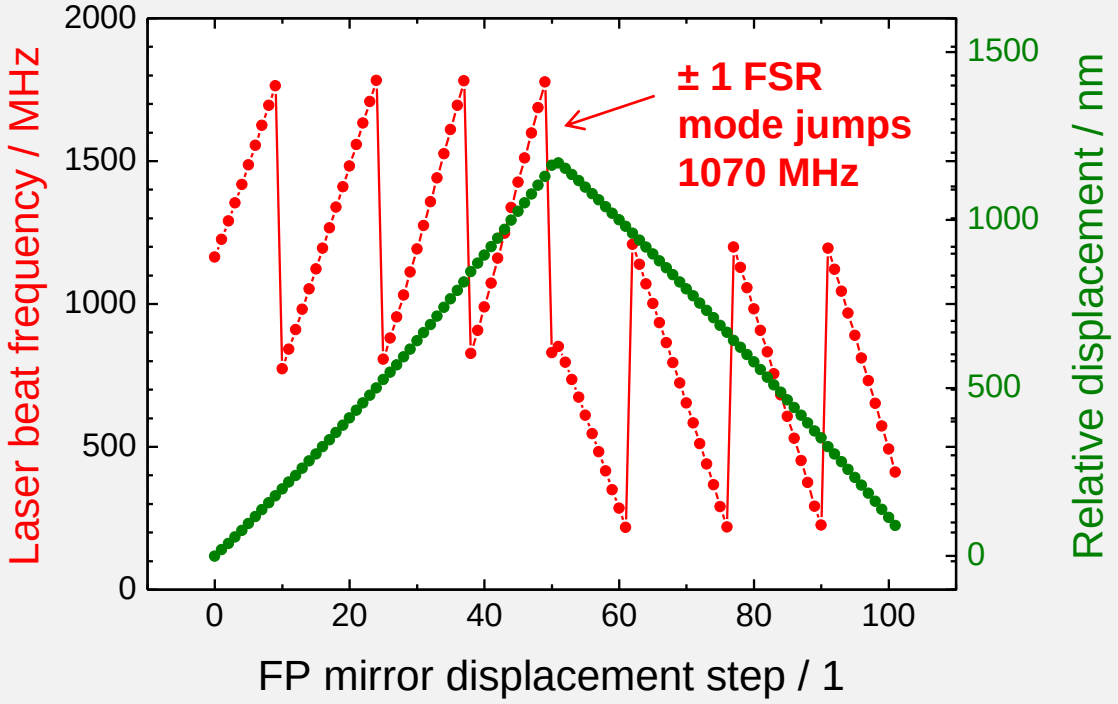
PhD thesis S.F.C.L. Wetzels, TU/e (1998)





Metrol. FPI – Measurement Process

- Scanning mirror generates up/down displacement
- Laser locking mode jumps (reference detection limits)



Metrol. FPI – Uncertainty Budget

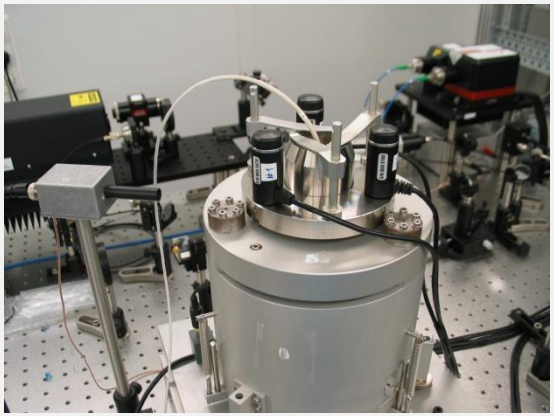
Uncertainty contribution	Displacement 0.3 µm Standard uncertainty / nm	Displacement 300 µm Standard uncertainty / nm
Frequency measurement	0.01	0.01
Laser lock	0.05	0.05
Alignment (sensor)	**0.05**	**10**
Cavity air gap	0.3	0.3
Brewster window	0.2	0.2
Thermo-mechanical stability	**0.5**	**0.5**
Cavity mirror tilt	0.0004	0.4
Laser gain profile	0.0002	0.002
Cavity length	0.13	0.13
Absolute air refractive index	0.00006	0.06
Total quadrature sum	**0.63**	**10.02**
Expanded Uncertainty (k=2)	**1.3 nm**	**20 nm**
Resolution	**0.05 nm**	**0.05 nm**

PhD thesis S.J.A.G.Cosijns, TU/e (2004)

R. Bergmans *et al.*, Proc. SPIE **4401**, 217 (2001)

FPI – Have Thermal Stability

- VSL *Nanolab* cleanroom 0.1 ºC stable
- External viewing / operating room
- Motorized sensor alignment
- Climate monitoring



European Metrology Research Programme

EMRP
European Metrology Research Programme
Programme of EURAMET

Strengthen metrology in Europe

- Joint Research Projects 2009–2016
- Total budget 400 M€
  - 50 % EU, 50 % national funding
  - funding for National Metrology Institutes and Designated Institutes
  - non-funded participation of partners
- **Generate (inter)national impact for industry and society**

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

EMRP Call 2012 – Target Programs

Metrology for Industry

- **innovation** in production for new and better products
- competitiveness and efficiency of European industry
- **project participation from industry**

SI Broader Scope

- development of SI, dissemination: **stakeholder needs**
- fundamental and applied

Open Excellence

- thematically open, techniques new to metrology

➔ ***Impact is leading !***

EMRP – Stakeholder Opportunities

Express your needs

- Call for Potential Research Topics (**PRT**, March 2012)
- Define the topics, submission open to all

  ➔ EURAMET selects research topics (**SRT**)

Participate in Joint Research Projects

- **Stakeholder:** express interest
- **Collaborator:** express support, contribute
- **Non-funded partner:** contractual **JRP** participant

Team up

- Partnering meetings (June), JRP proposal (Oct. 2012)
- **Contact VSL**, see also www.emrponline.eu

EMRP Call 2010 – TP Industry

JRP IND13, “Thermal design and time-dependent dimensional drift behaviour of sensors, materials and structures”

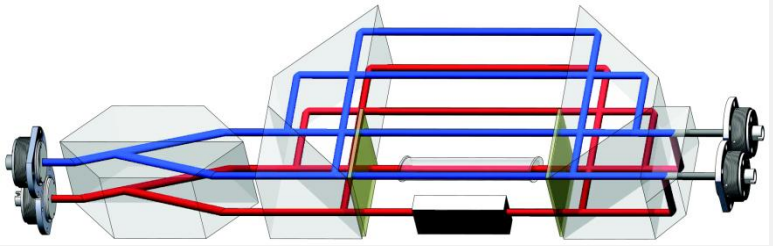
VSL: Development of **Picodrift Interferometry**

Measure samples from partners / collaborators

public summary

www.euramet.org

www.emrponline.eu



This JRP receives funding from the European Union.

Conclusion: Tell us your needs !

Sub-nanometer accuracy

- Uncertainty budget and traceability

Dimensional stability drift measurement

- Picodrift Interferometer

Displacement sensor calibration

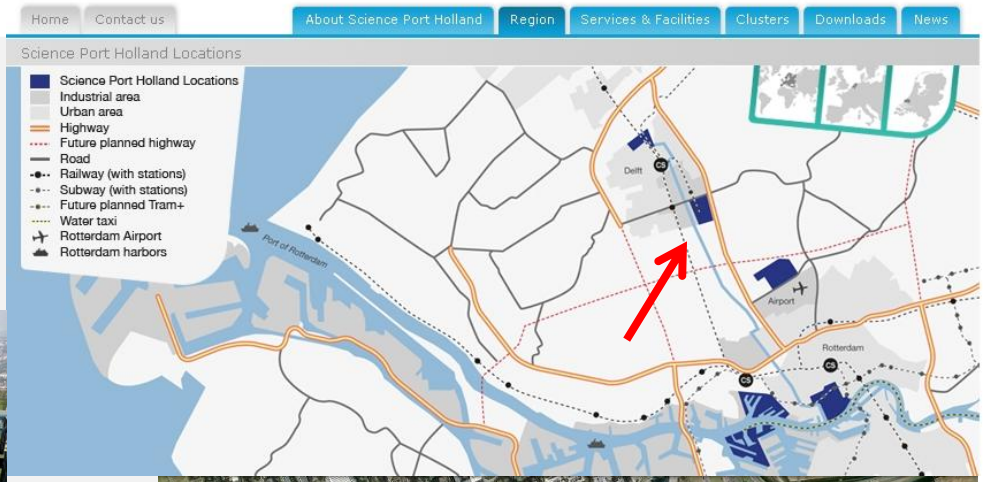
- Metrological Fabry-Pérot Interferometer

You can contribute to EMRP

- Get your metrology issues solved !

Find us in Delft *Technopolis*

Science Port Holland
Where technology innovation creates business



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Precision Fair 2011

Dutch Metrology Institute

Partners

TU Delft Technische Universiteit Delft

TNO innovation for life

Funding

Agentschap NL
Ministerie van Economische Zaken, Landbouw en Innovatie

Ministerie van Economische Zaken, Landbouw en Innovatie

EURAMET
European Association of National Metrology Institutes