Laser scanning approach to acquire operational deflection shapes of civil structures: the SCADD system

José L. Fernández, Rafael Comesaña, Cristina Trillo, Ángel F. Doval and J. Carlos López-Vázquez

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

INDEX

- Introduction
- Field data acquisition of vibrations of civil structures
- A new approach: the SCADD
- Experiment
- Conclusions

INDEX

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

STRUCTURAL HEALTH MONITORING

- Tool for the management of the existing civil structures
  - Monitoring in-service behaviour
  - Assessment of Integrity
  - Diagnosis for maintenance & reparation
  - Prediction of remaining service life

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

STRUCTURAL HEALTH MONITORING

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

- Two approaches to SHM
  - Direct damage detection
    - Visual, X-ray, ultrasound, thermography, …
    - Local methods
  - Indirect damage detection
    - Detecting changes in structural properties or system behaviour
    - Global methods
- Non-destructive tests
  - Static
  - Dynamic
    - More reliable than static tests
    - Allow “output only” tests (operational loads)

DYNAMIC TESTING OF STRUCTURES

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

Find dynamic response of the undamaged structure by test or analysis

↓

Obtain dynamic response of the damaged structure

↓

Select one or several dynamic system characteristics (DSC)

↓

Comparison between DSC’s of the undamaged and damaged structures

↓

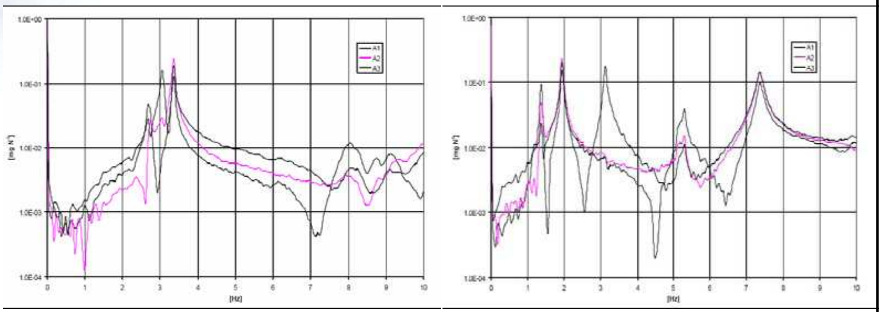
Develop a model of the dynamic behavior of the damaged structure

↓

Damage identification (inverse problem) from the differences between DSC of the damaged and undamaged structures

DYNAMIC SYSTEM CHARACTERISTICS

- Frequency response function (FRF)



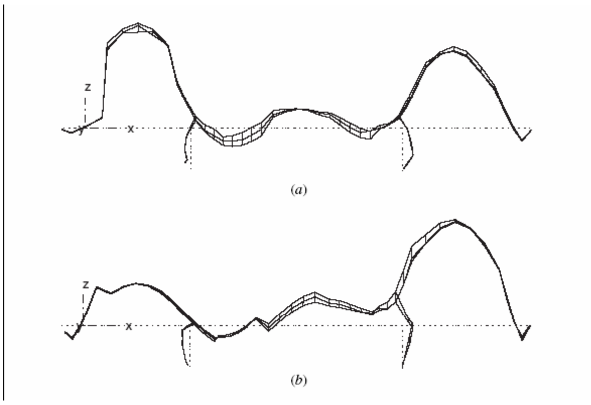
FRF for an undamaged structure (left) and for the same structure with damage (right).

Zonta, D., "*Structural damage detection and localization by using vibrational measurements*", doctoral dissertation, Bologna, Italia (2000).

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

DYNAMIC SYSTEM CHARACTERISTICS

- Modal analysis

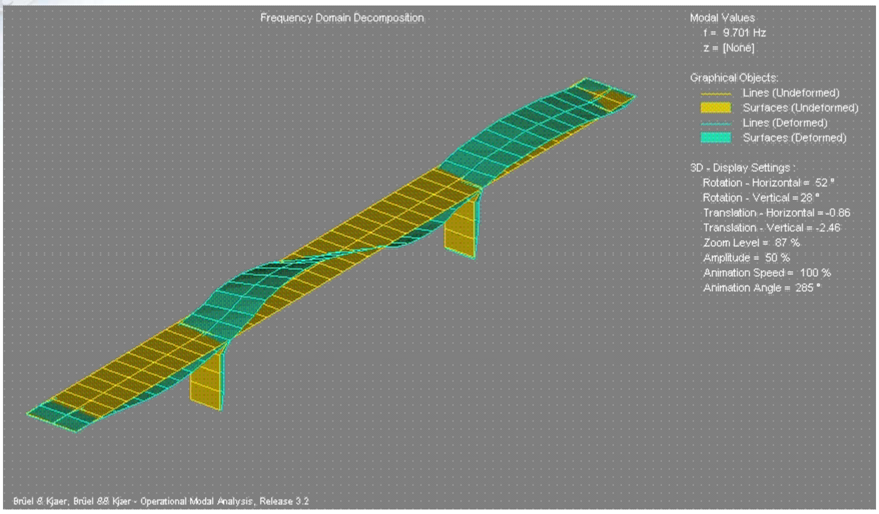


5th modal shape of a bridge: (a) undamaged, (b) after settlement of the right pier .

Maeck, J., de Roeck, G. "Damage assessment using vibration análisis on the Z24-bridge", *Mechanical Systems and Signal Processing* (2003) 17(1), 133-142.

DYNAMIC SYSTEM CHARACTERISTICS

- Modal analysis



Brüel & Kjaer technical information (2003)

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

INDEX

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

MEASURAND NATURE AND SYSTEM TOPOLOGY

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

- Nature of the measurand
  - Kinematic methods
    - Displacement
    - Velocity
    - Acceleration
  - Strain-based methods
    - Strain
- Measurement system topology
  - Single point
  - Multiple point

MEASUREMENT TECHNOLOGY

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

- Non-optical
  - Contact transducers
    - With external reference
      - LVDT and other transducers sensitive to relative motion between two elements
    - Self-referenced
      - Accelerometer
      - Inclinometer
      - Strain gauge
      - Geophone

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

MEASUREMENT TECHNOLOGY

- Accelerometer

Maeck, J., "*Damage Assessment of Civil Engineering Structures by Vibration Monitoring*", Ph.D. thesis, Civil Engineering Department, K. U. Leuven (2003).

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

MEASUREMENT TECHNOLOGY

- Optical
  - Contact transducers
    - Self-referenced
      - Fiber Bragg grating sensor
  - Non-contact transducers
    - With external reference
      - Moiré
      - Speckle pattern photography
      - Pointwise interferometry
      - Holographic and speckle interferometry
      - Geometrical techniques

MEASUREMENT TECHNOLOGY

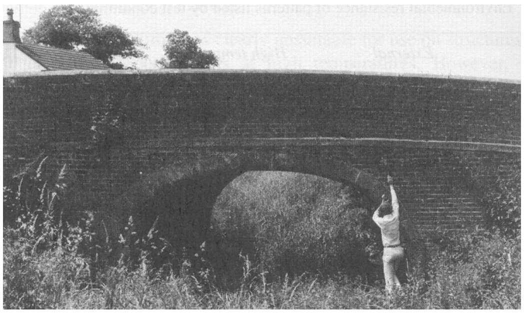
- Fiber Bragg grating sensor

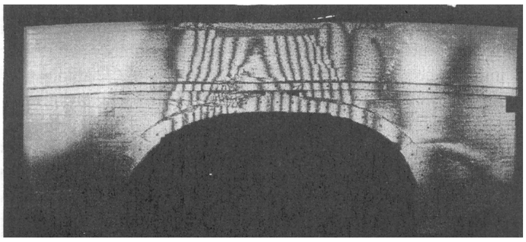
OSMOS News, Nº 14, 10-2006.
http://www.osmos-group.com/eng/pages/aktuell/akt-new14.pdf

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

MEASUREMENT TECHNOLOGY

- Moiré





C. Forno, "Moiré methods in strain measurement", in *Optical Methods in Engineering Metrology, D. C. Williams Ed., pp 339-384, Chapman & Hall, London (1993*)

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

MEASUREMENT TECHNOLOGY

❑ Speckle pattern photography (1)

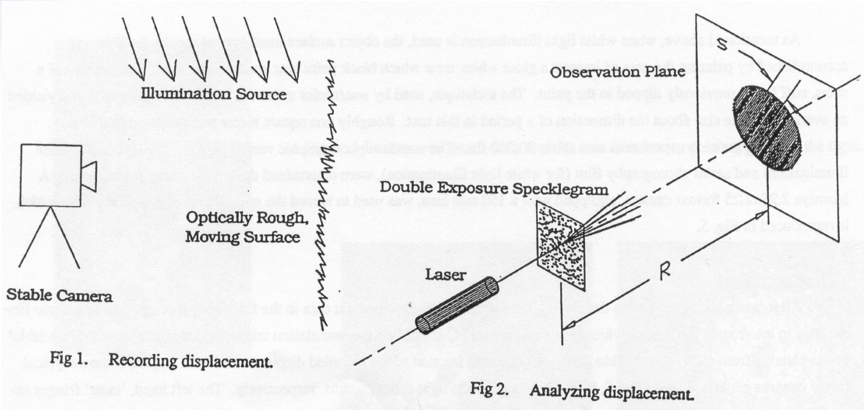


Fig 1. Recording displacement.

Fig 2. Analyzing displacement.

Conley, E., Morgan, C., "*Speckle photography applied to measure deformations of very large structures*", Proc. SPIE Vol. 2446, 161-168, Smart Structures and Materials (1995)

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

MEASUREMENT TECHNOLOGY

❑ Speckle pattern photography (2)

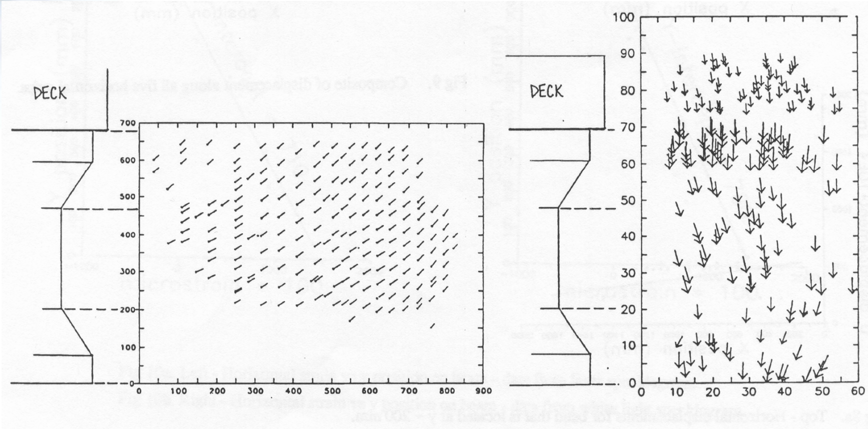


Fig 7a. Left - Displacement vectors projected onto the beam - data from laser illumination.
Fig 7b. Right - Displacement vectors projected onto the beam - data from white light illumination.

MEASUREMENT TECHNOLOGY

- Pointwise interferometry

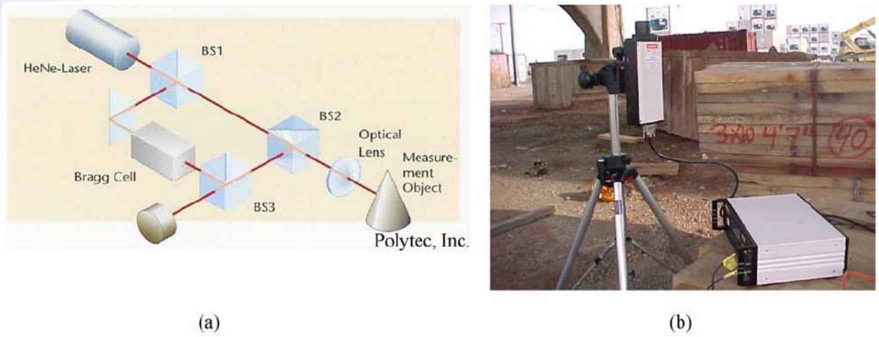


Fig. 2. Laser Doppler vibrometer (a) Optical configuration (b) Field setup.

Hani H. Nassifa, Mayrai Gindyb, Joe Davisa, "Comparison of laser Doppler vibrometer with contact sensors for monitoring bridge deflection and vibration", NDT&E International 38 (2005) 213–218

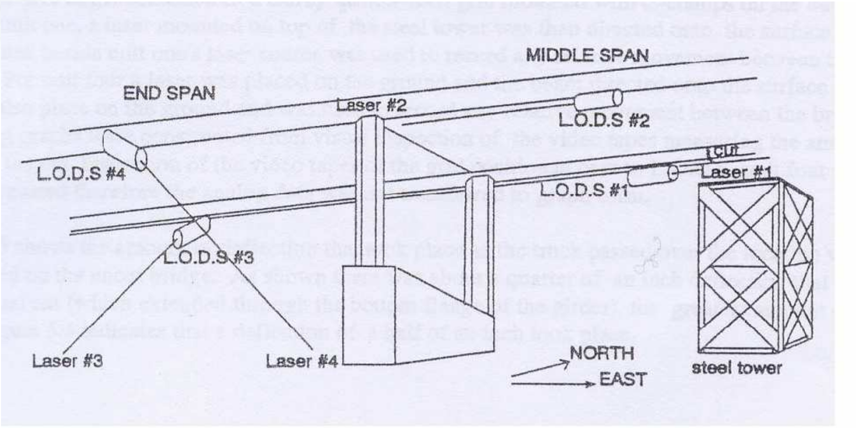
GEOMETRICAL OPTICAL TECHNIQUES

- Multiple point sequential
  - Laser alignment
  - Telemetry by triangulation
  - Telemetry by laser scanning
  - Telemetry by time-of-flight
- Image or whole-field
  - Alignment telescopes
  - Photogrammetry
  - Digital image correlation (DIC)
  - Theodolites
  - Shadow projection

GEOMETRICAL OPTICAL TECHNIQUES

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

❑ Laser alignment

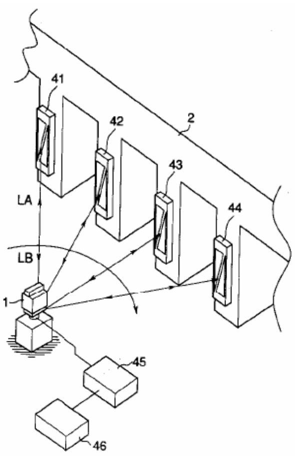


Starrit, L., Matthews, L.K. "*Laser Optical Displacement System*", Proc. SPIE Vol. 2446, 181-192, Smart Structures and Materials (1995)

GEOMETRICAL OPTICAL TECHNIQUES

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

❑ Telemetry by laser scanning



Eiichi, K., *Laser surveying system*. U.S. patent nº US5589939 (1996).

GEOMETRICAL OPTICAL TECHNIQUES

- Digital image correlation (DIC)

CHEN Junda, JIN Guanchang, MENG Libo, Applications of Digital Correlation Method to Structure Inspection, TSINGHUA SCIENCE AND TECHNOLOGY Volume 12, Number 3, pp 237-243 (2007)

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

INDEX

- Introduction
- Field data acquisition of vibrations of civil structures
- A new approach: the SCADD
- Experiment
- Conclusions

DESIRABLE PERFORMANCES OF A FIELD DATA ACQUISITION SYSTEM OF VIBRATIONS

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

- Distance range: tens of m
- Sensitivity direction: out-of-plane
- Accuracy: 0,1 mm
- Sampling in a set of points (10-100) of the structure
- Sampling frequency: 100-300 Hz
- Ruggedness, simplicity
- Ease of utilization
- Economy

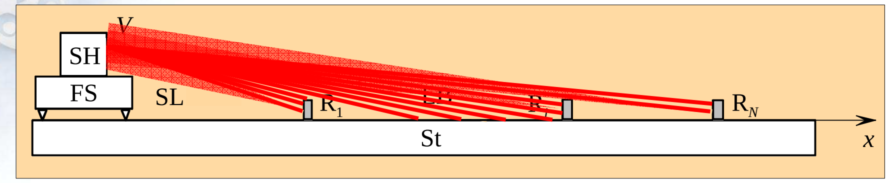
SCADD PRINCIPLE OF MEASUREMENT

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

- Kinematic method
  - Displacements
- Multiple point sequential
- Non-contact
- With external reference
- Geometrical technique
  - Telemetry by laser scanning

SCADD PRINCIPLE OF MEASUREMENT

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

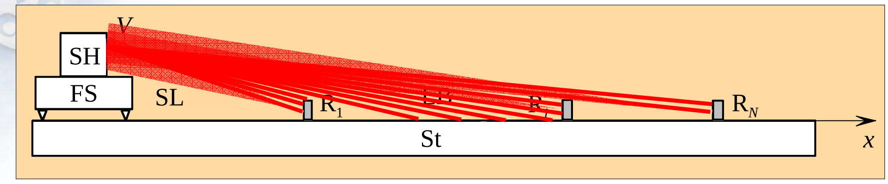


Operation geometry of the SCADD system.

SH: **SCADD head, which contains the emitter-receiver subsystem**
FS: **frame with suspension subsystem**
St: **structure to inspect**
LB: **scanning laser beam**
R_i: ***i*-th retroreflector**
SL: **light scattered from the retroreflectors**
x **axis: base line**
V: **scanning vertex.**

SCADD PRINCIPLE OF MEASUREMENT

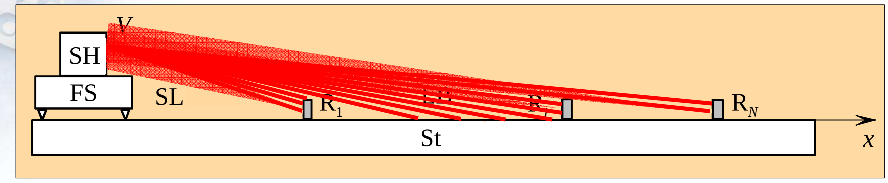
Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es



Operation geometry of the SCADD system.

SH: **SCADD head, which contains the emitter-receiver subsystem**
FS: **frame with suspension subsystem**
St: **structure to inspect**
LB: **scanning laser beam**
R_i: ***i*-th retroreflector**
SL: **light scattered from the retroreflectors**
x **axis: base line**
V: **scanning vertex.**

SCADD PRINCIPLE OF MEASUREMENT

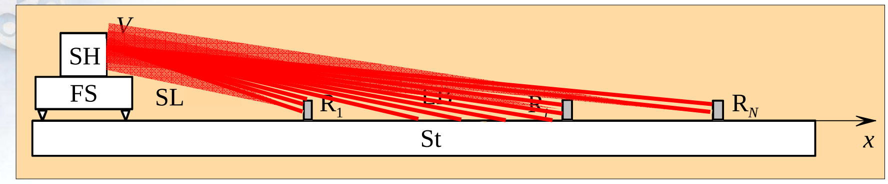


Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

Operation geometry of the SCADD system.

SH: **SCADD head, which contains the emitter-receiver subsystem**
FS: **frame with suspension subsystem**
St: **structure to inspect**
LB: **scanning laser beam**
R_i: ***i*-th retroreflector**
SL: **light scattered from the retroreflectors**
x **axis: base line**
V: **scanning vertex.**

SCADD PRINCIPLE OF MEASUREMENT

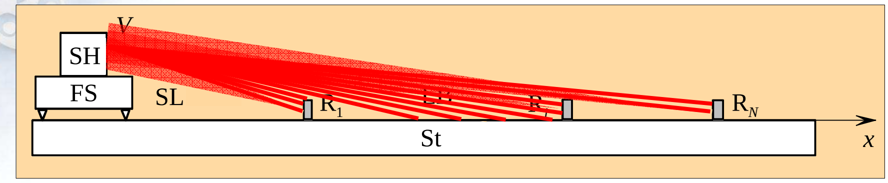


Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

Operation geometry of the SCADD system.

SH: **SCADD head, which contains the emitter-receiver subsystem**
FS: **frame with suspension subsystem**
St: **structure to inspect**
LB: **scanning laser beam**
R_i: ***i*-th retroreflector**
SL: **light scattered from the retroreflectors**
x **axis: base line**
V: **scanning vertex.**

SCADD PRINCIPLE OF MEASUREMENT

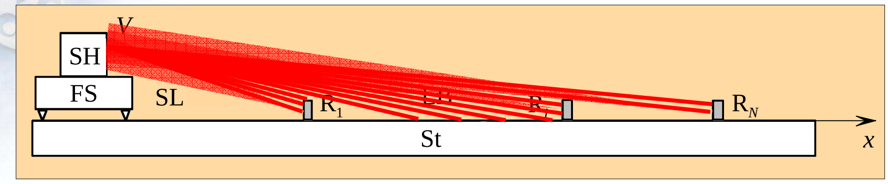


Operation geometry of the SCADD system.

SH: **SCADD head, which contains the emitter-receiver subsystem**
FS: **frame with suspension subsystem**
St: **structure to inspect**
LB: **scanning laser beam**
R_i: ***i*-th retroreflector**
SL: **light scattered from the retroreflectors**
x **axis: base line**
V: **scanning vertex.**

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

SCADD PRINCIPLE OF MEASUREMENT



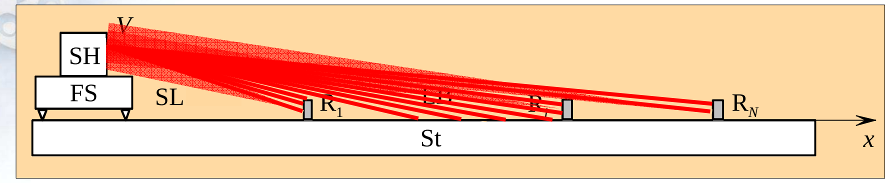
Operation geometry of the SCADD system.

SH: **SCADD head, which contains the emitter-receiver subsystem**
FS: **frame with suspension subsystem**
St: **structure to inspect**
LB: **scanning laser beam**
R_i: ***i*-th retroreflector**
SL: **light scattered from the retroreflectors**
x **axis: base line**
V: **scanning vertex.**

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

SCADD PRINCIPLE OF MEASUREMENT

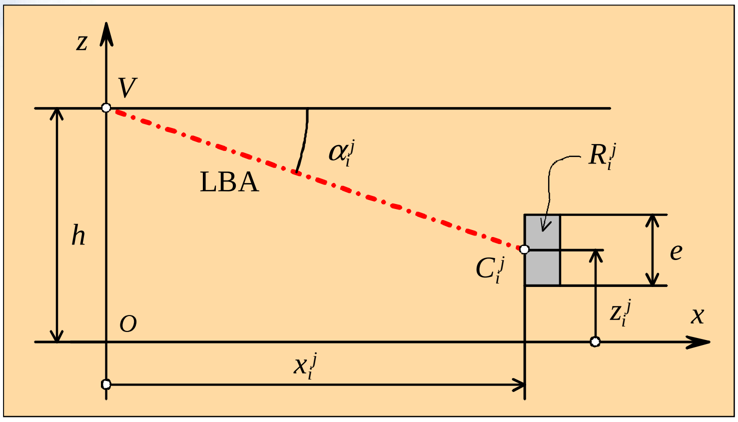


Operation geometry of the SCADD system.

SH: **SCADD head, which contains the emitter-receiver subsystem**
FS: **frame with suspension subsystem**
St: **structure to inspect**
LB: **scanning laser beam**
R_i: ***i*-th retroreflector**
SL: **light scattered from the retroreflectors**
x **axis: base line**
V: **scanning vertex.**

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

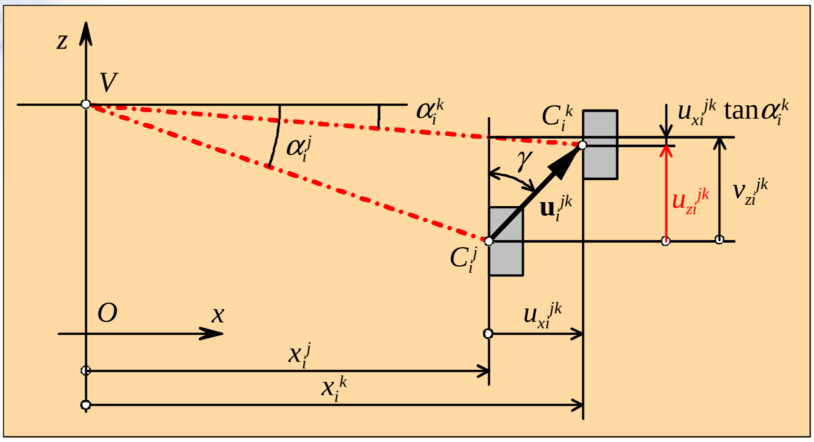
SCADD PRINCIPLE OF MEASUREMENT



Measurement of the position of the i-th control point in the j-th scanning cycle, C_i^j.

V: **scanning vertex**
α_i^j: **angular position (referred to the SCADD head frame) of** C_i^j
LBA: **laser beam axis**

SCADD PRINCIPLE OF MEASUREMENT



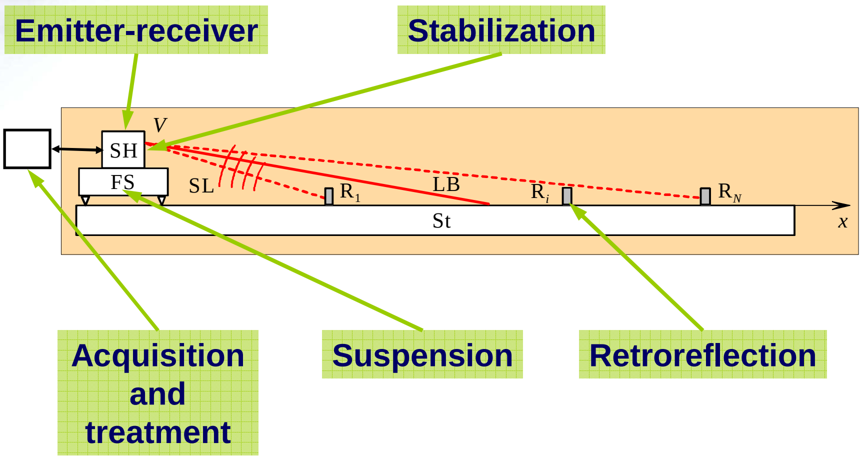
Measurement of the displacement u_i^{jk} of the control point C_i between the j-th and k-th scanning cycles.

$$u_{zi}^{jk} = \frac{\tan\alpha_i^j - \tan\alpha_i^k}{1 + \tan\gamma \tan\alpha_i^k} x_i^j$$

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

SCADD ARCHITECTURE

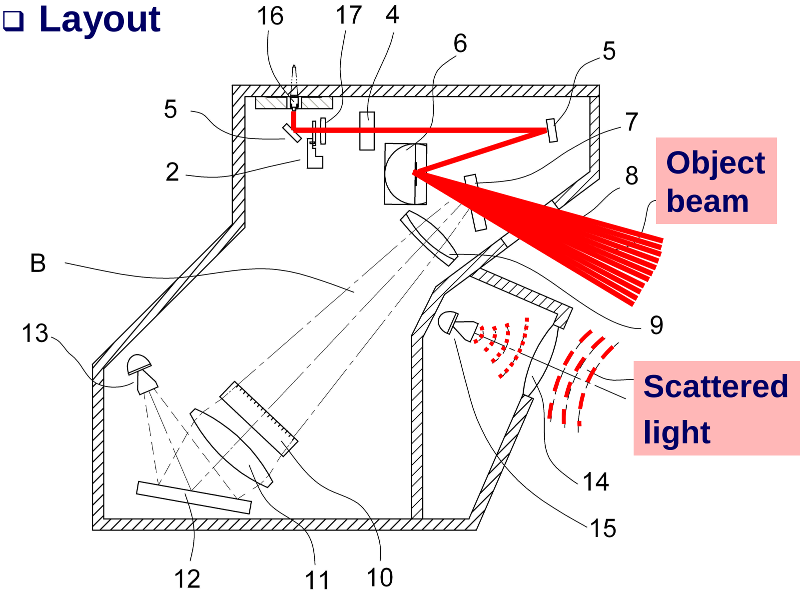
- **5 subsystems:**



Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

EMITTER-RECEIVER SUBSYSTEM

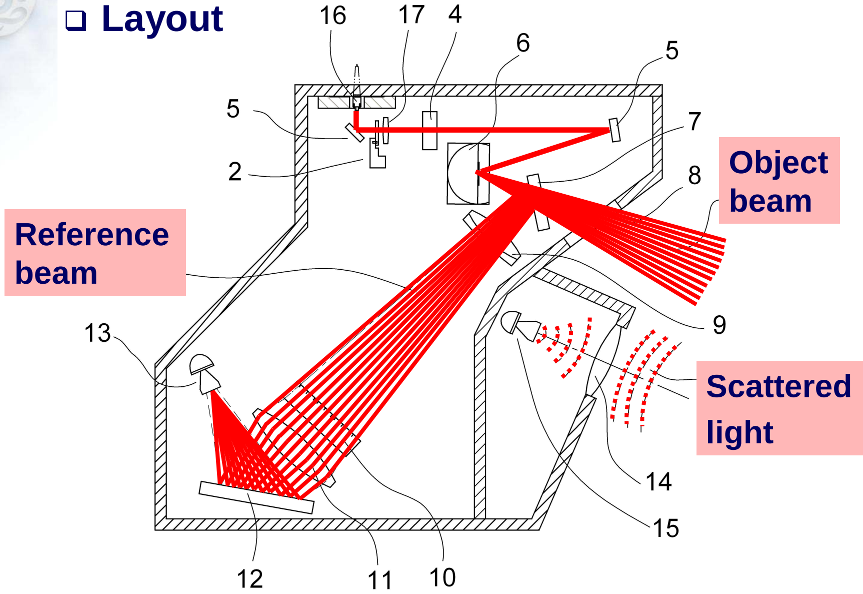
- Layout



Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

EMITTER-RECEIVER SUBSYSTEM

- Layout

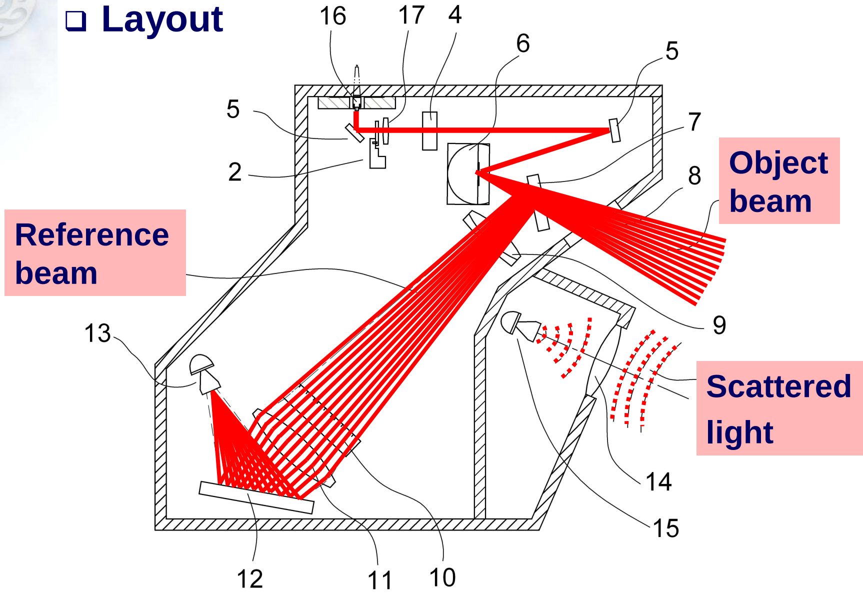


Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

EMITTER-RECEIVER SUBSYSTEM

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

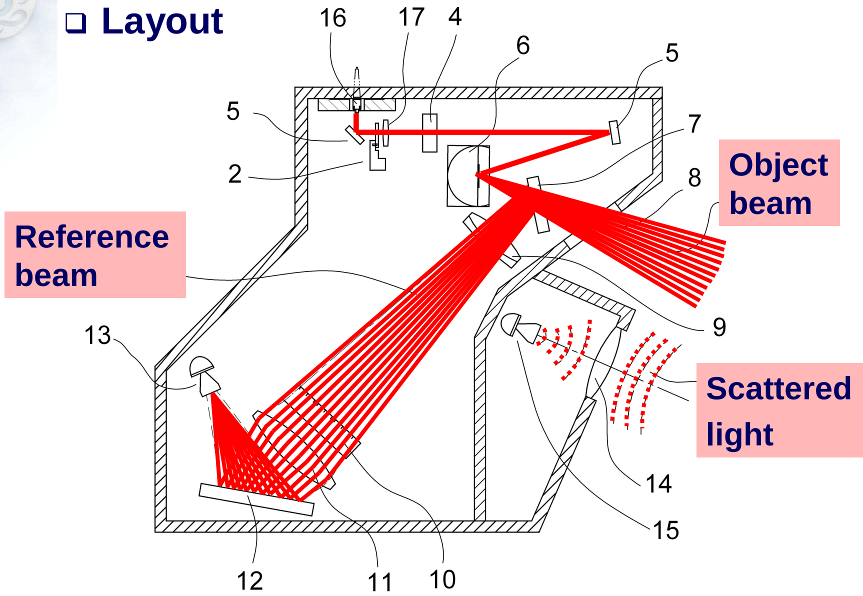
- Layout



EMITTER-RECEIVER SUBSYSTEM

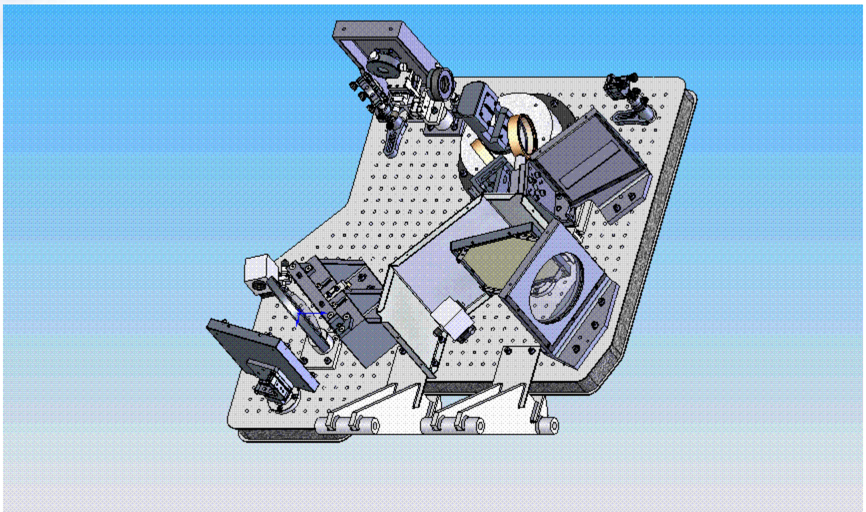
Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

- Layout



EMITTER-RECEIVER SUBSYSTEM

- Prototype design



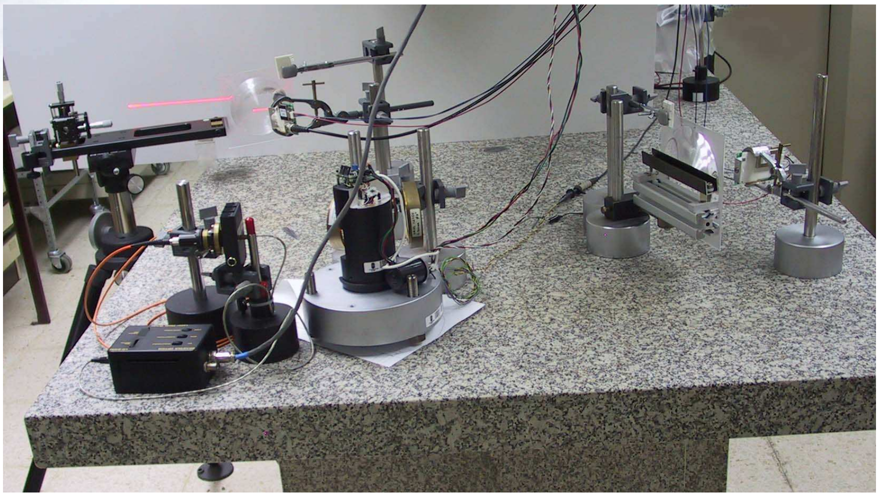
Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

INDEX

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

DEMONSTRATION PROTOTYPE

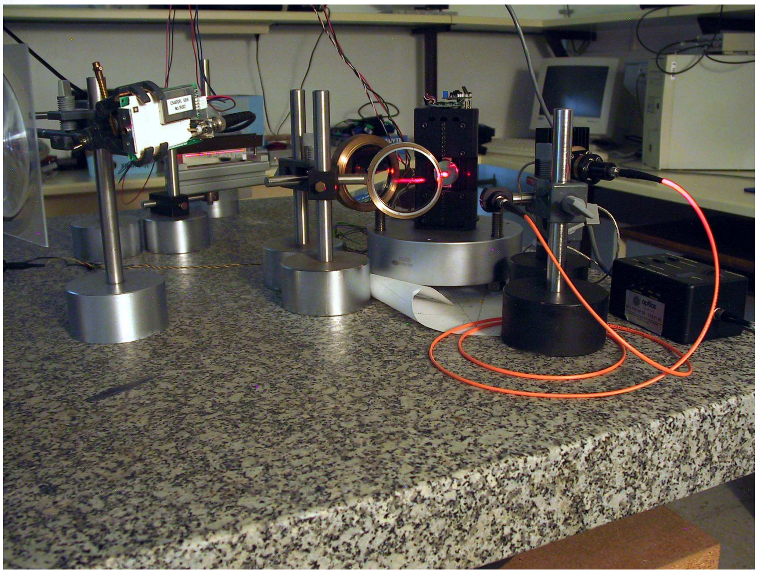
- General view



Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

DEMONSTRATION PROTOTYPE

- Scanner



Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

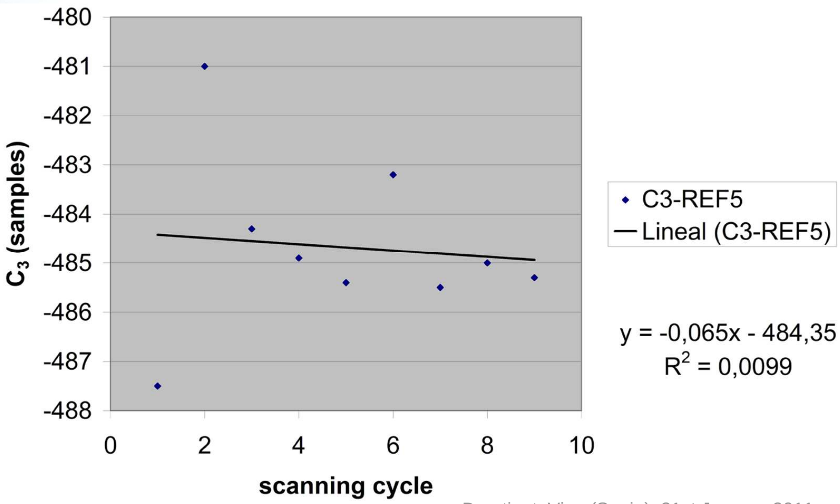
DEMONSTRATION PROTOTYPE

- Retroreflectors

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

RESULTS

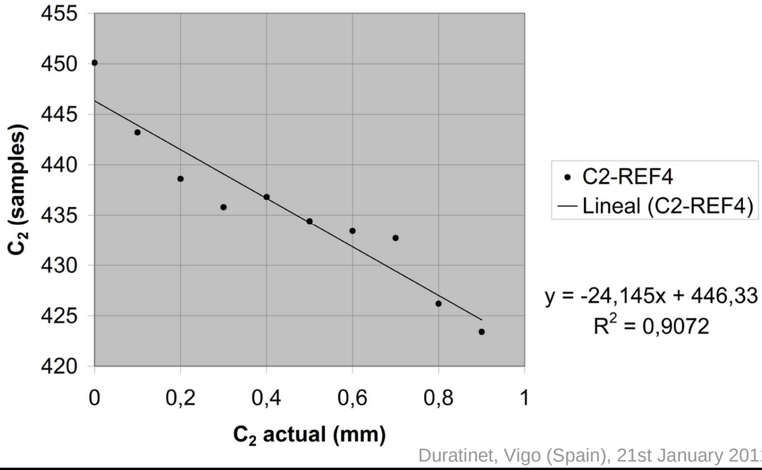
- **Jitter measurement**
  - **Static retroreflector at 18.1 m from SCADD head**
  - **Standard deviation = 5.7 μrad (single measurement without averaging)**



Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

RESULTS

- Sensitivity measurement
  - Translation of retroreflector (X stage)
  - Single measurement without averaging
  - Measured slope = 4.4 μrad/sample
  - Theoretical slope = 3.2 μrad/sample



Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

INDEX

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

CONCLUSIONS

- Conception of a novel instrument for field data acquisition of dynamic deflection shapes of civil structures
- Verification of measuring principle by a demonstration prototype
- Repeatability & sensitivity of the order of a few microradian ⇒ useful data for modal analysis techniques

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

CONCLUSIONS

- Advantages
  - Compared to tethered monitoring systems (e.g., accelerometer networks):
    - SCADD operates remotely from one end of the structure, being only necessary to attach a retroreflector to each point to be measured
    - The measured magnitude is directly a displacement. SCADD can be even utilized to acquire static deflection data
  - Compared to techniques based on displacement measuring sensors by mechanical contact (LVDT and similars):
    - No need of a reference frame to attach the transducers

CONCLUSIONS

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

- **Drawbacks**
  - **the control points must be aligned**
    - ??
  - **the accuracy strongly decreases with the distance between the SCADD head and the measured point**
    - **refinements in the design, intensive averaging**
  - **only one component of the structure displacements is measured**
    - **combined use of several SCADD units operating from different locations**

ACKNOWLEDGEMENTS

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

Universidade de Vigo
(project number 06VI1A07).

Laser Applications Research Group – Optical Metrology
Department of Applied Physics. University of Vigo. Spain.
www.laser.uvigo.es

Thank you for your attention