# Laboratory Testing & Measurement on Optical Imaging Systems

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27 April 2013
presented at SIECPC 2013,
Riyadh, Saudi Arabia

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# Overview of Workshop

**Part 1. Introduction & Context**

- Some history of Arabic Optics
- Context:  Global vs Local optical testing
- This workshop:  Discussion  &  Interaction

**Part 2. Optical imaging systems**

- Some defense applications

# Overview of Workshop

**Part 3.  Specifications of an Optical Imaging System**

**Part 4. Laboratory Testing & Measurement of Optical Imaging Systems**

- Image analysis  &  System testing

**Part 5.  Laboratory testing:  Impact of Local needs  & Benefits / Spin-offs from Testing Capability**

# Let us start

**Part 1. Introduction & Context**

Part 2. Optical imaging systems

Part 3. Specifications of an Optical Imaging System

Part 4. Laboratory Testing & Measurement of Optical Imaging Systems

Part 5. Laboratory testing: Impact of Local needs & Benefits / Spin-offs from Testing Capability

# Part 1.

# Introduction & Context

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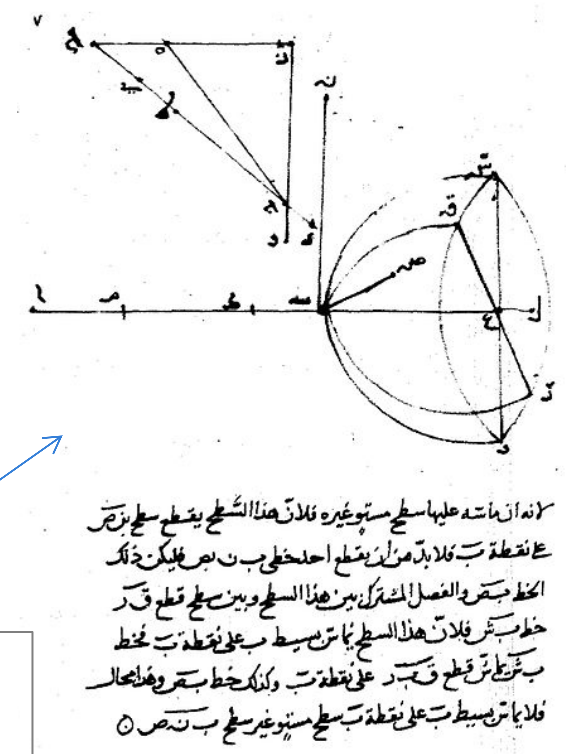
# Some History of Arabic Optics 1

- Arabic records of study of geometrical optics
  - Traced to Hellenistic (Greek) optics
  - Translated to Arabic
  - $9^{th}$ century
- Arabic contribution to geometric optics
  - Not just translation to Arabic
  - Innovative research
  - “Rectification” of Greek literature

See [4]



*Reproduction of a page of Ibn Sahl's manuscript showing his discovery of the law of refraction”, now known as Snell's law.* [5]

# Some History of Arabic Optics 2

- Arabic military interest in optics (Caliphs & Princes)
  - Burning mirrors – (Military application)
  - + Scientific & Philosophy

See [4]

Artists impression: Soldiers directing light to a ship, but could they really get it hot enough to burst into flame? [6]

Following stories of Archimedes (Greek) defeating fleet of Marcellus (Roman General).

# Some History of Arabic Optics 3

- Arabic records of study of human vision ("physiological optics")
- Arabic contribution to physiological optics
  - Not just translation to Arabic
  - Supplement shortcomings
  - Emphasis on observational experiments

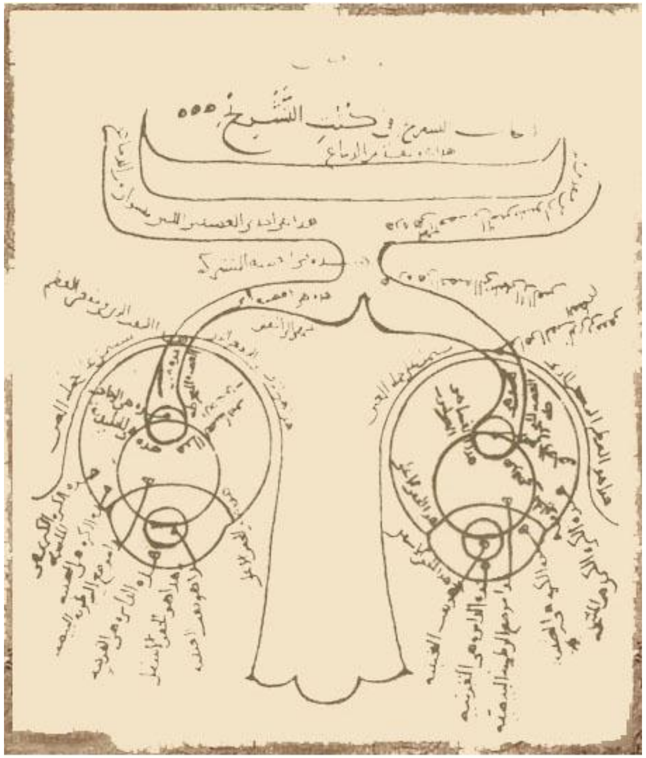


*Figure 1. Diagrammatic representation of the visual system from the oldest existing copy of the Book of Optics by Ibn Al-Haitham, an arab physicist written in the 11 century AD. From Polyak (1957).*

[7]

[4] Encyclopedia of the History of Arabic Science, Vol 2.

# The Context:
# Global vs Local Optical Testing 1

- Optical & electro-optical products available
  - Good, because it can be used everywhere
  - Range from excellent to poor quality
- Local  End-users & End-use applications in each country
  - End-users can be well-trained + experienced
  - But better to **also** have **some** local technical expertise


[8]



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# The Context:
# Global vs Local Optical Testing 2

- Defense & Military — is specialized field

  Surveillance cameras, Reconnaissance cameras,

  Infrared cameras Night surveillance

  Sighting systems for arms / scopes

- Specialized application

  = High cost & = Sensitive (Confidential / Secret)

- Expertise base built by some testing



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# Testing & Measurement is Important


"When you can measure what you are speaking
of and express it in numbers,
you know something about it.

**But**

when you cannot measure it
and cannot express it in numbers,
your knowledge is of
a very meagre and unsatisfactory kind"

- Lord Kelvin

# Local Expertise & Skills Base: How?

Hands-on / Practical laboratory testing & measurement

Exposure to the science / engineering / practical optics:

- Theory of optical imaging
- Application of theory to actual optical systems
- Relevant test & measurement methods
- Practical laboratory testing problems

- Expertise gained in Lab can be extended to Field Testing
- Expertise applied to appreciate maintenance demand

# Where are we

Part 1. Introduction & Context

**Part 2. Optical imaging systems**

Part 3. Specifications of an Optical Imaging System

Part 4. Laboratory Testing & Measurement of Optical Imaging Systems

Part 5. Laboratory testing: Impact of Local needs & Benefits / Spin-offs from Testing Capability

# Part 2.

# Optical Imaging Systems and some Defense Applications

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# Optical Imaging Systems: Quick Overview


- Cameras and Camera lenses
- Microscopes
- Telescopes, binoculars, …
- Scanners
- …

- Human vision

- Spectral regions: Visible, Near-infrared, thermal infrared, Ultraviolet
- Detectors
- Displays & Printers
- …

See [9]

# Defense Applications: Afocal optical systems

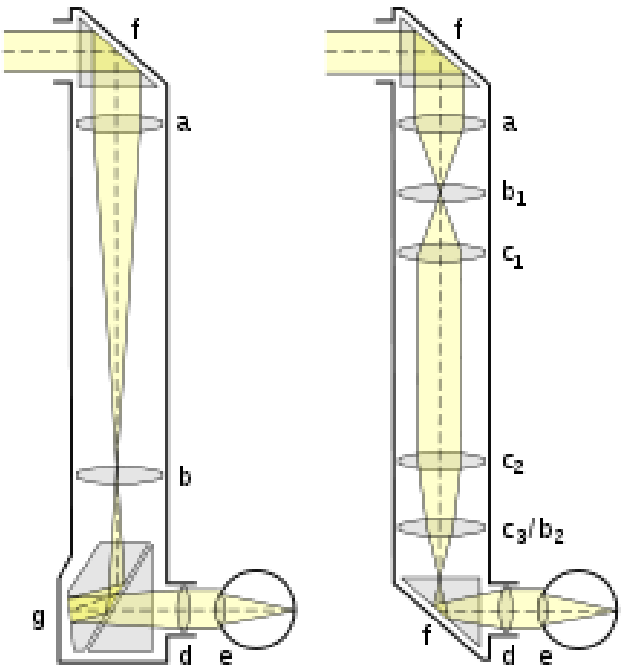
- Actually “afocal” = no image formed
  - For human eye as sensor
  - or  for image sensor if combined with a focusing lens
- Terrestrial telescopes
  - Binoculars
  - Theodolites
  - Range finders
  - Spotting scopes
  - Rifle scopes
  - Other

See [9] and [12]

# Defense Applications: Afocal optical systems

- Relay trains & periscopes
  ( owing to hostile environment or threats )

See [9]




[11]

[10]

# Defense Applications: Passive Scanning Sensors

- Remote sensing
  - Gun sights

  - Night vision (Navigation or Tactical )

  - Missiles
  - Surveillance

See [9]

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# Part 3.

# Specifications of an Optical Imaging System

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# Specifications: Three categories

- Basic system parameters
- Manufacturing specification
  or "Technology demonstrator" specifications
  in research & development context
- Performance specification

See [2], Table 56.2

# Specifications are Important. And understanding them!!!

"When you can measure what you are speaking of
and express it in numbers,
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# Basic System Parameters

- Basic system parameters
- Manufacturing specification
  or "Technology demonstrator" specifications
  in research & development context
- Performance specification

See [2], Table 56.2

# Basic system parameters 1

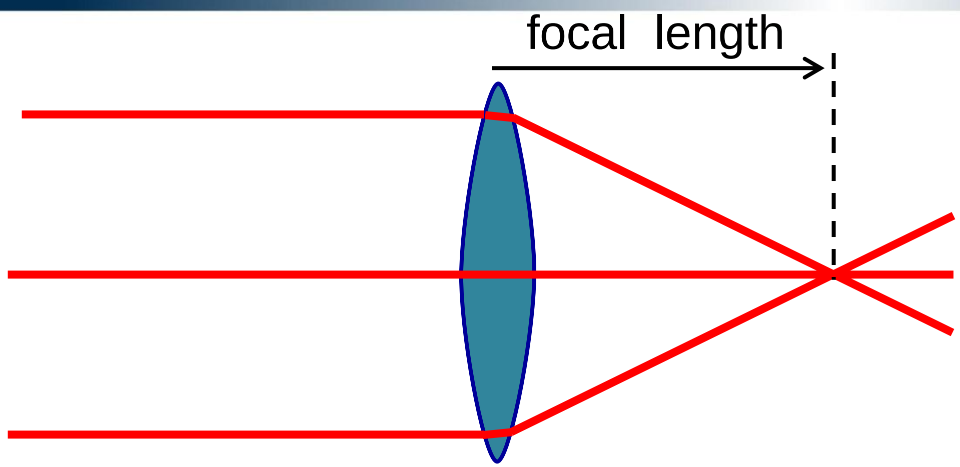
- Focal length
- Magnification

- Pupil diameter
- f-number
- Numerical aperture

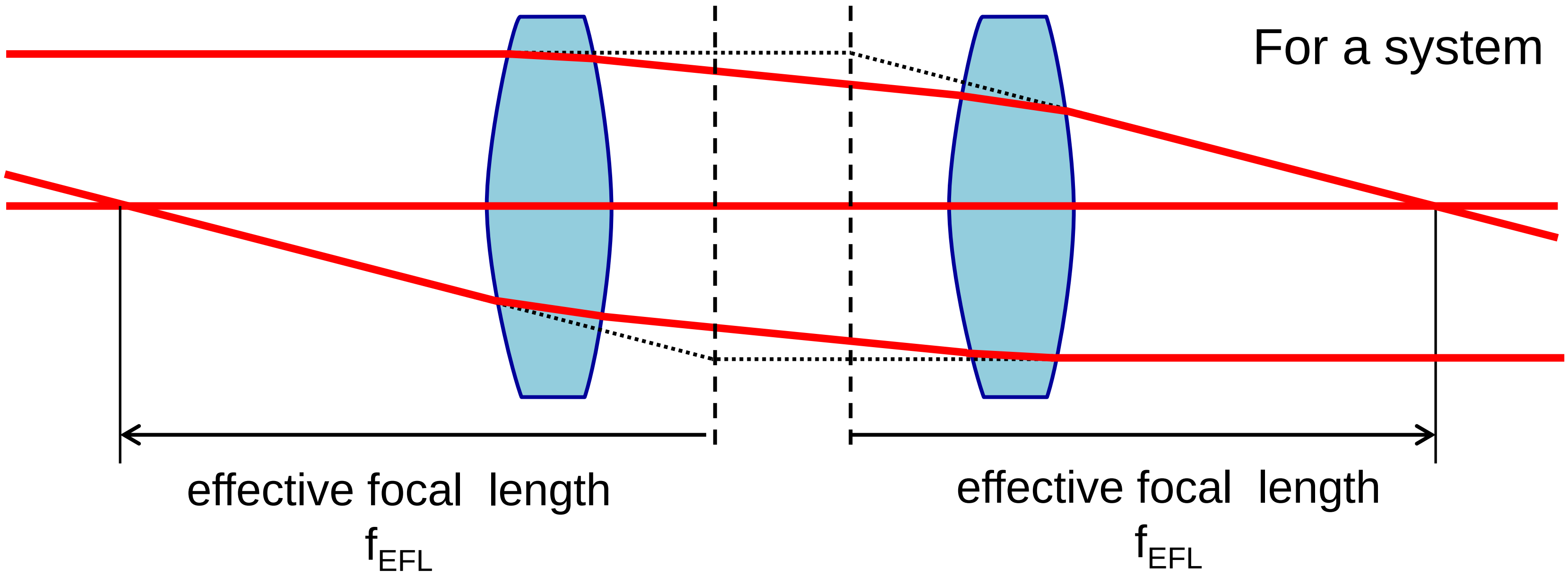
- Wavelength interval where optical system must work
- Spectral weighting

See [2], Table 56.2

# Specifications:  Focal length

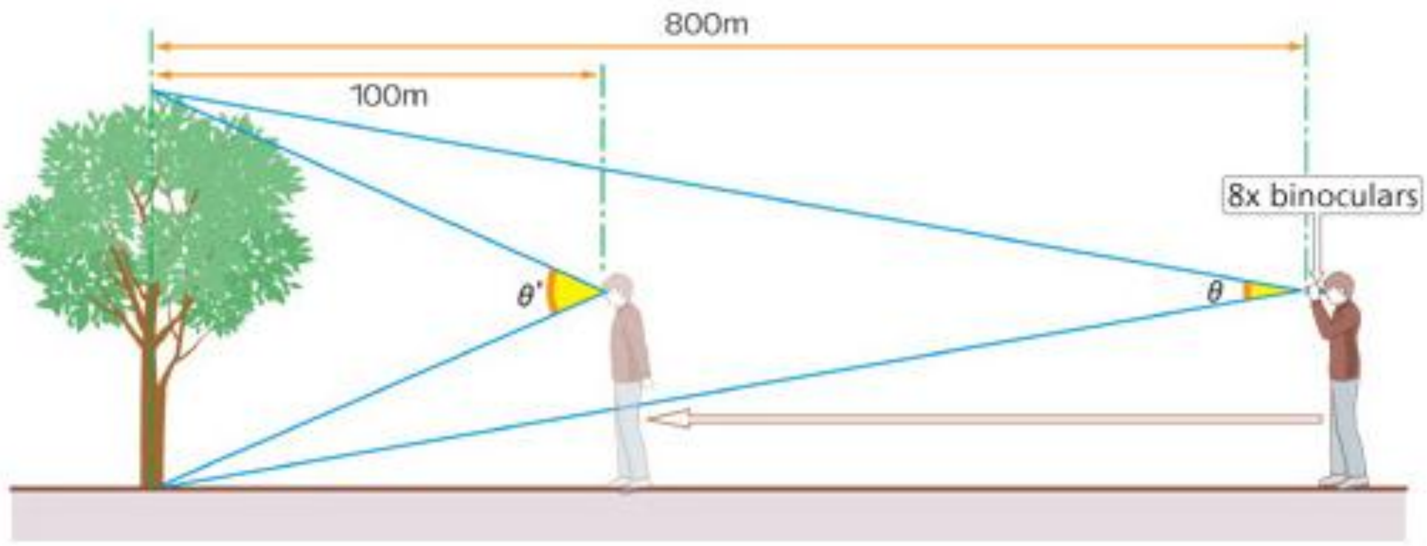



For a simple case



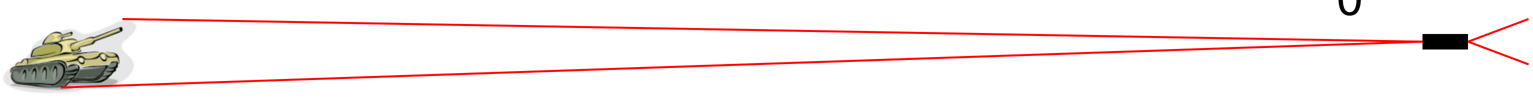

For a system

# Specifications: Magnification




[3]

M = θ / θ’



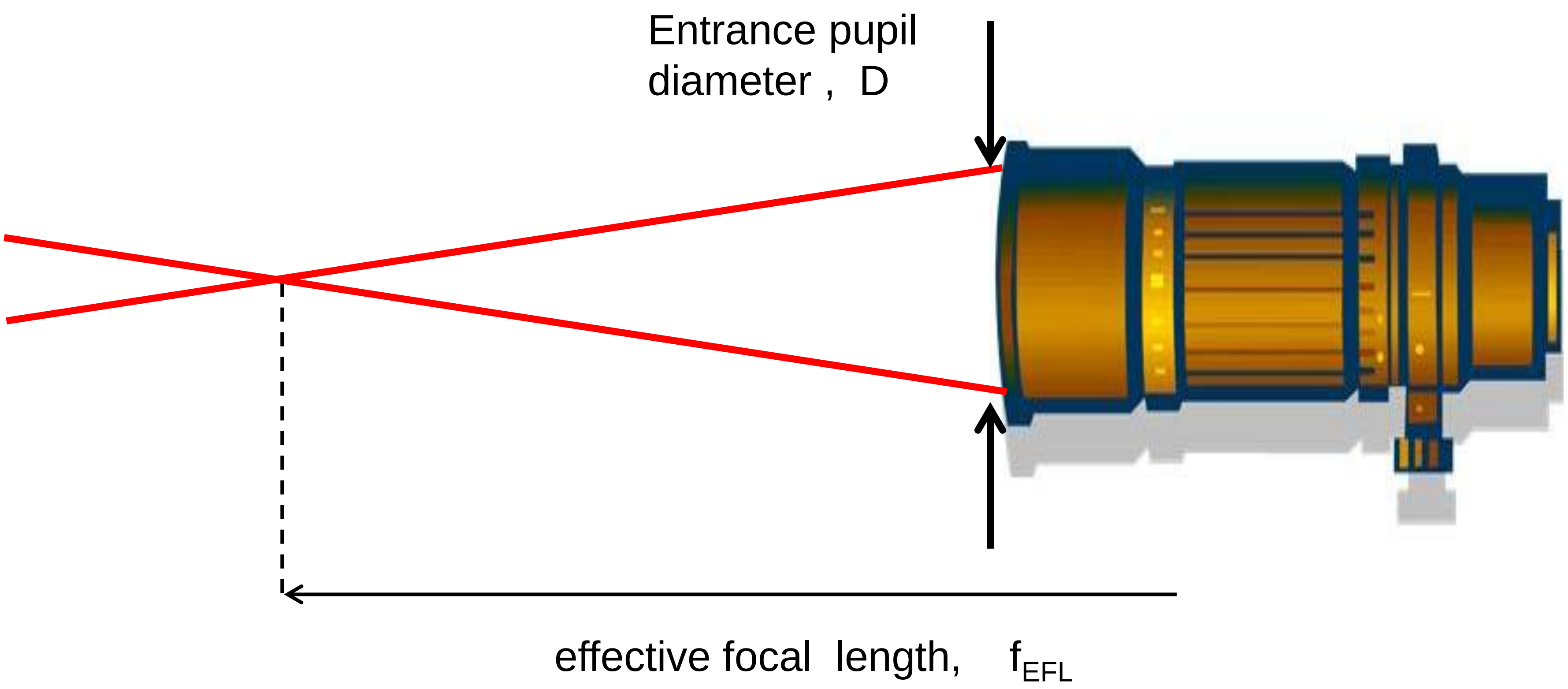
# Specifications:
# Entrance Pupil & Exit Pupil

- Entrance pupil location
- Entrance pupil diameter

- Exit pupil location
- Exit pupil diameter


See [2], Table 56.2

# Specifications: f-number

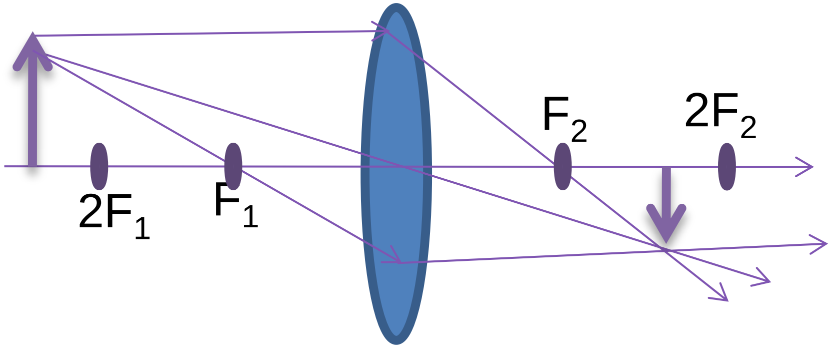



f-number = $f_{EFL} / D$

# Basic System Parameters 2

- Field of view
- Horizontal / Vertical aspect ratio


- Image distance
- Object distance



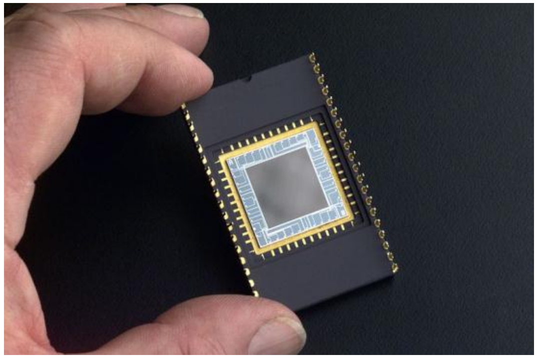

- Free working distance on object side

See [2], Table 56.2

# Basic System Parameters 3

- Zoom range
  - Minimum / Maximum values

- Sensor characteristics



See [2], Table 56.2

# Manufacturing Specification

- Basic system parameters

- Manufacturing specification

  or "Technology demonstrator" specifications
  in research & development context

- Performance specification

See [2], Table 56.2

# Manufacturing Specification 1

- Overall size / Total track
- Maximum diameter

- Number of lenses
- Cost of production
- Number of aspherics
- Material restrictions

- Coatings
- Maximum weight

See [2], Table 56.2

# Manufacturing Specification 2

- Use of diffractive elements
- **Use of off-the shelf components**
- Cosmetic properties

- Mechanical interface to mount the system
- Optical interface with connected systems

- Assembly requirements

See [2], Table 56.2

# Performance Specification

- Basic system parameters
- Manufacturing specifications
  or "Technology demonstrator" specifications
  in research & development context
- Performance specification

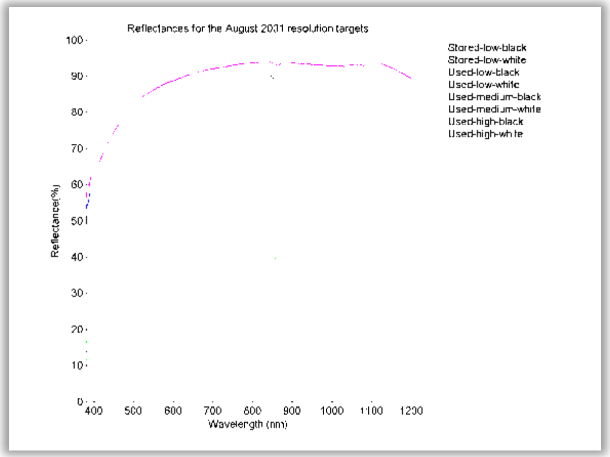
See [2], Table 56.2

# Performance Specification 1

- Spectral transmission
- Vignetting

- Image Quality
- Distortion
- Image field curvature

- Depth of focus
- Illumination uniformity




See [2], Table 56.2

# Performance Specification 2

- Temperature range
- Vibration resistance
- Shock survival

- ghost images
- Stray light / Veiling glare

- Telecentricity error
- Polarisation preservation

See [2], Table 56.2

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# Part 4.

# Testing & Measurement of optical systems

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# Optical Testing.
# Image Analysis & System Testing

- Image analysis
- Optical bench measurements on imaging systems
- Aberration & Resolution measurements
- Interferometric testing of optical systems
  and interferometric wavefront measurement [1,2]
- Non-interferometric wavefront sensing [1,2]
- General light beam measurements

# "Handbook of Optical Systems", vol 5 "Metrology of Optical Components & Systems" [2]

**This book covers wider range of measurement topics on optical systems**

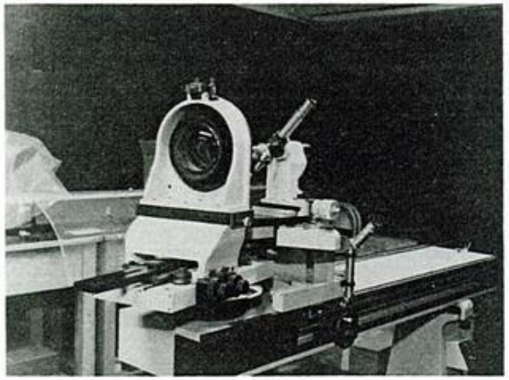
- Interferometry
- Non-interferometric wavefront sensing
- Radiometry
- **Image analysis**
- **System testing**
- …

# “Handbook of Optical Systems”, vol 5 “Metrology of Optical Components & Systems” [2]

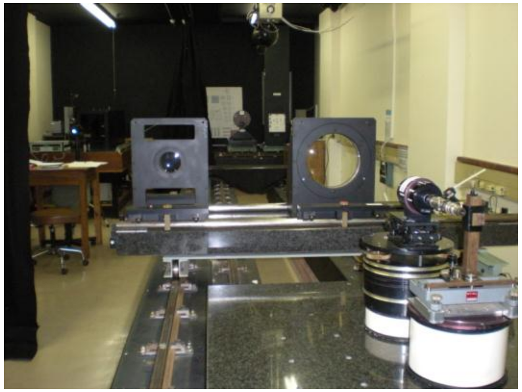
- …
- Testing the Quality of optical materials
- Testing the geometry of optical components
- Component measurements [1,2]
- Testing texture and imperfections on optical surfaces
- Testing the quality of coatings

# Optical bench measurements on imaging systems

- Effective focal length
- f-number
- Axial color
- Field curvature and distortion
- Transmission
- Relative illumination fall-off
- Veiling glare
- Thermal behavior



[1]

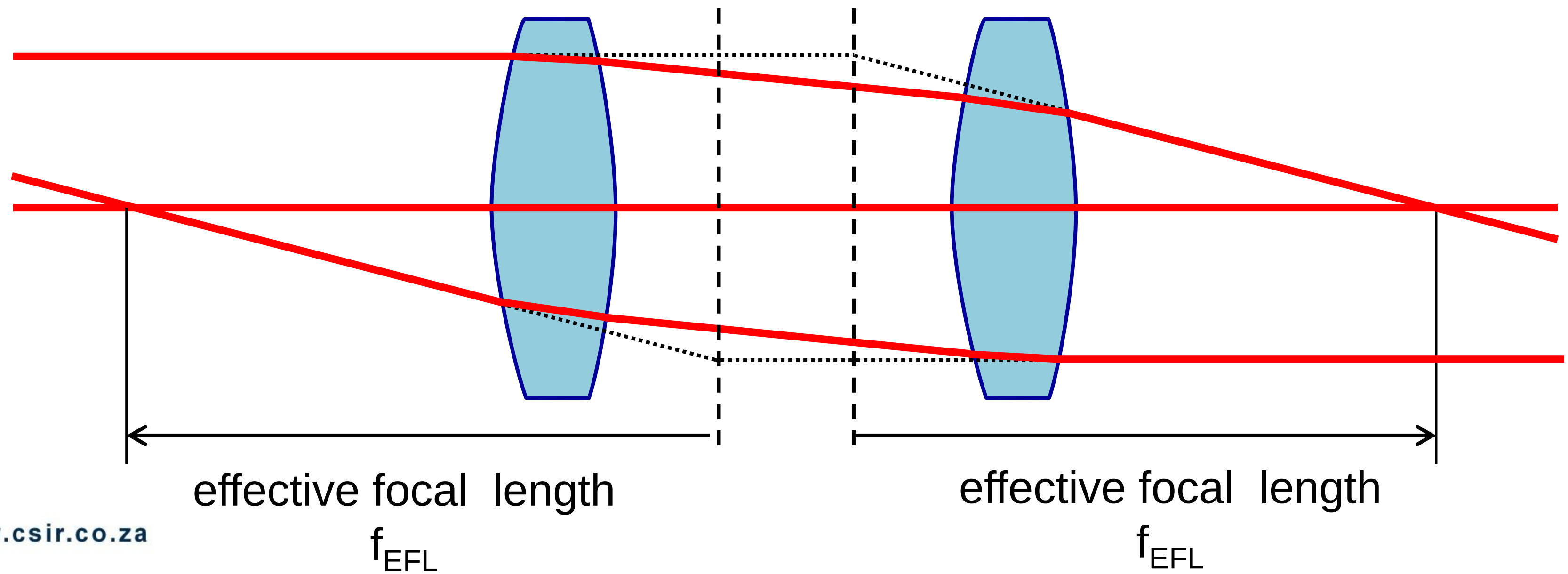


See [1] and [2] for more detail

# Focal length measurement methods

Three general methods [2]

- Methods based on image location
- Methods using relation between magnification & focal length
- Methods which determine wavefront curvature of a focused beam



# Aberration & Resolution measurements

- Spherical aberration
- Astigmatism
- Coma
- Image resolution
- Modulation transfer function tests

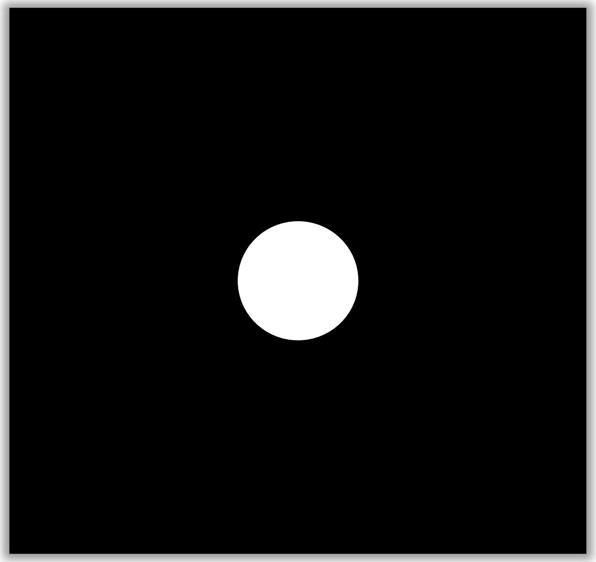
See [1] and [2] for more detail

# Aberrations:  Astigmatism

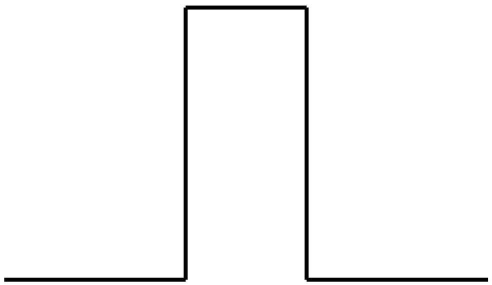
Original target patterns

Image with astigmatic aberration

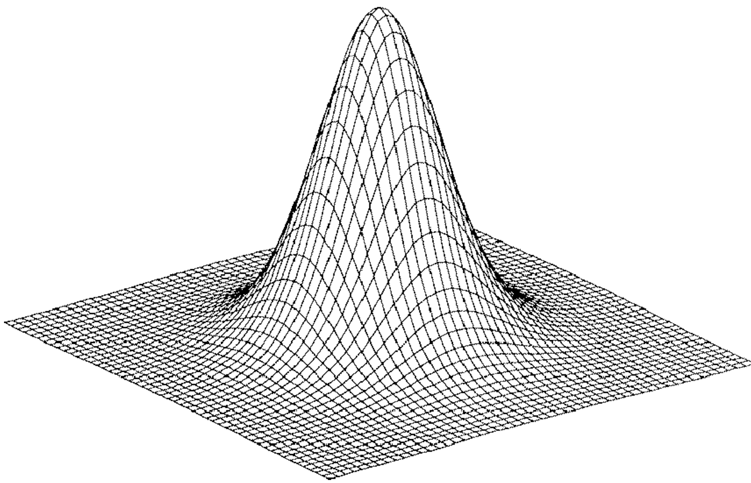
# Modulation Transfer Function (MTF) and Point Spread Function — 1



Point source target



brightness profile
at target

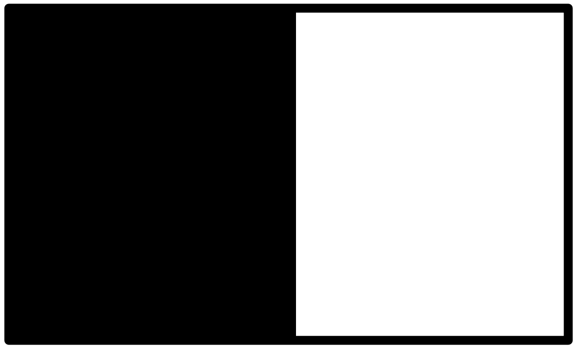


brightness profile
in image.
Point Spread Function
(PSF)

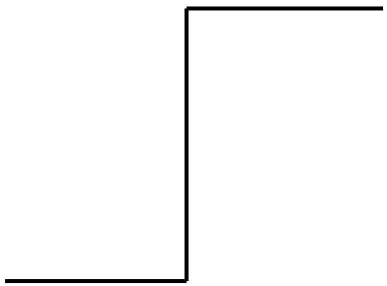
See [1] and [2] for more detail

# Modulation Transfer Function (MTF) and Edge Spread Function (ESF) — 1

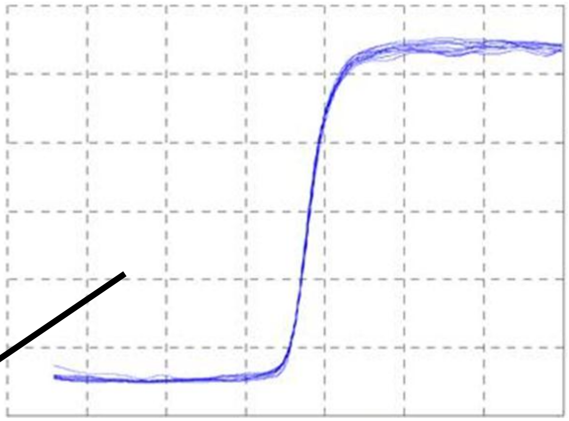
Edge target



brightness profile
at target

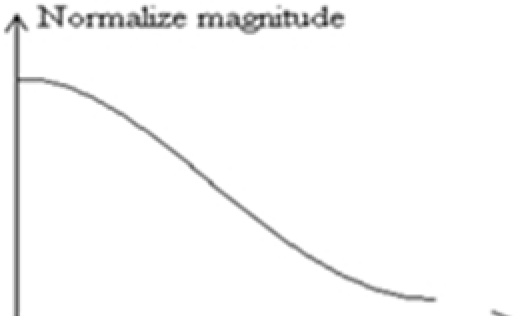


brightness profile
in image.
Edge Spread Function (ESF)



Line Spread Function

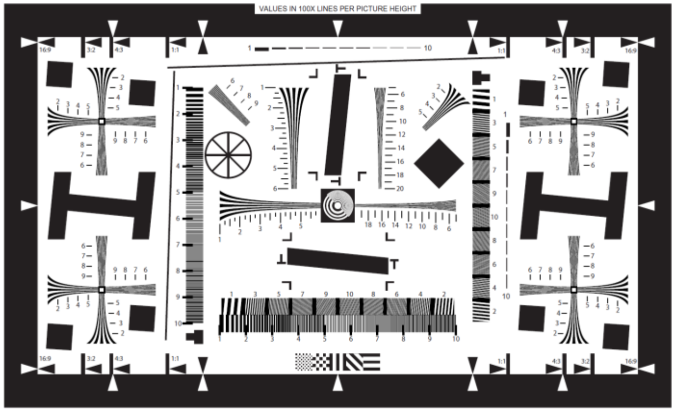
Fourier
Transform

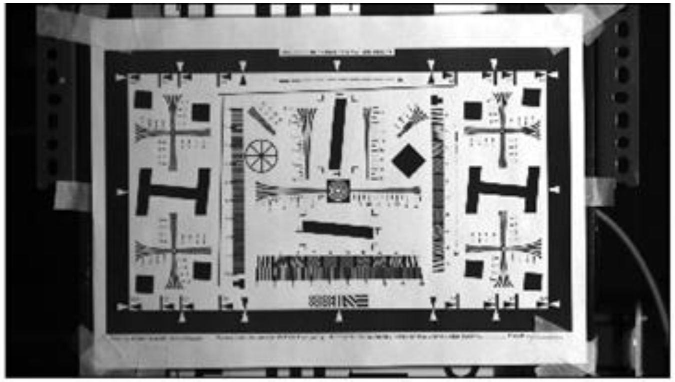



Modulation Trasfer Function

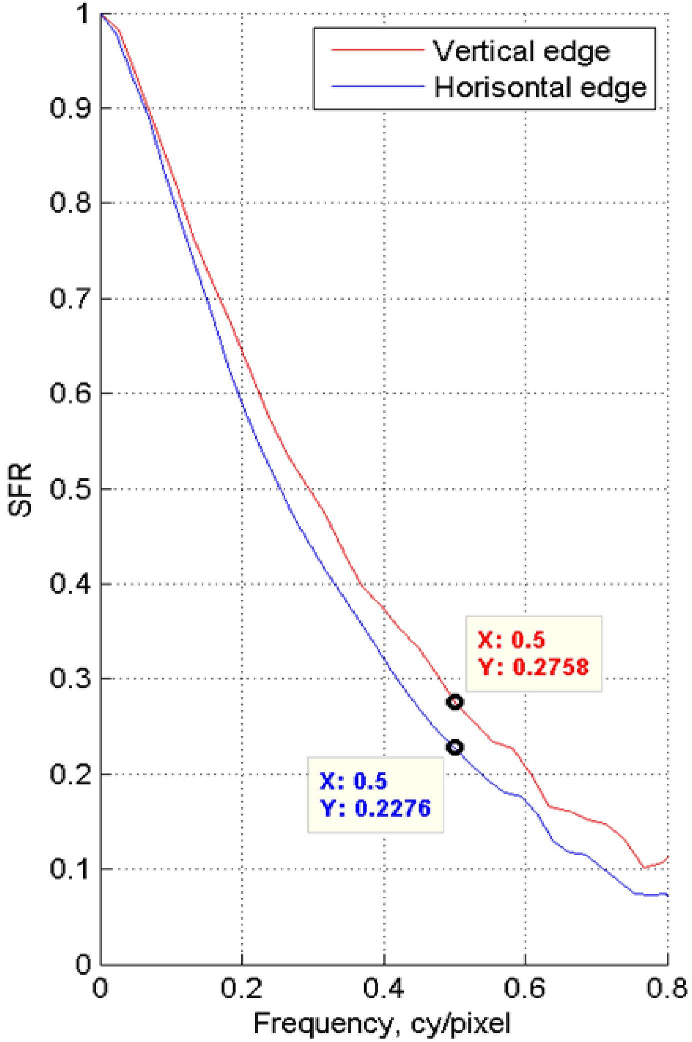
# System MTF via printed target

ISO 12233 target





Photographed



# Interferometric Testing of Optical systems

- Spherical aberration
- Astigmatism
- Coma
- Image resolution
- Modulation transfer function tests

See [1] and [2] for more detail

# Testing of Optical Imaging Systems

Some tests specific to Image Quality and Imaging

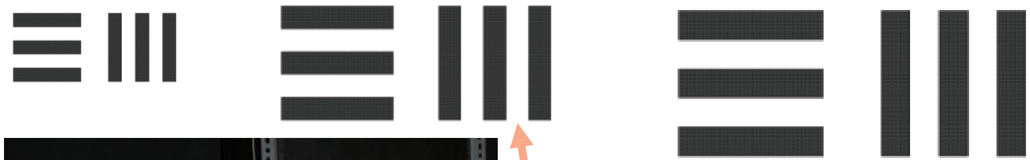
- Resolution testing
- MTF
- IR: MRTD, NETD
- Laser rangefinder characteristics

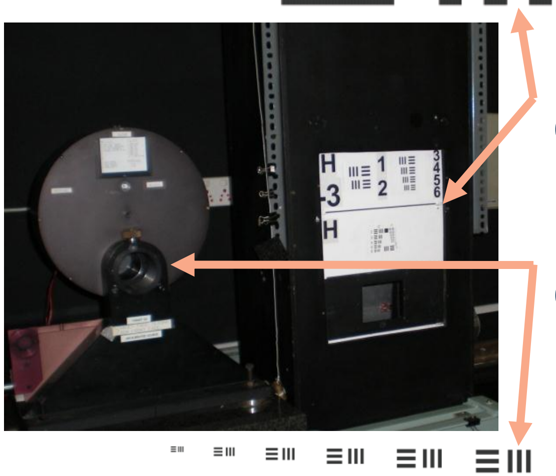
Supporting measurements

- Spectrophotometry
- Spectroradiometry
- Photometry

# Day & Night Resolution Testing

Targets for resolution tests





Lower spatial resolution target (“coarser” patterns)

Higher spatial resolution target (“finer” patterns)

Observation system on resolution testing bench

# MTF Testing

Actual Target (line-target)

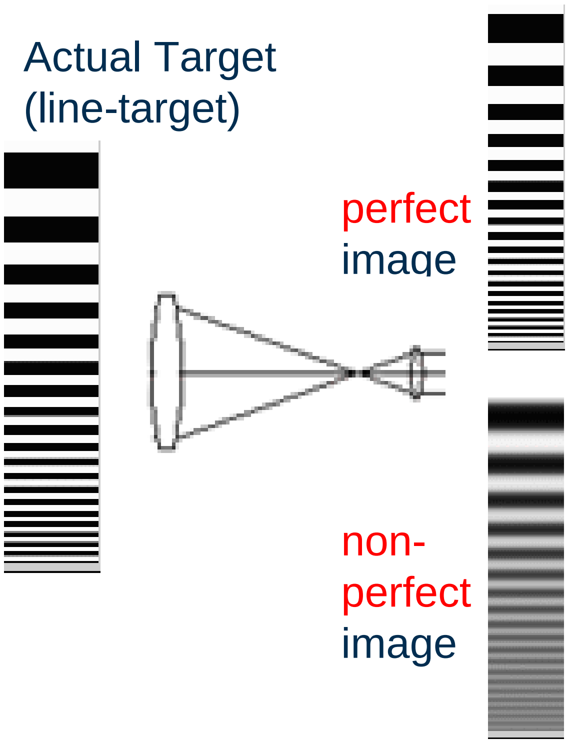
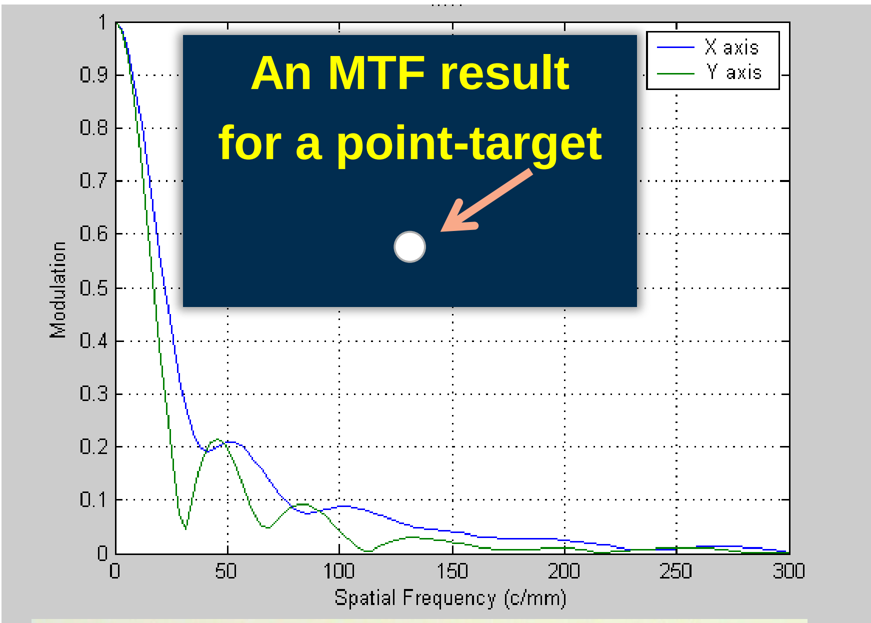
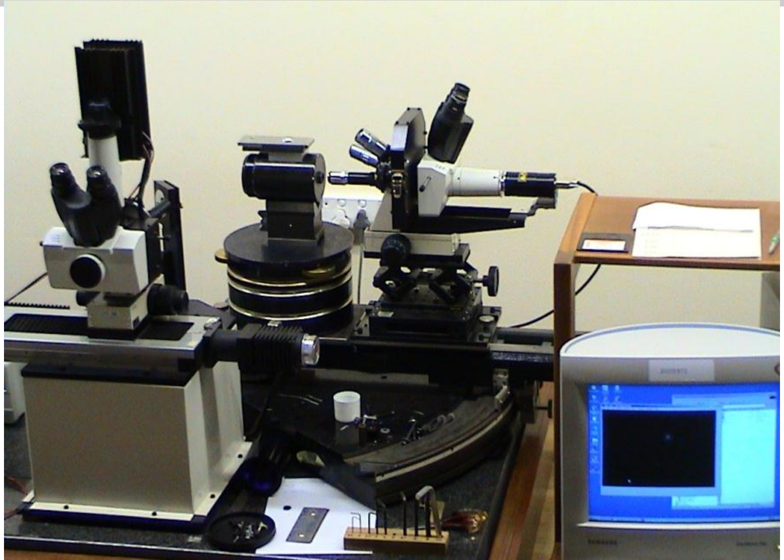



**Image by theoretical lens**

**Image by real lens**

lens aberrations and diffraction "smears" points in the image

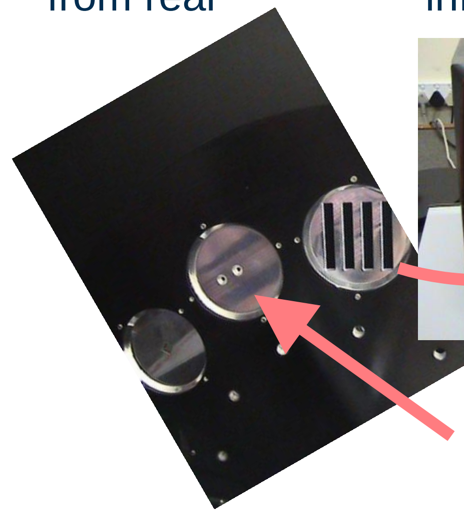


# Infrared Bench:
# MRTD, NETD, Noise, System MTF

Blackbody and target wheel

Part of target wheel seen from rear



Four-bar target Imaged by infrared camera

An MTF target

**MRTD = Minimum resolvable temperature difference**

Smallest temperature difference between a standard target at a given spatial frequency and its background, such that the target is "just resolved" by an observer.



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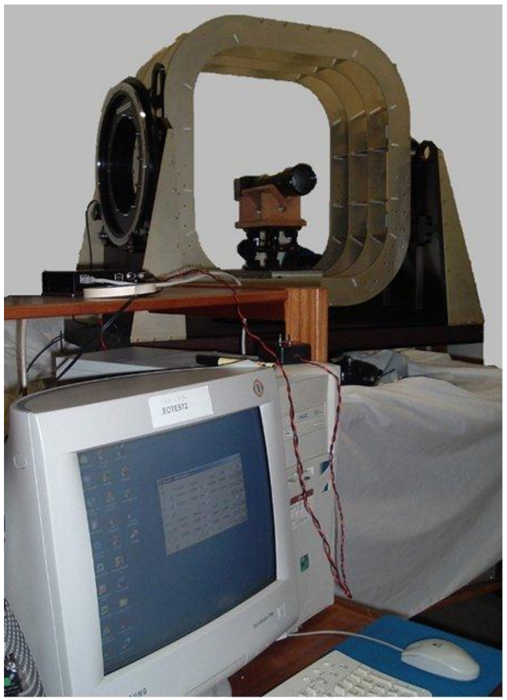
# Off-axis Performance Testing of Optical Systems



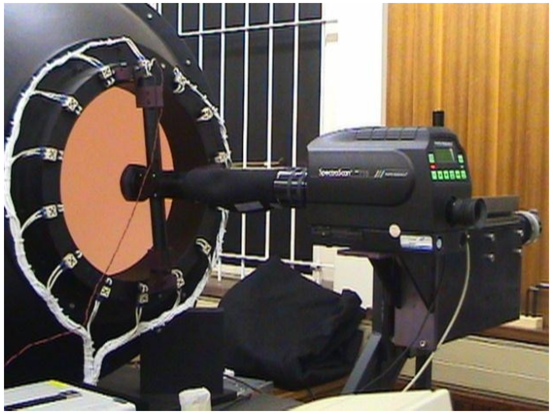
# Testing Thermal Effects on Optical Systems

Performance of optical systems

Use with other benches

- Day or Night resolution testing
- Lens or system MTF
- Infrared: MRTD, NETD, MTF, NETD, Noise

# Radiometry, Spectroradiometry, and Photometry. + Camera Uniformity



**Large uniform sphere source**

**&**

**a spectroradiometer**

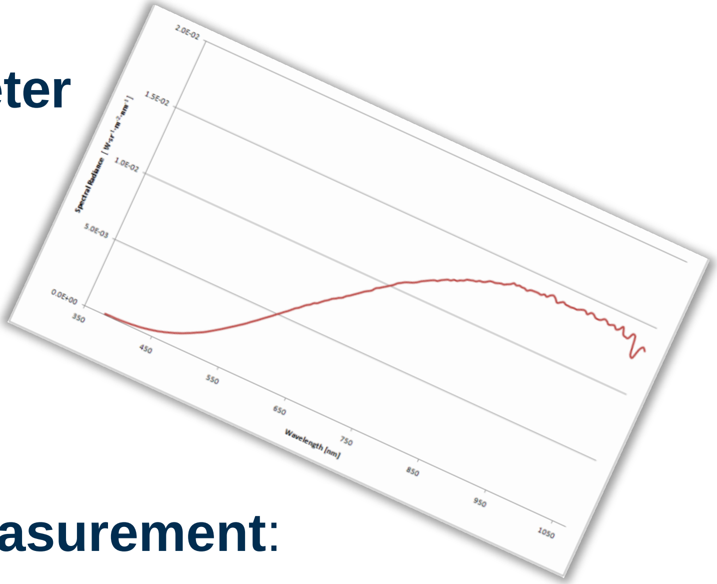


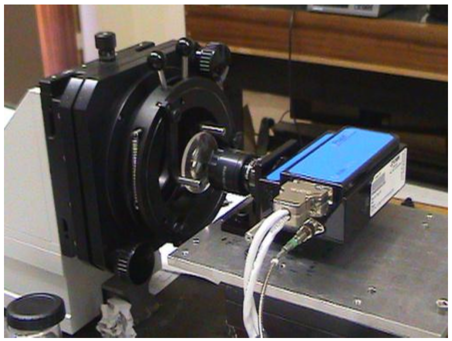

Photo from ASD Inc. brochure

Portable spectro-meter/spectroradiometer

**Laboratory and field measurement**:

- Visible – Near-infrared
- Camera uniformity characterisation using uniform sphere source

# Interferometric wavefront measurement

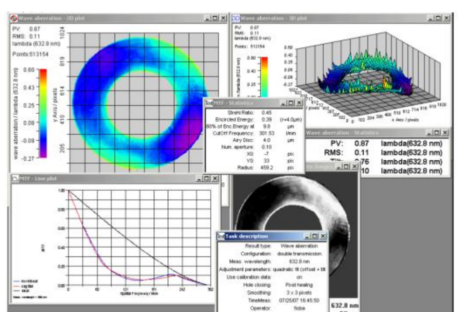


**Main applications**:

- Determine wavefront after traversal of an optical system.
- Determine shape & precision of optical surfaces, be they flat, spherical or aspherical.

**This enables**:

- Verification of component optical surfaces against specifications
- Integration of optical components to a very high degree of precision
- Verification of transmitted wavefront of complete optical sub-assembly or system



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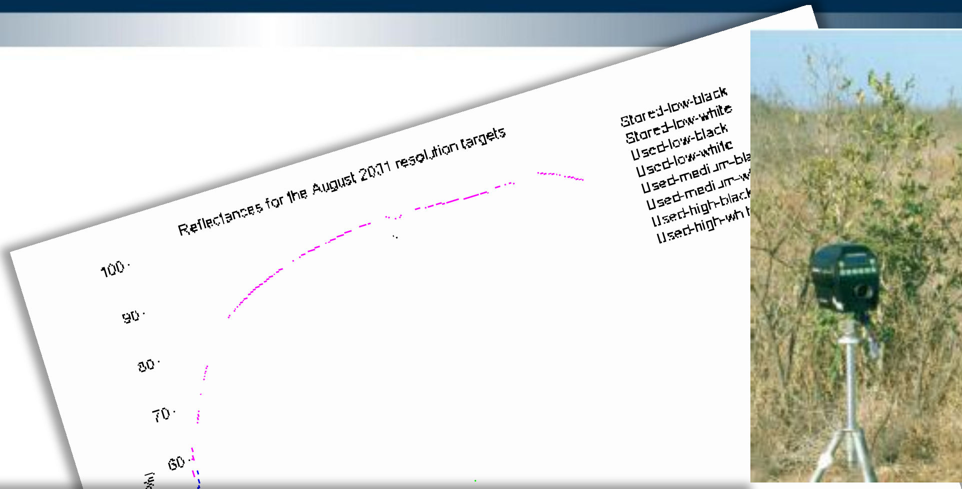
# Spectrophotometry and Colorimetry




**Laboratory and field spectral measurement**:

- Visible – Near-infrared
- UV – Visible – Near-infrared
- Diffuse & Specular
- Transmittance & Reflectance

**Example measurement applications**:

- For camouflage design & evaluation
- Optical materials & filter characterisation

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**Part 5. Laboratory testing: Impact of Local needs & Benefits / Spin-offs from Testing Capability**

## Part 5.

## Laboratory testing:
## Impact of Local needs
## &
## Benefits / Spin-offs from Laboratory Capability

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# Local needs & Spin-offs.
# Global vs Local Optical Testing

- Discussion

# End

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# Literature references


[1] J.M. Geary, Introduction to optical testing, SPIE, 1993

[2] B. Dörband, H. Müller, H. Gross, Handbook of optical systems, vol 5, Metrology of optical components and systems, Wiley, April 2012.

[3] "Basic information about binoculars: Magnification", http://www.nikon.com/products/sportoptics/how_to/guide/binoculars/basic/basic_03.htm, accessed 2013-04-26

[4] Rushdī Rāshid, Encyclopedia of the history of Arabic science. Vol 2. Mathematics and the physical sciences, Routledge, 1996

[5] image used: "Reproduction of a page of Ibn Sahl's manuscript showing his discovery of the law of refraction", now known as Snell's law.", image from http://en.wikipedia.org/wiki/History_of_optics, accessed on 2013-04-26

[6] image used: "Soldiers using multiple flat mirrors could concentrate light on a ship, but could they really get it hot enough to burst into flame?", from http://www.unmuseum.org/burning_mirror.htm, accessed 2013-04-26, Copyright credited to Lee Krystek, 2011

[7] image used: "Diagrammatic representation of the visual system from the oldest existing copy of the Book of Optics by Ibn Al-Haitham, an arab physicist written in the 11 century AD. From Polyak (1957)", online copy of image from http://webvision.med.utah.edu/book/part-ix-psychophysics-of-vision/the-primary-visual-cortex/, accessed 2013-04-26

[8] World map from: https://www.cia.gov/library/publications/the-world-factbook/maps/refmap_political_world.html, accessed 2013-04-26

[9] M Bass, ed., "Handbook of optics", 2nd ed. McGraw-Hill, 1995, (2 or more volumes. Newer edition exists)

# Literature references


[10] http://en.wikipedia.org/wiki/Submarine, accessed 2013-04-26

[11] http://en.wikipedia.org/wiki/Periscope, accessed 2013-04-26

[12] Francis B Patrick, “Military Optical Instruments”, in Applied Optics and Optical Engineering, Vol 5, Part II, R Kingslake, Academic Press, 1969