Astronomical observation through the earth atmosphere

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Astronomical observation through the earth atmosphere

1) Limit to angular resolution

2) Observation with the aid of a telescope;
   - telescope types
   - image field
   - influence of telescope aberration

3) Influence of the earth atmosphere;
   - effect on resolution
   - E-ELT and the ‘resolution solution’
Intensity distribution on the retina

**Ray optics**

**Wave optics**

Euclid

Fresnel

Astronomical imaging through the earth atmosphere

(KNAW  E-ELT mini-symposium, 22 November 2016, Joseph Braat)
Intensity distribution in focus

George B. Airy (1801-1892), Astronomer Royal 1835-1881

Publication:
“On the diffraction of an object glass”,
Transactions of the Philosophical Society of Cambridge,

\[ \delta_A = \left( 2.4 \frac{\lambda}{D} \right) f \]

\[ = 2 \alpha_A f \]

Eye:
\[ \alpha_A = 0.0002 \]

\[ \approx 1' \]
Illustration of two-star resolution
Testing of two-star resolution

A $s = 1.2 \delta_A$

B $s = 0.6 \delta_A$

Rayleigh criterion

C $s = 0.3 \delta_A$

D $s = 0$

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Lens telescope and (angular) magnification

Telescope: $m_A = \frac{a_1}{a_0} = \frac{f_0}{f_1}$ \hspace{1cm} $m_T = \frac{a_0}{a_1} = \frac{f_1}{f_0}$

Irradiance of a star image on the retina is $m_A^2$ LARGER

First observations with lens telescope by G. Galilei
Mirror telescope and aspheric surfaces
(conic sections and general aspheres)

Conic constant $\kappa$

- $\kappa < -1$ hyperbola
- $\kappa = -1$ parabola
- $-1 < \kappa < 0$ prolate ellipse
- $\kappa = 0$ sphere
- $\kappa > 0$ oblate ellipse

- - - - General Asphere
Astronomical imaging through the earth atmosphere

Mirror telescopes (8 m primary)

Theoretical resolution:
16 milli-arcsec = $8 \times 10^{-8}$

A - mirror paraboloid

$2a_0 = 3.10^{-5} = 6''$

$N = 5.10^4$

B - mirror paraboloid - hyperboloid (classical Cassegrain)

$2a_0 = 6.10^{-4} = 2'$

$N = 10^8$

C - mirror hyperboloid - hyperboloid (Ritchey-Chrétien)

$2a_0 = 15.10^{-4} = 5'$

$N = 6.10^8$

$F_1 F''$

$25$ m

$8$ m

$p = 0.7$ mm

$p = 40$ mm

$p = 100$ mm

ASTIGMATISM
Three-mirror telescopes


Example of a classical Paul-Baker design (primary mirror 39 m diameter)

NO COMA

NO ASTIGMATISM

NO FIELD CURVATURE

\[ f' = 75 \text{ m} \]

\[ p = 500 \text{ mm (sensor size)} \]

\[ 2a_0 = 6.4 \times 10^{-3} = 23' = 0.38^\circ \]

\[ N \approx 10^{+11} \]

Theoretical resolution ELT

3.4 milli-arcsec = \(1.7 \times 10^{-8}\)

(5 meter on the moon)
Three-mirror Paul-Baker telescope
Classical layout with general aspheres (39 meter primary)

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<th>$d_1 = \infty$</th>
<th>$c_1$</th>
<th>$-0.0100136102$</th>
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<td>$a_{2,1}$</td>
<td>$-0.50068051 \cdot 10^{-02}$</td>
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<table>
<thead>
<tr>
<th>Image quality</th>
<th>field angle $\gamma$</th>
<th>$OPD_{rms}$ (units of $\lambda$)</th>
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<tr>
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<td>0.0’</td>
<td>0.038</td>
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<td></td>
<td>3.7’</td>
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<td>7.3’</td>
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<tr>
<td></td>
<td>11.0’</td>
<td>0.051</td>
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</tbody>
</table>
Telescope aberrations: coma and astigmatism

- Coma
- Airy disc
- Astigmatism

One star and two stars images are shown.
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   - angular resolution

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Atmospheric turbulence (‘seeing’)

Star light

wavefront

ATMOSPHERE

angular spread rays: 0.8 to 1.2 arcsec

wavefront deviation: several micrometers

eye pupil

(4 mm)
NO BLUR,

ONLY TILT

E-ELT primary

(39000 mm)
SEVERE BLURRING

AND TILT
Atmospheric turbulence (‘seeing’)
Atmospheric turbulence (‘seeing’)
Conclusions

- a (passive) 39 meter telescope is unique with respect to light collection

- all mirror surfaces should be individually measured and adjusted down to a fraction (50 nanometer) of the wavelength of visible light (\(\lambda=550\) nanometer)

- ‘seeing’ at E-ELT-site is of the order of \(0.8\) arcsec (0.3 arcsec record low value) → enormous gap with the theoretical resolution of E-ELT: \(0.0034\) arcsec

- full imaging capability of the 39-meter telescope requires

  - mechanical deformations add up to optical aberrations smaller than \(100\) nm
  - seeing effects should be cancelled over an area of \(1100\) square meters

**HERCULEAN TASK for the E-ELT team of the European Southern Observatory**