What are the important issues when defining the specifications for a scientifically successful (LGS) AO system?
Lessons learned for adaptive optics

Review of AO for Astronomy
Davies & Kasper 2012, ARAA vol 50

1. from demonstration to scientific productivity
2. astrophysical vs technical target selection
3. AO performance metrics
4. performance in poor atmospheric conditions
5. mitigating the effects of atmospheric variability
6. concurrent telescope and AO design
7. significant operational effort
8. post-processing support

with thanks to:
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From demonstration to scientific productivity

• there is a vast gulf between demonstrating a technology and making it scientifically productive

delayed growth in publications (refereed observational papers in 7 main journals)

• first astronomical AO system on sky in early 1989
• 1998-2000: AO citation rate lower than average
• 2008-2010: AO citation rate from 8-m class telescopes higher than average (& higher than HST)

related to AO spending profile?

• total spent worldwide to date > 500 million $/€
• massive increase after 2000

related to technical limitations on target selection?

• a ‘threshold’ in science domain for high impact work: does resolution / number of targets / etc. lead to a new understanding of physical processes
Astrophysical vs Technical target selection

• AO ought to be accessible to targets for which the primary selection criteria are astrophysical rather than technical

• estimates of sky coverage based on statistical models of stellar distribution are no good
• observational progress depends on:
  - specific targets with prior knowledge & ancillary data
  - large representative samples
• most targets are hard for AO: low airmass, faint, far-off guide stars, etc
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The Butterfly Star – circumstellar disk around a YSO

- 60" radius
- R = 14.8 mag
- R = 19.3 mag

K-band (Wolf+ 03)

- Dense accretion disks form in T Tauri & Herbig Ae/Be stars
- Key process in planet formation
- High resolution multicolour infrared images yield:
  - dust distribution → disk geometry
  - grain properties → how they grow & settle towards midplane
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Arp 220 – prototypical merger

NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)
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ZC 406690 – a high redshift clumpy disk galaxy

Genzel+ 11, Förster Schreiber+ 11
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Growing bulges in z~2 disk galaxies

Genzel+ 08, Förster Schreiber+ 11
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Kinematics of z~2 galaxies

Förster Schreiber+ 06, 09, 11
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Kinematics of z~2 galaxies

- 6000 spectroscopically confirmed sources at 1.4<z<2.5 in central degree of COSMOS field
- Need emission lines brighter than some threshold & away from atmospheric OH: *factor 10 reduction*
- AO requirements (NGS/LGS): *factor 10 reduction*
- Only 60 sources left
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- Need to understand requirements on AO imposed by targets rather than vice-versa
- Current performance metrics are not suitable for this
Instrumental Trade-offs

• AO does not always need to provide highest Strehl & diffraction limited resolution

• lack of good guide stars
• IFUs: 3-way trade-off related to choice of pixel scale
  - signal-to-noise
  - spatial resolution
  - field of view

NGC6240

Max+ 07 (NIRC2/Keck)
Engel+ 10 (SINFONI/VLT)
Medling+ 11 (OSIRIS/Keck)

NGC3783

continuum

3.2"

[Si VI]

logarithmic scaling

0.8"
**AO performance Metrics**

- **strehl ratio**: good in some cases; but also conflicts due to faint & sparse tip-tilt stars.

- **sky coverage**: is crucial. Statistical estimates of sky coverage are of limited value, since progress in astrophysics relies on specific targets/fields. The scientific penalty for insufficient sky coverage is enormous.

- **spatial resolution**: often limited by signal-to-noise or instrument trade-offs.

- **encircled energy**: can be useful in specific cases, but is often defined in large apertures (e.g. 50% EE diameter) and lacks any information about resolution on smaller scales.

- **RMS wavefront error**: is necessary technically; but astronomers don’t even understand what it means.
AO performance Metrics

A simple set of AO performance metrics ought to be widely applicable to all types of astrophysical targets and science cases. Need metrics relevant to astronomers & AO designers, and appropriate for LGS AO, i.e. 2 metrics used together:

1. resolution (FWHM of PSF)
2. central energy concentration (fraction of PSF flux within FWHM)

→ related to Strehl for perfect tip-tilt correction

examples

resolution = diffraction limit:
central energy concentration is equivalent to Strehl ratio

resolution > diffraction limit, but central energy concentration high:
still good contrast in PSF, but tip-tilt requirements relaxed so sky coverage increases

resolution = pixel size:
central energy concentration is equivalent to encircled energy (e.g. as used in MUSE specs)
Performance in poor atmospheric conditions

- AO ought to provide a useful level of performance in moderate to poor atmospheric conditions

*SINS-zCOSMOS large programme*

- High-resolution SINFONI+AO tomography of z~2 star-forming galaxies: witnessing the growth of disks and bulges
- 60 hrs ‘pre-imaging’ and then 240 hrs of AO observations with SINFONI spread over 2 years (10 hrs on each of 24 targets); has taken 3 yrs and is still not finished

*MUSE science case 2004: galaxy formation & evolution*

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Limiting flux is in \( 10^{-19} \text{erg.s}^{-1}\text{.cm}^{-2} \) units.
Mitigating the effects of atmospheric variability

• AO performance ought to mitigate the effects of highly and rapidly variable atmospheric conditions

variability of turbulence profiles

altitude (km ASL)

0.0 0.3 0.6 0.9 1.2 1.5 1.8 2.1 2.4 2.7 3.0

average deviation of log ($C_n^2$)

0 2 4 6 8 10 12 14 16 18 20

stratosphere, moderately variable
tropopause, highly variable
boundary layer, weakly variable
mid troposphere, strongly variable
night to night
site to site
10 min to 10 min

Racine 2009
Mitigating the effects of atmospheric variability

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![Graph showing variability of turbulence profiles](image-url)
Conclusions

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3. A simple set of AO performance metrics ought to be widely applicable to all types of astrophysical targets and science cases:
   a) resolution
   b) central energy concentration

4. AO ought to provide a useful level of performance in moderate to poor atmospheric conditions.

5. AO performance ought to mitigate the effects of highly and rapidly variable atmospheric conditions.