Survey of Present and Future Ground-Based Imaging Systems

Olivier Guyon (guyon@naoj.org)
University of Arizona
Subaru Telescope

With material from:
Rich Dekany, Ben Oppenheimer (Palm 3000, P1640)
Bruce Macintosh (Gemini Planet Imager)
+ HiCIAO, NICI, SPHERE
Direct imaging of Exoplanets allows extensive characterization

Orbit

Atmosphere composition

Continents vs. Oceans?

Rotation period

Weather patterns

Planetary environment: Planets + dust
Exoplanet characterization with direct imaging

- **Astrometry**
  - Direct imaging of other systems
  - Transit spectra observations (nulling, ALMA...)
- **Radial Velocity**
  - Orbit, Mass, Radius
  - Inclination
- **Rotation period**
- **Atmosphere composition & structure**
- **Direct imaging (Visible or IR)**
  - Planet position
  - Spectra / colors
  - Time photometry & polarization
  - Exozodi map
- **Dynamical stability**
- **Planet formation models**
- **System dynamical stability**
- **Orbit belt**
- **Habitability**
- **Surface temperature, pressure & composition?**
- **Tidal forces**
- **Atmosphere variation?**
- **Drum function**
- **Eff. temp (IR)?**
- **albedo (VIS)?**
- **measurements on other systems**
- **Transit & microlensing statistics**
- **Impact frequency**
- **Volcanism**
- **Exoplanet characterization with direct imaging**
  - Dynamical model
  - Measureme
Why is it difficult? (even in space)

**High Contrast**

**Small angular separation**

**Low Flux**

What would it take to image an Earth-like planet around Sun-like star at 10pc?

~1e-10 contrast in visible light, h=1.6e-12 m (0.0012 nm) = 1e-10 speckle

1e-10 speckle (or 1e-10 contrast planet) around Sun at 10pc = 0.1 ph/sec/m²/um

On a 4-m telescope, with 10% efficiency and a 0.5 um spectral band:

Earth = 0.6 ph/sec

To measure phase and amplitude of speckle requires ~10 photon

10 photon = 16 sec

→ **This spatial frequency would need to be stable to 1/1000 nm over ~ minute**

(in near-IR, 1e-7 contrast → h = 0.16 nm)
Exoplanets: Contrast ratio, visible vs. infrared

In the visible, the contrast is very challenging unless the exoplanet is very close to the star (luminosity goes as d^{-2})
Required wavefront quality cannot be achieved from the ground. Habitable planets cannot be imaged from the ground, and will likely require dedicated space telescope+instrument.

In the near-IR (1-5 um), giant and young planets
• (“young Jupiters”) can be imaged:
  • Adaptive Optics systems work well in the near-IR
  • Giant planets emit their own light (thermal emission)
  • Young planets are still very hot, and cool slowly after formation

In the Thermal IR (~10 um & longer), contrast is even more favorable, and older giant planets can be imaged (this is one of the key science goals of JWST)
Exoplanets imaged with ground-based telescopes...
... tip of the iceberg (Young, massive, and large orbits)

2M1207 exoplanet (Chauvin et al., ESO, 2004)
Possibly the first direct image of an exoplanet

HR8799: first image of exoplanetary system with multiple planets
(Marois et al. 2009)

Beta Pic exoplanet and dust disk (Lagrange et al. 2009)

... using AO systems and camera which were not specifically designed for high contrast imaging (but often using optimized data acquisition and reduction techniques)

No coronagraph was used (in fact, coronagraphs are mostly useless on current AO systems)
Why coronagraphy?

Conventional imaging systems are not suitable for high contrast (even if perfect) due to diffraction.

Airy diffraction pattern, linear scale

Airy diffraction pattern, log scale

Typical young Jupiter, nearIR 5-10 AU orbit, 8m telescope

Earth in visible d=10pc, 2m telescope
**Why are coronagraphs (mostly) useless?**

A coronagraph can only remove a known & static diffraction pattern. Coronagraphs can’t remove unknown (when the coronagraph is designed) diffraction (including speckles due to WF errors). **BUT** static & known diffraction can be removed in the computer?

**Two fundamental reasons why a coronagraph is useful:**
(1) Reduce photon noise from diffraction
(2) Avoid coherent amplification between speckles and diffraction pattern

Coronagraphs serve no purpose if the dynamic speckle halo (due to residual wavefront errors) is higher than the static diffraction (due to pupil shape) … *which is the regime under which most current AO systems operate.*
Coherent amplification between speckles and diffraction pattern

**Final image = PSF diffraction (Airy) + speckle halo**

This equation is true in complex amplitude, not in intensity.

Intensity image will have product term → speckles are amplified by the PSF diffraction.

---

Aime & Soummer 2004
Need for good AO correction and good coronagraphs

1.5-m subaperture of Palomar + AO system + high perf coronagraph (Serabyn et al.)

Full aperture (10-m) No coronagraph, standard AO system (Marois et al.)
NICI system (Gemini South)

85-element curvature AO system  
Lyot type coronagraph  
Simultaneous dual band imaging (inside / outside methane abs. Band)

Currently surveying ~300 nearby young stars

Liu et al., 2010
NICI system (Gemini South)

Fig. 1.— Left: $J$, $H$, and $K_s$-band images of the PZ Tel system obtained with NICI in direct imaging mode at the Gemini-South Telescope in May 2010. North is up, east is left. The primary resides at the center of the translucent 0.22\" radius focal plane mask and is attenuated by a factor of 329 in $J$, 214 in $H$, and 131 in $K_s$-band. The confirmed companion is at 0.36\" separation and PA=59.4\° with flux ratios of $\Delta J = 5.40\pm0.13$, $\Delta H = 5.38\pm0.09$, and $\Delta K_s = 5.04\pm0.10$ mag. Right: Maskless ADI $H_2$ 2-1 (2.12 \text{ \mu m}) image from May 2010. Light from the primary has been removed by ADI processing.

NICI is the first system (coronagraph + AO) designed for a high contrast imaging survey of nearby young stars deployed on a 8-m class telescope

Combines together well-proven technologies:
- Curvature AO, 85 elements
- Lyot coronagraphy
- Spectral differential imaging
HiCIAO system (Subaru Telescope)

(see presentation by M. Tamura in this conference)

HiCIAO combines:
- Curvature AO, 188 elements
- Lyot coronagraphy
- Spectral differential imaging

AB Aur disk imaged with HiCIAO
Higher quality AO correction (Extreme-AO) is becoming available, and will make efficient use of coronagraphs
(Coronagraphs will soon become very useful !!!)
Higher quality AO correction (Extreme-AO) is not sufficient: **calibration and stability** are important.

Removing bias in AO correction

It is essential to minimize slow and static speckles that may look like planets. There are the limiting factor in current systems. Fast atmospheric speckles are OK, as they average out very rapidly into a smooth PSF halo.

Bias can come from non-common path error, bias in the wavefront sensor, uncorrected mode that is not detected by the WFS.

Calibrating residual speckle halo in the PSF

Using differential measurements, looking for:
- ways to change/modulate the speckle field without changing the planet image, or
- ways to change the planet image without changing the PSF halo.
PSF calibration strategies

- “classical” PSF subtraction: observe reference PSF, subtract
- Angular Differential Imaging: same-star subtraction thanks to sky rotation
  - works well at large angular separations, where aberrations have large static component
  - poor performance close in to the star (not enough rotation)
- Spectral differential imaging (dual band or IFS)
  - Speckle calibration works well at large angular separations, where speckles are spectrally elongated, but does not work as well close in to the star
  - Science (spectra) + speckle calibration from same data
  - IFS is more powerful and efficient than simultaneous differential imaging
- Polarimetric differential imaging
- Coherent differential imaging: speckles are coherent with starlight, real sources are not
  - Does not make any assumption about source (spectra, polarization)
  - combined wavefront sensing / PSF calibration
  - Works well very close to the star
  - works only within control radius of DM, requires good detector (fast readout favored)
From past/present to future instruments

“Conventional” AO imaging, usually without coronagraph

First Systems designed for high contrast imaging, combining existing techniques

HiCIAO

NICI

Lyot coronagraph
Differential spectral imaging
Good AO system

Extreme-AO coronagraphic systems designed

PALM3000+P1640:
First ExAO with IFS
GPI, SPHERE:
Large survey with high performance systems
SCExAO:
Pushing close in to the star

Better AO correction:
More actuators
Better WFSs

Improved PSF calibration:
IFS, coherent PSF detection

Better coronagraphs:
APLC, PIAA, 4 quadrant
The PALM-3000 upgrade to Palomar AO

• Science goals:
  • Comparative exoplanet and disk studies in the near-IR
  • Visible-light science at the diffraction-limit

• Deformable mirrors
  – 3388-actuator, 1µm stroke “tweeter”
  – 241-actuator, 5 µm stroke “woofer”

• Selectable WFS pupil sampling
  – 63x63, 32x32, 16x16, or 8x8
  – Up to 2kHz WFS frame rate

• Science instruments:
  • Project 1640 near-IR APLC coronagraphic IFS & CAL (AMNH & JPL)
  • PHARO near-IR Lyot and vortex coronagraph / spectrograph / imager (Cornell & JPL)
  • SWIFT visible-light IFS (Oxford)
  • Visible light imager and ‘red’ vortex coronagraph (Caltech & JPL)
  • Future option: Echelle fiber feed (Caltech)

PI: Richard Dekany
- Palomar 5m Telescope
- Apodized pupil Lyot coronagraph
- 200 x 200 spaxel JH IFS
  - $R \sim 30$; 20 mas / pixel
- < 5 nm RMS CAL
  - Currently 15 nm RMS
- Performance goals
  - $10^{-6}$ raw contrast (SNR = 1, 30s)
  - $10^{-7}$ post-LOC (SNR = 5, 30m)
- Schedule
  - First high-order lock: July 2011
  - 99-night Survey 2011-2014
Plan: Utilize the chromatic nature of speckles with a IFS.

Wavelength diversity enables differentiation between speckles and companions.

RED (1.8 μm)

Automatically provides spectra of any companions.

BLUE (1.0 μm)

Credit: B. Oppenheimer
PSF calibration with Integral Field Spectrograph

Speckle spatial scale and contrast changes with lambda IFS data can be used to fit speckle field image with a residual OPD error in the pupil plane.

Figure 9. PI640 contrast levels in the $H$ band for the star HD 204277 taken on 2009 June 28 UT. The star is occulted by the apodized pupil Lyot coronagraph. PSSP consistently provides a gain of at least one order of magnitude in sensitivity at subarcsecond separations.
Gemini Planet Imager (GPI)

- 44x44 MEMS AO system
- Static speckles minimized
  - Precision optics
  - Daytime speckle nulling calibration
  - On-sky IR interferometer WFS
- APLC
- IR integral field spectrograph
APLC coronagraph masks

Focal plane mask

Apodizer profile

Apodizer

Focal plane mask

Field transmission

Transmission error (%)
Calibration interferometer (JPL) measures slow aberrations to nanometer accuracy.
Individual optics < 1 nm
Integral field spectrograph
Performance models now on http://planetimgaer.org
Spectro-Polarimetric High Contrast Exoplanet REsearch (SPHERE)

- High order AO correction (SAXO)
  - 41x41 actuators DM
  - ~90% Strehl in H band
- Dual band near-IR imaging (IRDIS)
  - <10 nm differential error
- Integral Field Spectrograph (IFS)
- Visible differential polarimetric imager (ZIMPOL)
  - Direct imaging of disks and evolved planets (reflected light)

Large survey will start in ~2012
- Schedule and science goals similar to GPI
SPHERE & GPI:
high performance systems
+ large telescopes in good sites
+ large observing programs

Statistics: SPHERE & GPI will observe a large sample of stars to few MJ sensitivity
→ good planet statistics for >MJ planets at >5AU
  Complementary to RV and transits, which favor close in planets
  Will provide strong test for planetary formation theories (formation + migration)
  Sample will be sufficiently large for comparative planetary system architecture studies
  How do planetary systems change as function of stellar mass?

Characterization: SPHERE & GPI will obtain spectra of exoplanets
→ constrain planetary atmosphere models, cooling rate → better mass estimates
The Subaru Coronagraphic Extreme-AO (SCExAO) system

O. Guyon, F. Martinache, V. Garrel, C. Clergeon, J. Morino, T. Kudo, P. Stewart, T. Groff

High contrast imaging at small angular separation is scientifically extremely valuable:
- allows system to probe inner parts of young planetary systems (<10 AU)
- constrain planet formation in the habitable zone of stars
- direct imaging of reflected light planets may be possible (reflected flux goes as \(a^{-2}\))
- number of planet accessible scales as \(IWA^{-3}\)

Designed as a highly flexible, evolvable platform
→ uses new (more risky) techniques than GPI and SPHERE
Efficient use of AO188 system & HiCIAO camera
Ongoing telescope engineering runs (Feb 2011, Jul 2011)

1 \(\lambda/D\) PIAA coronagraph
NIR focal plane WF control/calibration
Coronagraphic low order WFS
ExAO-optimized visible WFS
High contrast imaging in lab reaches much higher performance than what is currently achieved on-sky: newer technologies, more stable environment, better calibrations.

SCExAO's goal is to deploy on the telescope new techniques which have been demonstrated in the lab to offer high performance, and to create the conditions necessary to achieve this high performance.
SCExAO at Subaru Telescope (Aug 2010)

Subaru facility
Adaptive Optics System (AO188)

SCExAO bench
HiCIAO support pads when used with SCExAO

AO188 frame
SCExAO / HiCIAO frame (can accept other instruments)
SCExAO Wavefront Control architecture and speckle calibration

Not available at first light (early 2011) Under development at Subaru, UofA, HIA

AO188

AO188 curvature WFS Uses photon-counting APDs
Facility AO sytem AO188 (bimorph curvature DM, 188 elements, 1 kHz update)

HiCIAO

Calibrated Science image
Science image

SCExAO

DM offset shape (initially flat)

Coherent light component
Tip-tilt, focus

High order aberrations, high speed

High speed high Sensitivity ExAO visible WFS (non-linear curvature)

Near-IR fast frame Imaging camera

Science focal plane Camera / WFS

Coronagraph

Focal plane AO loop (measures focal plane coherent and incoherent components)

32x32 actuators MEMS Deformable mirror (600 actuators Illuminated, low stroke, fast)

Facility AO sytem AO188 (bimorph curvature DM, 188 elements, 1 kHz update)

λ<600nm

H-band filter

λ>900nm

Estimate of light due to coronagraph leaks and fast speckles

λ>600nm

Science focal plane mask

Coronagraph

600nm<λ<900nm

Dichroic

λ<600nm

Coronagraph

λ>900nm

H-band

Science image

Focal plane AO loop (measures focal plane coherent and incoherent components)
The Subaru Coronagraphic Extreme-AO (SCExAO) system
The Subaru Coronagraphic Extreme-AO (SCExAO) system

- Internal source (Near-IR + vis)
- MEMS DM + tip-tilt mount
- Spider removal + PIAA optics
- Pupil Steering mirror
- Dichroic
- Focal Plane mask
- Inverse PIAA
- LOWFS camera
- High order WFS
- Visible camera
- nearIR Science camera
- Visible Science camera
- Internal source (Near-IR + vis)
Phase-Induced Amplitude Apodization (PIAA) coronagraph

Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in single diffraction peak (no Airy rings).

- high contrast (limited by WF quality)
- Nearly 100% throughput
- IWA $0.64 \frac{\lambda}{D}$ to $2 \frac{\lambda}{D}$
- 100% search area
- no loss in angular resol.
- can remove central obsc. and spiders
- achromatic (with mirrors)

Refs: Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present
3rd generation refractive PIAA optics

- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration
Spider Removal Plate

- 15 mm thick precision window
- Fused Silica
- Tilt angle: 5 +/- 0.02°
Beam shaping hardware
CLOWFS pointing control demonstrated to $1 \times 10^{-3} \frac{\lambda}{D}$ in visible
Coronagraph leaks calibrated to 1% in SCExAO (Vogt et al. 2011, submitted)

Co-added science image

Standard PSF subtraction

MMA

(a)

(b)

(c)

![Graph](image)

- Coronograph only
- Random match
- Best match

![Graph](image)

\[
\begin{array}{c}
\text{Detectability} \\
10^{-2} \quad 10^{-3} \quad 10^{-4} \quad 10^{-5} \quad 10^{-6} \quad 10^{-7}
\end{array}
\]

\[
\begin{array}{c}
\lambda/D \\
4.75 \quad 10.00 \quad 20.00 \quad 30.00 \quad 40.00 \quad 50.00 \quad 60.00
\end{array}
\]
Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)

\[ m \sim 13 \]

<table>
<thead>
<tr>
<th>WFS</th>
<th>Loop frequ</th>
<th>RMS</th>
<th>SR @ 0.85 µm</th>
<th>SR @ 1.6 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>nlCurv</td>
<td>260 Hz</td>
<td>101 nm</td>
<td>57%</td>
<td>85%</td>
</tr>
<tr>
<td>SH - D/9</td>
<td>180 Hz</td>
<td>315 nm</td>
<td>~4%</td>
<td>22%</td>
</tr>
<tr>
<td>SH - D/18</td>
<td>180 Hz</td>
<td>195 nm</td>
<td>~13%</td>
<td>56%</td>
</tr>
<tr>
<td>SH - D/36</td>
<td>160 Hz</td>
<td>183 nm</td>
<td>~16%</td>
<td>60%</td>
</tr>
<tr>
<td>SH - D/60</td>
<td>140 Hz</td>
<td>227 nm</td>
<td>~6%</td>
<td>45%</td>
</tr>
</tbody>
</table>
Focal plane AO and speckle calibration

Use Deformable Mirror (DM) to add speckles

**SENSING:** Put “test speckles” to measure speckles in the image, watch how they interfere

**CORRECTION:** Put “anti speckles” on top of “speckles” to have destructive interference between the two (Electric Field Conjugation, Give’on et al 2007)

**CALIBRATION:** If there is a real planet (and not a speckle) it will not interfere with the test speckles

Fundamental advantage: Uses science detector for wavefront sensing: “What you see is EXACTLY what needs to be removed / calibrated”
2e-7 raw contrast obtained at 2 $\lambda/D$

Incoherent light at 1e-7
Coherent fast light at 5e-8
Coherent bias <3.5e-9

Test demonstrates:
- ability to separate light into coherent/incoherent fast/slow components
- ability to slow and static remove speckles well below the dynamic speckle halo
Reflected light imaging

Initially very hard – requires ~1e-7 contrast and small inner working angle

Contrast is not a steep function of planet mass → small gains in contrast performance can lead to large science gain

Easiest targets are the closest stars (few pc) – stars can be old

High performance system on 8-m telescope can detect reflected light from a few of the known RV planets
This will be an important science case for ELTs

*Upcoming ExAO systems will validate technologies for reflected light imaging on larger telescopes*
Ultimate performance limit

Could Earth-like planets be imaged from the ground?

Assuming:
- perfect AO system, limited by photon noise in the WFS and speed of turbulence
- perfect coronagraph (to the contrast level reached by AO system)

At 0.85 um:
8-m telescope can reach better than ~1e6 RAW contrast
30-m telescope can reach better than ~1e7 RAW contrast

$m_i=5$ source, 0.05 um effective bandwidth, 1 hr exposure

Planet contrast = $1e10$
8-m telescope: 452 ph/hr for planet, 4.5e6 ph/hr from speckles $\rightarrow$ $\text{SNR}_{\text{ph noise}} = 0.2$
30-m telescope: 6356 ph/hr for planet, 6.4e6 ph/hr from speckles $\rightarrow$ $\text{SNR}_{\text{ph noise}} = 2.5$
Could Earth-like planets be imaged from the ground?

At nearIR (1.6 μm), PSF contrast is x2 better, number of planet photon similar.
30-m telescope: 6356 ph/hr for planet, 3.2e6 ph/hr from speckles → SNR_{ph noise} = 3.5

→ Earth-like planets cannot be imaged from ground with 30m telescope

Super-Earths?
Radius x3, contrast can be 10x better → SNR_{ph noise} = 35

Highly optimized system on ELT could image Super-Earth in habitable zone of nearby star. Low resolution spectroscopy would be possible if the planet is around a nearby star (d < 10pc), but mid-resolution spectroscopy would not be possible at high SNR.

With broader definition of “Earth” (nearby K, M? type main sequence star), SNR is much better, and target can be closer.