Wavefront control architecture and expected performance for the TMT planetary systems imager

TMT-PSI team

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Science Goals & Instrument Capabilities

Broad science reach, enabled by unprecedented angular resolution and sensitivity

Exoplanets and Disks (Core Science)
- Planetary systems architectures
- Exoplanets characteristics – Bulk properties, Atmosphere compositions
- **Exoplanet Habitability (search for biomarkers and habitable environments)**
- Disks: Morphology (planet/disk interaction), dust properties

Solar system
- Volcanic eruptions on Io
- Organics in Comets
- Asteroid multiples
- Planetary Atmospheres

Galactic Astronomy
- Stellar multiplicity
- Stellar evolution
- Inner Regions of Circumstellar Disks
- Ice Lines in Disks
- Dust streamers in Interacting Binaries
- Compact Objects

Extragalactic Astronomy
- QSOs / AGNs

Core Science drives instrument design
- → Broad wavelength coverage
- → Spectroscopy
- → Polarimetry
- → High Contrast Imaging
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High Contrast Habitable Planets Imaging and Characterization at near-IR/optical

This is the most challenging science goal: drives most WFS/C performance requirements

Focus of THIS presentation (everything else is easier)
Instrument Architecture (notional)

Wide wavelength coverage
3 science outputs for cameras/spectrographs:
- Thermal IR (> 8 μm) could be feeding MICHI
- Near-IR (2-5 μm)
- Optical (< 1.8 μm)
**Instrument Architecture (notional)**

PSI-Blue provides ExAO & high contrast. Its most challenging science goal is to image and characterize habitable planets.

Warm optics, **deployed at first light and upgradeable**: coronagraph masks, control algorithms, back-end instrumentation modules.

2+ um science does not critically rely on extreme AO/HCI performance (background-limited).

Common DM feeds all ports. Cryogenic coronagraph and relay optics. **Notionally deployed as facility-class instrument at first light**.
Wavefront control architecture for ExAO

Two-stage correction:
Common DM (~120x120 large stroke) → fast MEMs (~60x60 or larger)

Dual near-IR and visible WFS provides:
(1) Correction on a broad range of targets
(2) High ExAO performance:
   - Sensitivity: using both vis and nearIR
   - Robustness: nearIR WFS for coarse correction, visible for high precision

ExAO instrumentation is integral part of HCI WFS/C

Speckle control:
Post-coronagraphic image feeds control loop

Low-Order WFS/C:
Light discarded by coronagraph encodes low-order aberrations
Contrast and Angular separation
Hypothetical Earth-like planets

Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired [ assumes 1e-8 contrast limit, 1 $\lambda/D$ IWA ]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (speculative)

Thermal emission from habitable planets around nearby A, F, G type stars is detectable with GSMTs

Space-based observatories observing in visible and near-IR light

1 Re rocky planets in HZ for stars within 30pc (6041 stars)
Contrast / Separation requirements

PSI’s ultimate goal: habitable planet observations around nearby M-type stars:
Separation ~2 I/D, ~1e-8 contrast, mR~10

Small IWA coronagraphy
ExAO + Differential imaging
Efficient WFS, multi-band, multi-sensor, predictive control
TMT coronagraph design for 1 I/D IWA

- Pupil Plane
- PIAACMC lens 1 front surface (CaF2)
- PIAACMC lens 2 front surface (CaF2)
- PSF at 1600nm
- 3e-9 contrast in 1.2 to 8 I/D
- 80% off-axis throughput
- 1.2 I/D IWA
- CaF2 lenses
- SiO2 mask
Small-IWA coronagraphs already in operation on-sky

PIAACMC
measured IWA = 1.43 I/D

Vortex
measured IWA = 1.57 I/D

MPIAA + Vortex
measured IWA = 0.91 I/D

MPIAA + 8QPM
measured IWA = 1.70 I/D

SCExAO: new high-performance coronagraphs ready for science
Paper 10706-207, Time: 6:00 PM - 8:00 PM, Julien Lozi,
Keck/NIRC2 vortex gallery

Mawet et al. 2017
Reggiani et al. 2018
Wertz et al. 2016
Serabyn et al. 2017

Slide courtesy of Dimitri Mawet
Differential Detection Techniques

Angular Differential Imaging (ADI)
Does not address noise limit from slow speckles

Spectral Differential Imaging (SDI) (low spectral resolution)
Limited by chromaticity in speckles

High Resolution Spectroscopy (Snellen et al., Mawet et al.)
Very clean signal (narrow lines) not present in starlight
But few % of planet light used → photon noise (from starlight) limits use
(See Wang et al. 2017)

Polarization Differential Imaging
Polarized light fraction is small (<10% ?)
→ photon noise (from starlight) limits use

Coherent Differential Imaging
Can use 100% of light
Challenging to implement, calibration issues
High Dispersion Coronagraphy

Snellen et al. 2015; Mawet et al. 2017; Wang et al. 2017

See Ji Wang’s talk 10703-64 on Thursday pm

… another slide stolen from Dimitri
Coherent Speckle Differential Imaging
Key WFS/C questions

Q1: What is the optimal detection band for reflected light imaging of habitable planets?

Q2: What raw contrast is required?

Q3: What is the optimal wavefront sensing wavelength?

Q4: How to achieve the raw contrast: Challenges and solutions?
Q1: What is the optimal detection band for reflected light imaging of habitable planets?

**Scientific Value**

Blue/visible: Rayleigh scattering
760 nm Oxygen A band

NearIR rich in absorption bands:
Oxygen (1.27um), Water, Methane, Carbon Dioxyde

Thermal emission starts at ~3 um, rich in molecules

**Expected Instrument Capabilities**

Let us assume that:
(1) ExAO system can deliver 1e-6 raw contrast at 1um
(2) Every star has one Earth analog
(3) Photon noise limit from both starlight and planet light

We can scale contrast according to wavelength (C ~ lambda^-2)
.. and scale coronagraph according to wavelength (IWA ~ lambda)

We count, for each spectral band (V, I, J, H, K), how many planets are characterizable:
R=40 spectra at SNR=10 can be acquired in < 1hr
(approximate requirement for spectroscopic detection of key molecular species)
V band
Too much starlight left $\rightarrow$ 0 planet characterizable

Targets suitable for ExoEarth spectral characterization (V band)

528 planets SNR-accessible (no starlight)
0 planets characterizable

Circle size proportional log10 planet photon flux
Optimal wavelength range: J & H  /  Required raw contrast ~1e-5  /  Best targets are M0-M6
Q3: What is the optimal wavefront sensing wavelength?

Blue light: Better information content per photon, but fewer photons
Red light: More photons, but less signal per photon

Table 6  Optimal Wavefront Sensing Wavelength - Linear Regime

| Spectral Type | Teff [K] | Optimal Band<sup>a</sup> | Photon flux<sup>b</sup> [m<sup>-1</sup>.ms<sup>-1</sup>] | Flux gain relative to ...
<table>
<thead>
<tr>
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<td>B0V</td>
<td>31500</td>
<td>U</td>
<td>1.08e10</td>
<td>2.14</td>
<td>12.06</td>
<td>1337.0</td>
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<td>1.00</td>
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<td>2.03</td>
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<tr>
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<td>3200</td>
<td>I</td>
<td>4.65e3</td>
<td>12.5</td>
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<tr>
<td>M8V</td>
<td>2500</td>
<td>J</td>
<td>6.00e2</td>
<td>150.0</td>
<td>11.6</td>
<td>1.98</td>
</tr>
</tbody>
</table>

<sup>a</sup>Optimal bandwidth selected among standard astronomical spectral bands (U, B, R, I, J, H). Assumes fixed relative spectral bandwidth dλ/λ. Central wavelength listed; <sup>b</sup>Assuming 10% effective spectral band at optimal sensing wavelength, main sequence star at 10pc.

Prime wavelength range: 600nm to 900nm
Q4: How to get \( \sim 1e^{-5} \) to \( 1e^{-6} \) raw contrast in nearIR?

Approach:
We first establish contrast error budget for ExAO system on a 30m telescope
We assume a “conventional” ExAO system, visible SHWFS / nearIR science camera

→ Identify dominant error terms and explore solutions
D=8m telescope
High contrast imaging at 1.6 um
Wavefront sensing at 0.8 um
30% efficiency WFS
40% wide WFS spectral band
1 kHz WFS frame rate
Integrator controller with optimal gain setting
Wind speed = 8 m/s
Fried parameter r_0 = 0.15 m at 0.5 um
m_I = 8 target
SHWFS 15cm subapertures
Zenith angle = 40 deg
Aliasing and readout noise ignored
CHALLENGE #1: WFS sensitivity and time lag

Raw Contrast Terms in ExAO High Contrast Imaging

- Uncorrected Scintillation [CP_UAMP]
- Residual phase correction error - WFS photon noise [CP_OPHN]
- Residual phase correction error - Temporal error [CP_OTEM]
- Residual amplitude correction error - WFS photon noise [CP_APHN]
- Residual amplitude correction error - Temporal error [CP_ATEM]
- Chromatic OPD - Multiplicative refractivity [CP_OMUL]
- Chromatic amplitude - Multiplicative refractivity [CP_AMUL]
- Chromatic OPD - Fresnel propagation [CP_OPRO]
- Chromatic amplitude - Fresnel propagation [CP_ARPA]
- Chromatic OPD - refractive light path [CP_ARPA]
- Chromatic amplitude - refractive light path [CP_AHRA]
CHALLENGE #2: Chromaticity effects
CHALLENGE #3:
Scintillation

Raw Contrast Terms in ExAO High Contrast Imaging
# Solutions

## #1: WFS sensitivity and time lag
- PSI uses **diffraction-limited WFS approaches**, >1000x more sensitive than SHWFS
- Instrument architecture ensures that Pyramid WFS operates in diffraction-limited regime
- PSI uses **both visible and nearIR light** for WFS for optimal sensitivity
- PSI uses **predictive control** to replace time lag with (much smaller) prediction error

## #2: WFS chromaticity
- PSI uses near-IR WFS (pupil plane) and speckle control at/near science wavelength

## #3: Scintillation
- PSI uses focal plane speckle control to sense and correct scintillation speckles
Wavefront control architecture for ExAO

Two-stage correction:
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Dual near-IR and visible WFS provides:
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ExAO instrumentation is integral part of HCI WFS/C

Speckle control:
Post-coronagraphic image feeds control loop

Low-Order WFS/C:
Light discarded by coronagraph encodes low-order aberrations
Advanced ExAO requires Advanced Control Algorithms: Predictive Control and Sensor Fusion

**Conventional AO:**

**Measure** RM/CM

**Advanced AO control:**

Use past measurements (predictive control) and other measurements (sensor fusion) → control matrix is very big, and usually impossible to measure

**Derive** CM from WFS(s) telemetry

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The compute and control for adaptive optics (CACAO) real-time control software package
Olivier Guyon et al.
13 June 2018 • 11:40 AM - 12:00 PM
First on-sky results (2 kHz, 50 sec update) → 2.5x raw contrast improvement

OFF (integrator, gain=0.2)

ON

Average of 54 consecutives 0.5s images (26 sec exposure), 3 mn apart
Same star, same exposure time, same intensity scale
TMT PSI development, prototyping

In addition to lab activities, new on-sky instruments will be validating TMT-PSI subsystems:

**SCExAO @ Subaru**
- System-level prototype for PSI-blue, with similar overall architecture
- Multiple Coronagraphs
- Many WFSs, Camera, Modules → system-level testing of WFS/C algorithms
- Focal Plane Speckle Control with MKIDs + other cameras

**KPIC @ Keck**
- Integrates small-IWA coronagraphy, HDC and near-IR PyWFS
- Prototype for PSI-red (2-5 um)

**MagAO-X @ Magellan**
- Follows similar architecture as SCExAO
- Focus on short wavelength → validation/evaluation of PSI-blue solutions

**Possible SPHERE and GPI upgrades**
- Pyramid WFS, focal plane WFS, advance AO control
Subaru Coronagraphic Extreme Adaptive Optics
Subaru Coronagraphic Extreme Adaptive Optics

Facility Adaptive Optics system
- Sharpens image

Extreme-AO LOOP
- High speed pyramid wavefront sensor
  - Measures aberrations
  - 14,400 sensors (pix)
- 3.5 kHz

CORONAGRAPHIC LOW ORDER LOOP
- Near-IR camera
  - Measures low-order aberrations
- 10-200 Hz
- 800 – 2500 nm (rejected by coronagraph)

2000 actuator Deformable mirror
- Removes starlight
- ~2 kHz

CORONAGRAPHIC LOW ORDER LOOP
- MKIDs camera
  - Measures residual starlight
- 800 – 1350 nm

SPECKLE CONTROL LOOP
- CHARIS spectrograph
  - Exoplanet spectra
  - Slow speckle calibration

Visible light instruments
- VAMPIRES, FIRST, RHEA

Near-IR instruments
- Nuller, HiCIAO, IRD

Extreme-AO LOOP
- 2000 actuator Deformable mirror
- Removes starlight
- >800 nm
The wavefront control feeds a high Strehl PSF to various modules, from 600 nm to K band.

**Visible (600 - 950 nm):**

**VAMPIRES**, non-redundant masking, polarimetry, with spectral differential imaging capability (h-alpha, SII)

**FIRST**, non-redundant remapping interferometer, with spectroscopic analysis

**RHEA**, single mode fiber injection, high-res spectroscopy, high-spatial resolution on resolved stars

**IR (950-2400 nm):**

**HiCIAO** - high contrast image (y to K-band)

**SAPHIRA** - high-speed photon counting imager, (H-band for now)

**CHARIS** - IFS (J to K-band)

**MEC - MKIDs** detector, high-speed, energy discriminating photon counting imager (y to J-band)

**NIR single mode injection**, high throughput high resolution spectroscopy. Soon will be connected to the new IRD

**Various small IWA (1-3 l/D) coronagraphs** for high contrast imaging – PIAA, vector vortex, 8OPM

**GLINT** - NIR nulling interferometer based on photonics
Keck Planet Imager and Characterizer

**Keck II AO**
Xinetics 359-actuator DM
20x20 SH-WFS

**NIRC2**
High-Res Imager,
L/M vortex coronagraph
Aladdin 3 InSb
0.95-5 μm
R=100-1,000

**IR Pyramid WFS**
Leonardo/SAPHIRA
e-APD

**Fiber Injection Unit**
BMC kilo-DM
Vortex coronagraph
CRED2

**Fiber Extraction Unit**

**Giant Planet Imaging**

**NIRSPEC**
High-Res Spec
Hawaii 2 RG
0.95-5 μm
R=38,000
NearIR Pyramid WFS @ KPIC

See Charlotte Bond’s invited talk 10703-72, Thursday pm
Next steps, outstanding WFS/C questions

**Source faintness** remains a significant challenge
- Operating PyWFS at its full efficiency needs to be demonstrated
- Full benefits of predictive control needs to be quantified

**Multi-DM multi-sensor AO operation** is challenging
- How to optimally combine signals
- Need to develop real-time algorithm, machine learning

**Differential detection techniques** need to be developed and validated
- HDC validation
- CDI validation

**High speed focal plane WFS/C** is relatively immature
- Algorithm development
- On-sky validation
- Hardware: MKIDs, SAPHIRA, EMCCD

See:
The planetary systems imager: a high-contrast instrumentation platform for the Thirty Meter telescope
Paper 10702-74
Time: 5:00 PM - 5:20 PM
Michael P. Fitzgerald + PSI team