Ground-based capabilities for general astrophysics and exoplanets science

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HabEx Uniqueness

HabEx unique capabilities (not accessible from ground):

- Largest UV-Opt astronomical aperture in space
- Spectral coverage: UV not accessible from ground, continuous NIR coverage
- Angular resolution in UV .. and optical ?
- Ultra-high contrast
- High stability
  - astrometry
  - precision photometry, spectroscopy
Major ground facilities (Opt-NIR)

ELTs coming online in mid-2020s:
• E-ELT: 39m aperture, Chile
• TMT: 30m, Hawaii(?)
• GMT: 25m, Chile

8-m class survey telescope/instruments:
• Imaging: LSST
• Spectroscopy: Subaru-PFS

+ other dedicated survey facilities (LAMOST, PAN-STARRS PTF etc...
Wide FOV optical imaging: Subaru HSC
8m aperture, 1.5deg diam FOV
104 4kx2k CCDs
LSST

8m aperture, 3.5deg diam FOV
189 4kx4k CCDs
Subaru Prime Focus Spectrograph

2,400 fibers over 1.3 deg diam FOV
0.38 – 1.26 um
Increased image quality over moderate FOV in near-IR with GLAO

**example:** ULTIMATE-Subaru

### ULTIMATE key specifications: Ground-Layer AO

<table>
<thead>
<tr>
<th>Field of View</th>
<th>15 arcmin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus</td>
<td>Cassegrain</td>
</tr>
<tr>
<td>Corrector</td>
<td>Adaptive secondary, 33 actuators across the diameter</td>
</tr>
<tr>
<td>Sky Coverage</td>
<td>Almost all sky</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FWHMs at ‘Moderate’ condition</th>
<th>GLAO</th>
<th>Natural</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-band</td>
<td>0.20”</td>
<td>0.44”</td>
</tr>
<tr>
<td>H-band</td>
<td>0.23”</td>
<td>0.49”</td>
</tr>
<tr>
<td>J-band</td>
<td>0.27”</td>
<td>0.51”</td>
</tr>
<tr>
<td>R-band</td>
<td>0.41”</td>
<td>0.65”</td>
</tr>
</tbody>
</table>

### ULTIMATE-Subaru Instruments

1. **Wide-field imager (16’x12’)**
   - Focus on NB/MB imaging (to complement IR space missions)
   - Collaboration with Canada (HIA)

2. **Multi-object IFU spectroscopy**
   - 3D spectroscopy (at J +H band) for ~20-60 galaxies at once.
   - Collaboration with Australia (AAO)

3. **Multi-object spectrograph**
   - MOSFIRE-like instrument with GLAO: as extension of PFS toward H+K
   - No detailed technical study so far
ELTs
E-ELT first light instruments
E-ELT – First Light instruments

**MAORY + MICADO**
(Multi-conjugate Adaptive Optics RelaY for the E-ELT)
(Multi-AO Imaging Camera for Deep Observations)
0.8 – 2.4 um
diffraction-limited imaging (6 – 12 mas)
R=8000 spectroscopy

**HARMONI**
(High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph)
0.47 – 2.45 um
IFS
R = 3000 – 20,000 spectroscopy

**METIS**
10um imaging and spectroscopy
high contrast imaging
E-ELT instruments

Exoplanet science:
CODEX (precision RV), METIS (10um imaging) and EPICS/PCS (direct imaging, NIR)
Multi-Conjugate Adaptive Optics (MCAO)
Concept: Use several DMs conjugated at different altitudes to perform correction over a wide field of view
EAGLE (ESO E-ELT project)
MCAO system with 20 fields
0.8-2.45 μm

1. Shutter
2. Laser Guide Star Sensing System
3. Pick-off System (Focal Plane)
4. Target Reimaging and Magnification System (including Deformable Mirror)
5. Integral Field Unit and Spectrograph System
**TMT instruments**

- Wide FOV imager
  - NIR, 30"
  - AO system
  - + IRMS multi-slit spectro
- High contrast imaging
- Near-IR imaging (0.83-2.4um)
  - + IFU, R=4000-10000
- AO system
  - IRMS multi-slit spectro
- High resolution spectro
  - R=50,000
  - 0.31-1.1 um
  - (Seeing limited)
- Visible light MOS
  - 40 sq' FOV
  - R=1000-8000
  - 0.31-1.1 um
  - (Seeing limited)
- Wide FOV imager
  - NIR, 30"
- High res spectro
  - mid-IR
  - R=100,000
  - 4.5” slit length
  - 10” imaging FOV
- Multiple IFUs
  - 0.8-2.5 um
  - 3” FOV per IFU
  - MOAO-fed
AO-fed TMT instruments (First light)

IRIS

Rotator and NFIRAOS Interface
Internal chamber cooled to match NFIRAOS chamber.
T (internal) = -30°C

On-Instrument Wavefront Sensors
Cooling to match NFIRAOS chamber
T = -30°C

Science Dewar
Cryogenic
T = 77K – 120K

Cable Wrap
T = ambient

IRMS

Grating/Mirror Exchange Turret
Dewar Outer Window
Dewar Inner Window
Configurable Slit Unit (CSU)
Filter Wheels
Field Lens
Pupil Mechanism
Camera
Detector Head
Collimator
FCS Mirror
GMT instruments: Optical spectroscopy

0.35 – 0.95 um
R: 19,000 – 108,000

Exoplanets: precision radial velocity, transit spectroscopy
Stellar physics
Galaxies, cosmology

GMACS
0.35 – 0.95 um
R = 1,000 – 6,000

Multi-objects
(100s of spectra)

Galaxies, cosmology
GMT instruments: NIR spectroscopy

Near-IR IFU and Adaptive Optics Imager – GMTIFS

0.9 – 2.5µm IFU
R = 5,000 to 10,000
FOV: 20”x20” (imager), 0.3”x0.6”, 2.2”x4.5” (IFU)
5mas – 50mas resolution

IR Echelle Spectrograph – GMTNIRS

1.1 – 5.3µm
R = 50,000 to 75,000
Exoplanet capabilities - RV

Optical RV is making steady progress and will reveal lower mass planets. Mix of high precision instruments on largest telescopes (for example CODEX on E-ELT), and dedicated robotic RV facilities.

Near-IR RV will identify habitable planets around nearby M-type stars. First instruments being deployed NOW.
Habitable Zones within 5 pc (16 ly):
Astrometry and RV Signal Amplitudes for Earth Analogs

- Circle diameter is proportional to 1/distance
- Circle color indicates stellar temperature (see scale right of figure)
- Astrometry and RV amplitudes are given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

**Expected detection limit for space astrometry (NEAT, THEIA, STEP)**
F, G, K stars

**Expected detection limit for near-IR RV surveys (SPIROU, IRD + others)**
M-type stars
Exoplanet capabilities – Direct imaging

10um imaging: METIS @ E-ELT
→ thermal emission from Earth-size planets & larger around nearby stars

Near-IR / visible Extreme-AO:

8m telescopes: spectroscopy of self-luminous planets (young Jupiters)
.. and possibly reflected light imaging of nearby large planets

ELTs: detailed characterization of giant planets
Reflected light imaging and spectroscopy of Earths around M (& K?) type stars
Spectroscopic characterization of Earth-sized planets with ELTs

1 \( \frac{\lambda}{D} \), \( \lambda = 1600\text{nm} \)
- \( D = 30\text{m} \)

1 \( \frac{\lambda}{D} \), \( \lambda = 1600\text{nm} \)
- \( D = 8\text{m} \)

Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired [ assumes 1e-8 contrast limit, 1 \( \frac{\lambda}{D} \) IWA ]
Habitable Zones within 5 pc (16 ly)

- Radial Velocity (near-IR)
- ELT imaging (near-IR)
- Space astrometry
- ELT imaging (thermal-IR)

Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
Summary

Ground-based telescopes will provide excellent visible light wide field imaging and MOS in visible and near-IR
Low resolution spectroscopy (IFS) and high resolution (R~100,000)

Adaptive optics will provide diffraction limited imaging anywhere in the sky at near-IR, and around bright sources (m~12 and brighter) in visible light

AO may provide nearly full sky coverage diffraction limited images in visible light (see Keck visible AO development plans)

Exoplanets:

RV (especially nearIR) will identify habitable planets

Spectroscopic characterization with direct imaging: Giant planets with 8m telescopes, Earth-like planets with ELTs

Nearest M (&K)-type stars provide opportunities for direct imaging + RV/astrometry