Ground-based Thermal imaging of Habitable Exoplanets

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Why 10 microns?

Ground-based observations/characterization of habitable planets around Sun-like stars.
Earth at Alpha Cent
N=15.2

Optimize instrument
• Higher QE detector
• No dither/chop
• AO with gold coated optics
• Coronagraph
• Dedicated campaign

<table>
<thead>
<tr>
<th></th>
<th>T-RECS/ MICHELLE</th>
<th>8-m ExAO</th>
<th>30-m ExAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>On sky limit (5 sigma) 2h on sky</td>
<td>11.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Detector QE</td>
<td>20%</td>
<td>80% (+0.75 mag)</td>
<td>80% (+0.75 mag)</td>
</tr>
<tr>
<td>FWHM (arcsec)</td>
<td>0.50 (70%-ile)</td>
<td>0.26 (+0.7 mag)</td>
<td>0.069 (+4.3 mag)</td>
</tr>
<tr>
<td>Time for orbit to move by J/D at 1 arcsec around Alpha Centauri</td>
<td>28 days</td>
<td>14 days</td>
<td>4 days</td>
</tr>
<tr>
<td>Obs. efficiency¹</td>
<td>50%</td>
<td>90% (+0.32 mag)</td>
<td>90% (+0.32 mag)</td>
</tr>
<tr>
<td>Sequence length (hours)</td>
<td>2</td>
<td>100 (+2.12 mag)</td>
<td>30 (+1.47 mag)</td>
</tr>
<tr>
<td>Inst. throughput</td>
<td>50%</td>
<td>30% (-0.28 mag)</td>
<td>30% (-0.28 mag)</td>
</tr>
<tr>
<td>Warm low emissivity optics²³⁴⁵</td>
<td>1 + 2 surfaces from telescope</td>
<td>1 + 3 at 5C + 2 surfaces from telescope (-0.12 mag)</td>
<td>1 + 3 at 5C + 3 surfaces from telescope (-0.12 mag)</td>
</tr>
<tr>
<td>Optimize 10-13 microns filter for detection</td>
<td>-</td>
<td>1.5x SNR (+0.44 mag)</td>
<td>1.5x SNR (+0.44 mag)</td>
</tr>
<tr>
<td>5 sigma limit Basic characterization</td>
<td>11.1</td>
<td>15.0</td>
<td>18.0</td>
</tr>
<tr>
<td>3 sigma limit Detection only</td>
<td>11.7</td>
<td>15.6</td>
<td>18.6</td>
</tr>
</tbody>
</table>
Tab. 2 Apparent magnitude and required time for detection at 10-13 microns of various types of exo-Earth at 1.325pc (Alpha Centauri system)

<table>
<thead>
<tr>
<th></th>
<th>Radius (Earth)</th>
<th>Temp. (K)</th>
<th>App. Mag. 10 microns</th>
<th>Time on 8m 3.0 sig. det.(h)</th>
<th>Time on 30m 5 sig. det.(h)</th>
<th>Charact ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>1</td>
<td>288</td>
<td>15.2</td>
<td>50</td>
<td>0.17</td>
<td>Y (30m)</td>
</tr>
<tr>
<td>Super-Earth</td>
<td>2</td>
<td>288</td>
<td>13.7</td>
<td>3</td>
<td>0.01</td>
<td>Y</td>
</tr>
<tr>
<td>(Kepler 22b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm Earth</td>
<td>1</td>
<td>320</td>
<td>14.8</td>
<td>23</td>
<td>0.08</td>
<td>Y</td>
</tr>
<tr>
<td>(Dune planet)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab. 3 Apparent magnitude and required time at 10-13 microns of exo-Earth planets at 5pc

<table>
<thead>
<tr>
<th></th>
<th>Radius (Earth)</th>
<th>Temperature (K)</th>
<th>App. Mag. 10 microns</th>
<th>Time on 30m 5 sig. det. (h)</th>
<th>Charact ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>1</td>
<td>288</td>
<td>18.1</td>
<td>36</td>
<td>~Y</td>
</tr>
<tr>
<td>Super-Earth</td>
<td>2</td>
<td>288</td>
<td>16.6</td>
<td>2</td>
<td>Y</td>
</tr>
<tr>
<td>(Kepler 22b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm Earth</td>
<td>1</td>
<td>320</td>
<td>17.7</td>
<td>17</td>
<td>Y</td>
</tr>
<tr>
<td>(Dune planet)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tab. 4 Apparent magnitude and required time at 10-13 microns exo-Earth at 10pc

<table>
<thead>
<tr>
<th></th>
<th>Radius (Earth)</th>
<th>Temperature (K)</th>
<th>App. Mag. 10 microns</th>
<th>Time on 30m 5 sig. det. (h)</th>
<th>Charact ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>1</td>
<td>288</td>
<td>19.6</td>
<td>571</td>
<td>~Y</td>
</tr>
<tr>
<td>Super-Earth</td>
<td>2</td>
<td>288</td>
<td>18.2</td>
<td>43</td>
<td>~Y</td>
</tr>
<tr>
<td>(Kepler 22b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm Super-Earth</td>
<td>2</td>
<td>320</td>
<td>17.7</td>
<td>17</td>
<td>Y</td>
</tr>
<tr>
<td>(Kepler 22b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Thermal imaging of planets around Alpha Centauri A & B

For Alpha Centauri, HZ rocky planet imaging at 10 microns requires a contrast comparable to GPI/SPHERE at similar separations.
Alpha Centauri
TIKI preliminary optical design

Cryo. module
45k

Lyot WFS
Lens module
Lyot Stop+SCC
Filter
Sc. detector
OAE3
Focal plane
Vortex coro.

Telescope focus
Additionally, the image contains an inset showing the AO module (room temp) with WFS, DM, OAE1, and Acqu. cam. connected within the scheme.
Alpha Centauri @ 10 microns

Des Marais et al. (2002)

Tiki @ Gemini South
~2019, ~50h
Alpha Centauri @ 10 microns

Des Marais et al. (2002)

Tiki @ Gemini South
~2019, ~50h
Alpha Cent A & B with ELTs
Alpha Cent A & B with ELTs

50h 8m

25h TMT
What IF we find something?

Earth like

- Orbit
- Surface temperature
- O3
- Water
- CO2
- CH4
- Clouds/radius

10 microns remote sensing
Not Earth-like

Fig. 8. Expected spectrum for exo-Earth having various types of atmospheres. From Kempton et al. 2009
30m $\lambda/D$  

30h TMT  

Earth-size  

280K  

8m $\lambda/D$  

200h 8m  

Bialek & Marois in prep
Are 10m telescopes big enough?

Stellar Habitable Zone of Alpha Centauri A and B

Resolution power of current 10m telescopes at 10 microns

Two stars in the sky that we can do this NOW (not 0...)! 

NOTE: Stars to scale, but not with size of the habitable zone. Dotted circle corresponds to an orbit of 1 AU.

CREDIT: PHL @ UPR Arecibo
Stable orbits?

Quarles & Lissauer 2016 (astroph April 17, 2016)

B HZ: 0.5-1.4 AU

A HZ: 0.8-2.4 AU
Planet formation in a binary?

Qintana et al. 2002

Qintana et al. 2003

Alpha Cent A

Alpha Cent B

Kepler statistics:

“Our findings do not suggest that inner transiting exoplanets are rare in binary systems”
Vortex coronagraph

VLT NACO
Self coherent camera

Simple set-up: SCC + Four Quadrant Phase Mask coronagraph (FQPM)
Examples of Performance

More than 15 Publications (5 refereed or accepted papers)

Monochromatic (bandwidth < 10 nm) results

Contrast: < 2 \times 10^{-8} between 5 \, /D and 12 \, /D

THD1 Limitation = amplitude errors
Reduced by a factor > 20 on THD2

Achromaticity of the testbed

Contrast degrades by only a factor 3 for 250 nm bandwidth (37%)

30 nm to 300 nm bandwidth
SCC simulations @ UVic

Before SNWFC

DH: 7.3e-07

Nyquist region

After SNWFC

DH: 1.6e-07

Nyquist region

Contrast

1e-06
9e-07
8e-07
7e-07
6e-07
5e-07
4e-07
3e-07
2e-07
1e-07
Sky background Post-Processing