Science figures of merit

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w. Tom Greene, Jeremy Kasdin, Olivier Guyon (SDT)

ACW 3.5
4 December 2013

Context

• Initial science requirements set based on ambitious science goals
  – spectra of 6 planets
  – discovery of 4+ small planets
  – HZ zodiacal dust

• Science portion of coronagraph downselect matrix was defined as pass/no pass and only corresponding to baseline levels

• Performance had to be evaluated against 1.6 mas jitter
  – “Opportunity” line could account for future performance
Context continued

- Single round of coronagraph simulations -> no opportunity to optimize designs
- Uncertainty about final levels of jitter, speckle suppression
- 550 nm models scaling to longer wavelengths is uncertain
Updated strategy

• Identify must-pass ‘threshold’ requirements that are minimum necessary to justify mission and associated with conservative 1.6 mas performance

• Second level of ‘baseline’ requirements provide additional discrimination but are not must-pass

• Opportunity level for most optimistic performance cases
Other context points

• Simulations on known-Doppler understate number of detectable planets due to limited Doppler completeness

• Models available at 1.6, 0.8, 0.2 mas. Used 0.2 for optimistic; due to finite star effects 0.2 is probably similar 0.5

• Coronagraph and missions-strategy optimization will increase number of detected planets

• **These are not the final science yield predictions – just a stepping stone for the ACWG process**

• SDT will provide more robust numbers in final report
Threshold (must-pass) requirements

1. (Threshold) The coronagraph will operate from 430 to 980 nm in >10% bandpasses. The imager will provide at least five 10% filters at roughly 450, 550, 650, 800, 950 nm and to image separately or simultaneously in two polarization channels. The spectrograph will provide R~70 from 600 to 950 nm in at least 10% coverage per setting. The imager will have a FOV of 3”x3” (with no requirement on the coronagraph OWA) and sampling 50% better than Nyquist at 450 nm. The ifs will be Nyquist sampled at 600 nm and have a FOV of at least half the coronagraph OWA.
Threshold (must-pass) requirements

2. The AFTA coronagraph will be capable of detecting a disk of 100x our solar system’s zodiacal level at SNR=5 per resolution element at 2 AU separation around a star 8 pc away at 450 and 800 nm

   – In Traub models (see next page) this is a contrast of 6.4e-9 per resolution element; assuming x10 suppression of the speckle halo that requires 1.3e-8 raw contrast at 0.25 arcseconds
Threshold (must-pass) requirements

3. The AFTA coronagraph will be capable of a integrated depth of search of >10 for planets of 15 RE<R<4RE in a 6-month single-visit survey at 550 nm

– This corresponds to an ability to detect in broadband short-wavelength imaging ~2 doppler planets
Baseline requirements

4. The AFTA coronagraph will be capable of obtaining SNR=10 R=70 550 nm spectra of >=4 known RV planets in a 60 day campaign,
   - observed in optimal geometry, albedo = 0.2
   - Downscoped from 800 nm, though that remains a strong goal – models better at 550 nm and small number statistics improved (last-minute change made without giving Wes time to update his slides)
   - Evaluated for 0.2 mas jitter / x 30 suppression
   - Final SDT modeling will use different jitter / wavelength / etc. parameters
   - If we were to evaluate at 1.6 mas jitter, score becomes very small
Opportunity (maximum performance)

5. AFTA coronagraph will be capable of detecting a disk of 10x our solar system’s zodiacal level at SNR=5 per resolution element at 1 AU at 450 nm at 8 pc

– In Traub calculation (see next page) this is a contrast of 3e-9 per resolution element; assuming x10 suppression of the speckle halo that requires 6e-9 raw contrast at 0.13 arcseconds
Opportunity (maximum performance)

6. AFTA coronagraph will be capable of an integrated depth of search of $>2$ for planets of $R<4RE$ in a 6-month single-visit survey at 550 nm.

- For a Fressen et al. planet-radius extrapolated out to $\sim 1$ AU this would result in discovery and photometric characterization of $\sim 2$-4 planets of $<4$ RE.
SFOM for AFTA coronagraph: calculation results

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ACW 3.5
4 December 2013

RV Planets, shown at maximum elongation

RV planets (max elong)
- ▲ V = 1–6
- ○ V = 6–8
- ★ V = 8–9
signal (elec) = $n_{pl} \times t$  \hspace{1cm} \text{(within the FWHM of the planet image)}

noise (elec) = $\left[ n_{total} \times t + (f_{pp} \times n_{rawspeckle} \times t)^2 \right]^{1/2}$

$n_{total}(elec/s) = \left[ n_{pl} + n_{zodi} + n_{rawspeckle} + D_{c} \times m_{pix} + CIC \times m_{pix}/t_{frame} \right] \times ENF^2 + (N_{R}/G)^2 \times m_{pix}/t_{frame}$

signal/noise = $SNR_0$

\[
t (sec) = \frac{SNR_0^2 \times n_{total} (e/s)}{n_{pl}^2 - (SNR_0 \times f_{pp} \times n_{rawspeckle})^2}
\]
zodi & EKB model brightness

AFTA, zodi, EKB 10 pc

100*zodi

10*zodi

1*zodi

100*EKB

10 au

1 au

angle (arcsec)
Shaped Pupil Coronagraph

SPC, RV detections, 550 nm
8 planets, 50 days

- raw speckles/1.6mas
- floor/1.6mas/10x
- raw speckles/0.2mas
- floor/0.2mas/30x
PIAA Coronagraph

PIAA, RV detections, 550 nm
31 planets, 41 days

- raw speckles/1.6mas
- floor/1.6mas/10x
- raw speckles/0.2mas
- floor/0.2mas/30x
Hybrid Lyot Coronagraph

HLC, RV detections, 550 nm
15 planets, 42 days

- raw speckles/1.6mas
- floor/1.6mas/10x
- raw speckles/0.2mas
- floor/0.2mas/30x

contrast

angle (arcsec)
Vector Vortex Coronagraph

VVC, RV detections, 550 nm
0 planets, 60 days

- raw speckles/1.6mas
- floor/1.6mas/10x
- raw speckles/0.2mas
- floor/0.2mas/30x
Visibel Nuller Coronagraph 2

VNC2, RV detections, 550 nm
30 planets, 50 days

- raw speckles/1.6mas
- floor/1.6mas/10x
- raw speckles/0.2mas
- floor/0.2mas/30x
### RV planet detection in 1 band, example

Detection yield:
- 550 nm band (10% wide)
- $\text{SNR} = 5$
- $\text{albedo} = 0.40$
- 0.2 mas jitter
- 30 times reduction factor
- 60 day campaign:

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<tr>
<td>vnc2</td>
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<td>50</td>
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</table>
Photometric characterization: detection in 3 bands, example

Detection yield:
450, 550, & 650 nm bands (10% wide)
SNR = 5
albedo = 0.40
0.2 mas jitter
30 times reduction factor
60 day campaign:

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<td>vnc2</td>
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<td>74</td>
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Spectra, 800 nm band, resolution = 70
Spectral characterization

Characterization yield:
800 nm band (resolution = 70)
SNR = 10
albedo = 0.20
0.2 mas jitter
30 times reduction factor
60 day campaign:

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<td>- days</td>
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<tr>
<td>vnc2</td>
<td>13 planet spectra at 800nm</td>
<td>54 days</td>
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Backup charts follow
Exoplanet yield calculation: target count rate example

\[ n_{\text{star}} = 10^{p-0.4mV} \times BW \times A \times \eta \times f_{\text{psf}} = 2.89 \times 10^6 \quad \text{(elec/s)} \]

\[ n_{\text{pl}} = n_{\text{star}} \times C_{\text{pl}} = 1.16 \times 10^{-2} \quad \text{(elec/s)} \]

I count the electrons that fall within the FWHM boundary of the PSF. For AFTA, without a coronagraph, the width is FWHM = 0.96λ/D = 0.045 arcsec at 550 nm.

The fraction of collected photons in the FWHM is \( f = 0.35 \).

Both values are from John Krist. Both values will be different for each coronagraph.
zodi count rate example

\[ m_V(\text{local zodi}) = 22.1 \text{ mag/arcsec}^2 \]
\[ \Omega_{\text{tel}} = (\pi/4) \times (\text{FWHM})^2 \]
\[ n(\text{local zodi}) = \Omega_{\text{tel}} \times 10^{p-0.4m_V} \times BW \times A \times \eta \quad \text{(elec/s)} \]
\[ n_{\text{zodi}} = 2 \times n(\text{local zodi}) = 1.15 \times 10^{-2} \quad \text{(elec/s)} \]

\[ n_{\text{spec}} = 0.010 \quad \text{(elec/s)} \]
\[ m_{\text{pix}} = (\pi/4) \times (2.5)^2 = 4.9 \quad \text{(pixels)} \]
\[ n_{\text{min}} = n_{\text{spec}} \times f_{\text{pp}} \quad \text{(elec/s)} \]
detector count rate example

\[ n_{\text{total}} = \left[ n_{\text{pl}} + n_{\text{zodi}} + n_{\text{spec}} \times (1 + f_{\text{pp}}) + D_c \times m_{\text{pix}} + \text{ClC} \times m_{\text{pix}} / t_{\text{frame}} \right] \times \text{ENF}^2 \]

\[ + (N_R/G)^2 \times m_{\text{pix}} / t_{\text{frame}} \quad \text{elec/s} \]

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<th>EMCCD typical value</th>
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<td>(n_{\text{zodi}})</td>
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<td>0.012</td>
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<td>(n_{\text{spec}})</td>
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<td>(D_c)</td>
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<td>(t_{\text{frame}})</td>
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<td>(t)</td>
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cumulative detections vs time example

- 30° phase angle
- 50° phase angle
- 70° phase angle
- 90° phase angle
- 110° phase angle
- 130° phase angle
- 150° phase angle

44% of orbit

~20 detections/month (in this example)
ExoCat (2347 stars within 30 pc, 53 parameters)

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<th>GL/LTT</th>
<th>COMMON</th>
<th>WDS</th>
<th>sep(&quot;)</th>
<th>dM(mag)</th>
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<th>RAhms</th>
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Catalog is all Hipparcos stars within 30 pc, corrected for errors. Star parameters are current best estimates.

Authorship: Maggie Turnbull, Geoff Bryden, Maggie Thompson, Brian Mason.
## RV Cat (436 RV planets)

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<th>SMA (AU)</th>
<th>ECC</th>
<th>s (arcsec)</th>
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Author is Dmitry Savransky.
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<td>P</td>
<td>P</td>
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<td></td>
<td>Wavelength 430-980 nm 10% bandpass; pol.</td>
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<tr>
<td>2:</td>
<td>5e-9 @ 0.27</td>
<td></td>
<td>5e-8 @ 0.5”</td>
<td></td>
<td>5e-9 @ 0.27</td>
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<tr>
<td></td>
<td>Outer disk: 100 zodi at 2 AU = 6e-9 at 0.25” @ 550 nm</td>
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<td>3:</td>
<td>11.5</td>
<td>14.5</td>
<td>0.04</td>
<td>10.0</td>
<td>23.0</td>
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<tr>
<td></td>
<td>Depth &gt; 10 (thresh: &gt;10) for 4-14 RE</td>
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<td>3b:</td>
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<td>15</td>
<td>0</td>
<td>0</td>
<td>1</td>
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<td></td>
<td>550 nm photometry of doppler planets</td>
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</tbody>
</table>

**Notes:**
- Req: Requirement
- HLC: High Light Collection
- VVC: Very Very Collection
- SP: Standard Performance
- PIAA: Performance Improvement Area
- VNC2: Very New Collection 2
# Performance against baseline and opportunity reqs

<table>
<thead>
<tr>
<th>Req</th>
<th>HLC</th>
<th>VVC</th>
<th>SP</th>
<th>PIAA</th>
<th>VNC2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.6 / x10</td>
<td>0.2 / x30</td>
<td>1.6 / x10</td>
<td>0.2 / x30</td>
<td>1.6 / x10</td>
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<tr>
<td>4: Spectrum of Doppler planets at 550nm, 2 months</td>
<td>0</td>
<td>5</td>
<td>0</td>
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<td>5. HZdisk: 10 zodi at 1 AU =raw 1e-8 at 0.13’’ @ 450 nm</td>
<td>1e-8</td>
<td>&gt;1e-7</td>
<td>1e-7</td>
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<td>NA</td>
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<tr>
<td>6. Depth &gt; 2 for &lt;4 RE</td>
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<td>3.6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
</tr>
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</table>
Some conclusions

• Coronagraph design has to be iterative with telescope and wavefront control – work in this area should begin immediately
  – Optimized cases may perform better to much better
  – We have to understand the physics!
  – Need a well-integrated modeling team

• For SDT report, much more coronagraph and science modeling modeling is needed, in DRM-like ways

• Science is still exciting but range of possible outcomes is broad