Multi-Star Wavefront Control: A Method for Exoplanet Imaging in Multi-Star Systems

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Supported by NASA SMD’s APRA program and ARC CIF+IRAD (4/2015 – 3/2017, work successfully completed)
Continued development recently funded by HQ directed work package based on SAT / TDEM proposal

αCenA

αCenB

ExEP Technology Web Colloquium, October 24, 2017
Exoplanets Technologies group at NASA ARC

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Rus Belikov

Part-time members (not pictured): Pete Zell, Fred Witteborn, Jack Lissauer, Steve Bryson, Chris Henze
Importance of Multi-Star Systems

- Most non-Mdwarf stars are in multi-star systems. For example, within 4pc:
  - 5 Multiples: aCen, Sirius, Procyon, 61 Cyg, e Ind
  - 2 Single: e Eri, t Cet

- Alpha Centauri is an unusually favorable outlier

Missions that can benefit from multi-star suppression

<table>
<thead>
<tr>
<th>Mission</th>
<th>Telescope Size</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centauri</td>
<td>0.15m</td>
<td>Bendek et al. 2015</td>
</tr>
<tr>
<td>ACESat</td>
<td>0.45m</td>
<td>Belkov et al. 2015</td>
</tr>
<tr>
<td>EXCEDE</td>
<td>0.7m</td>
<td>Schneider et al. 2015</td>
</tr>
<tr>
<td>Exo-C</td>
<td>1.5m</td>
<td>Stapelfeldt et al. 2015</td>
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<tr>
<td>Exo-S</td>
<td>1.1m w/ starshade</td>
<td>Seager et al. 2015</td>
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<tr>
<td>WFIRST</td>
<td>2.4m</td>
<td>NASA Directed 2015</td>
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<tr>
<td>LUVOIR/HabEx</td>
<td>5m+</td>
<td>(5m+)</td>
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</tbody>
</table>

Simulations of exo-Earth detections around Alpha Centauri A (if the other star could be suppressed)
Nearby FGK Targets for WFIRST

<table>
<thead>
<tr>
<th>common_name</th>
<th>sptype</th>
<th>Vmag</th>
<th>d (pc)</th>
<th>M</th>
<th>Sol. Lum.</th>
<th>BB Temp</th>
<th>IHZ (AU)</th>
<th>IHZ (as)</th>
<th>IHZ (ld)</th>
<th>OHZ (AU)</th>
<th>OHZ (as)</th>
<th>OHZ (ld)</th>
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<tbody>
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<td>* alf Cen A</td>
<td>G2V</td>
<td>0.01</td>
<td>1.32</td>
<td>4.40</td>
<td>1.45</td>
<td>5568</td>
<td>1.13</td>
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<td>15.31</td>
<td>2.08</td>
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<td>* alf Cen B</td>
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<td>0.39</td>
<td>5051</td>
<td>0.60</td>
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<td>8.58</td>
<td>1.12</td>
<td>0.90</td>
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<td>* eps Eri</td>
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<td>3.73</td>
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<td>0.51</td>
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<td>5.21</td>
<td>3.49</td>
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<td>4348</td>
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<td>* alf Cmi A</td>
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<td>1.86</td>
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<td>tau Cet</td>
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</tr>
</tbody>
</table>

Nearest 20 Stars:
13 Multi-Stars
4/7 Multi-Star Hab. Zones w/in WFIRST FOV

Legend:
**BOLD** – Binaries
Color – Hab.Zone w/in WFIRST FOV
Green – Single-Star
WFC Solution
**Red** – Multi-Star
WFC Solution

Dan Sirbu
Multi-Star Direct Imaging Science with WFIRST

Multi-Star Science Statistics:
- 70 FGK stars within 10pc
- 43 multi-stars (dynamical)
- 28 stars limited at > $1e^{-9}$
- 8 stars with sep. < $N/2 \lambda/D$

WFIRST assumptions:
- $D = 2.4m$
- $\lambda = 650nm$
- $\lambda/20$ RMS with $f^{-3}$ power spectrum
- 48x48 DM

Note: Contrast floor for an on-axis coronagraph/starshade due to unsuppressed off-axis companion star

Multi-Star Science Statistics:
- 517 FGK stars within 20pc
- 259 multi-stars (optical or dynamical)
- 193 stars limited at > 1e-10
  - 40 stars with sep. < N/2 λ/D

HabEx assumptions:
- D = 4m
- λ = 650nm
- λ/20 RMS with f^3 power spectrum
- 48x48 DM

*Note: Contrast floor for an on-axis coronagraph/starshade due to unsuppressed off-axis companion star*
Alpha Centauri: not your typical target

Simulations of an Earth twin detection for a ~1.5 class telescope (similar to Exo-C, Exo-S)

α Cen (A)  τ Cet (~ best of everything else)

1.5m aperture, 1 hour exposure

If Alpha Centauri was not a binary, it would probably be the best target for any direct imaging mission, by a large margin
\(\alpha\) Cen System Overview
Both HZs are fully accessible with a 0.4\" (0.5AU) inner working angle (IWA).
Orbits are stable out to \(\sim 2.5\) AU (Holman & Wiegert 1999, Quarles and Lissauer 2016)

see Quarles and Lissauer 2016 for aCen stability
https://arxiv.org/abs/1604.04917
ACESat: Alpha Centauri Exoplanet Satellite

Mission Time
Life and Orbit
SMEX-Class, launch 2020, 2-Years, Earth trailing

Instrument/Telescope
Unobstructed 45cm, Full Silicon Carbide

Coronagraph architecture
Baseline: PIAA Embedded on Secondary and tertiary telescope mirror.

Coronagraph performance
1x10^-8 raw
6x10^-11 @ 0.4” (with ODI)
2x10^-11 @ 0.7” (with ODI)

Wavelength
400 to 700 nm, 5 bands @ 10% each.

proposed to SMEX, 2014

Belikov, R. (PI), Bendek, E. (DPI)
Batalha, N.
Kuchner, M.
Lissauer, J.
Males, J.
Marley, M.
Quarles, B.
Quintana, E.
Robinson, T.
Schneider, G.
Traub, W.
Turnbull, M.
Chakrabarti, S.
Guyon, O.
Kasdin, J.
Lozi, J.
McElwain, M.
Pluzhnik, E.
Thomas, S.
Vanderbei, B.
et al.
Project Blue
Simulation parameters (ACESat mission)
- $D = 45\text{cm}$
- PIAA coronagraph
- $1e^{-8}$ starting contrast (assumed after MSWC)
- 0.5mas (1$\sigma$ rms) random tip/tilt jitter
- 5 color filters
- 2-year mission
- Photon noise included (dominates over read)

After filtering:

After shift-and-add

"Venus"  "Earth"  "pMars"

Note: "pMars" is larger but farther away than Solar Mars
<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>WC SOLUTIONS</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-axis blocker</td>
<td>Off-axis blocker</td>
<td>Star Separation at &lt; N/2 λ/D*</td>
</tr>
<tr>
<td>Coronagraph</td>
<td>None (WC only)</td>
<td>MSWC-0</td>
</tr>
<tr>
<td>Coronagraph</td>
<td>2nd Coronagraph</td>
<td>MSWC-0</td>
</tr>
<tr>
<td>Coronagraph</td>
<td>Starshade (i.e. standard WC)</td>
<td>SSWC (i.e. standard WC)</td>
</tr>
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</tr>
<tr>
<td>Starshade</td>
<td>2nd Starshade</td>
<td>No WC required</td>
</tr>
</tbody>
</table>

**SSWC**=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, **MSWC-0** = Multi-Star WC (0th order, or sub-Nyquist) **MSWC-s** = Multi-Star WC (super-Nyquist)
### SCENARIO

<table>
<thead>
<tr>
<th>On-axis blocker</th>
<th>Off-axis blocker</th>
<th>Star Separation at $&lt; N/2 \lambda/D^*$</th>
<th>Star Separation at $&gt; N/2 \lambda/D^*$</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronagraph</td>
<td>None (WC only)</td>
<td>MSWC-0</td>
<td>MSWC-s</td>
<td>Existing coronagraphic mission concepts are already capable of MSWC-0 with no hardware modifications. MSWC-s requires quilting on the DM or a mild grating in the pupil plane.</td>
</tr>
<tr>
<td>Coronagraph</td>
<td>2nd Coronagraph</td>
<td>MSWC-0</td>
<td>MSWC-s</td>
<td>The second (off-axis) coronagraph would require an additional mask. It can be helpful if diffraction rings from the off-axis star are significant. MSWC is still required if wavefront error is significant.</td>
</tr>
<tr>
<td>Coronagraph</td>
<td>Starshade</td>
<td>SSWC (i.e. standard WC)</td>
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<td>Adding a starshade effectively reduces binaries to single-star suppression problem, at a cost of adding a starshade.</td>
</tr>
<tr>
<td>Starshade</td>
<td>None (WC only)</td>
<td>SSWC (i.e. standard WC)</td>
<td>SNWC</td>
<td>Adding a deformable mirror (without a coronagraph) to a starshade mission theoretically enables double-star suppression.</td>
</tr>
<tr>
<td>Starshade</td>
<td>Coronagraph</td>
<td>SSWC (i.e. standard WC)</td>
<td>SNWC</td>
<td>The off-axis coronagraph is not necessary for a well-baffled telescope, but may relax the stroke requirement on the DM for close stars.</td>
</tr>
<tr>
<td>Starshade</td>
<td>2nd Starshade</td>
<td>No WC required</td>
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<td>Adding a starshade for the off-axis star effectively reduces binaries to single-star suppression problem, but at a cost of adding a second starshade.</td>
</tr>
</tbody>
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*Assuming DM = NxN actuators*

SSWC = Single Star Wavefront Control (WC), SNWC = Super-Nyquist WC, MSWC-0 = Multi-Star WC (0th order, or sub-Nyquist) MSWC-s = Multi-Star WC (super-Nyquist)
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SSWC = Single Star Wavefront Control (WC), SNWC = Super-Nyquist WC, MSWC-0 = Multi-Star WC (0th order, or sub-Nyquist) MSWC-s = Multi-Star WC (super-Nyquist)
Challenges in coronagraphic multi-star high contrast imaging

Star A

Star B

Both stars (incoherent sum)
Challenges in coronagraphic multi-star high contrast imaging

- Second coronagraph helps, but if aberrations from the second star are significant, active suppression (wavefront control) of both stars is required
  - Speckles from the two stars are mutually incoherent and must be suppressed independently
- Wavefront control of second star may be sufficient to suppress it
  - DM effectively acts as a phase mask coronagraph on the second star, in addition to active speckle correction.
  - All direct imaging missions being designed right now are potentially capable of multi-star high contrast imaging
  - Multi-star coronagraph can still help of course and under some conditions may be sufficient (AJ Riggs)
    - Especially to help with blooming / pixel cross-talk due to 2nd star
How to Block 2nd Star? (work by AJ Riggs)

Option 1: Simple Starshade
- Low contrast: Only ~10^{-4} needed
- Small: 5m-10m diameter fine.
  - Inexpensive
  - ~2.5 hours for SNR=5 at 10^{-10} contrast for α Cen A & B

Option 2: Extra Mask inside WFIRST CGI

Occult off-axis star upstream of SPC

<=1 day to get SNR=5 at 10^{-10} contrast for α Cen A
Multi-Star Wavefront Control
Multi-Star Wavefront Control

A +/- 16 \lambda/D
In these regions, independent DM modes are used for the two stars and therefore speckles from the two stars can be independently controlled.

\[ \begin{align*}
A &\quad 8-16 \ \lambda/D \\
I &\quad B &\quad 0-8 \ \lambda/D \\
&\quad B &\quad 8-16 \ \lambda/D \\
&\quad 0-8 \ \lambda/D \\
\end{align*} \]

\[ A \pm 16 \ \lambda/D \]

\[ B \pm 16 \ \lambda/D \]
### MSWC-0 generalization of EFC

#### Single star-EFC (monochromatic)
Solve:

\[ G\tilde{a} = -E_{ab} \]

#### n-star MSWC-0 (monochromatic)
Solve:

\[
\begin{bmatrix}
G_1 \\
\vdots \\
G_n
\end{bmatrix}
\begin{bmatrix}
\tilde{a}_1 \\
\vdots \\
\tilde{a}_n
\end{bmatrix}
= 
\begin{bmatrix}
E_{ab,1} \\
\vdots \\
E_{ab,n}
\end{bmatrix}
\]

#### n-star broadband MSWC-0
Solve:

\[
\begin{bmatrix}
G_1(\lambda_1) \\
G_1(\lambda_2) \\
G_1(\lambda_3) \\
G_2(\lambda_1) \\
G_2(\lambda_2) \\
G_2(\lambda_3)
\end{bmatrix}
\begin{bmatrix}
\tilde{a}_{1,1} \\
\tilde{a}_{1,2} \\
\tilde{a}_{1,3} \\
\tilde{a}_{2,1} \\
\tilde{a}_{2,2} \\
\tilde{a}_{2,3}
\end{bmatrix}
= 
\begin{bmatrix}
E_{ab,1}(\lambda_1) \\
E_{ab,1}(\lambda_2) \\
E_{ab,1}(\lambda_3) \\
E_{ab,2}(\lambda_1) \\
E_{ab,2}(\lambda_2) \\
E_{ab,2}(\lambda_3)
\end{bmatrix}
\]

- **E**: array of electric field values at CCD pixels (flattened into a vector)
- **\(a\)**: DM actuator coefficients
- **G**: Matrix representing the instrument, relating DM actuator coefficients to EFs
Main idea: use different DM modes for star A and star B
- Note: complete separation is impossible due to second-order effects, but these effects can be ignored in closed loop
- Requires a “non-redundant” dark zone, i.e. a zone where DM modes used for A star do not overlap with those used for B
- Corollaries:
  - 2-star problem is reduced to 2 simultaneous 1-star problems. Can be solved by
    - "stacking" the G-matrixes for A and B, and using standard EFC
    - interlacing A and B iterations with standard EFC or speckle nulling
  - Area of dark zone is $\frac{1}{2}$ of the single star case
- Everything generalizes to N stars, but dark zone shrinks by a factor of $\frac{1}{N}$
Ames Coronagraph Experiment (ACE) Laboratory

Team

Two thermally stabilized testbeds

BMC DM: 32 x 32 actuators

(see Bendek et al. 2016 for a new compact DM driver)
Lab tests of MSWC-0
(for now, without coronagraph)

Lab images (Pluzhnik)

Simulation (Sirbu)

655nm light
No coronagraph (for simplicity)
10 λ/D star separation
Equal brightness

Belikov et al. 2016
Lab tests of MSWC-0

Before MSWC

star A

contrast = 5.5e-04

star B

contrast = 7.9e-05

both stars

contrast = 6.3e-04

After MSWC

(both images: same DM setting)

star A

contrast = 4.4e-06

star B

contrast = 2.1e-06

both stars

contrast = 6.4e-06

WFC run by Eugene Pluzhnik
Horizontal slices

Star A, before MSWC (5.5e-4)

Star B, before MSWC (7.9e-5)

Both stars, after MSWC (6.4e-6)
Multi-Star Wavefront Control broadband simulations. 10% @ 650nm

Mean contrast: $8.3 \times 10^{-9}$

Multi-Star Wavefront Control

- Coronagraph for second star is neither sufficient nor necessary!
- MSWC works by using different independent DM spatial modes for each star
- No hardware change is required for MSWC – should work for any mission with a DM (WFIRST, LUVOIR, HabEx)

SNMSWC needs a DM with a quilting (print-through) pattern or other grating

Mean contrast: $8.4 \times 10^{-8}$

Super-Nyquist Multi-Star Wavefront Control

- 10% @ 650nm
- 0.35m aperture
- PIAA coronagraph
- 32 x 32 actuator DM

Preliminary broadband test (MSWC-0)

Scanning from 0 to 50% band
<table>
<thead>
<tr>
<th>On-axis blocker</th>
<th>Off-axis blocker</th>
<th>Star Separation at &lt; $N/2 \lambda/D^*$</th>
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**SSWC**=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, **MSWC-0** = Multi-Star WC (0th order, or sub-Nyquist), **MSWC-s** = Multi-Star WC (super-Nyquist)
DM “quilting”: a feature, not a bug

Phase microscope image of a BMC deformable mirror surface
Super-Nyquist WC principle

- Main idea: Diffraction orders or non-smooth influence functions enable the DM to modulate light beyond the Nyquist limit.
  - Diffraction order effectively acts as a pseudo star, and almost any WF algorithm can be used to dig a dark hole (at a sub-Nyquist distance) around a diffraction order.
  - Can also be understood in terms of aliasing.
- If grating periodicity = DM actuator periodicity, then controllable diffraction order regions fully tile the entire focal plane (theoretically to infinity).
Super-Nyquist Wavefront Control
(single star, or multi-star w/starshade)

Simulations by D. Sirbu
Also see Thomas et al. (2015), Belikov et al. (2016)
Super Nyquist WC Lab demo at 100 $\lambda/D$

(representative of aCen w / WFIRST-size telescope and starshade)

Details of this demonstration:

- In order to isolate pure WFC effects, coronagraph was not used
- For this initial demo, monochromatic light was used (655nm) rather than broadband
- DM: Boston Micromachines kilo (32x32)
- Performed at the Ames Coronagraph Experiment laboratory

Belikov et al. 2017, SNWC operated by Pluzhnik

Factor of 10 suppression demonstrated at 100 $\lambda/D$
SNWC using quilting or grating

Pupil plane

Focal plane

Solid: influence function
Dashed: DM field perturbation

Grating (green) or beamsplitter (blue)

DM field perturbation

Sub-Nyquist controllability curve

Super-Nyquist controllability curves (solid)

SNWC using special influence functions

Pupil plane

- DM actuator coefficients
- Influence functions

Focal plane

- SNWC Controllability

10% Broadband SNWC simulation @ 100 $\lambda/D$
(similar to of aCen w/WFIRST)

Alpha Cen B @100 $\lambda/D$

Super-Nyquist Wavefront Control
Mean Contrast: 2.76e-11

Control Diffraction Orders for B

Dark Hole

Residual light from Alpha Cen A

Zoom Region

Sky Angular Separation, $\lambda_0/D$

Sky Angular Separation, $\lambda_0/D$

Simulation by D. Sirbu
<table>
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*Assuming DM = NxN actuators

**SSWC**=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, MSWC-0 = Multi-Star WC (0th order, or sub-Nyquist) MSWC-s = Multi-Star WC (super-Nyquist)

- **Existing coronagraphic mission concepts are already capable** of MSWC-0 with no hardware modifications. MSWC-s requires quilting on the DM or a mild grating in the pupil plane.
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- Adding a starshade effectively reduces binaries to single-star suppression problem, at a cost of adding a starshade.
- Adding a deformable mirror (without a coronagraph) to a starshade mission theoretically enables double-star suppression.
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- Adding a starshade for the off-axis star effectively reduces binaries to single-star suppression problem, but at a cost of adding a second starshade.
MSWC with super-Nyquist separations (MSWC-s)

Conventional (single star) wavefront control

- Suppressed star
- Planet (pale blue dot)
- Residual starlight (speckles)
- DM control region (suppressed speckles)
- DM Nyquist frequency

- Suppressed star (on-axis)
- Planet (no longer visible)
- Residual starlight (speckles) from both stars

- Companion star (off-axis)
  - DM control region. Speckles may be suppressed for off-axis star, but not on-axis.

MSWC-s

- Suppressed star A (on-axis)
- Planet
  - Diffracted copy of star B
  - Sub-Nyquist region of star A
  - Residual starlight (speckles) from both stars

- Companion star B (off-axis)
  - Sub-Nyquist region of star B
MSWC with Super-Nyquist separations (MSWC-s) simulation

Control Region A
Control Region B
Sub-Nyquist Region for A
Sub-Nyquist Region for B

Sky Angular Separation, $\lambda_0/D$

Simulations by D. Sirbu
MSWC-s in 10% broadband light (simulation)

Mean Contrast: 3.18e-09

Sub-Nyquist Regions

Zoom Region

Diffraction Orders

Alpha Cen A (blocked by coronagraph)

Alpha Cen B

Multi-star dark hole

Alpha Cen B @ 160 L/D

Alpha Cen A (blocked by coronagraph)
MSWC-s lab demonstration @ ~100 λ/D

Target star only  off-axis star only  both stars

Belikov et al., 2017 (MSWC-s operation by Pluzhnik)
How to create “proxy stars” on WFIRST

1) Add a filter with just dots on the surface in an open position on the pupil mask wheel.

Then, only the HCL can be used.
Side note for WFIRST wide field camera

WFIRST wide field camera, Pasquale et al, 2016.

**Figure 7. WFI Ray Trace Views**

Adding a DP filter at the pupil stop can calibrate:
- Any distortions induced by the last mirror
- Detector motions
- Individual pixels motions were the spikes are located.

Also, for exoplanet stellar astrometric measurements, it allows to put the target star in chip gap to allow longer integration and achieve a similar brightness between the spikes and the background stars,
Future work

- Recently funded TDEM (CY18 – 19): TRL 3 -> 4
  - 1. Simulations of MSWC with mission instrument models and real binary star geometries
  - 2. Testing of MSWC on SCExAO (Subaru Telescope)
  - 3. Testing of MSWC at ACE testbed with apertures representative of missions, as well as with a coronagraph
- HCIT vacuum testing? (TRL4 -> 5)
  - Potential collaborations with existing tests at HCIT
  - Stand-alone proposals for FY19 or late FY18.
Conclusions

- Multi-star high contrast imaging opens up the majority of (non-M-dwarf) star systems
  - Alpha Centauri in particular
    - If aCen has a rocky planet in HZ, it may be possible to directly image it in 5-10 years (ACESat or WFIRST)

- General binary star suppression requires binary star wavefront control algorithms
  - Solution: MSWC (-0 and -s versions)
  - 3e-11 in 10% achieved in simulation

- TRL ~3 lab demonstrations
  - Super-Nyquist dark zones demonstrated at 16-300 λ/D with a 32x32 DM
  - MSWC for (effectively) 2 light sources
    - both sub- and super-Nyquist versions

Ruslan Belikov, NASA Ames Exoplanet Technologies Group
A Method to Enable High Contrast Imaging in Multi-Star Systems
PI: Ruslan Belikov / NASA ARC

Description and Objectives:
• Develop technology to directly image exoplanets in multi-star systems, the most common type of (Sun-like) star system

Key Challenge/Innovation:
• Challenges:
  • Starlight from both stars needs to be independently suppressed
  • Star separation is usually beyond the outer working angle of the deformable mirror
• Innovations:
  • Using different deformable mirror (DM) modes for different stars
  • Using quilting pattern on DM or a grating to overcome its outer working angle limitation

Approach:
• Develop three algorithms in simulation and then perform a lab demonstration:
  • Super-Nyquist Wavefront Control (SNWC) to overcome DM outer working angle limitation
  • 0-th order Multi-Star Wavefront Control (MSWC-0) to suppress binary stars at sub-Nyquist separations
  • Combination of MSWC-0 and SNWC (MSWC-s) to suppress binary stars at super-Nyquist separations

Key Collaborators:
• NASA Ames Research Center: Ruslan Belikov, Eduardo Bendek, Eugene Pluzhnik, Dan Sirbu, Chris Henze, Sandrine Thomas
• University of Arizona: Olivier Guyon

Development Period:
• 4/2015 – 3/2017

Accomplishments and Next Milestones:
• Methods proved in computer simulations for 10% broadband light:
  • SNWC: 3e-11 contrast at 100 l/D
  • MSWC-0 (with coronagraph): 8.3e-9 contrast for αCen AB with a 35cm telescope
  • MSWC-s (with coronagraph): 2.3e-9 contrast for αCen AB with HabEx – size telescope
• All milestones so far met: SNWC and MSWC lab demos
• Next: follow-on SAT / TDEM effort to raise from TRL3 to 4

Publications:
• Belikov, R., Pluzhnik, E., Bendek, E., Sirbu, D., SPIE (2017)
• Sirbu, D., Belikov, R., Bendek, E., Holte, E., et al., SPIE (2017)
• Belikov, R., Bendek, E., Pluzhnik, E., Sirbu, D., et al., SPIE (2016)
• Belikov, R., Bendek, E., Thomas, S., Males, J., Lozi, J., SPIE (2015)
• Thomas, S., J., Belikov, R., Bendek, E.A., SPIE (2015)

TRLin = 1  TRLcurrent = 3  TRLtarget = 3
BACKUP SLIDES
MSWC-s in 10% broadband

\[ \text{Mean Contrast: } 3.18 \times 10^{-9} \]

- **Sub-Nyquist Regions**
- **Diffraction Orders**
- **Zoom Region**
- **Alpha Cen A** (blocked by coronagraph)
- **Alpha Cen B**

\[ 48 \times 48 \text{ DM's nominal Nyquist Limit is } 24 \frac{\lambda}{D} \]
How to create PSF replica?

- We can use DM manufacturing dots
- Use a Diffractive Pupil to generate dots at an arbitrary distance.
Super-Nyquist Wavefront Control
Preliminary Lab Demo

Details of this demonstration:

- In order to isolate pure WFC effects, coronagraph was not used.
- For this initial demo, monochromatic light was used (655nm) rather than broadband.
- DM: Boston Micromachines kilo (32x32)
- Performed at the Ames Coronagraph Experiment laboratory.

SNWC Theory+simulations: Thomas, Belikov, Bendek 2015
Fundamental challenges in high contrast imaging

- **Challenge #1:** Diffraction (known a priori)
  - Solution: Coronagraph / Starshade
  - Coronagraph is not necessary for second star

- **Challenge #2:** Aberrations (random error)
  - Wavefront Control (WFC)
  - Multi-star wavefront control is necessary
MSSNWC Simulation with a coronagraph

- monochromatic light
- Star separations: 25 \( \lambda/d \)
- Contrast achieved: \( 2 \times 10^{-8} \) with a 6x6 \( \lambda/d \) region.
- With a 4x4 \( \lambda/d \) region contrast is < \( 10^{-8} \)

Simulation by Sandrine Thomas
Example of a different dark zone geometry (lab image)
Multi-star wavefront correction
Proof of principle simulation
### Contrast comparison

<table>
<thead>
<tr>
<th></th>
<th>2 star WC</th>
<th>On axis WC</th>
<th>Off axis WC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>1.3e-4</td>
<td>1e-4</td>
<td>7.7e-6</td>
</tr>
<tr>
<td>After</td>
<td>5.2e-8</td>
<td>4.5e-8</td>
<td>1.6e-9</td>
</tr>
<tr>
<td>1 star</td>
<td>n/a</td>
<td>&lt; 1.9e-8</td>
<td>&lt; 6.2e-10</td>
</tr>
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![Image of contrast comparison with before and after results](image-url)
Diffraction vs. Aberrations at large angles

Diffraction from the off axis star: 3.4 e-8 (median)

25 nm rms Aberrations
leakage from the off axis star: 4 e-7 (median)
How to suppress the second star?

- Challenge #1: Diffraction

- Challenge #2: Aberrations
  - Challenge #2a: Speckle suppression beyond the Nyquist frequency of DM
  - Challenge #2b: Independent speckle suppression of two (mutually incoherent) stars
Harmonic SNWC preliminary demo (for DMs without quilting)
SNWC Broadband simulations

- **Simulation example: a Cen with a 1.5m telescope**
  - Assume on-axis star is fully suppressed
  - 10" separation with a 1.5m telescope = 100 λ/D @ 770nm.
  - Diffraction grid of 50 cycles per aperture
  - Dark zone at 104 λ/D of size 4x8 λ/D region.
  - The DM used has 32x32 actuators

- **Monochromatic 770 nm) results**
  - Aberrations: $F^2$, 25nm rms at 770nm
  - Before correction: 4.26 $e^{-7}$
  - After correction: 1.15 $e^{-9}$
  - Over a factor 100 improvement

- **Preliminary broadband results**
  - 3% wavelength band
  - Aberrations: $F^2$, 20nm rms at 770nm
  - Before correction: 1.61 $e^{-6}$
  - After correction: 3.41 $e^{-9}$
  - Over a factor 100 improvement

Thomas et al. 2015
Diffraction and Aberrations

Contrast

sky angle ($\xi/D$)
Nyquist limit of the DM: is it really a limit?

On axis light suppressed by coronagraph

Sub-Nyquist frequency region \((N/2^N \lambda/d)\) = usually only of the order of a few arcsec with an 8m telescope

Residual speckles in the “uncorrectable” Super-Nyquist region

Credit: B. Macintosh
Super-Nyquist WC principle

- Main idea: Diffraction orders or non-smooth influence functions enable the DM to modulate light beyond the Nyquist limit
  - Diffraction order effectively acts as a pseudo star, and almost any WF algorithm can be used to dig a dark hole (at a sub-Nyquist distance) around a diffraction order
  - Can also be understood in terms of aliasing
- If grating periodicity = DM actuator periodicity, then controllable diffraction order regions fully tile the entire focal plane (theoretically to infinity)
SNWC using influence functions

Pupil plane

Focal plane

DM actuator coefficients

Influence functions

DM field perturbation

SNWC Controllability

FT
SNWC using quilting or grating

Pupil plane

Focal plane

Solid: influence function
Dashed: DM field perturbation

Grating (green) or beamsplitter (blue)

DM field perturbation

Sub-Nyquist controllability curve

Super-Nyquist controllability curves (solid)
Challenge 2a solution:
Super-Nyquist Wavefront Control

- Two approaches:
  - Aliasing from diffraction orders
    - Using DM quilting or segmented DM or a diffractive pupil
  - 2nd order diffraction from nonlinearity between DM shape and Electric Field
Putting it all together

- **Challenge 1:** outside DM control region
  - Super-Nyquist WC
- **Challenge 2:** speckles from both stars are incoherent
  - Multi-star WC
- **Combination:**
  - MSSNWC
Model validation of harmonic speckle modulation

Super-Nyquist speckle modulation using 2nd order harmonic

- Modulated 2nd order speckle (lab measurement)
- Modulated 2nd order speckle (theory)
- Unmodulated speckle

DM spatial sine wave phase (radians)

Ruslan Belikov, NASA Ames Coronagraph Laboratory
Testbeds and PIAA hardware

ACE testbed

Lockheed Martin

PIAA lenses

PIAA mirrors

JPL

Deformable mirror

State of the art performance in the lab

Ruslan Belikov, NASA Ames Coronagraph Laboratory
Super-Nyquist Wavefront Control

With a grid of 50 cycles per aperture, 100 lambda/d, 4x8 lambda/d region, monochromatic, 770 nm

Diffracted star image at 100 λ/D

Super-Nyquist dark zone at 104 λ/D with a 32x32 DM

No aberrations
Before correction: 3.35 e-8
After correction: 2.55 e-10
Factor 100 improvement

25nm rms
Before correction: 4.26 e-7
After correction: 1.15 e-9
Over a factor 100 improvement

(Thomas, Belikov, Bendek, in prep.)
Ames Coronagraph Experiment (ACE) Laboratory

Team

Thermally stabilized testbed

BMC DM: 32 x 32 actuators

(see Bendek et al. 9909-299 for a new compact DM driver)

Ruslan Belikov, NASA Ames Coronagraph Laboratory
What if star separation is beyond DM control region?

Diffraction from the off axis star: 3.4 e-8 (median)

25 nm rms Aberrations leakage from the off axis star: 4 e-7 (median)
Conclusions

- Multi-star high contrast imaging opens up the majority of (non-M-dwarf) star systems
  - Alpha Centauri in particular

- Main challenge seems to be in wavefront control algorithms
  - Existing mission designs may already be capable of some multi-star high contrast imaging

- Milestones met on budget and on schedule
  - Lab demo of MSWC
  - Lab demo of SNWC
Instrument Building blocks

45 cm off-axis telescope with an **embedded** PIAA -> 10^{-5} (1.6 – 10\(\lambda/D\))

**WFC (Multi-Star Wave Front Control)** -> 10^{-8}

**Continuous observation ODI** -> 10^{-11}

Diffraction from on-axis star (no coronagraph)

Coronagraph (w/o WFC)

Aberrations from on-axis star; diffraction + aberrations
Multi-Spectral Imager

- **Wavelength**: 400 nm to 700 nm (Contains 40% aCen A flux)
- **Five channels** of 10% bandwidth each.
- **SW (400nm)**: Blue rayleigh scattering indicates earth-like atmosphere. (Const. coatings and QE)
- **LW (700)**: CH₄ absorption bands. Limited by QE and WFC bandwidth.

- E2v EMCCD 201-20 almost zero RON
- Short 10s exposure time to avoid cosmic rays
Telescope Hardware

- Full SiC 45cm, Off-axis telescope, L/25 max end-to-end WFE (Total 45Kg mass)
- Active thermal control to maintain 10°C operation with 0.1°C PV stability
- 0.5mas RMS stability LOWFS (Demonstrated for CAT III EXCEDE Lockheed Martin)
Mission operations

High stability pointing spacecraft
Unperturbed observation per quarter, 1.6 days/band/star

Quarterly operations:
- **DSN Downlink** and reaction wheels desaturation and quarter end.
- **90° Roll** to keep sunshield in position
- **Calibration** per quarter (Speckle MSWC, LOWFS)

---

![Diagram of spacecraft orbit and operations](image)
SNWC Main design constraints

- **Location**: a diffraction order is required within a sub-Nyquist distance of desired dark hole
  - This is guaranteed if grating periodicity = DM pitch

- **Energy conservation**: total speckle energy to be suppressed < total energy of active diffraction order. For example, 32x32 DM and a 1e-3 diffraction order:
  - Up to $10^{-4}$ speckles in a 3 x 3 I/D region
  - Up to $10^{-6}$ speckles in a 32 x 16 I/D region

- **Conservation of degrees of freedom**: SNWC allows shifting the sub-Nyquist dark zone beyond the Nyquist limit, but does not allow enlarging it
  - Multiple dark zones can be stitched to achieve a larger dark zone

- **Blind spots at locations of the diffraction orders**
  - Telescope can be rotated to move them away