Simplified Starshade Interface to WFIRST

Stefan Martin, Stuart Shaklan
Jet Propulsion Laboratory,
California Institute of Technology.

© 2016 California Institute of Technology. Government sponsorship acknowledged.

Summary

- Baseline is for minimal changes to WFIRST CGI.
  - 3 optics to be added to Occulting Mask selector wheel
- Three main options A, AA and AAA provide increasing performance
  - Baseline is A, embodying the minimum set of modifications to CGI.
    - AA adds 34% BW science imaging (compared with 10% BW) in the blue wavelength band.
    - AAA adds spectroscopy in the blue wavelength band.
  - Option A+ enhances planet finding performance
- LOWFS is used for Starshade guiding and pointing jitter control
- Baseline assumes use of a laser beacon on the Starshade
  - With beacon on, FSM runs fast loop for jitter control. Similar to existing CGI pointing control function.
  - With beacon off, LOWFS sensor reports Starshade lateral position wrt star.
  - LOWFS alternates between fast pointing and guiding with duty cycle eg. 9:1 (TBR)
  - Further study will examine a no-beacon scenario with simultaneous jitter and position control on the LOWFS
- WFIRST WFC used in formation acquisition.
- Telescope pointing control is identical to normal control during CGI operations

Option space

Option	CGI	A (Baseline)		AA	AAA
Description	Coronagraph	Coronagraph IFS		Coronagraph IFS	Broadband IFS
Features		Minimal changes		Broad band spectroscopy. Broad band blue imaging.	Adds blue spectrum
Instantaneous optical bandwidth	18%	18%		34%	34%
IFS Spectral ranges	600-970 nm in 3 ranges	600-970 nm in 3 ranges		600-970 nm in 2 ranges	425-1000 nm in 3 ranges
Imager spectral ranges	440-490 nm HLC 540-590 nm HLC 810-860 nm SPC 860-880 nm SPC	All CGI imager and IFS bands (left)		430-970 nm in 3x 34% ranges	425-1000 nm in 3x 34% ranges
New hardware/optics		3 dichroic/ masks at Occulting Mask changer	**A+**: also add 1 BP filter to Color Filter wheel	As A, plus MLA rotator and 3 BP filters in Color Filter wheel	As AA, plus broadband IFS
Detail on spectral ranges					
IFS Spectral ranges	*600-720 nm* *700-840 nm* *810-970 nm*	*600-720 nm* *700-840 nm* *810-970 nm*		*600-850 nm* *685-970 nm*	*425-600 nm* *600-725 nm* *706-1000 nm*
Imager spectral ranges	*440-490 nm HLC* *590-540 nm HLC* *860-810 nm SPC* *880-860 nm SPC*	*600-720 nm* *700-840 nm* *810-970 nm* *2 blue 10% ranges (HLC, left)*		*430-600 nm* *600-850 nm* *685-970 nm*	*425-600 nm* *600-725 nm* *706-1000 nm*

Variant Option A+ consists of Option A, adding one 34% BP filter to color filter wheel giving broadband blue imaging for ~10x faster integration than Option A

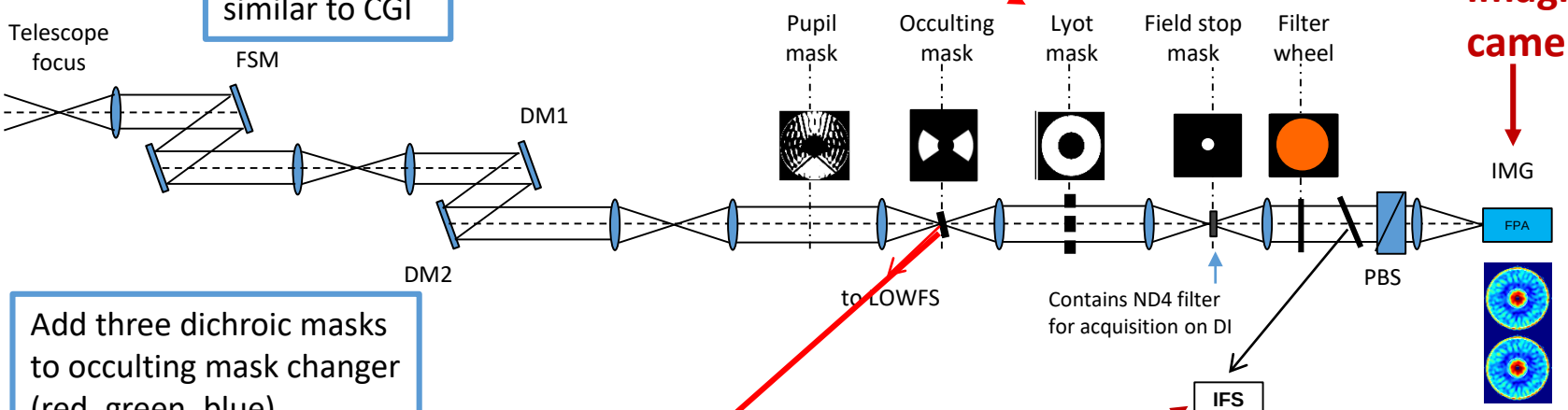
WFIRST Coronagraph beamtrain

Use these masks in existing open positions

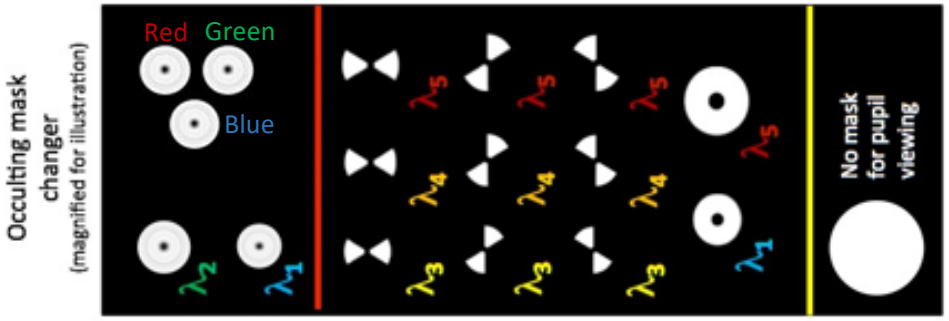
Use this filter wheel in existing open position.
Option AA, AAA: add 3 filters.
Option A+: add 1 filter

Drive FSM from LOWFS, similar to CGI

Same as CGI
Imaging camera



Add three dichroic masks to occulting mask changer (red, green, blue)



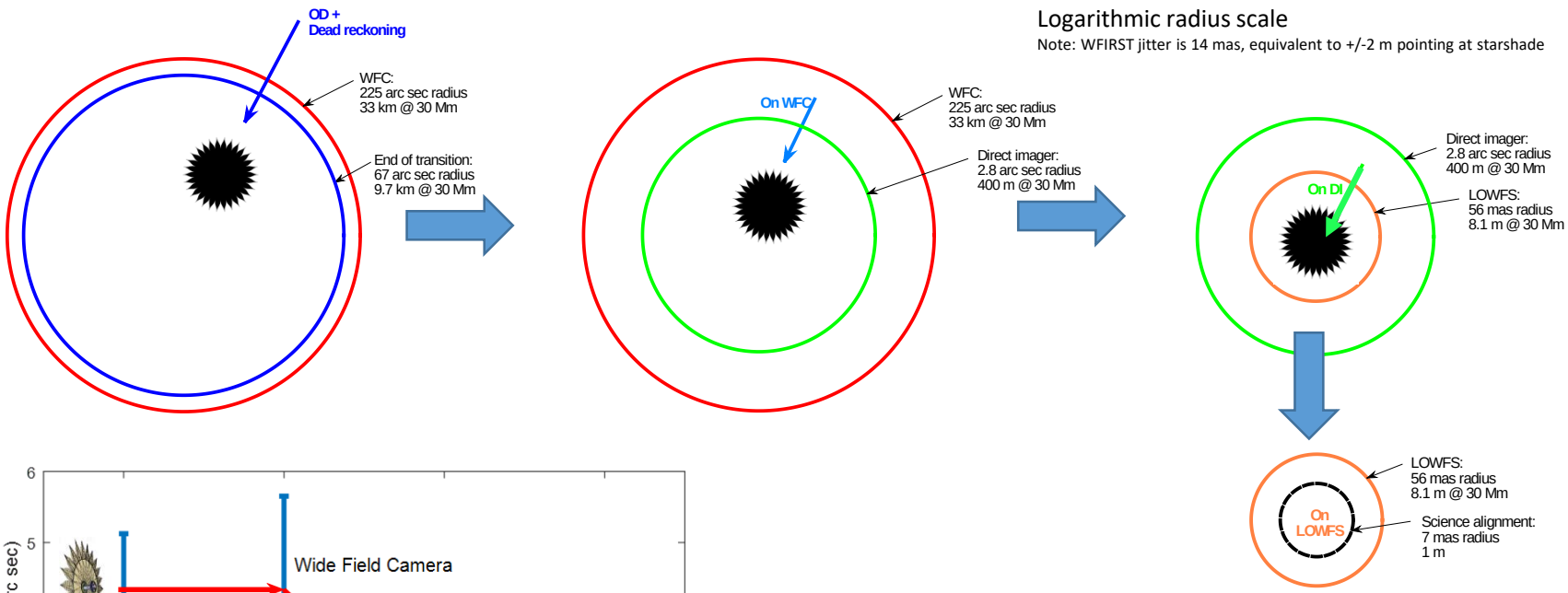
Shared with CGI.
Option AA, AAA: rotating MLA
Option AAA: Broadband IFS

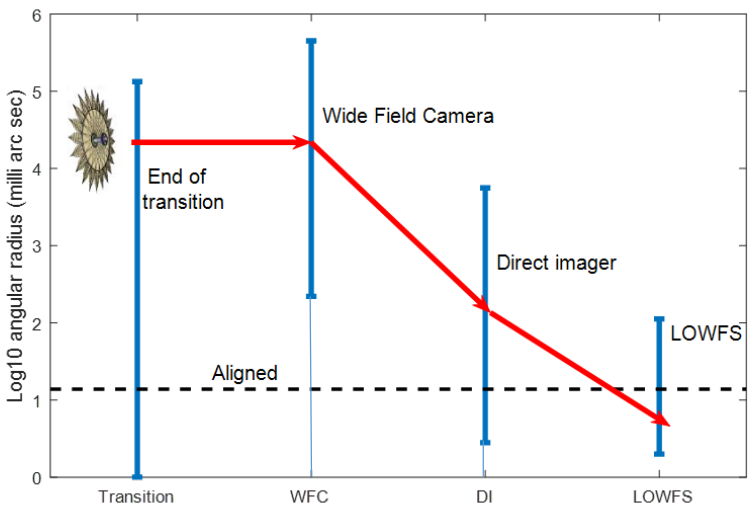
Same as CGI
Polarization imaging

Starshade Optical System Summary

- Formation Flying
  - Wide Field Camera
    - Transition mode (coarse): Tracks LED beacon on starshade at start and end of retargeting maneuvers.
  - Direct Imager
    - Transition mode (fine): Tracks laser beacon on starshade and light from the target star.
  - LOWFS
    - Science mode: Tracks laser beacon on starshade and light from the target star.
  - Communications system
    - Starshade range obtained from telescope-starshade communications link
  - Shuttering/readout/thruster fire synchronization
    - Thruster firings will occur about every 650 s (average, worst case) or less frequently
      - Thruster plume scatters sunlight to telescope
      - A rough estimate predicts brightness equivalent to a 10th magnitude star in each affected pixel- saturates the well.
        - Estimate depends on fraction of ammonia in plume (assumed 50% by mass, the rest gaseous)
      - Requires the science CCD to be read out before the thruster firing and then reset/ read out before resuming integration.
      - Starshade will flag pending thruster firings to WFIRST
      - Since thruster firings will be at variable intervals, the interval between CCD reads will also be variable

Establishing the formation





Sequence of events:
Departure; origin position based on WFIRST OD at current star =>
Burn =>
Dead reckoning plus trajectory determination using WFC plus fine adjustment =>
Arrival; WFC (coarse positioning) =>
Direct Imager (fine positioning) =>
LOWFS (science mode)

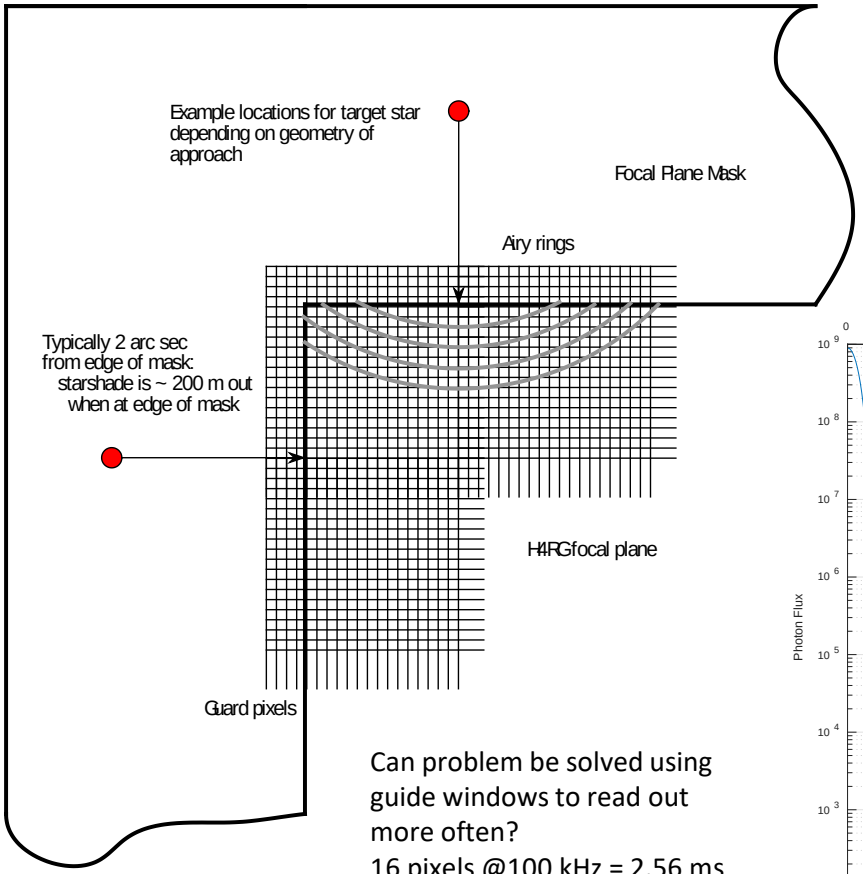
Formation Flying Summary

- Transition
  1. Starshade departs for new target
  2. Starshade completes retargeting burn and rotates to show beacon to WFIRST
  3. WFC tracks Starshade to verify trajectory ~30 mins (TBR).
     - Starshade can then make small corrections to trajectory: guarantees very accurate arrival position and rapid formation acquisition
  4. WFIRST resumes normal science operations
- Acquisition
  1. Starshade arrives at new target (within 67”) , rotates to show beacon to WFIRST.
  2. WFIRST points WFC at target star (star will actually be just off the FPA)
  3. Starshade range obtained from telescope-starshade communications link
  4. Any Starshade range correction required is performed by Starshade
  5. WFC used to guide Starshade to within the field of view of Direct Imager (DI)
     - Uses IR LED (λ TBD) and starlight
     - Star and starshade within 2.8” of one another
  6. WFC rotates to place target star at center of DI (ND4 filter in place).
  7. WFIRST maintains mean pointing of the telescope (offset from DI FOV) using star trackers or WFC.
  8. Direct Imager used to guide Starshade to within the field of view of LOWFS (56 mas)
  9. LOWFS used to guide Starshade to within the science area
- Science
  1. LOWFS tracks laser beacon on starshade and light from the target star
  2. With beacon on, control loop on FSM corrects fast pointing jitter and boresight drift (offload to telescope).
  3. With beacon off, control loop on Starshade corrects starshade drift from line of sight.

Dealing with bright target stars

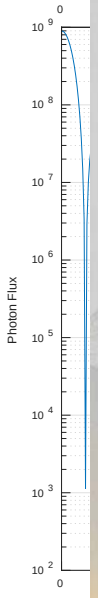
- Position target star on a suitable location of the mask surrounding the focal plane. May need to test four different edge locations to see the starshade- do this by attitude adjustment of telescope.

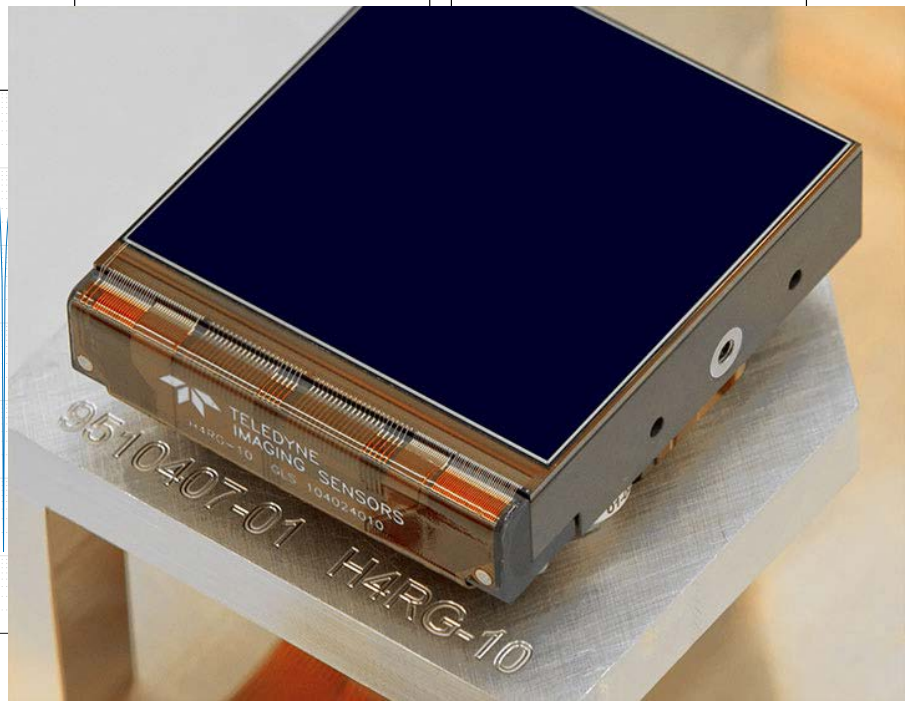
Airy rings of reduced intensity relative to core of PSF are seen on FP.



Can problem be solved using guide windows to read out more often?
16 pixels @100 kHz = 2.56 ms
Accumulated flux in this time is still too high- 2.3e6

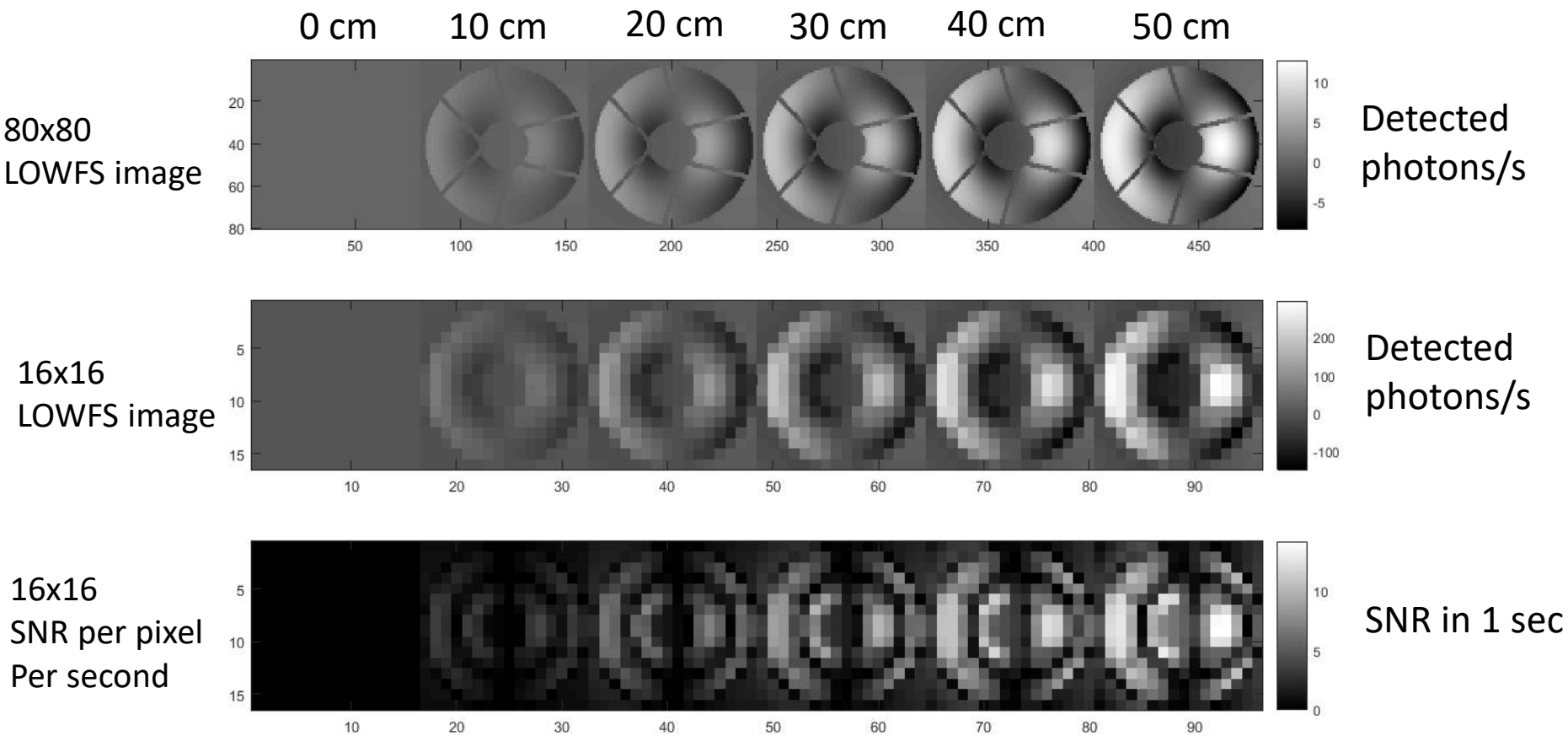
- Assume Z band filter (minimizes flux)
- R = 4, Z band flux 9e8 ph/s
- Assume read out at maximum rate of 5.25 s per frame
- Well depth 55k.





Starshade Offset Sensing with the LOWFS

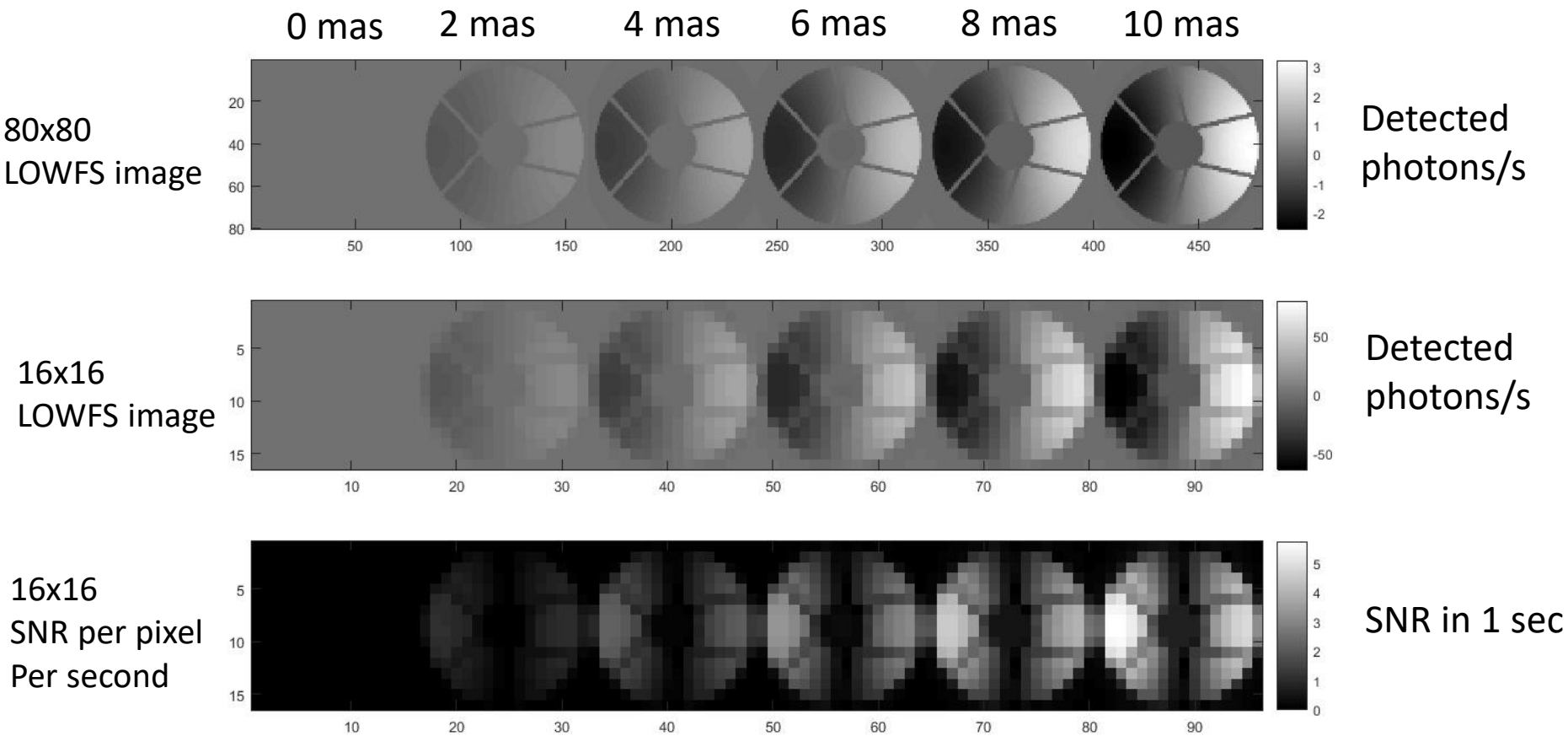
Science band: 425-575 nm. Detection band on LOWFS: 900 -1000 nm



These plots show the differential LOWFS image when the out-of-band 900 nm starlight diffracts around the starshade and is imaged on the LOWFS detector.

Telescope Pointing Sensing with the LOWFS beacon

Science band: 425-575 nm. Pointing band on LOWFS: 900 -1000 nm



These plots show the differential LOWFS image when the beacon is turned on and imaged on the LOWFS detector. Beacon brightness set to equal nominal leaked starlight.

Backup/detail

Formation Flying Scenario (draft)

Using the Wide Field Camera (WFC).

Sequence starts when Starshade leaves last target position, initiating a Transition.

1. WFIRST WFC observes trajectory of Starshade, 30 mins (TBR). Fine OD and trajectory information transmitted to starshade
2. WFIRST resumes observing schedule.
3. Starshade makes fine trajectory correction.
4. Typically several days later Starshade initiates burn.
5. Dead reckoning brings Starshade within 40 km (TBR) of star-starshade line.
   - If this is Starshade's initial arrival at L2, it is navigated from the ground.
   - Originating OD is position at previous target; data provided by WFIRST
   - Angle 67 arcsec.
6. Starshade rotates to point axis at the target star.
7. Based on anticipated arrival time, WFIRST points WFC at target star
   - WFC has 450 arc sec (full width) field of view on each detector array.
   - Because star is bright, positions it on FPA mask, just off the array.
8. WFC detects IR beacon (flashing) and target star (from position knowledge relative to guide stars, or based on Airy rings)
   - Yields angle between both targets
   - Note 1W beacon 3.7e7 ph/s
9. Starshade and WFIRST establish communications
   - Note: synchronize beacon flashes
   - Note: more detailed timing diagram forthcoming
10. WFIRST starts transmitting Starshade-Star differential bearings from WFC
11. Starshade moves under closed loop (Control loop #1)
    - Thruster firings may be 10th magnitude per pixel near the starshade

Formation Flying Scenario (draft) (cont.)

12. Once both star and Starshade are within FOV of Direct Imager, WFIRST rotates (~1°) to place star and starshade laser beacon in FOV of DI

    12. WFC resolution is 17 m, Direct imager FOV is 420 m.

13. WFIRST picks up guide stars on WFC or star trackers and runs its standard pointing control loop (with jitter limited to CGI reqts).

14. IR Beacon turns off

15. Beacon laser turns on (flashing). Color selected by WFIRST observing sequence.
    - Note: One IR beacon for WFIRST WFC, one red beacon (~900 nm) for LOWFS (blue science), one blue beacon (~425 nm) (red or green science)

12. WFIRST sets required CGI selector wheel setup.

16. WFIRST starts transmitting DI bearing data

17. Starshade moves under Control loop #2.

18. Once within FOV of LOWFS, WFIRST starts sending bearing data (deltas between beacon on and off) from LOWFS

    - DI resolution is 1 m, LOWFS FOV is ~8 m.

19. Starshade moves under Control loop #3.

    - When beacon is off WFIRST measures apparent position of starshade across line to star. When beacon is on, WFIRST measures apparent bearing angle to Starshade. Duty cycle 50/50.

20. Once in science position WFIRST starts using Control loop #4:

    - Within CGI, a fast control loop on FSM is active when beacon is on. This maintains CGI beamtrain pointing on Starshade (surrogate for star). When beacon is off, (FSM holds current position) WFIRST measures apparent lateral offset of starshade . At end of each cycle (which has uneven duty cycle (90/10 TBD)) WFIRST sends starshade offset to Starshade.

21. WFIRST resets science CCD (IFS or DI) and starts integrating.

22. Periodically (~650 s intervals) Starshade flags an upcoming thruster firing. WFIRST stops integrating and reads out science camera.

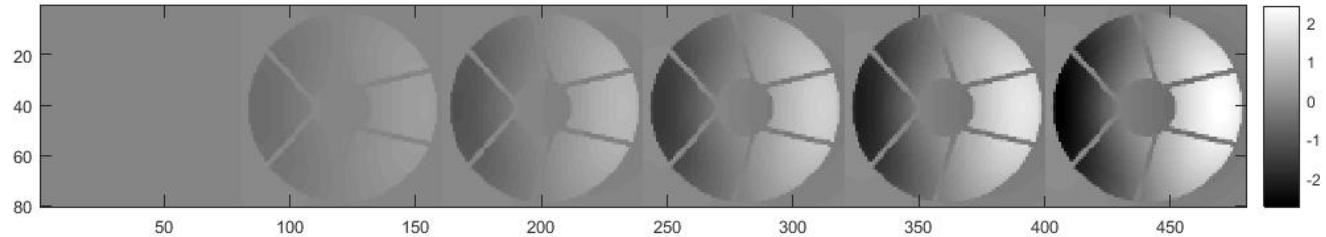
23. Starshade fires thrusters, repeat from 20.

Telescope Pointing Sensing with the LOWFS (no beacon)

Alternative
Science band: 425-575 nm. Pointing band on LOWFS: 900 -1000 nm

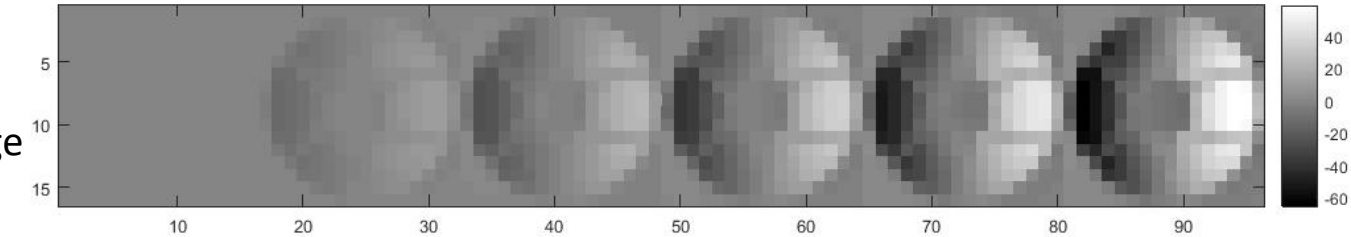
0 mas 2 mas 4 mas 6 mas 8 mas 10 mas

80x80
LOWFS image



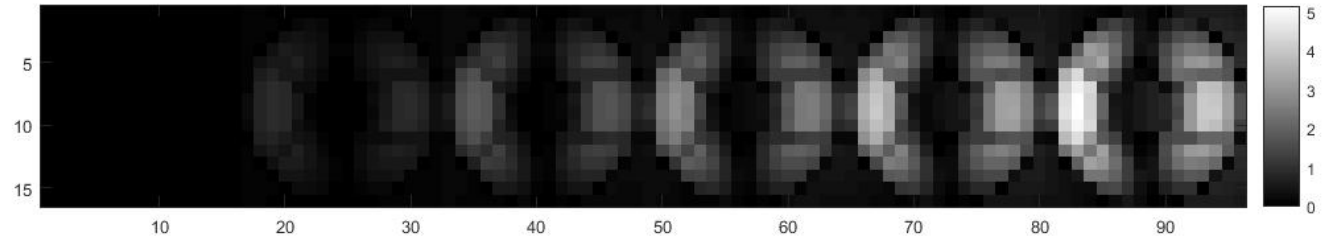
Detected photons/s

16x16
LOWFS image



Detected photons/s

16x16
SNR per pixel
Per second



SNR in 1 sec

These plots show the differential LOWFS image when the beacon is turned off and the out of band starlight is imaged on the LOWFS detector.

Coronagraph Mechanisms

9 mechanisms, of which 6 filter changers are identical designs

Mechanism	Description
Fast Steering Mirror	Tip and tilt at pupil (PM conjugate) Operates at up to 1 KHz based on feedback from low-order wave-front sensor (LOWFS) Dynamic range = 30 as / 60 mas = 500 (TBR) Resolution of 60 mas (TBR) (to correct telescope pointing to 1mas = 120mas in coronagraph = 60mas in mirror angle.) ✓ Add beacon oriented s/w for starshade guiding
Shaped Pupil Mask Changer	5 positions (4 SP masks, 1HL flat mirror) ✓
Focal Plane (occulting) Mask Changer	14 positions (11 SP masks, 2 HL masks, 1 open) Add three filter/masks for starshade guiding
Lyot Stop Changer	3 positions (1 SP mask, 1 HL mask, 1 open) ✓
Field Stop Changer	3 positions (1 SP open, 2 HL stops) ✓
Color Filter Changer	12 positions ([4] 5% filters, [3] 10% filters, [3] 18% filters, 1 open, 1 dark) ✓ Options AA, AAA: add three bandpass filters for starshade
Camera Selector Changer	Dark, mirror, imaging lens, pupil lens, open, focus diversity (x3) ✓
Focus Mirror Adjust	Continuous positioning for focus adjustment ✓
Option AAA: MLA rotator/switcher	(Options AA, AAA) Rotates or swaps out microlens array to suit starshade or coronagraph

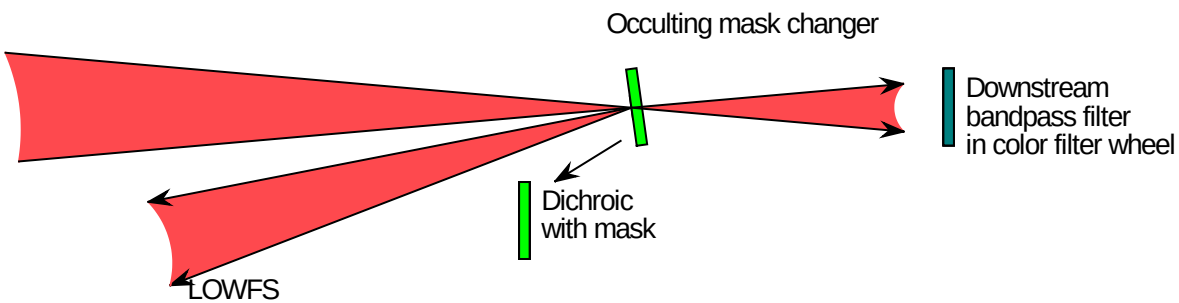
Filters, Masks and Science Wavelengths

Mask/filter sets for Coronagraph and Starshade CS

Mask/filter wheel	SPC (Imaging)	SPC (IFS)	HLS (Imaging)	Starshade (IFS and Imaging)	Baseline Filter Wheel Positions Req'd	Starshade-ready Filter Wheel Positions Req'd
Pupil Mask	1	3	open	open	5	5
Focal Plane Mask	2	9	2	2 or 3	14	16 or 17
Lyot Mask	1	1	1	open	4	4
Field Stop Mask	open	open	2	1	3	4
Color Filters	2	3	2	open	8	8
IFS/Guide select	Dark, mirror, imaging lens, pupil lens, open, focus diversity (x3)			As needed	8	8

Option A: New dichroic/masks in Focal Plane Mask wheel
Option AA and AAA: plus bandpass filters downstream

Science band	Blue	Green	Red	Option
Dichroic reflects	600-1000 nm	400-600 nm	400-706 nm	A, A+ AA, AAA
Bandpass transmits	425 to 600 nm	600 to 850 nm	706 to 1000 nm	AA, AAA
	425 to 600 nm			A+



1. Dichroic reflects bright guide light to LOWFS (similar to existing LOWFS masks)
2. A downstream filter stack performs band limiting of light passed through to IFS and imager.

Distances and angles

Starshade Range	3.00E+07	m	3.00E+04	km							
	Radial FOV				Distance at range				Pixels	Resolution	
WFC	225	arc sec	1.09E-03	radian	32725	m	32.72	km	4096	16.0	m
Navigation accuracy	280	arc sec	1.36E-03	radian	40724	m	40.72	km			
DI	2.8	arc sec	1.36E-05	radian	407	m	0.407	km	512	1.6	m
LOWFS	0.056	arc sec	2.71E-07	radian	8.1	m	0.008	km	16		
WFIRST Jitter	0.015	arc sec	7.27E-08	radian	2.2	m	0.002	km			
Science alignment	0.007	arc sec	3.39E-08	radian	1.0	m	0.001	km			
900 nm PSF	0.098	arc sec	4.77E-07	radian	14.3	m	0.014	km			
WFC pixel	0.110	arc sec	5.33E-07	radian	16.0	m	0.016	km			
CCD gaps (2.5 mm)	27.5	arc sec	1.33E-04	radian	4000	m	X, Y1				
CCD gaps (8.5 mm)	93.5	arc sec	4.53E-04	radian	13599	m	Y2				