Jet Propulsion Laboratory
California Institute of Technology

EXOPLANET EXPLORATION PROGRAM ANALYSIS GROUP #9, National Harbor, MD

Exoplanet Exploration Program Update

Gary Blackwood, Exoplanet Exploration Program Manager
Jet Propulsion Laboratory, California Institute of Technology

January 4, 2014

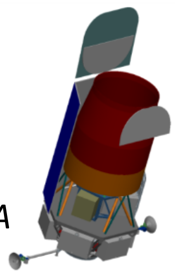
The Exoplanet Exploration Program: Exploring New Worlds

ExEP
ExoPlanet Exploration Program

***Exploring** How the Universe Works*
***Discovering** and Characterizing Exoplanets*
***Searching** for Signs of Life in the Galaxy*

Space Missions and Mission Studies

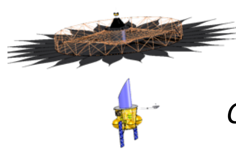
Kepler



AFTA

Probe-Scale:

External Occulter (Starshade)



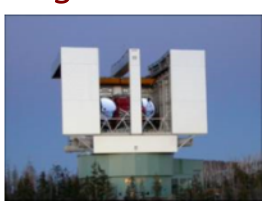
Coronagraph

Public Engagement

Supporting Research & Technology

Key Sustaining Research

Keck Single Aperture Imaging and RV



Large Binocular Telescope Interferometer

Technology Development

High Contrast Imaging

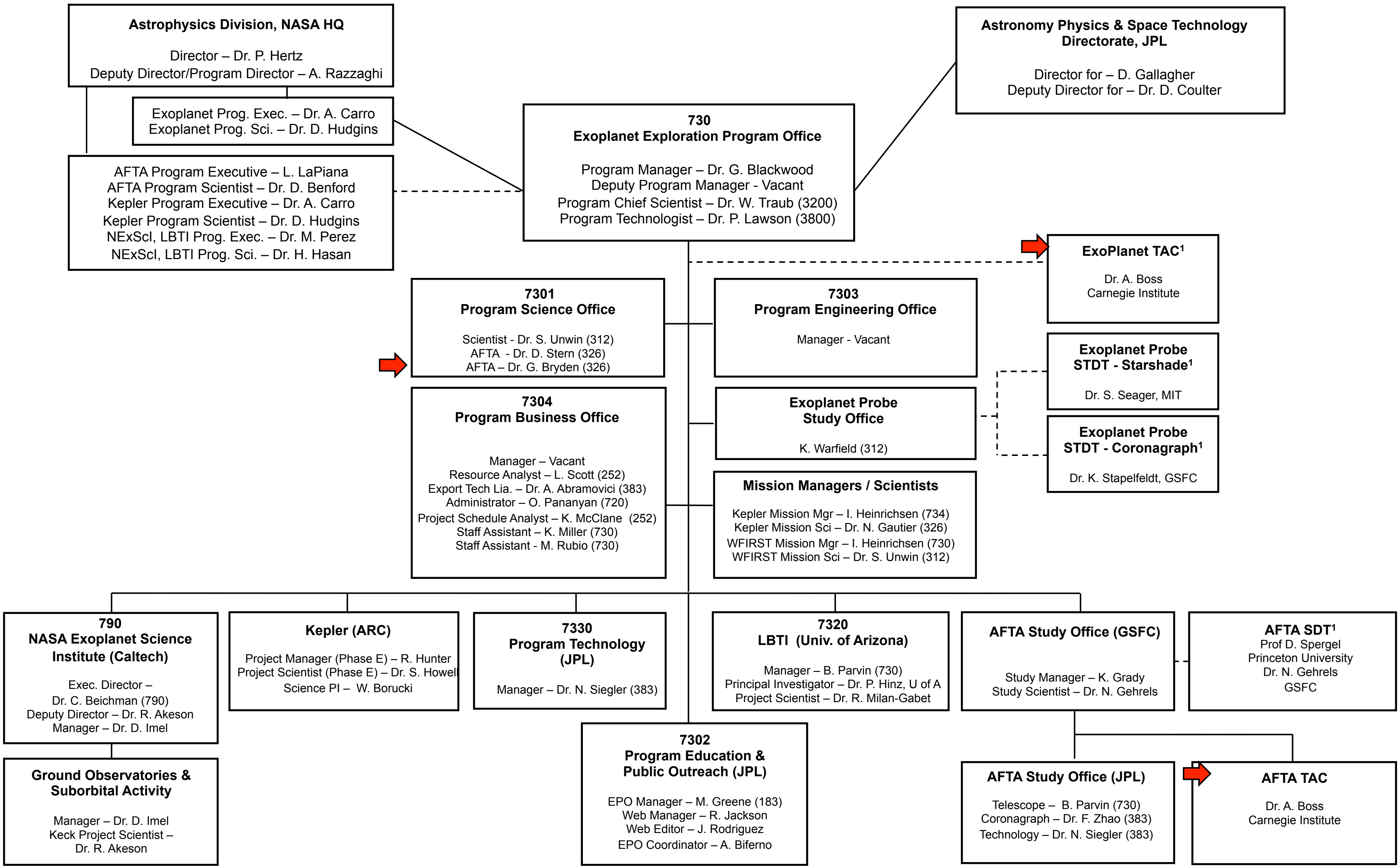
Deployable Star Shades

Archives, Tools & Professional Education

NASA Exoplanet Science Institute

Exoplanet Exploration Program Organization Chart

ExoPlanet Exploration Program



Jan 02 2014
G. Blackwood
Exoplanet Exploration Program

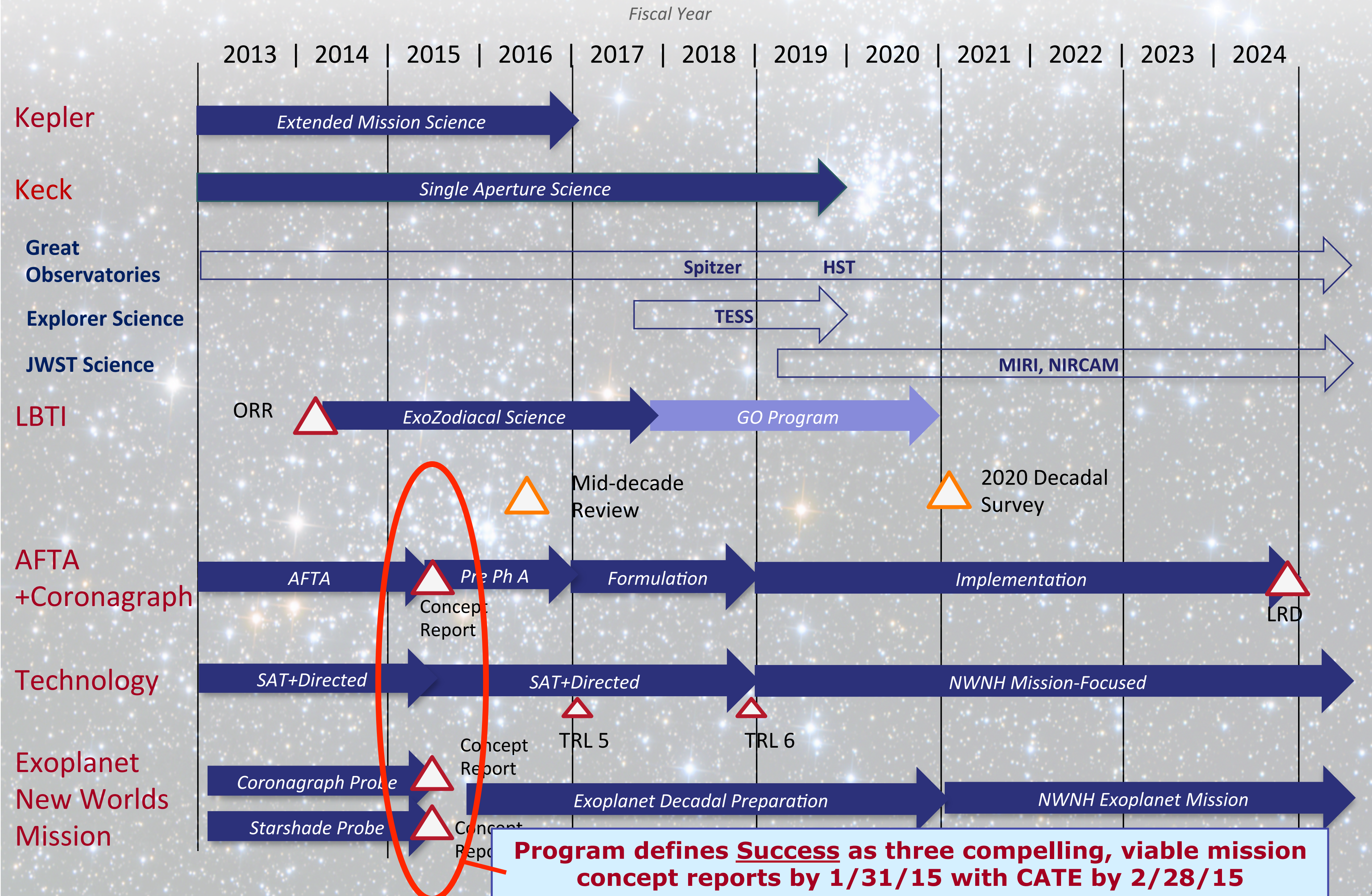
[1]Reports to HQs APD

Exoplanet Exploration: A Decade Horizon

NASA-sponsored efforts

ExEP

ExoPlanet Exploration Program

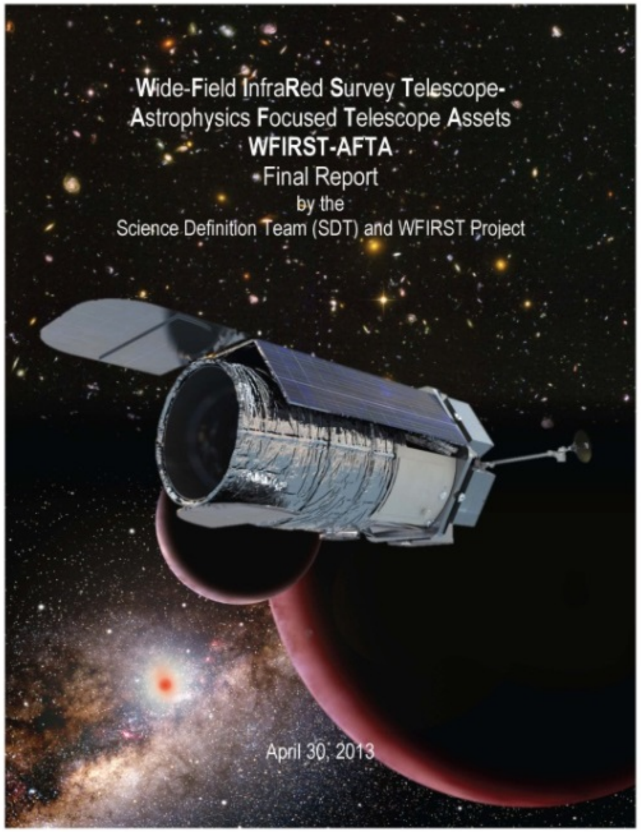


Recent Program Highlights

AFTA/ExEPO	Primary and Backup architecture selected, science yield estimated, STMD funding collaboration established
Kepler	Approved to submit two-wheel concept to Senior Review
LBTI	ORR delayed to March due to secondary failures (now recovered); closed loop fringe tracking and sequence demonstrated 12/30
Public Outreach	In discussion with National Air and Space Museum for "Eyes on Exoplanets" display
NExScI	Sagan workshop approved for July 2014 Major release of data content and tools, including Q1-16 Kepler TCEs Community Follow-up Program supported
Keck Single Aperture	2014A Keck Observing season allocated; will release OSIRIS instrument data in Keck Observatory Archive
Probe – Starshade, Coronagraph	Significant progress on mission concepts, technology prioritization, lifecycle cost estimates
Technology	PIAA coronagraph in HCIT-2 for broadband contrast tests Successful starshade deployment from stowed, furled configuration
Program Office	ExoTAC membership update same (5) as AFTA-TAC for coronagraph ExoCAT: new catalog of stars within 30 parsec to suppt simulations

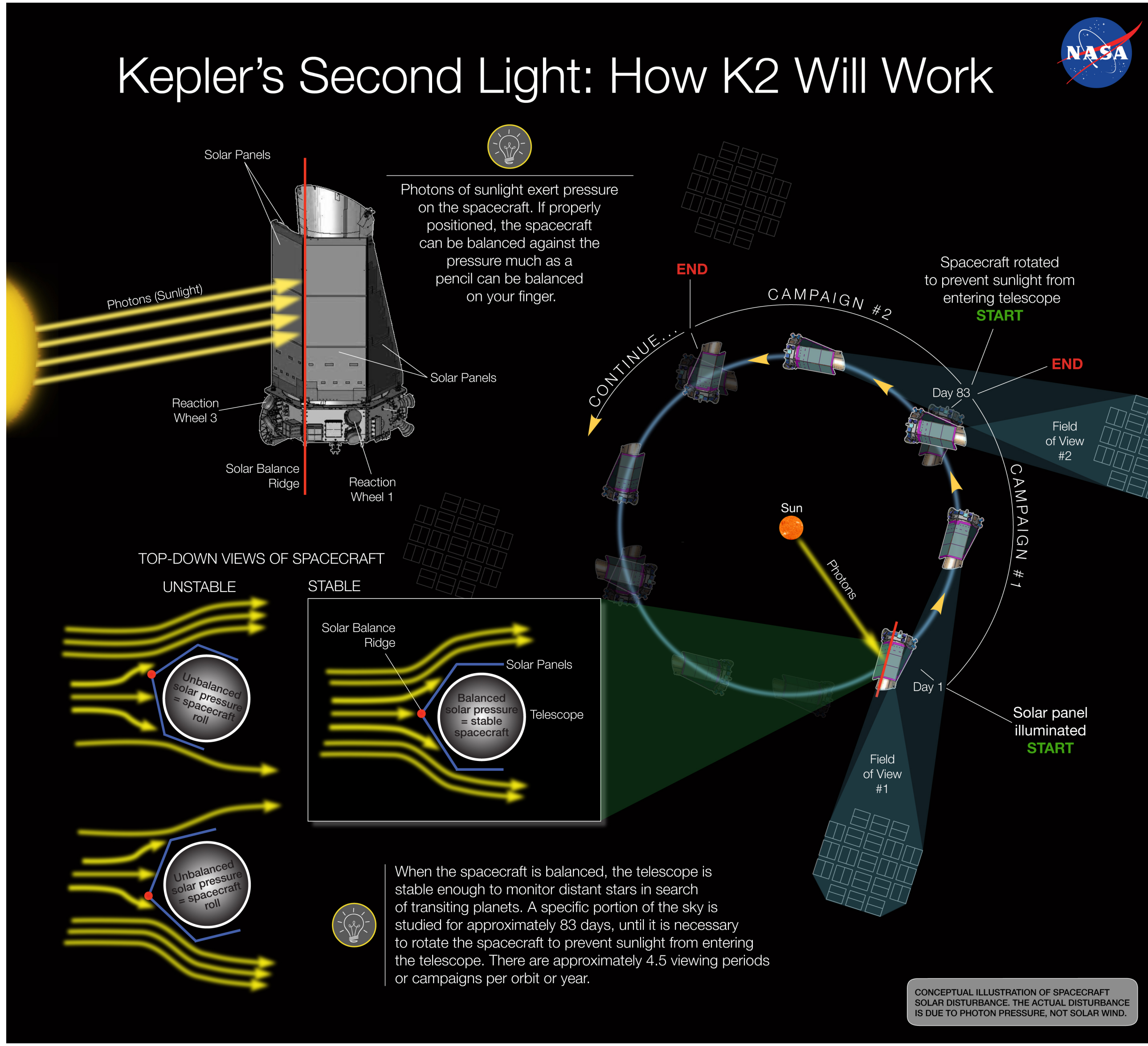
AFTA Coronagraph: Architecture Selection

- AFTA Coronagraph Working Group completed intensive workshops during July-Dec 2013
- 12/23: Coronagraph architectures selected for continued study:
  - Primary: Occulting Mask Coronagraph (OMC), single optical design incorporating both Hybrid Lyot (HL) and Shaped Pupil (SP) masks
  - Backup: Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAA-CMC)
- Observatory jitter analysis phased forward. Latest jitter estimates (lower) plus re-optimized HL permits detection of ~18 existing RV planets.
- Next steps on coronagraph:
  - Prepare milestones (1/31) and final tech plan (2/28)
  - Implement competed technology per plan (more than just masks)
- H4RG-10 detectors: 3 of 4 under test GSFC



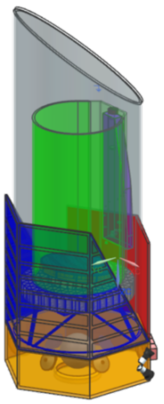
Kepler: Closeout Plan, and K2

- Closeout plan in preparation
- Engineering and science tests ongoing to fully characterize the two-wheel flight system
- Kepler invited by APD to the Senior Review, proposal due 1/28
- Kepler Science Conference II: "22% of sun-like stars harbor Earth-sized planets orbiting in their habitable zones", Petigura et al

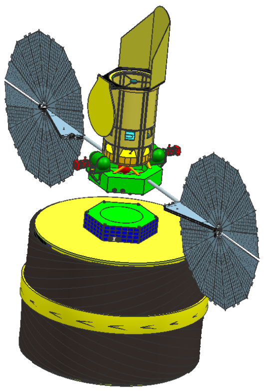


Probe-Scale Missions

- Trades well underway, preparation of interim report
- Initial Aerospace review of baseline concepts
- Science evaluations suggest compelling science
- Exo-C (Coronagraph)
  - Primary mirror 1.5m
  - Kepler-class telescope and spacecraft
  - Thermal and pointing architectures settled
  - Earth-trailing orbit
- Exo-S (Starshade)
  - Earth-leading orbit
  - Starshade stationary, telescope moves
  - Primary mirror 1.1m
- Technology gap lists and plans being prepared, prioritized

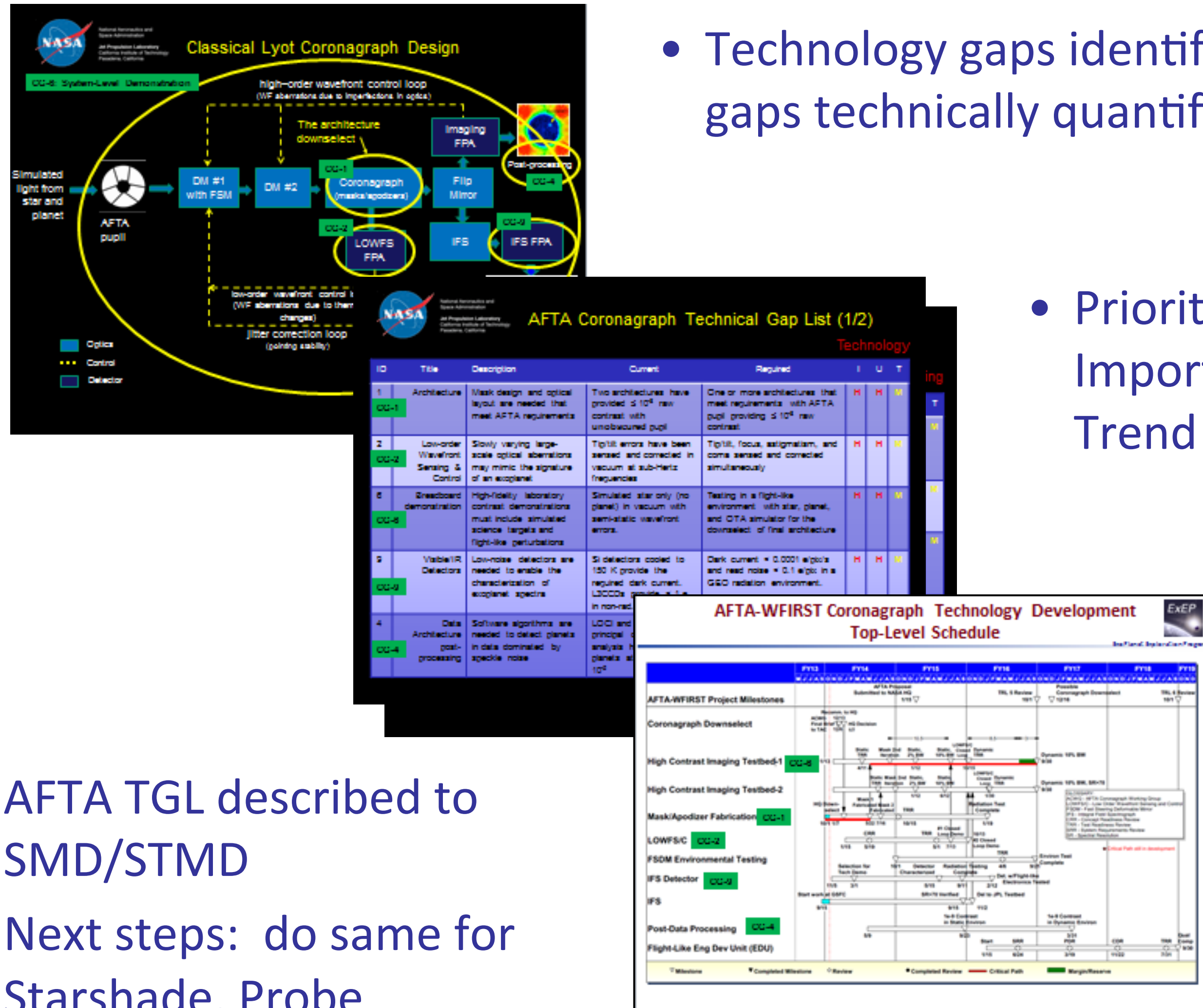


EXO-C



EXO-S

Prioritization: the Technology Gap List



- Technology gaps identified and described, gaps technically quantified
- Prioritized for relative Importance, Urgency, and Trend
- Plans created to retire the top priorities in time
- AFTA TGL described to SMD/STMD
- Next steps: do same for Starshade, Probe Coronagraph

Technology Gap Lists: Key Gaps

STARSHADE

ID	Title	Description
S-1	Control of Scattered Sunlight	Sunlight scattered from starshade edges and surfaces risks being the dominant source of measurement noise.
S-2	Starshade Deployment	Demonstrate that an starshade can be deployed to within the budgeted tolerances.
S-3	Validation of starshade optical models	Experimentally validate the equations that predict the contrasts achievable with a starshade
S-4	Thermal & Mechanical Dynamic Stability	The deployed tolerances must be maintained under typical observing conditions, including starshade rotation.
S-5	Formation Flying GN&C	Demonstrate that the GN&C system for an occulter will enable the required slew from star to star and positional stability for science observations.
S-6	Flight Performance System Modeling	Demonstrate using experimental data and validated thermo-mechanical and optical models that the full-scale flight occulter will achieve its baseline performance.

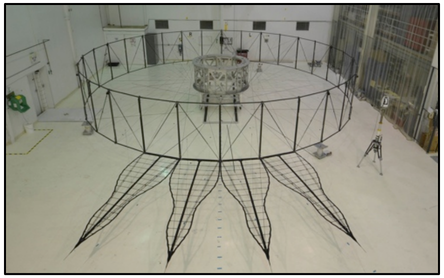
- Gap lists are work-in-progress by Probe STDTs, per their charter
- These program summaries will form basis of next Technology Plan Appendix, referenced by TDEM-13 call
- Intended Result: quality proposals that address the breadth of top priorities

See Lawson, AAS 2014, and upcoming Tech Plan Appendix

CORONAGRAPH

ID	Title	Description
C-1	Starlight suppression optics	Masks, apodizers, or beam-shaping optics to provide improved planet detection capability.
C-2	Low-order Wavefront Sensing & Control	Slowly varying large-scale optical aberrations may mimic the signature of an exoplanet.
C-3	Exoplanet detection under flight-like conditions	High-fidelity laboratory contrast demonstrations that include simulated science targets and flight-like perturbations.
C-4	Deformable mirrors	Maturation of deformable mirror technology to flight readiness.
C-5	Pointing Control System Design	Validation of pointing control design for instrument fine steering mirror and spacecraft body pointing.
C-6	Flight Performance System Modeling	Demonstrate using experimental data and validated thermo-mechanical and optical models that the full-scale flight coronagraph will achieve its baseline performance.

The ExEP Newsletter: 'NASA's New Worlds News'



ExEP's Newsletter, NASA's New Worlds News, was released on November 7th, and was delivered to 2,060 subscribers. Topics featured in this issue included Discovery channel filming of the starshade, direct detection mission concept studies, Kepler status, introductions to exoplanet fellows and their work, and the official release of Eyes on Exoplanets.

National Aeronautics and Space Administration

NASA's New Worlds News

The Exoplanet Exploration Program Newsletter

Issue 12 - October 2013

Click here for a printable PDF

HEADLINES

1. New Vision for Kepler
2. Direct Detection of Exoplanets: Mission Studies Are Underway
3. August Was a Month of "Discovery" for Starshade Technology
4. X-Ray Observations of Exoplanet Atmospheres
5. Finding Nearby Habitable Zone Exoplanets, Inexpensively
6. LBTI -The Monsoon Season Is Finally Over!
7. Science Update
8. Technology Update
9. Sagan Fellowship Call Goes Out
10. Bringing Strange New Worlds to Your Desktop

Genius Granted

Sara Seager
Professor of Planetary Science and Physics
Massachusetts Institute of Technology
2013 MacArthur Fellow

Program Update

Update from Gary Blackwood, NASA Exoplanet Exploration Program Manager

Director's Update

Message from Paul Hertz, NASA Astrophysics Division Director

1. New Vision for Kepler

By Steve Howell and Nick Gautier

In May 2013, the Kepler spacecraft suffered its second failure of a momentum wheel. Kepler uses momentum wheels to point itself accurately and stably to obtain the extremely precise brightness measurements of stars that have allowed the spacecraft to detect small planets around the target stars in its exoplanet survey. Kepler started its mission with four operational momentum wheels and requires three operational wheels to maintain stable pointing. With the failure of a second wheel on Kepler, the existing pointing-system software can no longer control the spacecraft as before, thus ending the ability to search for Earth-size planets orbiting Sun-like stars. For now, science data collection has stopped and the Kepler spacecraft has been placed in a fuel-efficient safe mode while we decide what to do next. Read More...

3,602 CANDIDATES 931 CONFIRMED 4,533 EXOPLANETS

EXOPLANETS IN THE NEWS

October 1, 2013
Mapping Distant Clouds
BBC, Time

August 19, 2013
A year in 8 hours or less
The Los Angeles Times, National Geographic, Fox News

August 16, 2013
Kepler's New Mission
Time, The New York Times

August 8, 2013
Hot Pink Planet
National Geographic, Huffington Post

July 11, 2013
Glass rain may give planet blue hue
BBC, Time

EVENTS

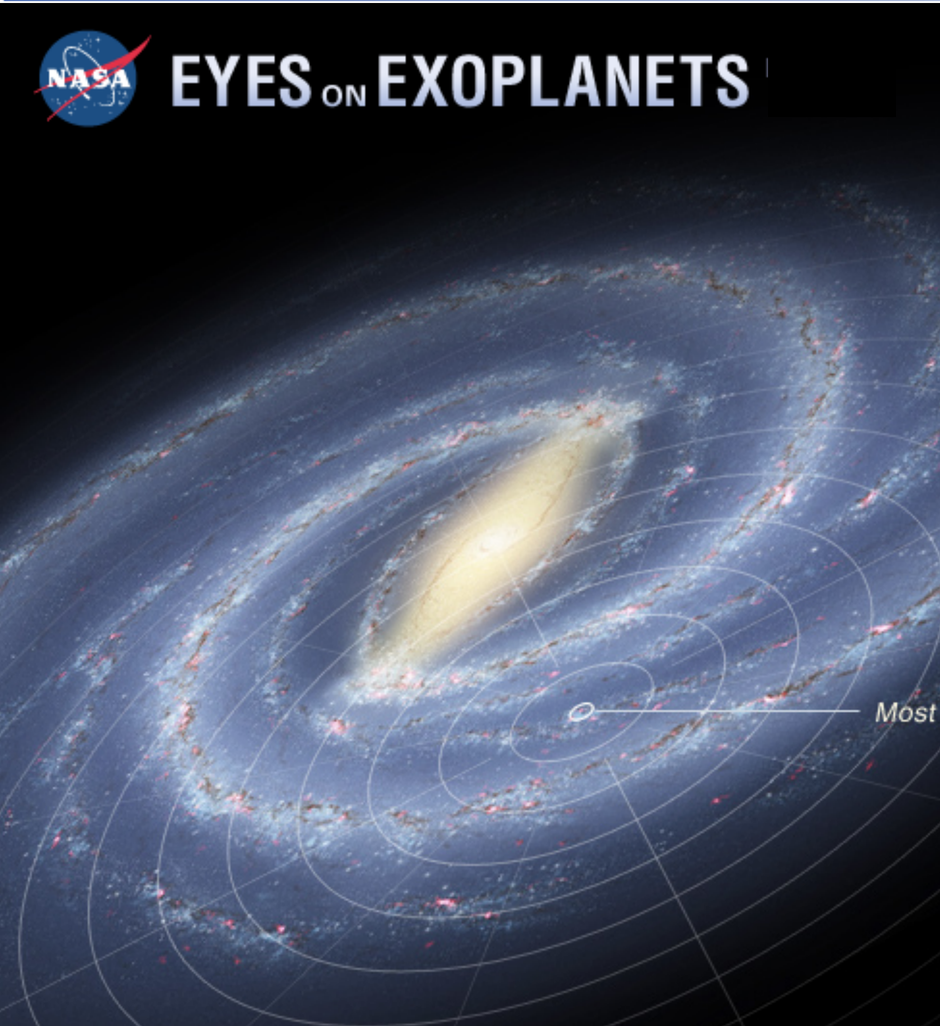
GSA's 125th Annual Meeting - October 27-30
Location: Denver, Colorado

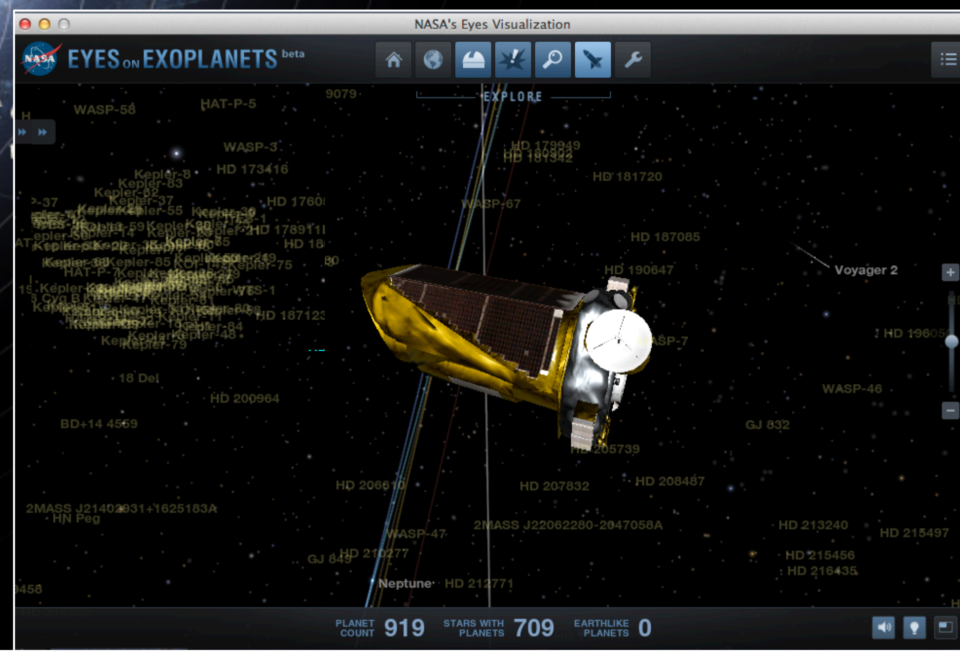
Second Kepler Science Conference - November 4-8
Location: NASA Ames Research Center, Moffett Field, CA

XIV Latin American Regional

http://exep.jpl.nasa.gov

‘Eyes on Exoplanets’
Kepler Candidates–Available November 2013





- All 3,600 candidate systems shown in FOV
- Each confirmed planet can be visited
- Continuously updated as planets are confirmed

Selected Upcoming Conferences and Workshops

- 1/7 223th AAS, Exoplanet Exploration Program Evening session
- 1/8 223th AAS, AFTA Evening session
- 1/9-10 AFTA SDT (National Harbor)
- 1/20-22: Microlensing 18, Santa Barbara

- 2/27-28 LOWFSC & PSF for Exoplanets, Caltech
- 3/17-21: Search for Life Beyond the Solar System: Exoplanets, Biomarkers and Instruments, UofA
- 4/28-5/1 Habitable Worlds Across Time and Space, STSCi
- 5/31-6/1 ExoPAG10, Boston
- 6/2-6 224th AAS Meeting – AFTA science conference, Boston
- 6/8-13 Gordon Research Conference on Image Science, Boston
- 6/22-27 SPIE Astronomical Telescopes and Instrumentation, Montreal
- 7/21-25 Sagan Workshop: Imaging Planets and Disks, Caltech

Looking Forward: Selected Milestones

AFTA/ExEPO	NRC Review of AFTA SDT report (start: 1/12)
Kepler	Submit two-wheel concept to Senior Review (1/28)
LBTI	Risk mitigation plan due 2/26; replan Operational Readiness Review Next commissioning run 2/6-14
NExScI	Sagan workshop registration opens mid-February "Imaging Planets and Disks"
Probe – Starshade, Coronagraph	Exo-S meets 1/28-29, Exo-C meets 2/3-5, Mid-term report and briefing to CAA 3/3
Technology	TDEM Pre-Proposal Telecon (updated Program Technology Plan Appendix 1/21 TDEM-13 proposals due 3/21

BACKUP: AFTA DOWNSELECT BRIEFING

Purpose and Approach

- **Objective:** Recommend a primary and backup coronagraph architecture to focus design and technology development to maximize readiness for new mission start in FY17
- Recommendation by ExEPO and ASO based on inputs from
  - **AFTA SDT:** Sets the science requirements
  - **ACWG:** Delivers technical FOMs and technology plans
    - > *Aim for the positive: a consensus product*
    - > SDT delivers science FOMs
  - **TAC:** Analysis of technical FOM, TRL readiness plans, and risks
- **ExEPO and ASO** recommendation to **APD Director** based on:
  - Technical and Programmatic criteria
  - Musts (Requirements), Wants (Goals), and Risks
  - Opportunities
- **APD Director** will make the decision

ACWG = AFTA Coronagraph Working Group: representatives of ExEPO, ASO, SDT, Community

Acronyms:
ExEPO: Exoplanet Expl. Prog. Office
ASO: AFTA Study Office
SDT: Science Definition Team
FOM: Figure of Merit
TRL: Technology Readiness Level

TAC: Technical Analysis Committee
Alan Boss (Carnegie Inst.)
Joe Pitman (EXSCI)
Steve Ridgway (NOAO)
Lisa Poyneer (LLNL)
Ben Oppenheimer (AMNH)

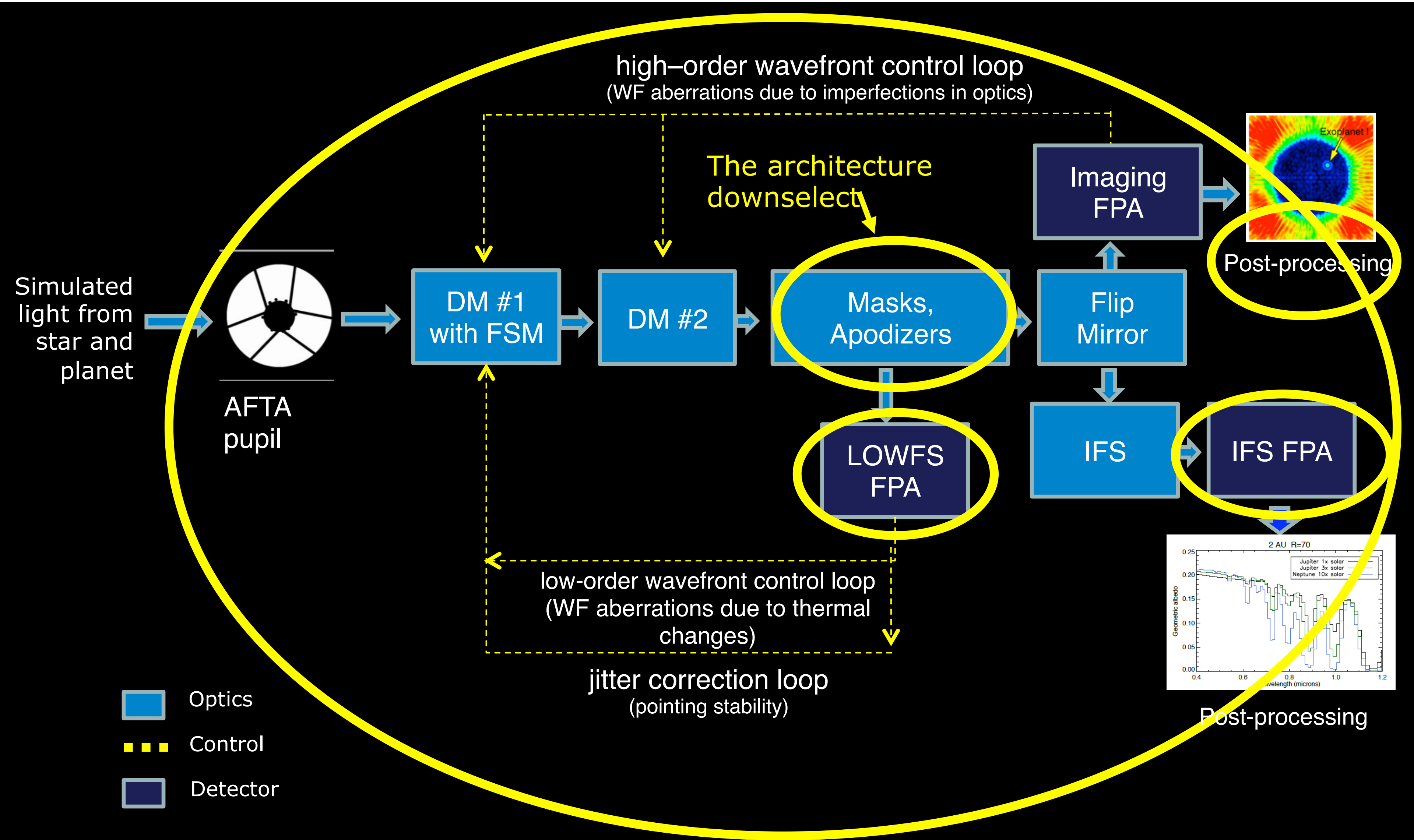
Gary Blackwood
Kevin Grady

Executive Summary

- **Intended Results of this Briefing:**
  - Provide Recommendation for Primary and Backup coronagraph architectures for AFTA
  - Request APD approval and announcement
- **Executive Summary:**
  - Community working group conducted an open, technical evaluation using public evaluation criteria in a series of workshops and telecons since July 2013
  - We reached a broad consensus on the basis for the recommendation
  - Three strong technologies emerged, spanning the risk/performance continuum
  - The independent Technical Analysis Committee (TAC) concurred with the basis and with findings of ACWG
  - <u>Recommendation:</u>
    - **Primary Architecture:** Occulting Mask Coronagraph (OMC) that includes masks for Shaped Pupil Coronagraph (SPC) and Hybrid Lyot Coronagraph (HLC)
    - **Backup Architecture:** Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)
  - Recommendation best minimizes risk, preserves options to protect the project schedule, advances technologies, and preserves possibilities of increased science yield
  - Plan for Recommendation to reach TRL 5 is feasible (technically) and credible within existing resources (schedule, cost)

Coronagraph Instrument: Several Technologies

Example: Classical Lyot Coronagraph Design



Evaluation Criteria:
Defining a Successful Outcome for AFTA

Decision Statement: Recommend one Primary and one Backup coronagraph *architecture* (option) to focus design and technology development

Description	Name		Weights	Option 1 SPC	Option 2 PIAACMC	Option 3 HLC	Option 4 VVC	Option 5 VNC - DA	Option 6 VNC - PO
Musts		Programmatic							
	M1 - T	Science: Meet Threshold requirements? (1.6, x10)							
	M2	Interfaces: Meets the DCIL**?							
	M3	TRL Gates: For baseline science is there a credible plan to meet TRL5 at start of FY17 and TRL6 at start of FY19 within available resources?							
	M4	Ready for 11/21 TAC briefing							
	M5	Architecture applicable to future earth-characterization missions							

✓ yes, or expected likely
? unknown
✕ no, or expected showstopper

Evaluation			Weights	SPC	PIAACMC	HLC	VVC	VNC-DA	VNC - PO
Wants									
	W1	Science	40						
	a	Relative Science yield (1.6, x10) beyond M1-T							
	W2	Technical	30						
	a	Relative demands on observatory (DCIL), except for jitter and thermal stability							
	b	Relative sensitivities of post-processing to low order aberrations							
	c	Demonstrated Performance in 10% Light							
	d	Relative complexity of design							
	e	Relative difficulty in alignment, calibration, ops							
	W3	Programmatic	30						
	a	Relative Cost of plans to meet TRL gates							
		Wt. sum =>	100%						

Identify "Best" and others are:
-Wash
-Small Difference
-Significant Difference
-Very Large Difference

Risks		(all judged to be Hgh consequence)	SPC C	SPC L	PIAACMC C	PIAACMC L	HLC C	HLC L	VVC C	VVC L	VNC-DA C	VNC-DA L	VNC - PO C	VNC - PO L
	Risk 1	Technical risk in meeting TRL5 gate												
	Risk 2	Schedule or Cost risk in meeting TRL5 Gate												
	Risk 3	Schedule or Cost risk in meeting TRL6 Gate												
	Risk 4	Risk of not meeting at least threshold science												
	Risk 5	Risk of mnfr tolerances not meeting BL science												
	Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt												
	Risk 7	Risk that wrong architecture is chosen due to any assumption made for practicality/simplicity												
	Risk 8	Risk that ACWG simulations (by JK and BM) overestimate the science yield due to model fidelity												

H M L

Opportunities		(judged to be High benefit)	SPC B	SPC L	PIAACMC B	PIAACMC L	HLC B	HLC L	VVC B	VVC L	VNC-DA B	VNC-DA L	VNC - PO B	VNC - PO L
	Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30												

H M L

Final Decision, Accounting for Risks and Opportunities:

C = Consequence, L = Likelihood, B=Benefit
**DCIL = Dave C C = Consequence, L = Likelihood, B=Benefit

➪ Indicates Sig. Discriminator

← **Science Threshold**

← **Science Beyond Threshold**

Where is Science Considered?

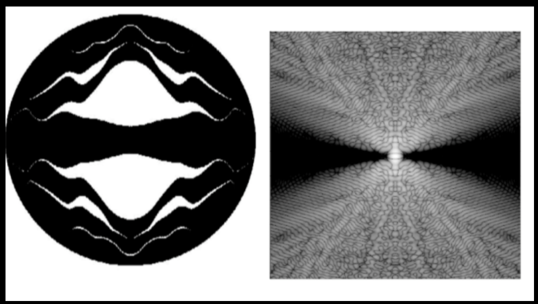
Where is Technology Plan and Risk Considered?

← **Risk of not meeting Threshold**

← **Oppty: Science if Jitter lower, Speckle subtraction better**

Coronagraph Mask Architectures

SPC



Pupil Masking (Kasdin, Princeton University)

HLC

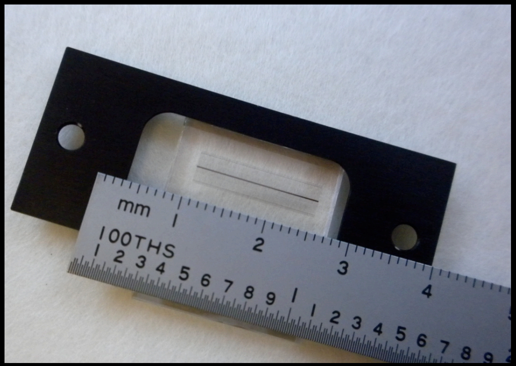
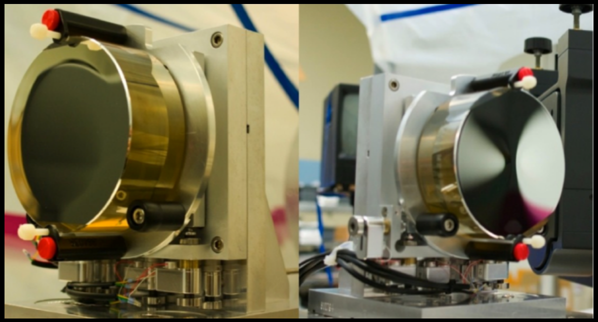


Image Plane Amplitude & Phase Mask (Trauger, JPL)

PIAACMC



Pupil Mapping (Guyon, Univ. Arizona)

VVC

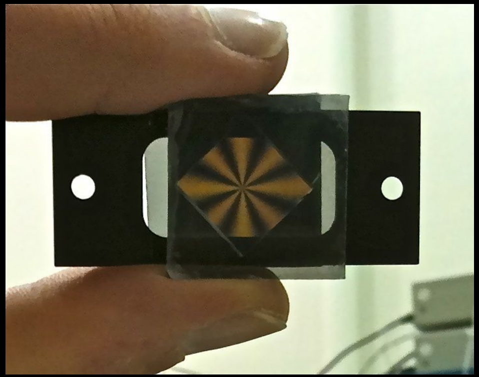
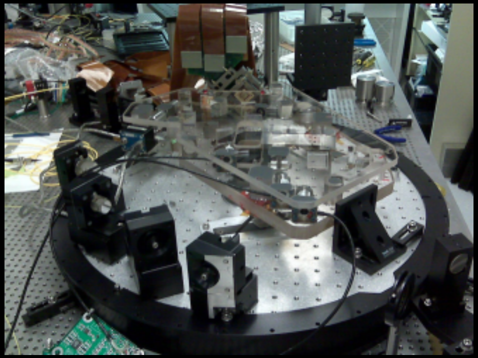


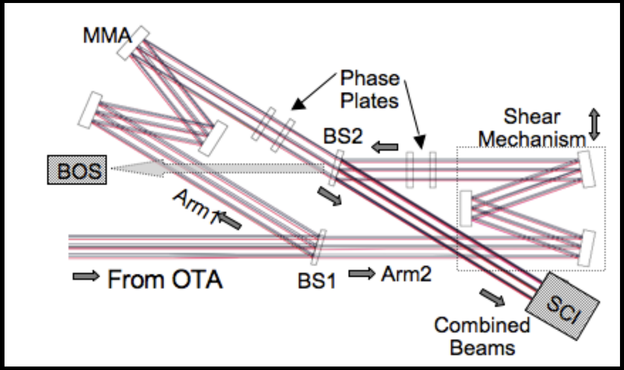
Image Plane Phase Mask (Serabyn, JPL)

VNC(2) - DAVINCI



Visible Nulller - DAVINCI (Shao, JPL)

VNC-PO



Visible Nuller – Phase Occulting (Clampin, NASA GSFC)

Results: Full Trade Matrix

ExoPlanet Exploration Program

Decision Statement: Recommend one Primary and one Backup coronagraph *architecture* (option) to focus design and technology development

Descr	Name		Weights	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Notes
				SPC	PIAACMC	HLC	VVC	VNC - DA	VNC - PO	
Musts		**Programmatic**								
	M1 - T	Science: Meet Threshold requirements? (1.6, x10)		Yes	Yes	Yes	No	No	U	
	M2	Interfaces: Meets the DCIL**?		Yes	Yes	Yes	Yes	Yes	U	
	M3	TRL Gates: For baseline science is there a credible plan to meet TRL5 at start of FY17 and TRL6 at start of FY19 within available resources?		Yes	Yes	Yes	U	No	U	
	M4	Ready for 11/21 TAC briefing		Yes	Yes	Yes	Yes	Yes	No	
	M5	Architecture applicable to future earth-characterization missions		Yes	Yes	Yes	Yes	Yes	U	
Wants			**Weights**	SPC	PIAACMC	HLC	VVC	VNC-DA	VNC - PO	
Evaluation	W1	**Science**	40							
	a	Relative Science yield (1.6, x10) beyond M1-T		Sm/Sig	Best	Sm/Sig	VL	VL		Range of opinions between "significant and small". For SPC and VNC2 the search area is ~3 times less than 360deg, and that was taken into acct in comparisons
	W2	**Technical**	30							
	a	Relative demands on observatory (DCIL), except for jitter and thermal stability		Best	Best	Best	Best	Small		
	b	Relative sensitivities of post-processing to low order aberrations		Best	Sig	Sig	VL	U		For n-lambda over D or different amplitudes the designs will have the same relative ranking
	c	Demonstrated Performance in 10% Light		Small	Sig	Best	Sig	VL		Demonstrated Performance (10%) and Prediction
	d	Relative complexity of design		Best	Small	Best	Small	Sig		
	e	Relative difficulty in alignment, calibration, ops		Best	Small	Best	Small	Sig/Sm		
	W3	**Programmatic**	30							
	a	Relative Cost of plans to meet TRL gates		Best	Small	Best	Sig	Sig		
		Wt. sum =>	100%							

yes, or expected likely	unknown	no, or expected showstopper
✓	?	✗

Identify "Best" and others are:
- -Wash
- -Small Difference
- -Significant Difference
- -Very Large Difference

Risks	(all judged to be Hgh consequence)	SPC (C)	SPC (L)	PIAACMC (C)	PIAACMC (L)	HLC (C)	HLC (L)	VVC (C)	VVC (L)	VNC-DA (C)	VNC-DA (L)	VNC - PO (C)	VNC - PO (L)	Notes
Risk 1	Technical risk in meeting TRL5 gate		L		M		M/L		M/H		H			PIAA trend over the last three working days lower, but recommendation to keep M
Risk 2	Schedule or Cost risk in meeting TRL5 Gate		L		M		M/L		M/H		H			
Risk 3	Schedule or Cost risk in meeting TRL6 Gate		L		L		L		M		M			
Risk 4	Risk of not meeting at least threshold science		L		L		L		H		H			
Risk 5	Risk of mnfr tolerances not meeting BL science		L		L		L		M/L		H			One dissent, previous TDEM performance track record and Bala's assessment should be taken into account.
Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt		L		M/H		M		M/H		M			
Risk 7	Risk that wrong architecture is chosen due to any assumption made for practicality/simplicity	open ended question, spawned evaluations on Risk 5, Risk 6, Risk 8, and Oppty 1												
Risk 8	Risk that ACWG simulations (by JK and BM) overestimate the science yield due to model fidelity	discussed; not enough understanding at this time to make an evaluation.												Model validation is a risk that needs to be evaluated in the future

Opportunities	(judged to be High benefit)	SPC (B)	SPC (L)	PIAACMC (B)	PIAACMC (L)	HLC (B)	HLC (L)	VVC (B)	VVC (L)	VNC-DA (B)	VNC-DA (L)	VNC - PO (B)	VNC - PO (L)
Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30		L		M/H		M		L		H		

Final Decision, Accounting for Risks and Opportunities:

C = Consequence, L = Likelihood, B=Benefit

**DCIL = Dave Content Interface List

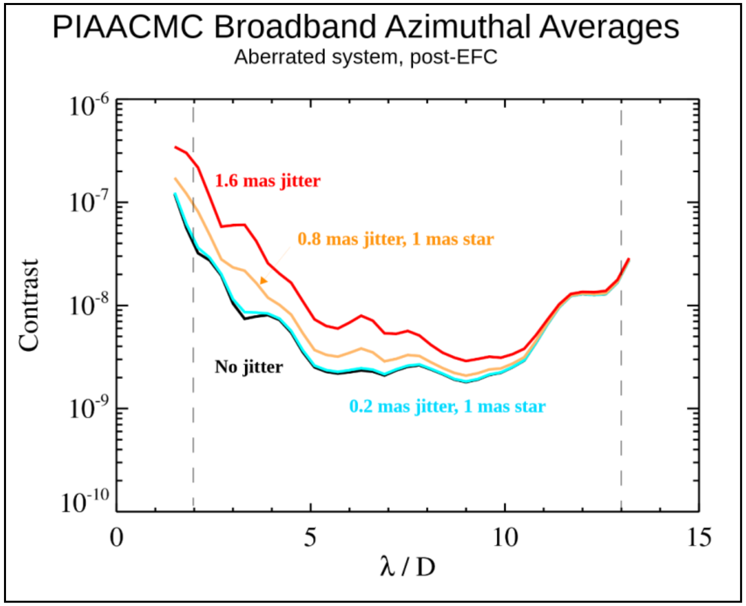
Yellow: indicates those few areas where consensus was not achieved

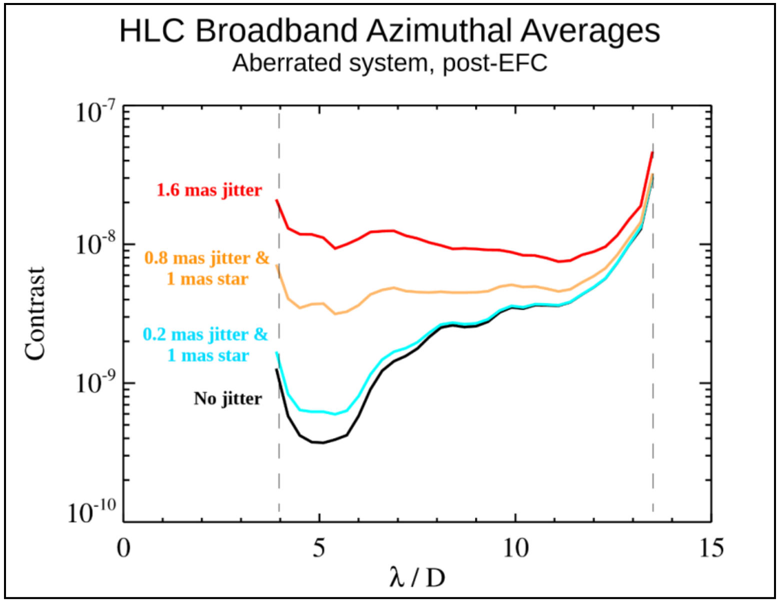
White: consensus achieved on balance of matrix

➪ Indicates Sig. Discriminator in ACWG discussion

- Scores entered as group
- Consensus sought but not required; no dissent received
- Consensus reached after ~24 hours of group discussion on all points but those indicated in yellow
- Other colors for evaluation added afterwards for presentation clarity

Intermediate Result: Performance Sensitivity to Jitter (examples)





- Dark Hole contrast improves with decreasing jitter
- Technologies have different sensitivities:
  - Strong sensitivity to jitter:
    - PIAACMC (shown)
    - HLC (shown)
    - VVC
    - VNC
  - Insensitive to jitter:
    - SPC (not shown)
- Results shown are for simple "opportunity" evaluation
- To fully realize yield of lower jitter, masks must undergo another design cycle at the lower jitter number

Results (Opportunity): Greater Science Yield for Lower Jitter, Greater Speckle Suppression

- Revisit Opportunity Science:

Colors indicate pass/fail vs Threshold

Values indicate the Science Want "Beyond the Must" for Design Point (1.6mas, x10)

M1-T

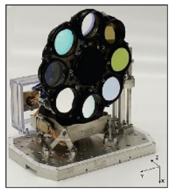
Threshold	@1.6mas, x10	Value	SPC	PIAA	HLC
1	**Wavelength:** 430-980 nm, 10% bandpass, pol.		yes	yes	yes
2	**Outer Disk:** 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	6 (E-9)	5	6	5
3	**Gas Giant Detection:** Depth>10 for 4-14 RE	10	10	11	12
	550 nm photometry of doppler planets		1	3	0
Oppty	@ 0.2mas, x30	**Value**	**SPC**	**PIAA**	**HLC**
2	**Outer Disk:** 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	<6 (E-9)	2	0.4	0.6
5	**HZ Disk:** 10 zodi@1AU = 10e-9@ 130mas @450 nm	< 10 (E-9)	n/a	10	10
3	**Gas Giant Detection:** Depth>10 for 4-14 RE	>10	23	43	14
	550 nm photometry of doppler planets		8	31	15
4	**Gas Giant Spectrum:** Doppler planets at 550nm, 2 months	Max	1	12	5
6	**Ice Giant Detection:** Depth >2 for < 4RE	>2	0.4	3	3.6

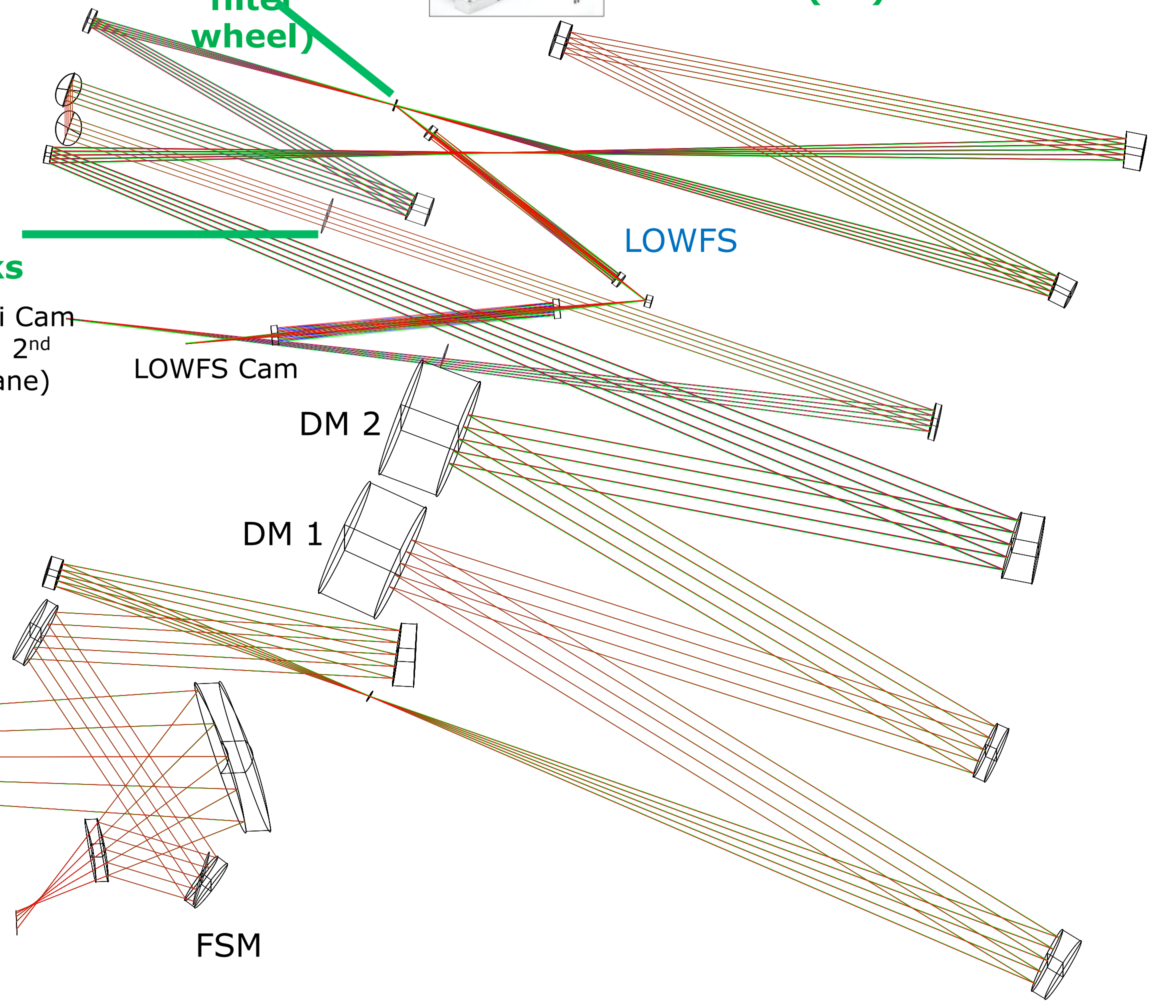
3 leaders have different science strengths

Can we choose a primary architecture that plays to combined strengths?

Colors indicate degree of Science Benefit for Oppty (0.2mas, x30)

OMC:
SPC + HLC Instrument Layout





Components	SPC +HLC	HLC	SPC
Coronagraph parabolas	4	2	4
Coronagraph flat optics	4	2	4
Coronagraph FP masks (SP: 19, HL: 6)	25	6	19
Coronagraph Lyot masks (HL: 6, SP: 1 - open)	7	6	0
Shaped pupil masks (SP: 4, HL: 1-mirror)	5	0	4
Filter wheel mechanisms	4	3	3

Low increase in overall complexity to include both SPC and HLC masks

Technology Plan Overview (Preliminary)

Planning Baseline:

HCIT1: Primary Design

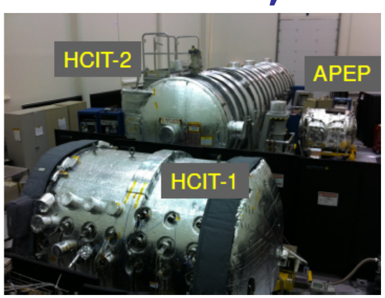
4/14 — Static Test — 8/15 LOWFS/C #1 — Dynamic Test — 9/16 TRL-5

HCIT2: Backup Design

7/14 — Static Test — 10/15 LOWFS/C #2 — Dynamic Test — 9/16 TRL-5 (goal)

Option 7 Fits the Schedule:

HCIT1: HLC, SPC



Primary: 4/14 — HLC Static Test — 8/15 LOWFS/C #1 — HLC+SP Dynamic Test (closed loop) — 9/16 TRL-5

HCIT2: SP, PIAA

Backup: 1/14 PIAA — 3/14 — SP Static Test — 8/14 — 6/15 — PIAA Static Test and dynamics test (open loop) — 9/16 TRL-5 (goal)

PIAA TDEM refocused on AFTA-relevant work

48x48 DMs

Backup does not include 2nd LOWFSC for closed Loop dynamics. Could be added to reduce risk

Final Trade Evaluation considering OMC=Option 7

Decision Statement: Recommend one Primary and one Backup coronagraph *architecture* (option) to focus design

Descr		Name		Option 7 OMC	Option 1 SPC	Option 2 PIAACMC	Option 3 HLC
Musts		Programmatic		Yes	Yes	Yes	Yes
Wants			**Weight**	**ABC**	**SPC**	**PIAACMC**	**HLC**
Evaluation	W1	Science	40				
	a	Relative Science yield (1.6, x10) beyond M1-T		Sm/Sig	Sm/Sig	Best	Sm/Sig
	W2	Technical	30				
	a	Relative demands on observatory (DCIL), except for jitter and thermal stability		Wash	Best	Best	Best
	b	Relative sensitivities of post-processing to low order aberrations		Best	Best	Sig	Sig
	c	Demonstrated Performance in 10% Light		Best	Small	Sig	Best
	d	Relative complexity of design		Best	Best	Small	Best
	e	Relative difficulty in alignment, calibration, ops		Best	Best	Small	Best
	W3	Programmatic	30				
	a	Relative Cost of plans to meet TRL gates		Small	Best	Small	Best
		Wt. sum =>	100%				

Risks	(all judged to be Hgh consequence)	ABC C	ABC L	SPC C	SPC L	PIAACMC C	PIAACMC L	HLC C	HLC L
Risk 1	Technical risk in meeting TRL5 gate		L		L		M		M/L
Risk 2	Schedule or Cost risk in meeting TRL5 Gate		L		L		M		M/L
Risk 3	Schedule or Cost risk in meeting TRL6 Gate		L		L		L		L
Risk 4	Risk of not meeting at least threshold science		L		L		L		L
Risk 5	Risk of mnfr tolerances not meeting BL science		L		L		L		L
Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt		L		L		M/H		M

Opportunities	(judged to be High benefit)	ABC B	ABC L	SPC B	SPC L	PIAACMC B	PIAACMC L	HLC B	HLC L
Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30		M		L		M/H		M

Primary (Option 7 OMC) **Backup** (Option 2 PIAACMC)

- Define OMC = Occulting Mask Coronagraph
- Includes SPC+HL masks on different filter wheels
- OMC emerges as strongest candidate for Primary Architecture
- PIAACMC emerges as the candidate for the Backup Architecture

Gary Blackwood
Kevin Grady

Recommendation

- Summary Observation:
  - *Three leading technologies, all with different strengths and weaknesses, all will benefit from further design optimization cycles and high contrast lab testing.*
- Recommendation: Primary Architecture - **Occulting Mask Coronagraph (OMC)** and Back-up Architecture – **PIAACMC**
- Assumptions:
  - Plan is to mature both Primary and Backup architecture technologies. The OMC primary includes both HL and SP masks in a single optical design, and the current thinking is that we would fly both masks.
  - If programmatic, technical or scientific factors suggest off-ramping of one approach is appropriate (either part of the primary or the backup), the project will implement that, to maximize performance and minimize risk going forward.
  - HCIT testbeds will be utilized to exploit their maximum utilization based on the availability of hardware and the benefit to the project.
- Benefits:
  - OMC in its "SP mode" provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and "use-as-is" telescope. This translates to low cost/schedule risk and a design that has a high probability to pass thru the CATE process.
  - In its "HL mode", the OMC affords the potential for greater science, however the increased risk is mitigated by the SP safety net.
  - PIAACMC offers the possibility of even greater science and at greater complexity. Hardware demonstrations and more detailed analyses are necessary to substantiate projected performance.
  - Taken together, the primary & backup architectures afford numerous "built-in descopes" and/or opportunities to accept greater risk due to the diversity of the approach.

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