Jet Propulsion Laboratory
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Choosing the Future: The Kepner-Tregoe Matrix for Complex Trades

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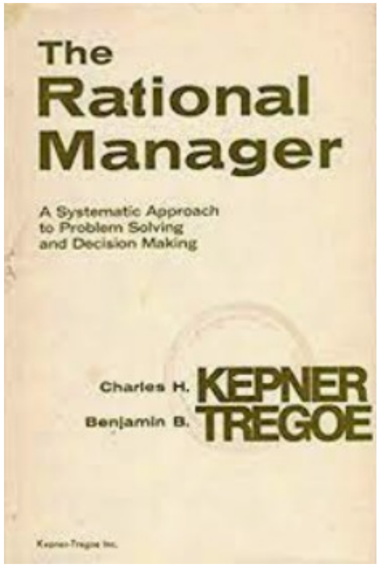
Introduction

- Technology roadmaps and precursor science require, or will lead to, decision points (onramps, offramps) to prioritize, include or close out investments.
- Technical leaders and management will be faced with difficult decisions (trades) to make.
- There are many different methodologies to making decisions (**performing trades**) - I'd like to share one technique that was developed in the 1950s by the Rand Corporation. It's called the **Kepner-Tregoe Matrix** and I and others have been using it to help APD make important decisions for over 10 years.
- The technique is very **transparent, thorough, objective, creative,** and **inclusive.** Facilitates **consensus.**
- Additionally, the technique can be **initiated early** to **open a trade space** and motivate risk reduction, while allowing a **later trade closure.**



Decision Statement									
Description				Option 1		Option 2		Option 3	
	Feature 1								
	Feature 2								
	Feature 3								
Evaluation	Musts								
	M1			✓		✓		✓	
	M2			✓		?		?	
	M3			✓		✓		✗	
	Wants	Weights							
	W1	w1%		Rel score		Rel score		Rel score	
	W2	w2%		Rel score		Rel score		Rel score	
	W3	w3%		Rel score		Rel score		Rel score	
		100%	Wt sum =>	Score 1		Score 2		Score 3	
Risks				C	L	C	L	C	L
	Risk 1			M	L	M	L		
	Risk 2			H	H	M	M		
Final Decision, Accounting for Risks									
				C = Consequence, L = Likelihood					

Trade (Decision) Process: Why, What, and How

- **Why** have a trade (decision) process?
- Lots of ways to make decisions (autocratic, democratic, consensus, list of pros-and-cons, running simulations, multi-vote), and many methods to choose from
- One familiar example:

A

B

<u>May work for:</u>

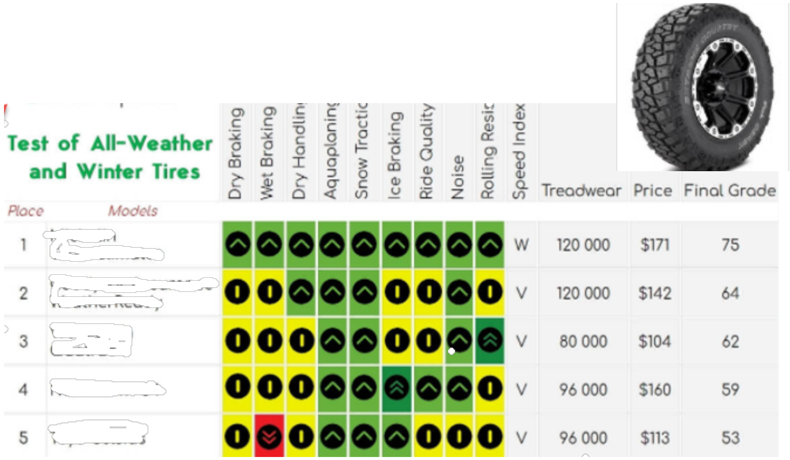
- Simple or low-stakes trades
- Y/N or Either/Or
- Where outcome is known a priori
- Selling an outcome
- Summarizing a valid trade process

<u>Disadvantages:</u>

- Hard to see absolute strengths and weaknesses
- Hard to see all relevant criteria and relative importance
- Harder to account for risks (and opportunities)
- Hard to infer the “basis” for the trade (thoroughness)
- As presented, doesn’t admit other options (creativity)
- Thus not suited for complex trades with high stakes

Trade (Decision) Process: Why, What, and How

- Another familiar example:



Test of All-Weather and Winter Tires

Place	Models	Dry Braking	Wet Braking	Dry Handlin	Aquaplaning	Snow Tractio	Ice Braking	Ride Quality	Noise	Rolling Resis	Speed Index	Treadwear	Price	Final Grade
1											W	120 000	$171	75
2											V	120 000	$142	64
3											V	80 000	$104	62
4											V	96 000	$160	59
5											V	96 000	$113	53

Example of structured, rational trade process

May work well when:

- There are multiple criteria
- There are many options
- Evaluation is complex
- The outcome is not prescribed a priori – creativity accepted or needed
- Stakeholders need transparency

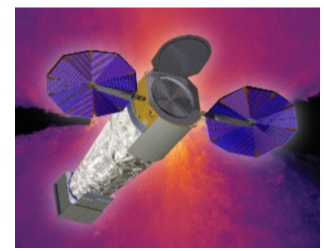
Structured trade process useful when:

- A decision has to be made (including leaving options open)
- The stakes are high
- The decision needs to stick (consensus is important, need buy-in)
- Requires figures-of-merit determined by analysis, simulations
- The decision will be revisited when new information is available
- Significant uncertainty or risks prevail
- **Transparency, thoroughness, objectivity, creativity,** and **inclusion** are important

A Useful Trade Process for our Applications

- I can show you one process that has worked well in similar technology / concept trade applications:

- Roman CGI coronagraph architecture
- Starshade Working Group
- Extreme Precision Radial Velocity
- Origins Concept
- HabEx Concept
- Lynx Concept
- in-Space Assembled Telescopes
- Deformable Mirror Survey
- Purchasing a home in LA…



- It is very easy to set up in use in your applications!

Decision (Trade) Process

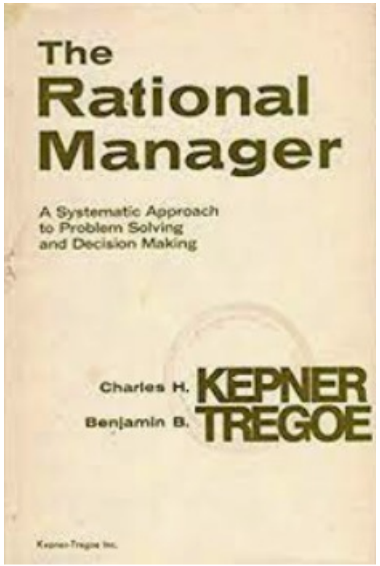
- Decision Process is a bit like a recipe:
  - It has a "best format" (ingredients) - the “what”
  - It has "best practices" (steps to follow) - the “how”
- In this case, it's ~1 part Excel matrix (“what”) and ~3 parts best practices (“how” you do it)
- Like any recipe one can improvise and take shortcuts, (within some limits)

THE WHAT

Best Format

Best format is the **Kepner-Tregoe method** for rational decision making

- Fundamentally one page, allows
  - Creativity (development of new options, alternatives)
  - Transparency
  - Inclusion
  - Objectivity (Quantitative)
  - Consensus
  - Re-visitation when new information is available
- Developed in the 1950's – developed by Rand Corporation
- I learned at a UCLA Extension 3-day course



Decision Statement									
Description				Option 1		Option 2		Option 3	
	Feature 1								
	Feature 2								
	Feature 3								
Evaluation	**Musts**								
	M1			✔		✔		✔	
	M2			✔		?		?	
	M3			✔		✔		✕	
	Wants	Weights							
	W1	w1%		Rel score		Rel score		Rel score	
	W2	w2%		Rel score		Rel score		Rel score	
	W3	w3%		Rel score		Rel score		Rel score	
		100%	Wt sum =>	Score 1		Score 2		Score 3	
	Risks			C	L	C	L	C	L
	Risk 1			M	L	M	L		
	Risk 2			H	H	M	M		
Final Decision, Accounting for Risks									
				C = Consequence, L = Likelihood					

Context for K-T Trade Method

- Adapted from Kepner-Tregoe methods. The Rational Manager, Kepner and Tregoe, 1965
- A systematic approach for decision making.

Decision Statement									
Description				*Option 1*		*Option 2*		*Option 3*	
	Feature 1								
	Feature 2								
	Feature 3								
Evaluation	**Musts**								
	M1			✓		✓		✓	
	M2			✓		?		?	
	M3			✓		✓		✗	
	Wants	*Weights*							
	W1	*w1%*		*Rel score*		*Rel score*			
	W2	*w2%*		*Rel score*		*Rel score*			
	W3	*w3%*		*Rel score*		*Rel score*			
		100%	Wt sum =>	*Score 1*		*Score 2*			
Risks				C	L	C	L	C	L
	Risk 1			M	L	M	L		
	Risk 2			H	H	M	M		
Final Decision, Accounting for Risks									
				C = Consequence, L = Likelihood					

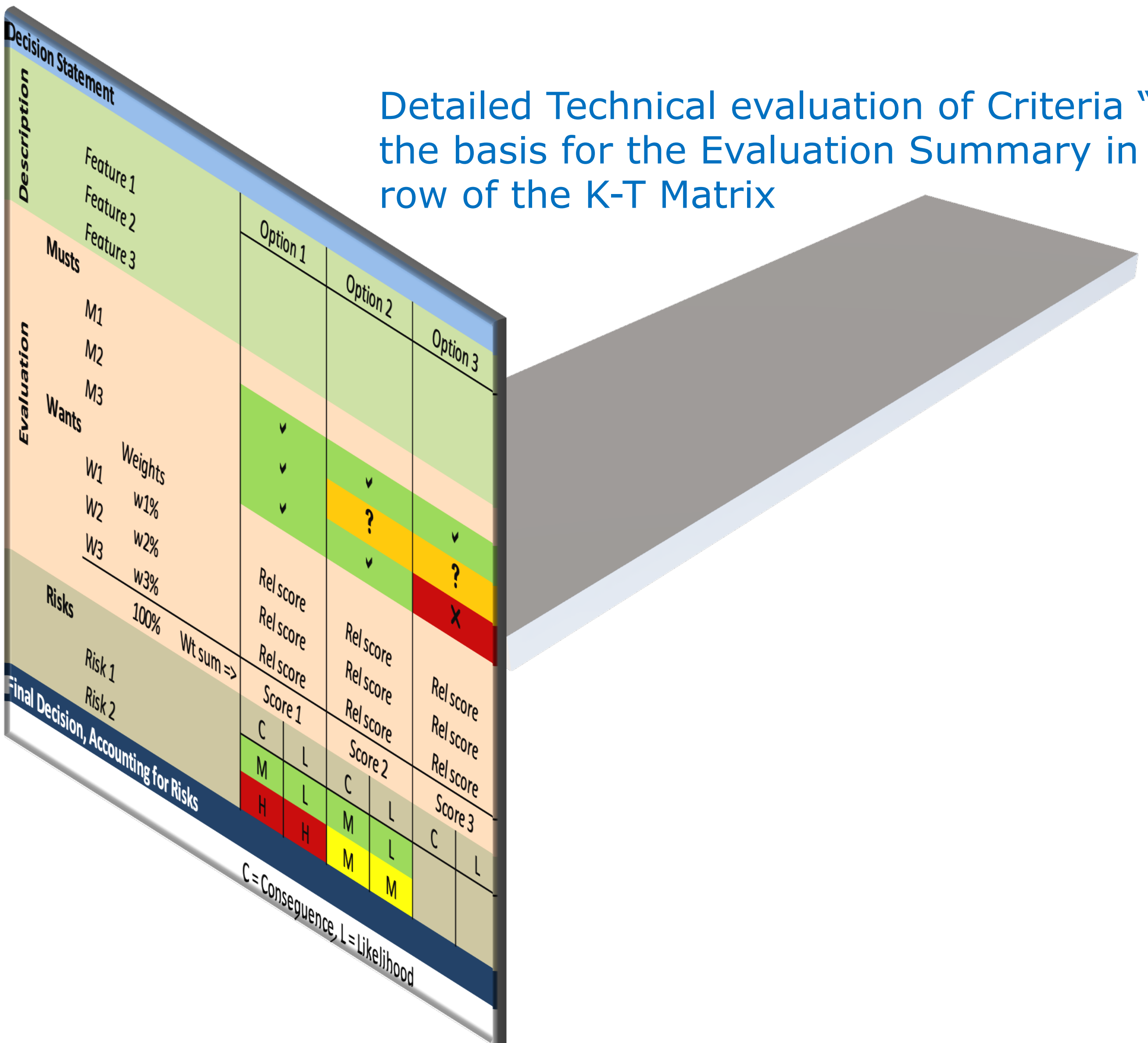
K-T Trade Method

Decision Statement

1. **Decision Statement:** raises or lowers the scope of the decision
2. **Criteria: Musts and Wants.** Sets viability, then preference
3. Assign **Weights** to Wants
4. Describe **Options**
5. **Screen** Options **vs Musts**
6. **Evaluate** Options vs **Wants**
7. Calculate **Weighted Sum**
8. Evaluate **Risks**
9. (Evaluate **Opportunities**)
10. **Final Decision, Accounting for Risks and Opportunities**

But What about Technical Rigor?

Detailed Technical evaluation of Criteria “can be” the basis for the Evaluation Summary in each row of the K-T Matrix



Musts, Wants, and Risks & Opportunities

- Typically categorize into

  Science (e.g. beyond state of the ground at launch)

  Technical (e.g. TRL by TBD NASA Key Decision Point)

  Schedule (e.g. launch by TBD date)

  Cost (e.g. likely target cost box)

- **Musts** relate to threshold, **Wants** can include “reflected Musts” (ie, go beyond the Must). Examples:
  - Must: characterize at least ~25 Hab-zone Earths, or,
  - Want: maximize # characterizations
- **Musts** are go/no_go, **Wants** are relative and weighted
- **Risks/Opportunities** are handled, but separately, as in, would the answer change if this risk (or opportunity) came true?
  - Example: would architecture change if the frequency of exo-earths was 3x lower or higher than assumed?

A Relevant Example

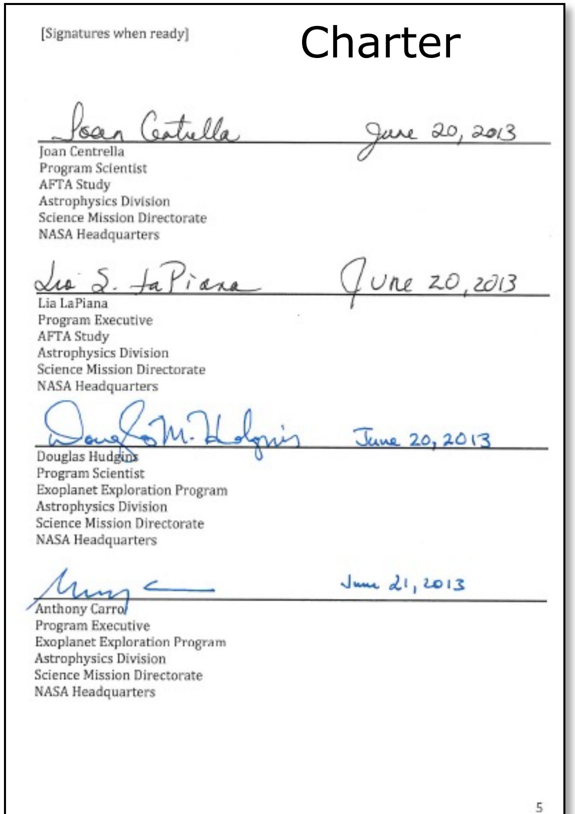
- AFTA Coronagraph Working Group
  AFTA => WFIRST => Roman CGI

  - Final presentation: follow link at bottom this page
    - http://exep.jpl.nasa.gov/presentations/

    http://wfirst.gsfc.nasa.gov/science/AFTA_Coronagraph_Arch_Selection/Coronagraph_Downselect_Rec_Dec13_2013.pdf

ACWG Membership

- These represent Program, Study Office, SDT, and Community:


[Signatures when ready]

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5

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Trade Criteria: Defining a Successful Outcome

DECISION STATEMENT: Recommend a primary and backup coronagraph architecture (option) to focus design and technology investments

MUSTS (Requirements): ***Go/No_Go***

1. Science: Does the proposed architecture meet the threshold science drivers?
2. Interfaces: For the threshold science, does the architecture meet telescope and spacecraft requirements of the observatory as specified by the AFTA project (DCIL[1])
3. Technology Readiness Level (TRL) Gates: For threshold science, is there a credible plan to be at TRL5 at start of FY17 and at TRL6 at start of FY19 within available resources?
4. Is the option ready in time for this selection process?
5. Is the architecture applicable to future earth-characterization missions (no showstoppers)?

WANTS (Goals): ***Relative to each other, for those that pass the Musts:***

1. Science: Relative strength of science beyond the threshold
2. Technical: Relative technical criteria
   - See details
3. Programmatic: Relative cost of plan to meet TRL Gates

RISKS and OPPORTUNITIES – scored as H,M,L

[1]DCIL = Dave Content Interface List

Evaluation Criteria:
Defining a Successful Outcome

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
				SPC	PIAACMC	HLC	VVC	VNC - DA	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							
Wants			**Weights**	SPC	PIAACMC	HLC	VVC	VNC-DA	VNC - PO
Evaluation	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%						
Risks		(all judged to be Hgh consequence)		SPC	PIAACMC	HLC	VVC	VNC-DA	VNC - PO
				C | L	C | L	C | L	C | L	C | L	C | 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							
Opportunities		(judged to be High benefit)		SPC	PIAACMC	HLC	VVC	VNC-DA	VNC - PO
				B | L	B | L	B | L	B | L	B | L	B | L
	Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30							

Final Decision, Accounting for Risks and Opportunities:

C = Consequence, L = Likelihood, B=Benefit

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

Legend (Musts): ✓ yes, or expected likely; ? unknown; ✕ no, or expected showstopper

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

Risks: H M L

Opportunities: H M L

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

Criteria: Wants

Evaluation

Wants			Weights
	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%

- Relative Science yield beyond the threshold "Must"
- Post processing algorithms required to remove dark hole speckles, and degree of speckles sensitivity to optical low-order aberrations (static and dynamic). How sensitive are the dark holes of the technologies to these aberrations?
- Demonstrated performance in 10% light: what has been accomplished through investments to date?

Criteria: Risks and Opportunities

Risks		(all judged to be Hgh consequence)
	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
Opportunities		(judged to be High benefit)
	Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30

- Risks account for uncertainties in the prior evaluations:
  - In the Musts: credible plan, threshold science
  - In the Wants: the relative cost, the science beyond the Must)
- Also considered any parameters in the decision matrix to which the trade evaluations may be sensitive (e.g., jitter)
- Opportunity: considers improved science yield if the actual jitter is lower, and speckle subtraction is better

Results: Full Trade Matrix

Indicates Sig. Discriminator in ACWG discussion

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

Descr	Name			Option 1 SPC	Option 2 PIAACMC	Option 3 HLC	Option 4 VVC	Option 5 VNC - DA	Option 6 VNC - PO	Notes
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	
	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%							

Evaluation									

✓	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

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

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)

Final Trade Evaluation considering OMC=Option 7

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

Descr		Name	Weight	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

THE HOW

The HOW: Best Practices

- A Facilitator that does not have a stake in the outcome, other than that there IS an outcome
- A good Recorder
  - Next steps: experiment with collaborative tools
- First agree on Decision Statement, and Criteria
- Careful distinction of description vs evaluation (always in 2 steps)
- Useful to establish SFOM, TFOM, PFOM
  - Science, Technical, and Programmatic figures-of-merit
  - Sub-teams for evaluation of SFOM, TFOM, PFOM
- Handling consensus and dissent
- Timeline expectations: long form and short form

Working version of Consensus (yes, NASA has a policy)

- Prefer consensus in the time available, else, dissent will be captured and we will move on
  - Will follow 7120.5E, Ch 3.4, “Process for Handling Dissenting Opinion”
    - Three options: (1) Agree, (2) Disagree but fully support the decision, (3) Disagree and raise a dissenting opinion
    - Treat (1) and (2) as consensus for STDT
    - Dissents (3) will be documented and delivered to senior NASA management (APD DD) per 7120.5E

Results (Musts)

DECISION STATEMENT: Recommend **one DRM concept** Mirror Optical Assembly Architecture to **focus the design** for the final report and identify any **feasible alternates**

			Adjustable	Full Shell	Silicon Meta Shell
MUSTS					
	Science	Per defn / analysis of SET			
M1	Optical performance will meet reqts flowing down from Science Trace Matrix		Y	Y	Y
	Technical	Per defn / analysis of TET			
M2	Credible roadmap from today's status to predict flight on-orbit performance		Y	Y	Y
M3	Performance modeling tools related to current results are demonstrated to be credible		Y	Y	Y
M4	Repeatable fabrication process based on current status		Y	Y	Y
M5	Credible error budget that flows down to each mirror element		Y	Y	Y
M6	Expected to survive launch		Y	Y	Y
	Programmatic	Per defn / analysis of PET			
M7	Show a credible plan to meet TRL 4-6		Y	Y	Y
M8	Produce the mirror assembly within the Program schedule allocation		Y	Y	Y

- All 3 architectures passed the “Musts”.
- One note related to the Science criteria is that the full-shell optical design used for this study requires additional integration time for some observations. This was deemed by the LMAT to have minor consequence and can be mitigated.

Final Trade Matrix

- Consensus reached on all Musts, Wants, Risks and Opportunities in 20 hours of LMAT clock time
- One Want was not in consensus (see dissenting opinion)
- Only Key Wants (78 points of 100) were scored in weighted sum
- Effect of non-Key Wants and Dissent did not change Final Recommendation
- <u>Final Consensus Recommendation:</u> (accounting for Risks and Opportunities): **Silicon Meta Shell** as DRM concept, Adjustable and Full Shell as feasible alternates

DECISION STATEMENT: Recommend **one DRM concept** Mirror Optical Assembly Architecture to **focus the design** for the final report and identify any **feasible alternates**

						Adjustable		Full Shell		Silicon Meta Shell
MUSTS										
	Science	Per defn / analysis of SET								
M1	Optical performance will meet reqts flowing down from Science Trace Matrix					Y		Y		Y
	Technical	Per defn / analysis of TET								
M2	Credible roadmap from today's status to predict flight on-orbit performance					Y		Y		Y
M3	Performance modeling tools related to current results are demonstrated to be credible					Y		Y		Y
M4	Repeatable fabrication process based on current status					Y		Y		Y
M5	Credible error budget that flows down to each mirror element					Y		Y		Y
M6	Expected to survive launch					Y		Y		Y
	Programmatic	Per defn / analysis of PET								
M7	Show a credible plan to meet TRL 4-6					Y		Y		Y
M8	Produce the mirror assembly within the Program schedule allocation					Y		Y		Y
WANTS		***Key***	***Driving***	***Weights***						
	Technical	Per defn / analysis of TET			*Score*		*Score*		*Score*	
W1	Highest predicted technology readiness at Astro2020 by March 2020	K	D	12	7	small-significant	7	small-significant	10	Small difference
W2	Relative demonstrated performance	K	D	12	4	**SIG./VL DIFFERENCE**	4	**SIG./VL DIFFERENCE**	10	BEST
W3	Relative credibility of roadmaps from today's status to predict flight on-orbit performance (reflects M2)	K	D	12	5	SIG. DIFFERENCE	5	SIG. DIFFERENCE	10	BEST
W4	Relative simplicity of mirror assembly production process and test	K		10	8	small difference	10	BEST	10	BEST
W5	Relative contamination control (cost, complexity)			1		DIFFERENCE		BEST		DIFFERENCE
W6	Relative ease of implementing stray light control			3		DIFFERENCE		BEST		DIFFERENCE
W7	Relative ease of implementing thermal control and baffling			4		DIFFERENCE		BEST		BEST
W8	Relative ease of creating a system option for charged particle mitigation			1		*WASH*		*WASH*		*WASH*
W10	Relative confidence in launch survivability (reflects M6)			3		*WASH*		*WASH*		*WASH*
W11	Relative complexity and accuracy of ground calibration of mirror assembly	K		6	8	small difference	10	BEST	10	BEST
W13	Relative impact of technical accommodation (cost, mass, spacecraft resources, etc...)	K	D	10	8	small difference	5	SIG. DIFFERENCE	10	BEST
	Subtotal					**400**		**402**		**620**
	Programmatic	Per defn / analysis of PET								
W12	Relative cost and credibility of grass-roots cost estimate of the mirror assembly through delivery	K		10	10	*WASH*	10	*WASH*	10	*WASH*
W14	Lowest relative cost to reach TRL5 and 6			3		*WASH*		*WASH*		*WASH*
W16	Best assessment of the cost of ground calibration of mirror assembly			3		DIFFERENCE		BEST		BEST
W17	Earliest date to reach TRL5 and 6			4		DIFFERENCE		BEST		DIFFERENCE
W18	Best assessment of the schedule to mirror assembly delivery (reflects M8)	K		6	8	small difference	10	BEST	8	small difference
	Subtotal					**148**		**160**		**148**
	Total			100	**548**		**562**		**768**	
RISKS	*See wording for each in TET package*			PET Ref#		**C, L**		**C, L**		**C, L**
R1	Credible Roadmap (WRT M2)					3, 3		3, 2		3, 2
R2	Repeatable correct fabrication					5, 1		5, 1		5, 1
R3-5	Credible Error Budget					5, 1		3, 1		3, 2
R6	Launch Survival (risk of running out of design space to meet margin)					3, 1		3, 1		3, 1
R7	Programmatic impact of Low Mirror yield IF the process yield is less than expected then it will			R1		3, 3		4,3		4,2
R8	Mirror Technology Maturation (only risk related to M7)			R2		3, 4		3, 4		3,2
R9	Industry Engagement (lack of insufficient)			R3		4, 2		4, 1		4, 3
R10	Efficiency of Mirror Alignment and Bonding (no eval for full shell)			R4		3, 2				3, 4
R11	Difference in Execution of Repetitive Activities (including metrology environment)			R5		2, 3		1,3		3, 1
R12	Mirror Shell delivery by Corning			R6		n/a		4, 2		n/a
R13	Adhesive Cure Time			R7						3, 2
R14	Risk of observatory mass exceeding LV requrements If the mirror assembly mass increases beyond 2600kg (includes MGA)					4,1		4,3		4, 1
R15	Meeting 1.2 arc seconds: If cannot meet 1.2 arc seconds due to =>					5,2		5,2		5,2
OPPORTUNITIES	*See wording for each in TET package*			PET Ref#		**B, L**		**B, L**		**B, L**
O1	Coatings					4, 4		4, 4		4, 4
O2	Adjustability to help meet requirements before and after launch									
O3	ESA and ASI Partnership (Full Shell)			O1						
O5	If the mirror assembly can be redesigned (while meeting all other requirements) to improve grasp at					3,4		3,4		3,5

Risk Evaluation

ExEP

Weighted Score of Key Wants

- Out of 780 possible points.

DECISION STATEMENT: Recommend **one DRM concept** Mirror Optical Assembly Architecture to **focus the design** for the final report and identify any **feasible alternates**

					Adjustable		Full Shell		Silicon Meta Shell	
	WANTS	***Key***	***Driving***	***Weight***						
	Technical	Per defn / analysis of TET			*Score*		*Score*		*Score*	
W1	Highest predicted technology readiness at Astro2020 by March 2020	K	D	12	7	small-significant	7	small-significant	10	Small difference
W2	Relative demonstrated performance	K	D	12	4	**SIG./VL DIFFERENCE**	4	**SIG./VL DIFFERENCE**	10	BEST
W3	Relative credibility of roadmaps from today's status to predict flight on-orbit performance (reflects M2)	K	D	12	5	SIG. DIFFERENCE	5	SIG. DIFFERENCE	10	BEST
W4	Relative simplicity of mirror assembly production process and test	K		10	8	small difference	10	BEST	10	BEST
W11	Relative complexity and accuracy of ground calibration of mirror assembly	K		6	8	small difference	10	BEST	10	BEST
W13	Relative impact of technical accommodation (cost, mass, spacecraft resources, etc...)	K	D	10	8	small difference	5	SIG. DIFFERENCE	10	BEST
	Subtotal					**400**		**402**		**620**
	Programmatic	Per defn / analysis of PET								
W12	Relative cost and credibility of grass-roots cost estimate of the mirror assembly through delivery	K		10	10	***WASH***	10	***WASH***	10	***WASH***
W18	Best assessment of the schedule to mirror assembly delivery (reflects M8)	K		6	8	small difference	10	BEST	8	small difference
	Subtotal					**148**		**160**		**148**
	Total			100	**548**		**562**		**768**	

W4, W11, W12, W18 were Key but not Driving
W3 was Dissented – see detail following pages

Come Back to: Buying a Home

Summary

- A rationale decision process is needed when the decision matters
  1. A decision has to be made (including leaving options open)
  2. The stakes are high
  3. The decision needs to stick (consensus is important, need buy-in)
  4. Requires figures-of-merit determined by analysis, simulations
  5. The decision will be revisited when new information is available
  6. Significant uncertainty or risks prevail
  7. **Transparency, thoroughness, objectivity, creativity,** and **inclusion** are important
- A great format exists and has been used effectively
- A set of best practices are essential
- It is very easy to set up in use in your applications!
- KT methods may be useful in the very near future for the IROUV

BACKUP