National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

TPF Terrestrial Planet Finder

TPF-I Emma X-Array: 2007 Design Team Study

Stefan Martin
TPF-I Design Team Lead

with contributions from
Jose Rodriguez, Dan Scharf, Jim Smith, David McKinstry,
Richie Wirz, George Purcell, Len Wayne,
Larry Scherr, Bertrand Mennesson, and Oliver Lay

Jet Propulsion Laboratory
California Institute of Technology

16 April 2007

TPF Terrestrial Planet Finder

TPF-Emma Design Summary

Stefan Martin, Jose Rodriguez, Dan Scharf, Jim Smith,
David McKinstry, Richie Wirz, George Purcell, Len Wayne,
Larry Scherr, Bertrand Mennesson, Oliver Lay

Jet Propulsion Laboratory
California Institute of Technology

Scope of work

- To study an Emma design for TPF Formation Flying Interferometer
- Develop a design with reduced cost compared to TPF-I X-Array baseline
    - Goal of cost <$2B
    - Goal of launch on Ariane V ECA or smaller
- Derive mass and cost estimates
- Study thermal and radiation issues

Scope of presentation

- What this is:
  - The results of ~ 2 to 3 months work
  - A first cut at a design
  - The first review of the total package

- What this isn't
  - Complete
  - Finished
  - Always self-consistent

Requirements (1)

TPF Terrestrial Planet Finder

	Requirement	Value	Unit	Comment
	Level 0			
1	Cost	< $2B		
2	Spacecraft fit in Ariane 5 size launch vehicle			
	Level 1			
3	Maximum fairing diameter	4	m	
4	Maximum total mass	6600	kg	Includes 20% margin
5	Minimum mirror size	3	m	
6	5 year nominal mission length,10 year goal			
7	Rotation period	50000	s	For 200 m baseline
8	How long to do a turn as a function of radius?			
9	# of collectors	4		
10	Sky coverage requirement	95° to 135°		Angle between line to star and line to sun
11	Array size, maximum	400	m	Measured along diagonal
12	Array size, minimum	120	m	Measured along diagonal
13	Minimum collector separation	<20	m	

Allowed increase to 4.57 m

Requirements (2)

	Level 2			
14	Collector mirror temperature	50	K	
15	Temperature gradient of collector mirror	5	K	
	Position control			
16	Collector-combiner distance	1200	m	
17	Optical delay range	+/- 50	mm	
18	collector-collector	+/- 2	m	
19	collector-combiner	+/- 25	mm	
	Collector s/c			
20	Tilt	+/- 0.5	arc sec	
21	In-plane motion	+/- 1	m	
22	Out of plane motion	+/- 20	mm	
	Combiner s/c		arc min	
23	Tilt	+/- 1	arc min	

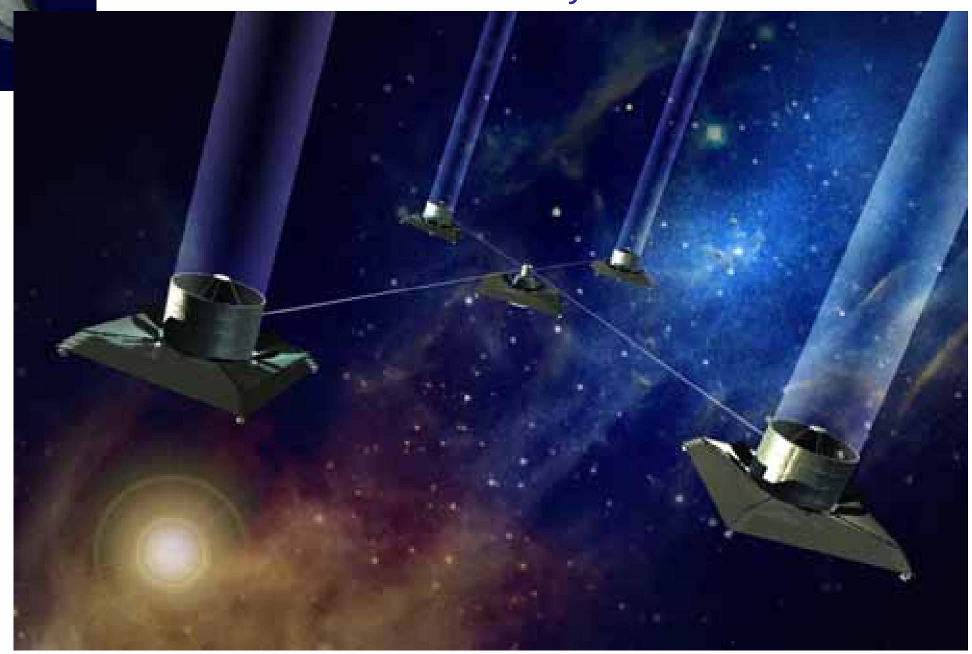
Will be exceeded in some configurations

TPF Terrestrial Planet Finder

TPF-I FFI

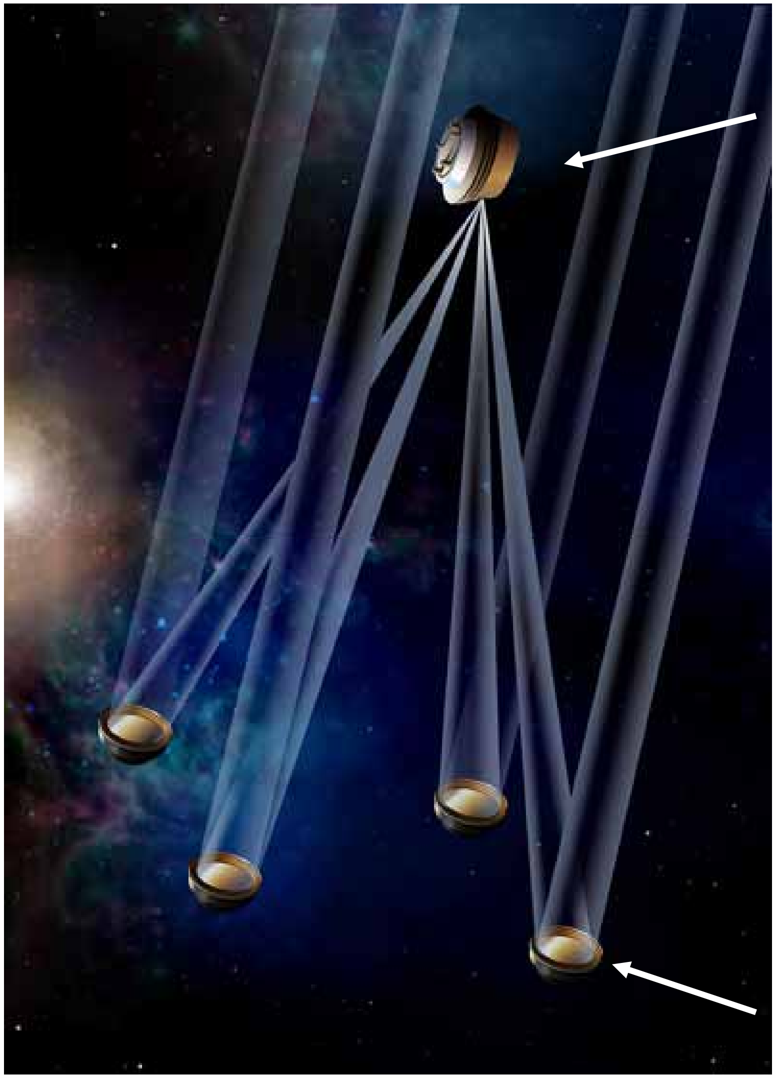
TPF-I Linear Array

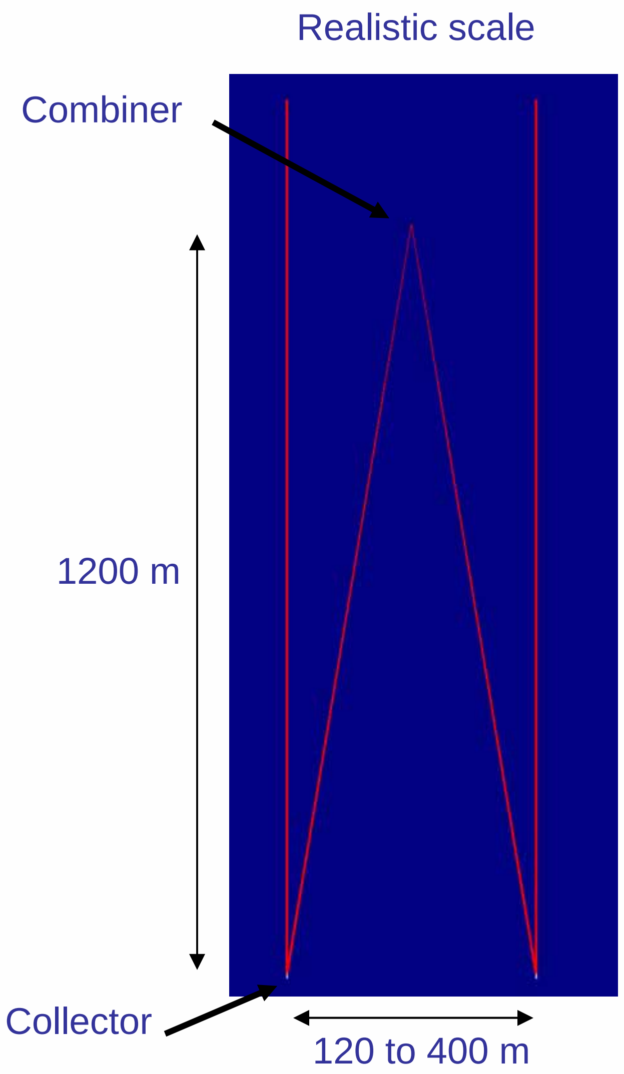
TPF-I X-Array



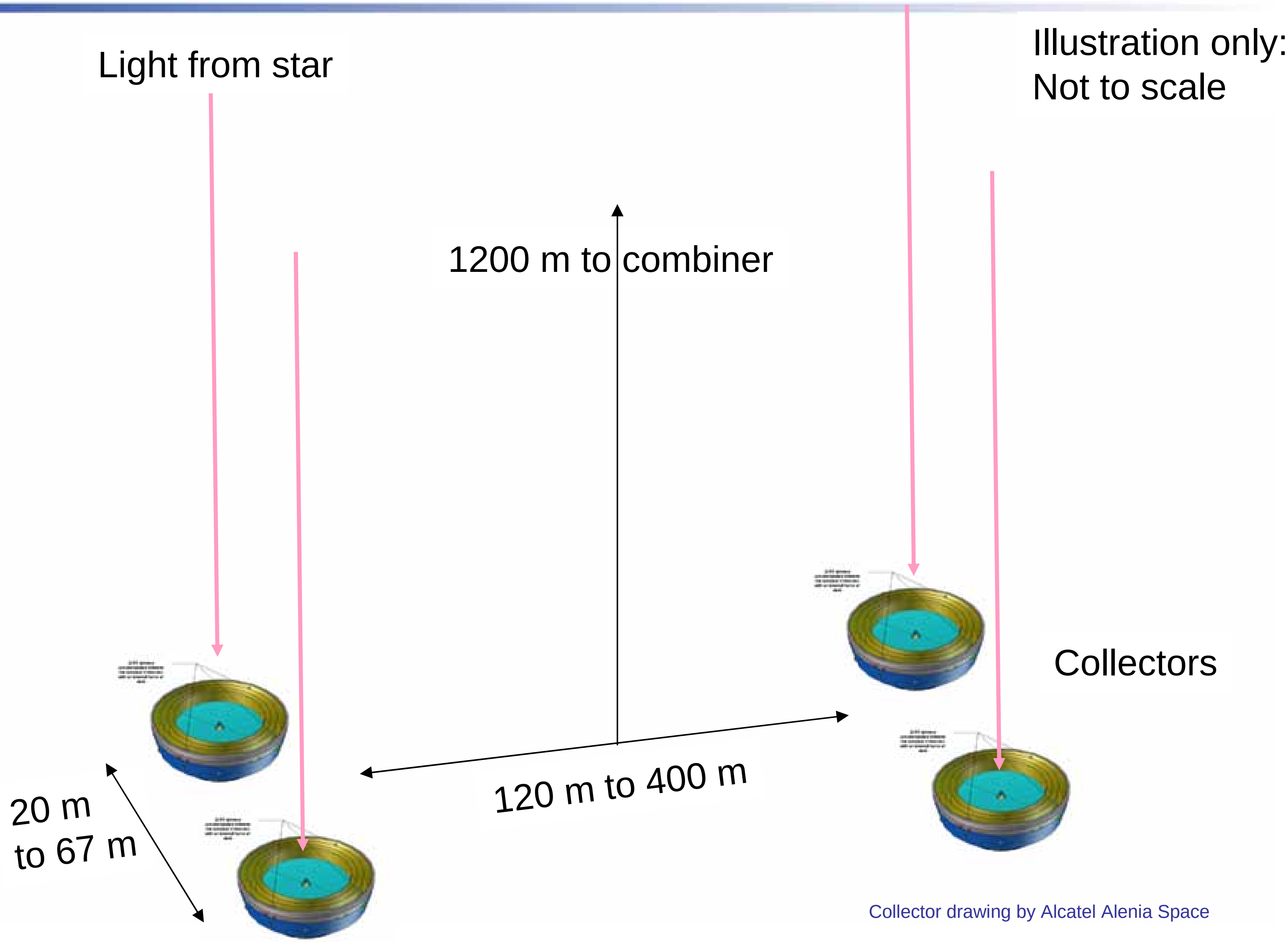
TPF-Emma

Combiner to collector distance is greatly shortened



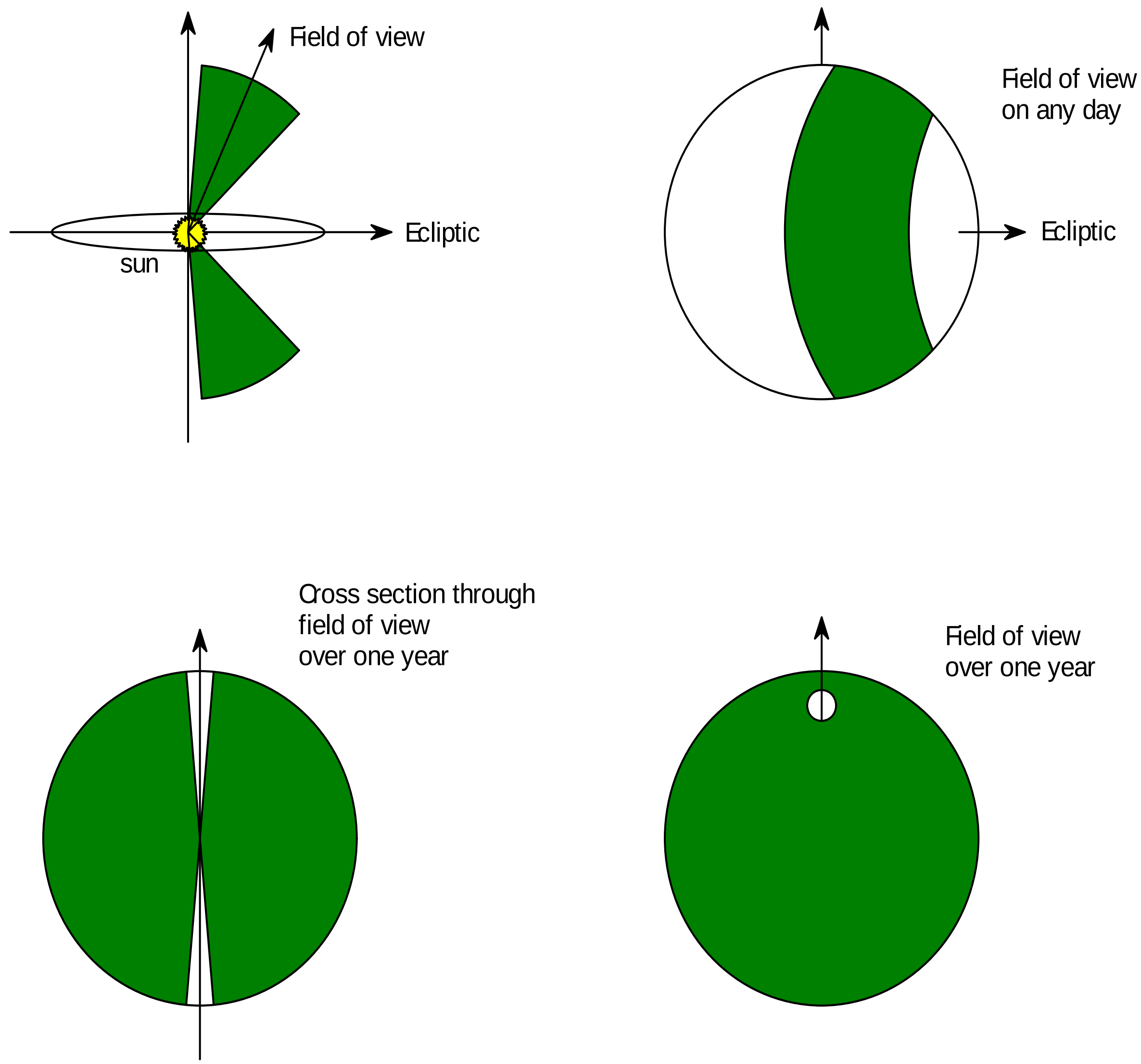


Formation geometry



Collector drawing by Alcatel Alenia Space

Emma Field of Regard



TPF-Emma: a new paradigm

	TPF-I FFI	TPF-Emma
Number of telescopes	4	4
Beam combiner s/c	4 beam nulling combiner	4 beam nulling combiner
Collector s/c	Complex telescope	Simple reflector
Collecting area	50 m^2	28 m^2
Formation geometry	X-array, in-plane combiner	X-array, out of plane combiner
Closest approach	5 m	20 m
Largest dimensions	15 x 15 m sunshades	4.5 m diameter spacecraft
Collector attitude accuracy	1 arc min	1 arc sec
Formation control system	Reaction wheels, pulsed plasma thrusters	Miniature Xenon ion (MiXI) thrusters
Deployments	15 m sq 5 layer sunshade Telescope secondary Telescope shroud Thermal radiators Stray light baffles	None
Observable sky	71%	99%

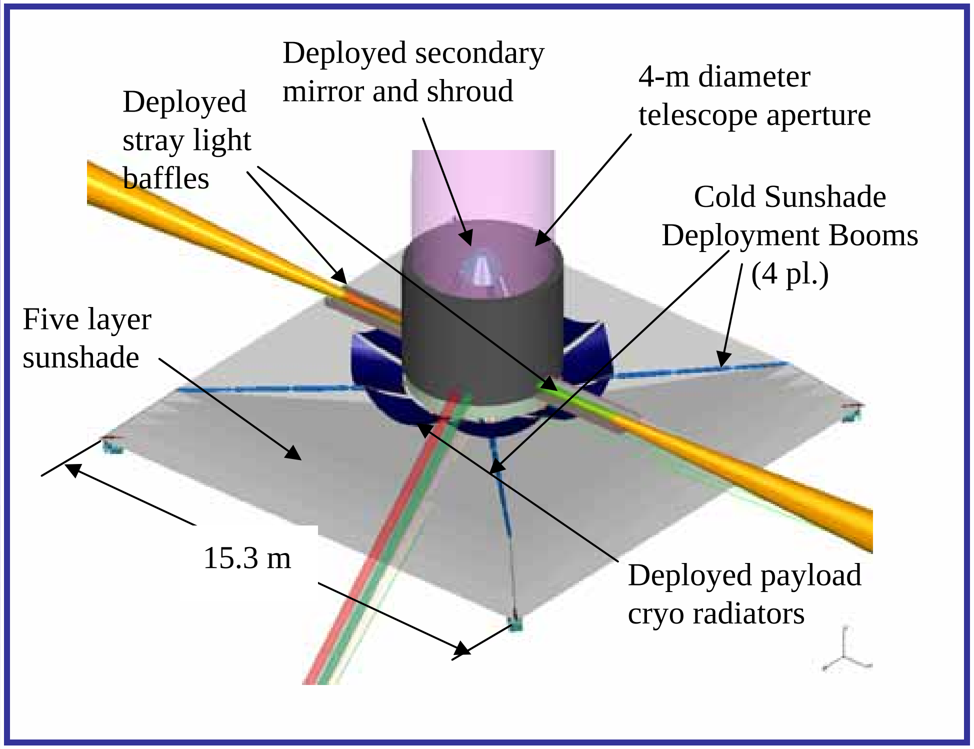
TPF-I and TPF-Emma comparison

TPF Terrestrial Planet Finder

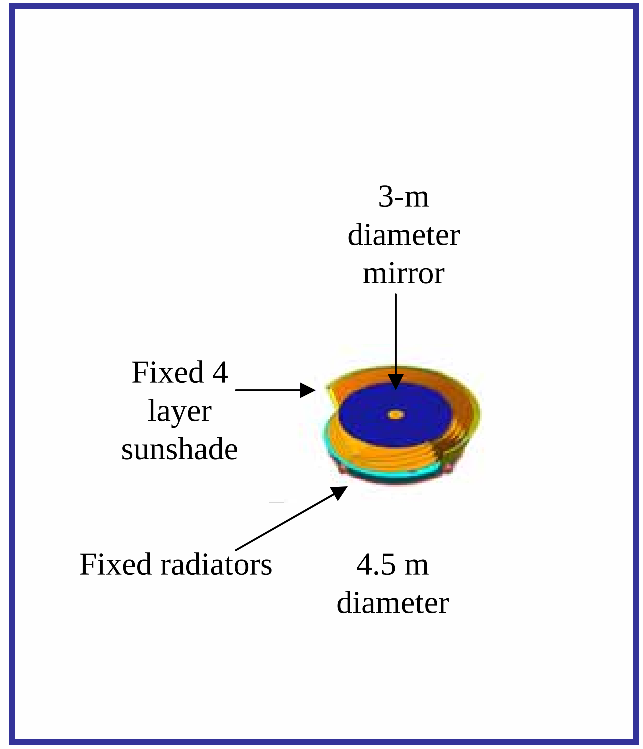
Collector spacecraft

in rough scale

TPF-I FFI collector spacecraft

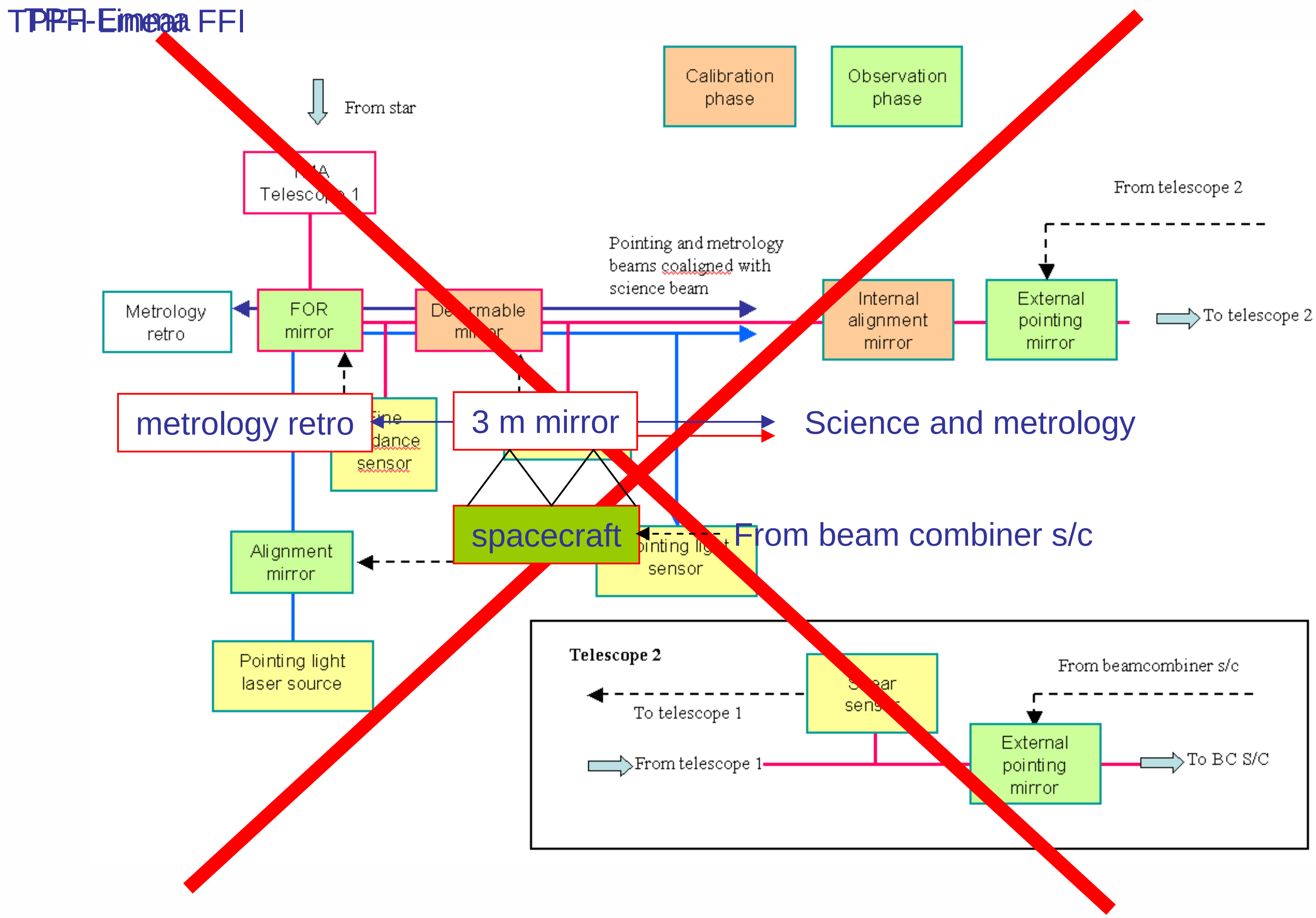


TPF-I Emma collector spacecraft



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Telescope spacecraft optical controls and sensors



Optical systems part count

	Actuators	Sensors	Devices		
Collector					Emma Collector
	FOR mirror				✗
	DM				✗
		Fine guidance			✗
		Wavefront			✗
		Pointing reference			✗
					✗
	Reference alignment mirror				✗
	Internal alignment mirror				✗
	External pointing mirror				✗

Collector is greatly simplified

Combiner is similar to TPF FFI concept

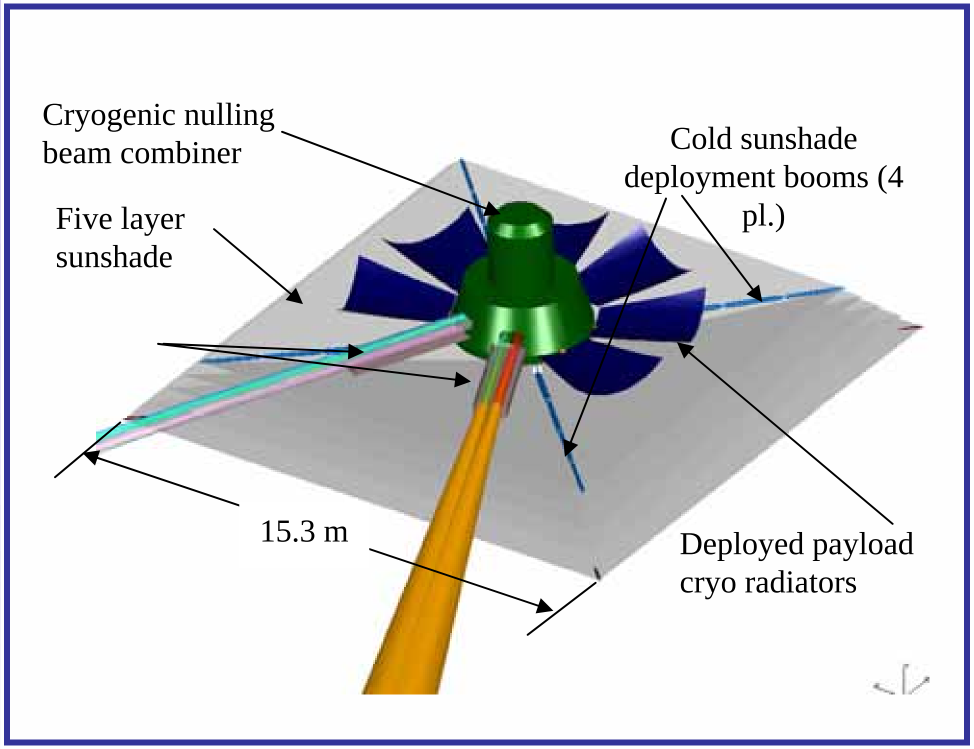
	Actuators	Sensors	Devices		
Combiner					Emma Combiner
		Input beam shear sensor			✓
	Coarse pointing mirror				✓
			Compressor		✗
					Re-imager
			K mirror		✓
		Tilt sensor			✗
	Metrology alignment				✓
			Delay lines		✓
	Fine pointing mirror				✓
	Fine shearing mirror				✓
			Adaptive nuller		✓
		Pointing sensor			✓
		Internal shear sensor			✓

TPF-I and TPF-Emma comparison

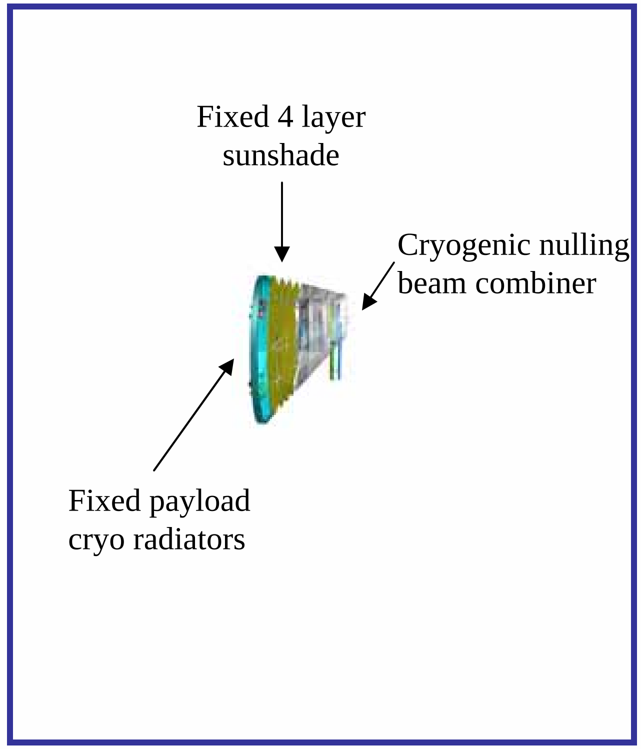
Combiner spacecraft

in rough scale

TPF-I FFI combiner spacecraft

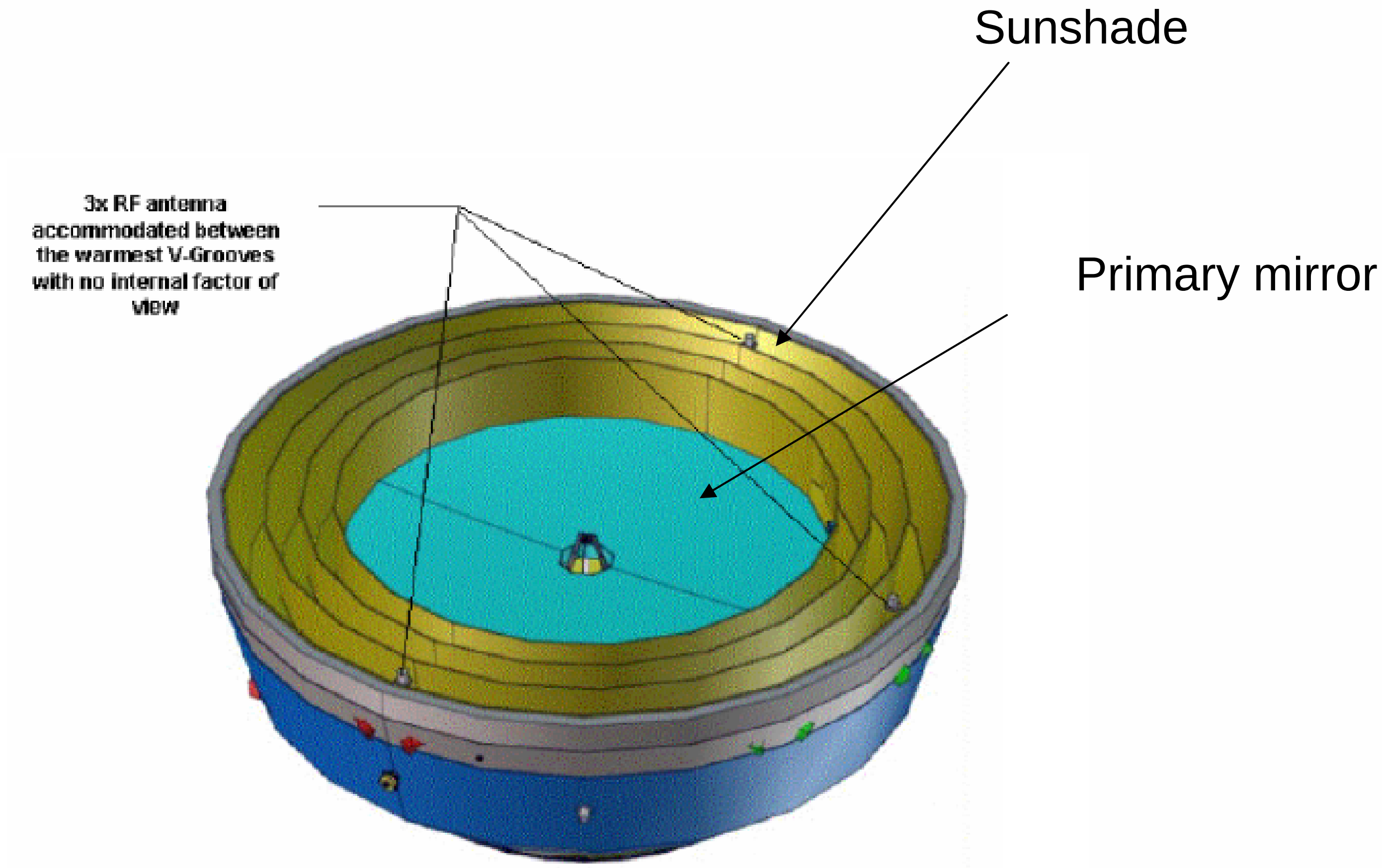


TPF-I Emma combiner spacecraft



ESA's Collector spacecraft

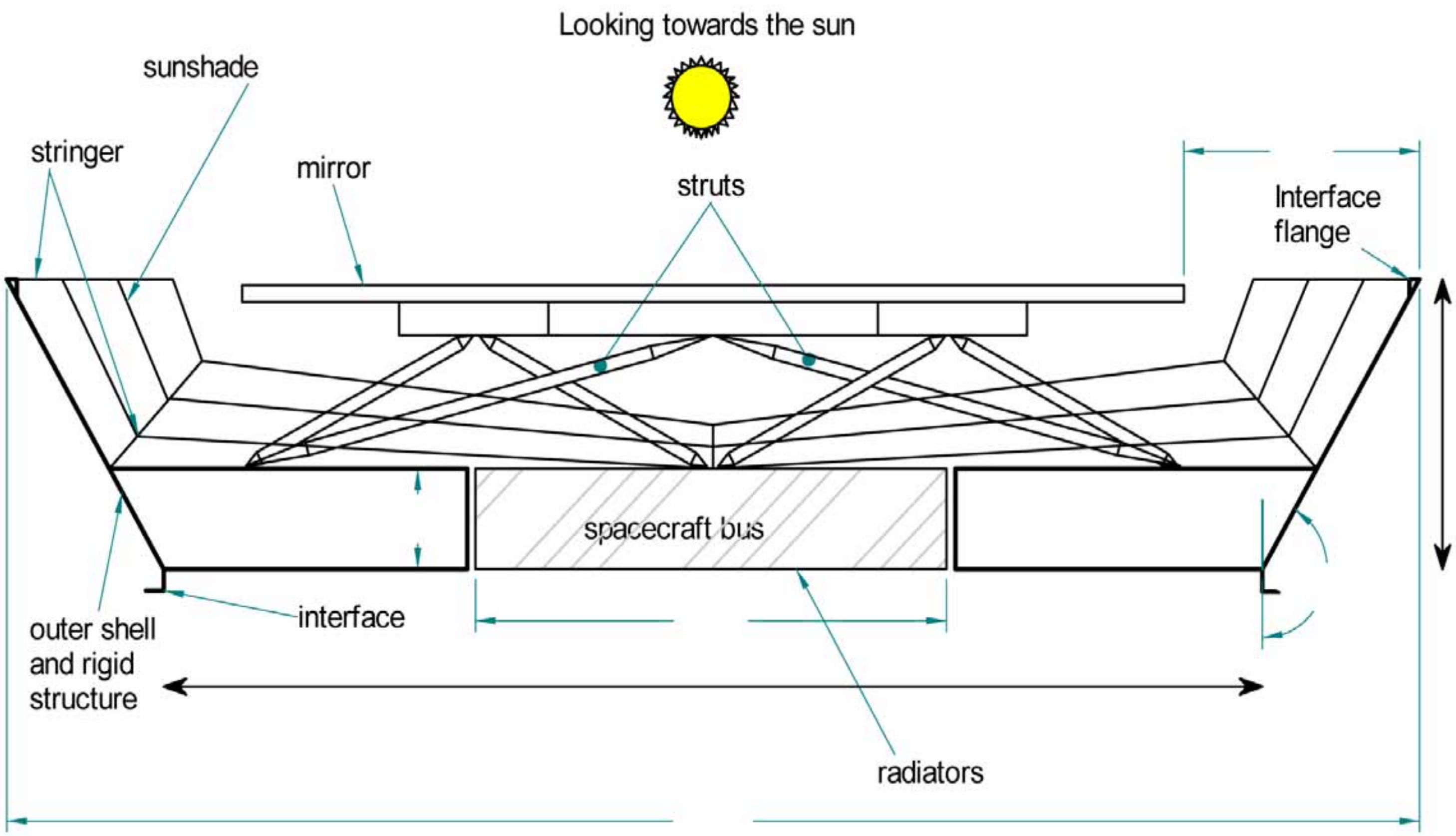
Alcatel-Alenia Space concept



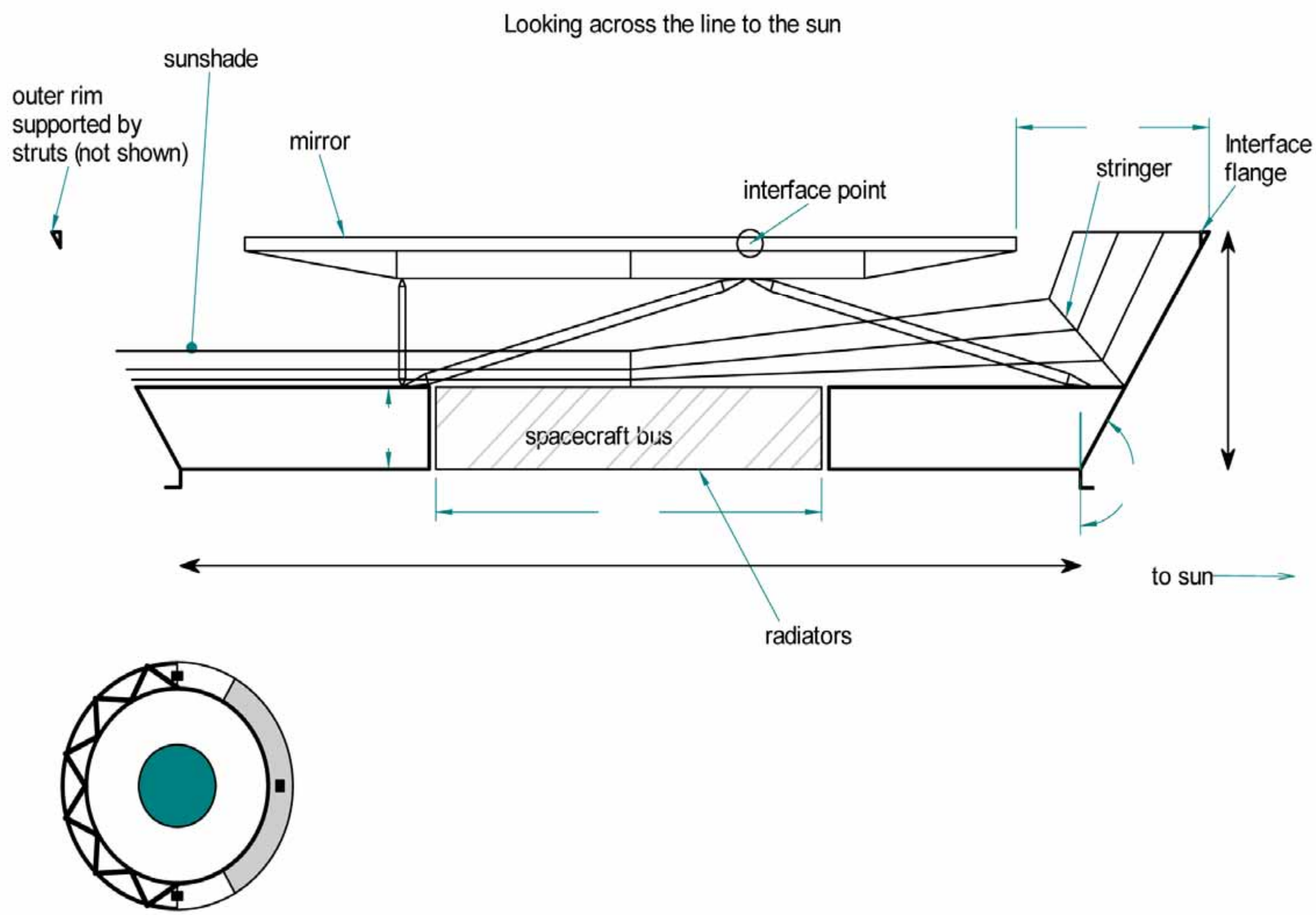
Collector drawing by Alcatel Alenia Space

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

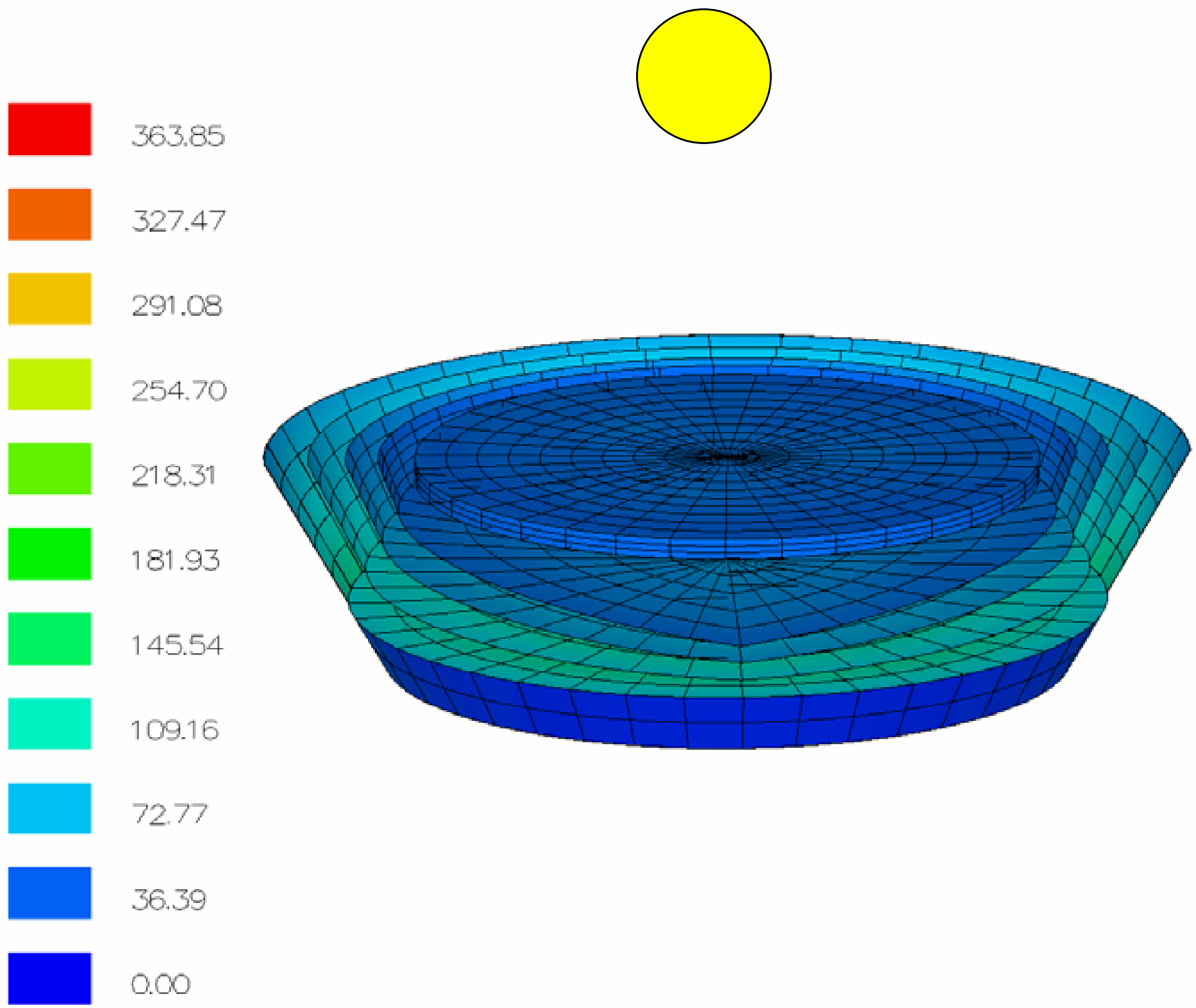
TPF-Emma collector spacecraft



Collector spacecraft

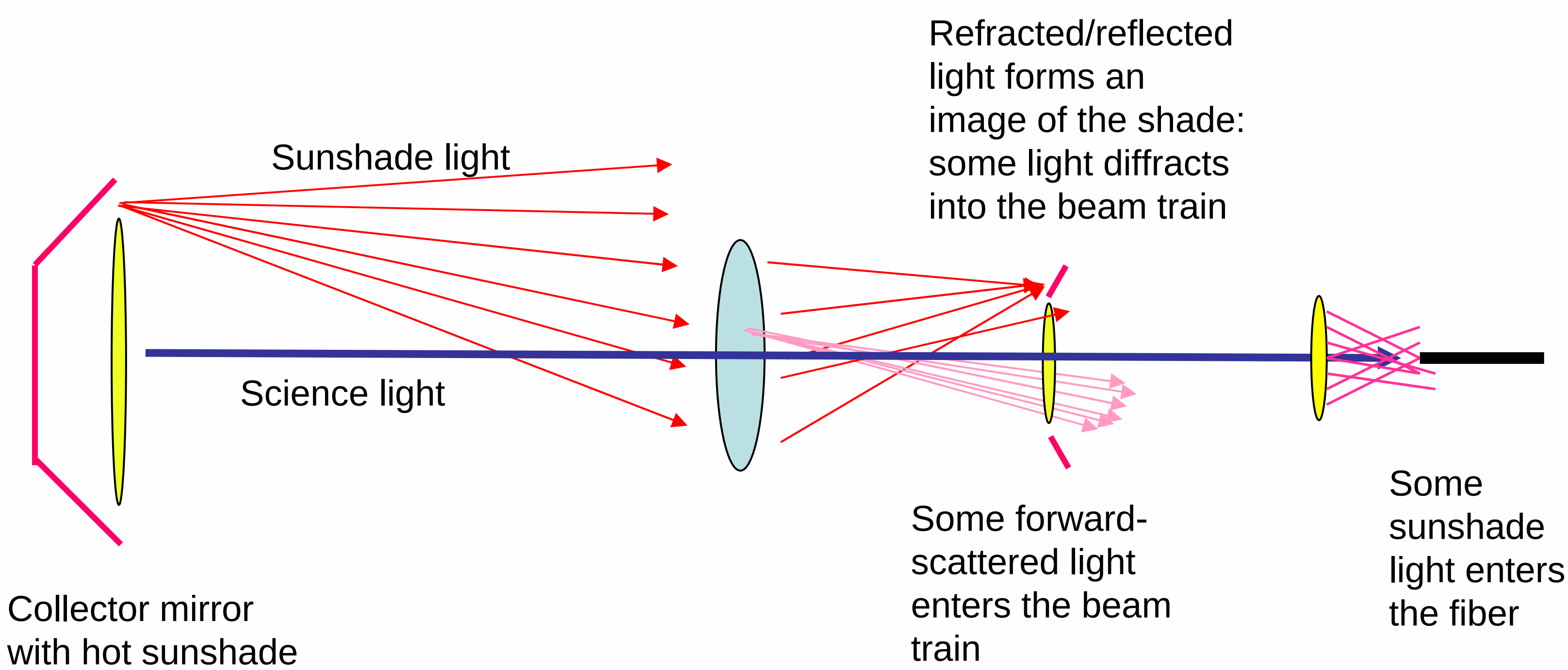


Thermal view of collector looking towards the sun



Emma Optical Issues

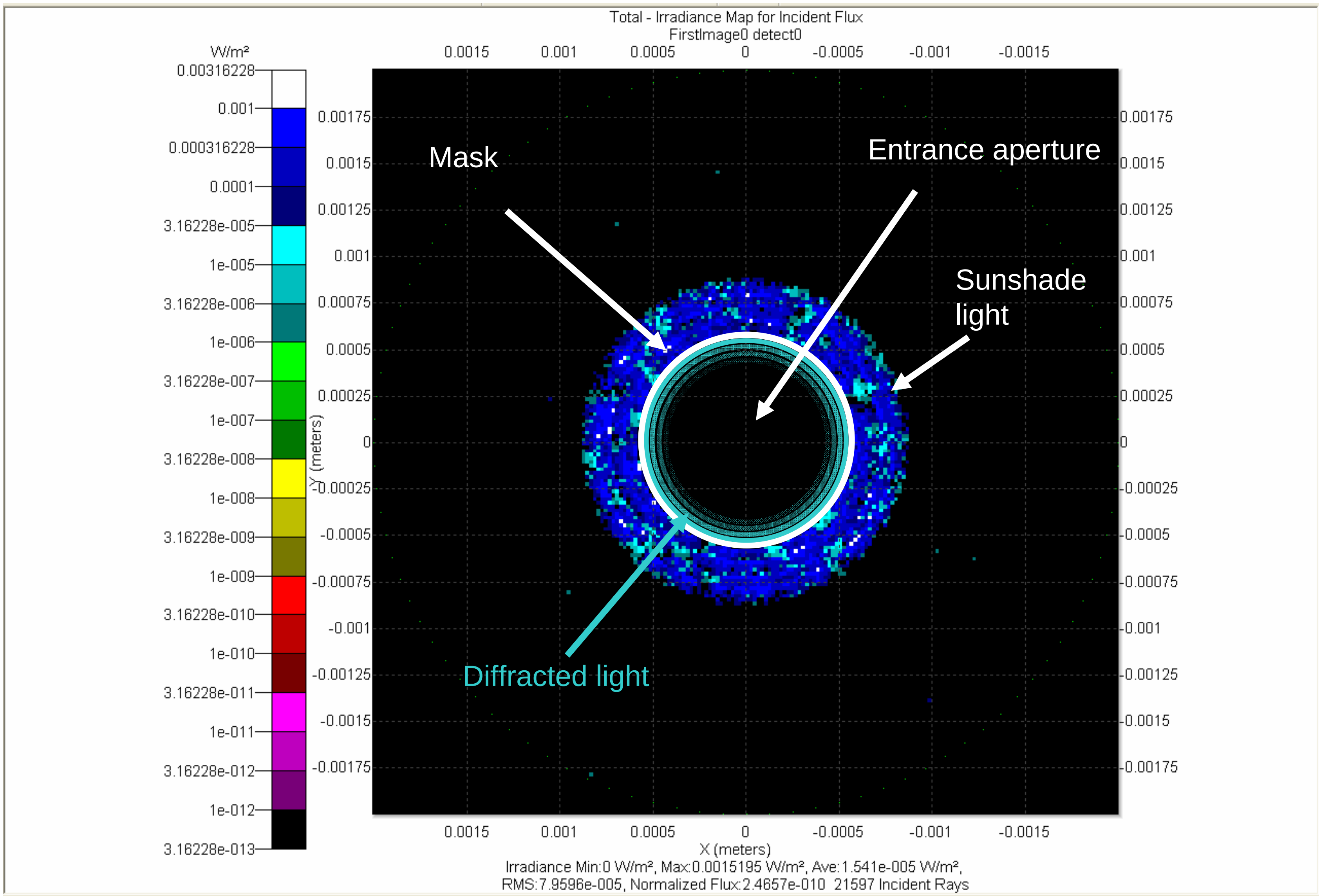
- Hot sunshade is visible at the combiner spacecraft
  - Two issues result:
    - Light from the sunshade can be diffracted into the science beam path
    - Light from the sunshade can be scattered into the science beam path



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Stray light at the sunshade mask

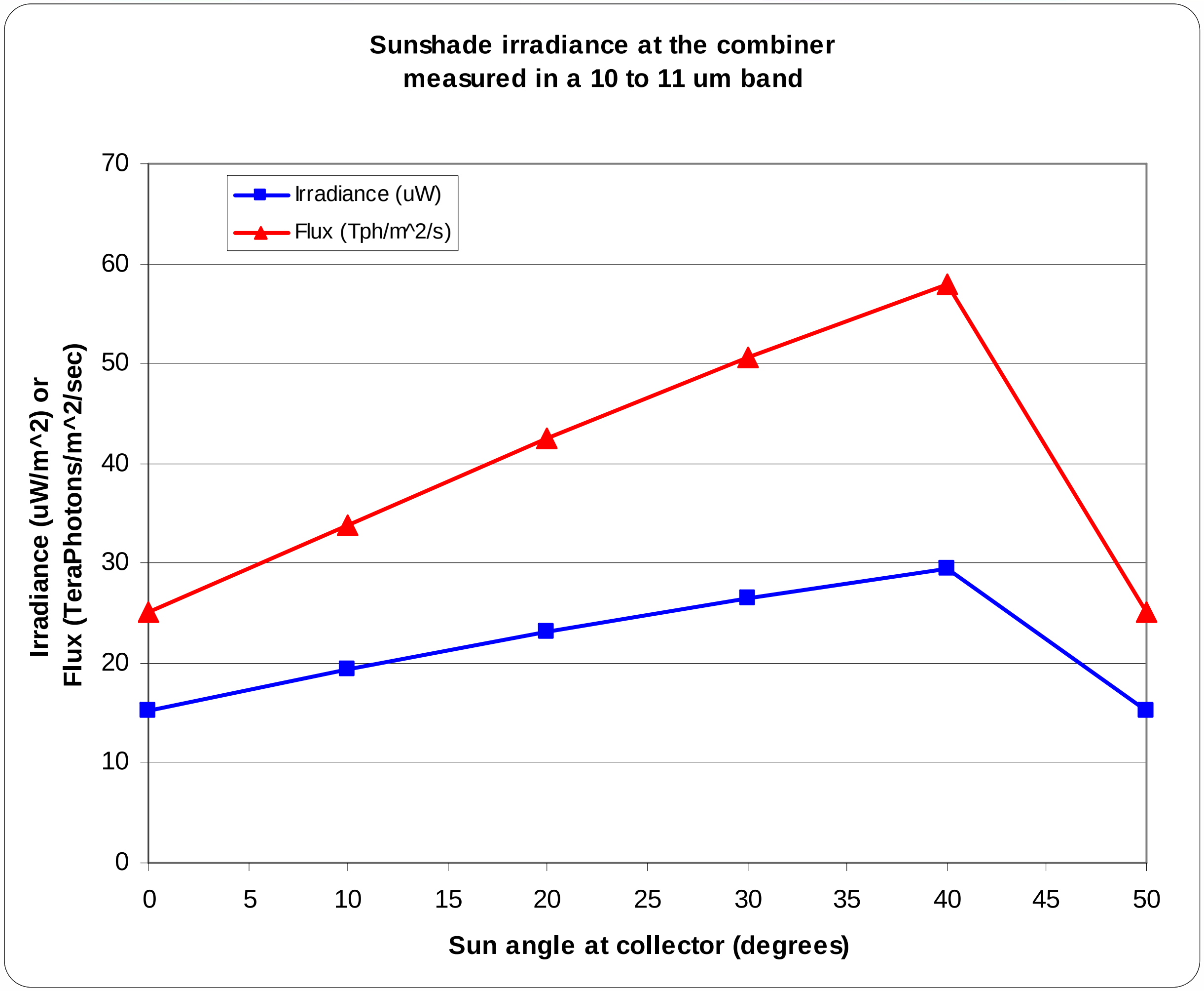
Sunshade image forms the ring. Scattered rays show in other locations.



Terrestrial Planet Finder
TPF

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Irradiance at the combiner



Back of envelope calculation was: Sunshade photon flux is 300 TeraPhoton/s/m^2

Estimated throughput to fiber from the thermal model: ~400 photons/sec: OK

Light scattering calculations

Mirror surface scatter:

For a mirror with 50 Angstrom RMS roughness and Cleanliness Level 500:
Its surface scatter is dominated by the dust contamination at a 10.6micron wavelength.

The integrated BRDF is 4.2E-3 for the CL500 dust model.
The integrated BRDF for 50 Angstrom RMS roughness surface is 1.6E-4.

The BRDF for the EMMA setup is expected to be ~0.07 1/sr.

From the thermal model we found the worst case irradiance due to the sunshade at the combiner is 60 Tphotons/m^2/sec. With a 250 mm diameter collection optic, the light scattered into the fiber will be approximately 30 photons/sec- not an issue.

Diffracted light after mask:

~ 0.1 Tphotons/sec for a 250 mm diameter optic
~12 photons/sec enter the fiber. (To be revised)

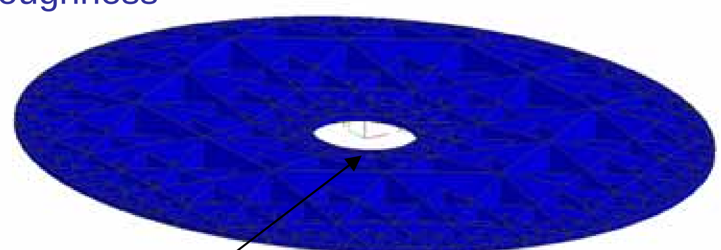
Light-weight mirror in Silicon Carbide

Herschel mirror

3.5 m diameter, 300 kg
SiC by Coorstek, Boostec, Astrium
CVD SiC facesheet
Operating temperature 70 to 90 K

Twelve petals form the mirror.
Petals braised together.
Stiffening ground off.

TPF-Emma
3 m diameter, 192 kg, SiC
Double arch backing structure
CVD facesheet can be polished to 5 Angstrom roughness



Space for
metrology retro

Launch vehicles

Ariane 5 ECA: 9600 kg to GTO

Delta IV Heavy: 13000 kg to GTO

TPF-I FFI Book-kept Delta IV Heavy Launch Capability 9408 kg

Other options: Ariane 5

9323 kg to GTO
6800 kg to GTO

All have 4.57 m fairing diameter (useable envelope)

Mass estimates

- TPF FFI mass estimate

	Mass kg	Predicted	Allocated
Total Collector Element		1340	1622
Total Collectors (Qty. 4)		5362	6490
Total Combiner Element		1330	1615
Total Cruise Stage Element		2110	2478
Total All Flight Elements		8802	10583

- TPF Emma mass estimate

	Mass kg	Predicted	Allocated
Total Collector Element		773	1004
Total Collectors (Qty. 4)		3092	4020
Total Combiner Element		1188	1544
Total Cruise Stage Element		1048~	1390~
Total All Flight Elements		5328	6950

TPF-Emma has ~70% of the mass of TPF-FFI.

Cost estimate

TPF Terrestrial Planet Finder

- Sources:
  - Cost tools on NASA Johnson web site
    - Advanced Missions Cost Model (AMCM)
    - Reduction factor for quantity
    - Difficulty weightings
      - Very low, Low, Average, High, Very High
  - Conversation with Keith Warfield (Latest Team X NICM model)
    Collector spacecraft is atypical- may not be modeled well

- TPF Emma spacecraft cost estimate using AMCM

	Predicted mass kg	Cost M$	Difficulty Weighting	Type
Total Collector Element	**773**	**373**	**Average**	**Spacecraft- Physics and Astronomy**
Total Collectors (Qty. 4)	**3092**	**851**	**Average**	**Spacecraft- Physics and Astronomy**
Total Combiner Element	**1188**	**769**	**High**	**Spacecraft- Physics and Astronomy**
Total Cruise Stage Element	**1048~**	**113**	**Low**	**Space transport upper stage**
Total All Flight Elements	**5328**	**1733**		

Plus launch vehicle cost; budget $200M to $400M

Cost estimate comparison

TPF Terrestrial Planet Finder

- TPF Emma spacecraft cost estimate using AMCM

	Predicted mass kg	Cost M$	Difficulty Weighting	Type
Total Collector Element	773	373	Average	Spacecraft- Physics and Astronomy
Total Collectors (Qty. 4)	3092	851	Average	Spacecraft- Physics and Astronomy
Total Combiner Element	1188	769	High	Spacecraft- Physics and Astronomy
Total Cruise Stage Element	1048~	113	Low	Space transport upper stage
Total All Flight Elements	**5328**	**1733**		

Savings $1.2 Billion

- TPF-I FFI spacecraft cost estimate using AMCM

	Predicted mass kg	Cost M$	Difficulty Weighting	Type
Total Collector Element	1340	832	High	Spacecraft- Physics and Astronomy
Total Collectors (Qty. 4)	5362	1896	High	Spacecraft- Physics and Astronomy
Total Combiner Element	1330	828	High	Spacecraft- Physics and Astronomy
Total Cruise Stage Element	2110	190	Low	Space transport upper stage
Total All Flight Elements	**8802**	**2914**		

Plus launch vehicle cost; budget $200M to $400M

A smorgasbord of further work

- Improved cost estimate using NICM model; uses mass, power estimate
- Study formation configurations for inter-spacecraft heating effects
- Improved shade design studies
- Thruster plume radiation
- Thruster plume shielding for shades
- Thruster geometries

Conclusions and Summary

- Emma design concept is an improvement on the TPF-I planar array design
  - Very simple collector spacecraft
  - 30% less mass
    - but only 54% of the mirror area
  - No deployments
    - except antennas
  - Similar beam combiner spacecraft complexity
  - Three or four launch options instead of one
    - excluding margin
- Stray light concerns largely put to rest
- Rugged spacecraft design and wider spacing mitigate collision worries
  - Collector s/c very distant
- Considerable potential cost savings of $1.2B

Acknowledgments

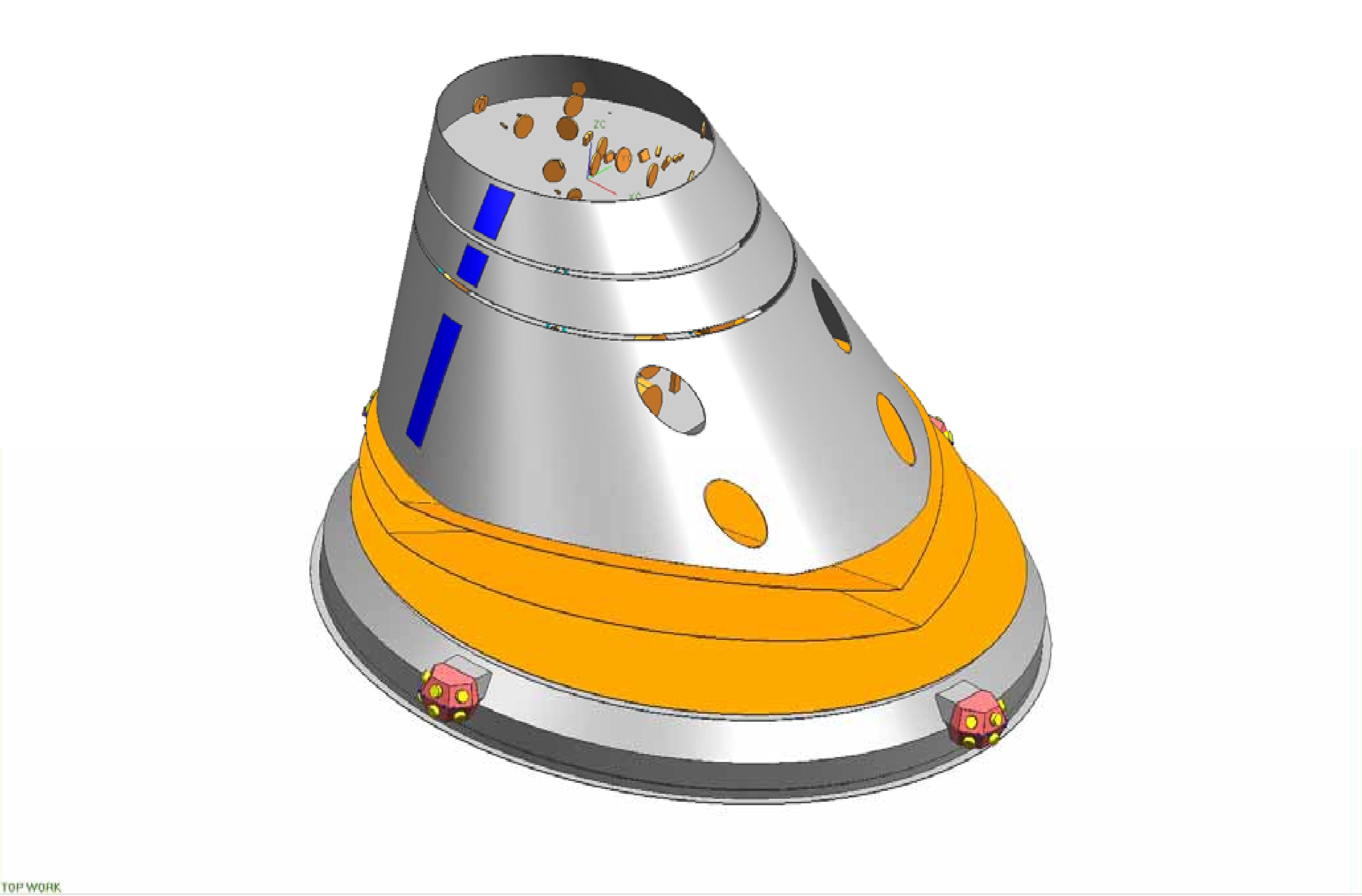
- This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

TPF Terrestrial Planet Finder

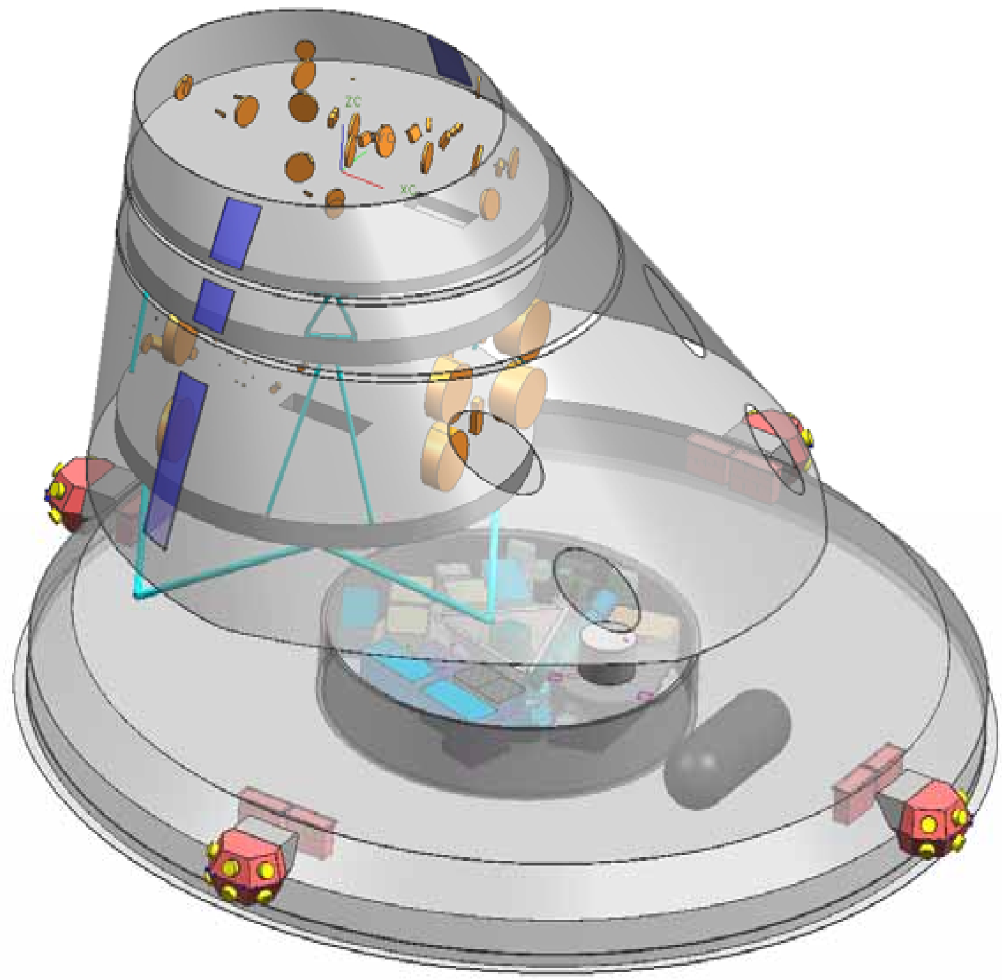
Views of the TPF-I Emma X-Array

Stefan Martin and David McKinstry

Jet Propulsion Laboratory
California Institute of Technology

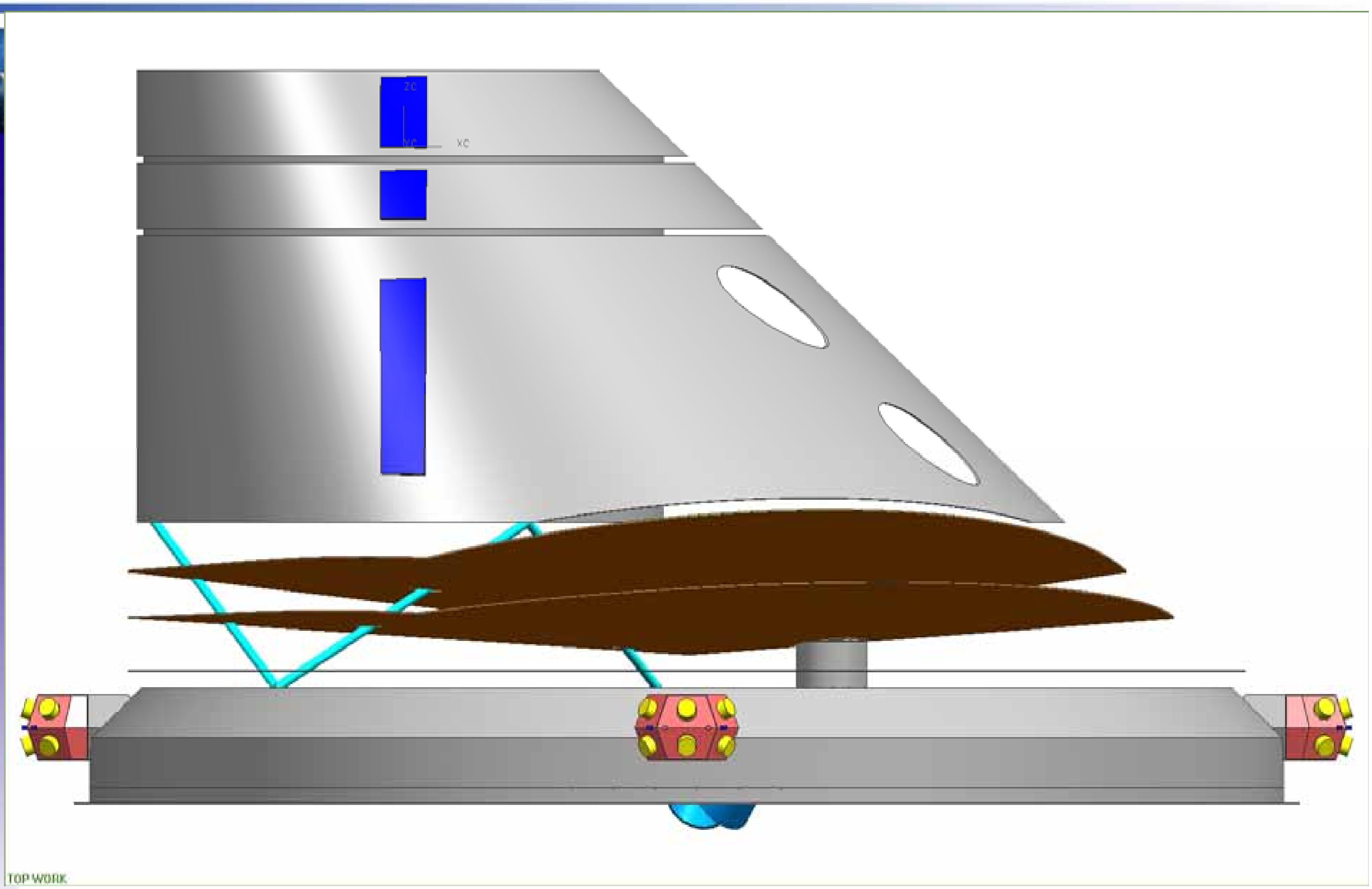

TOP WORK

BEAM COMBINER (TRANSPARENT COMP)



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

BEAM COMBINER-FRONT



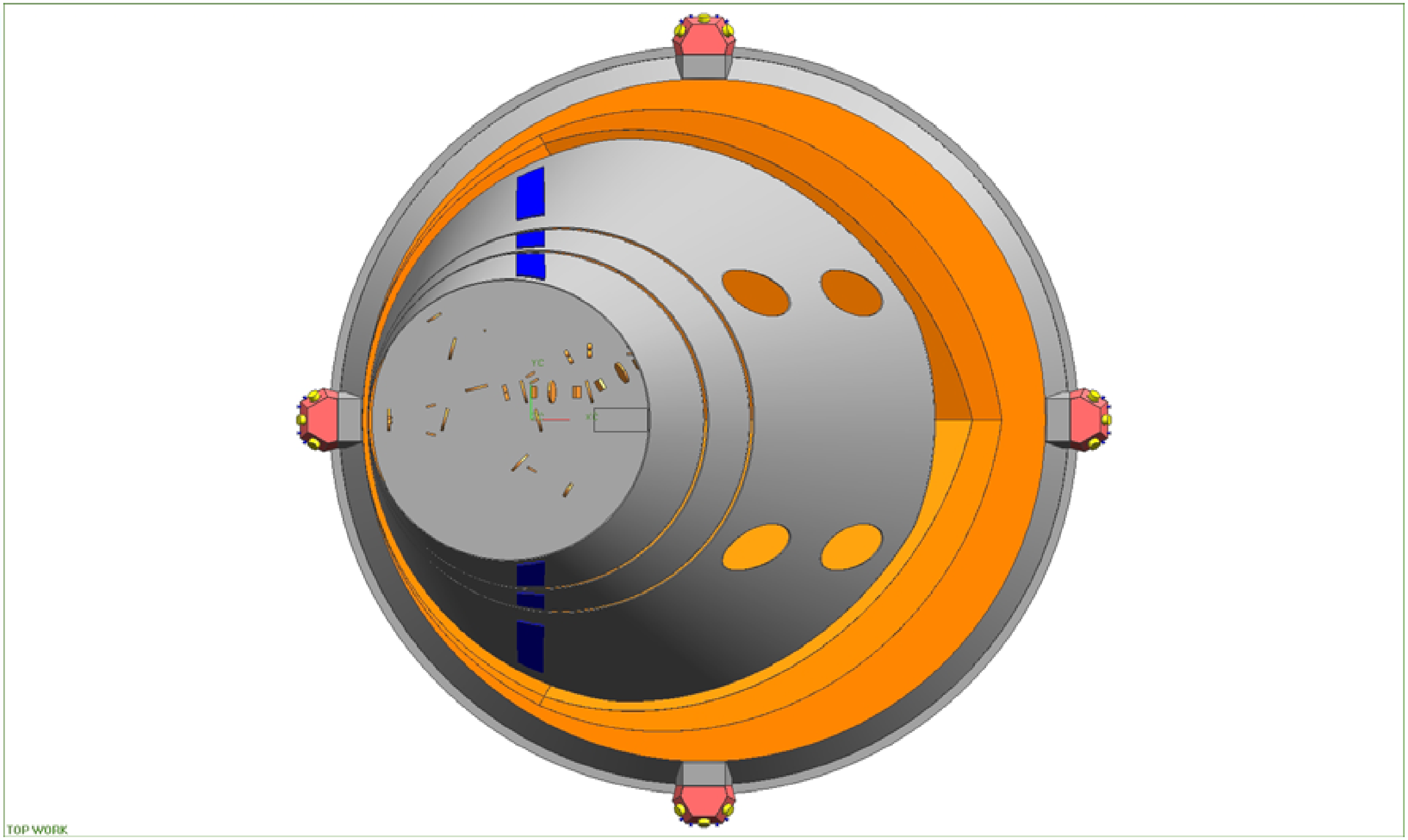
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

BEAM COMBINER (TRANSPARENT)

TPF Terrestrial Planet Finder

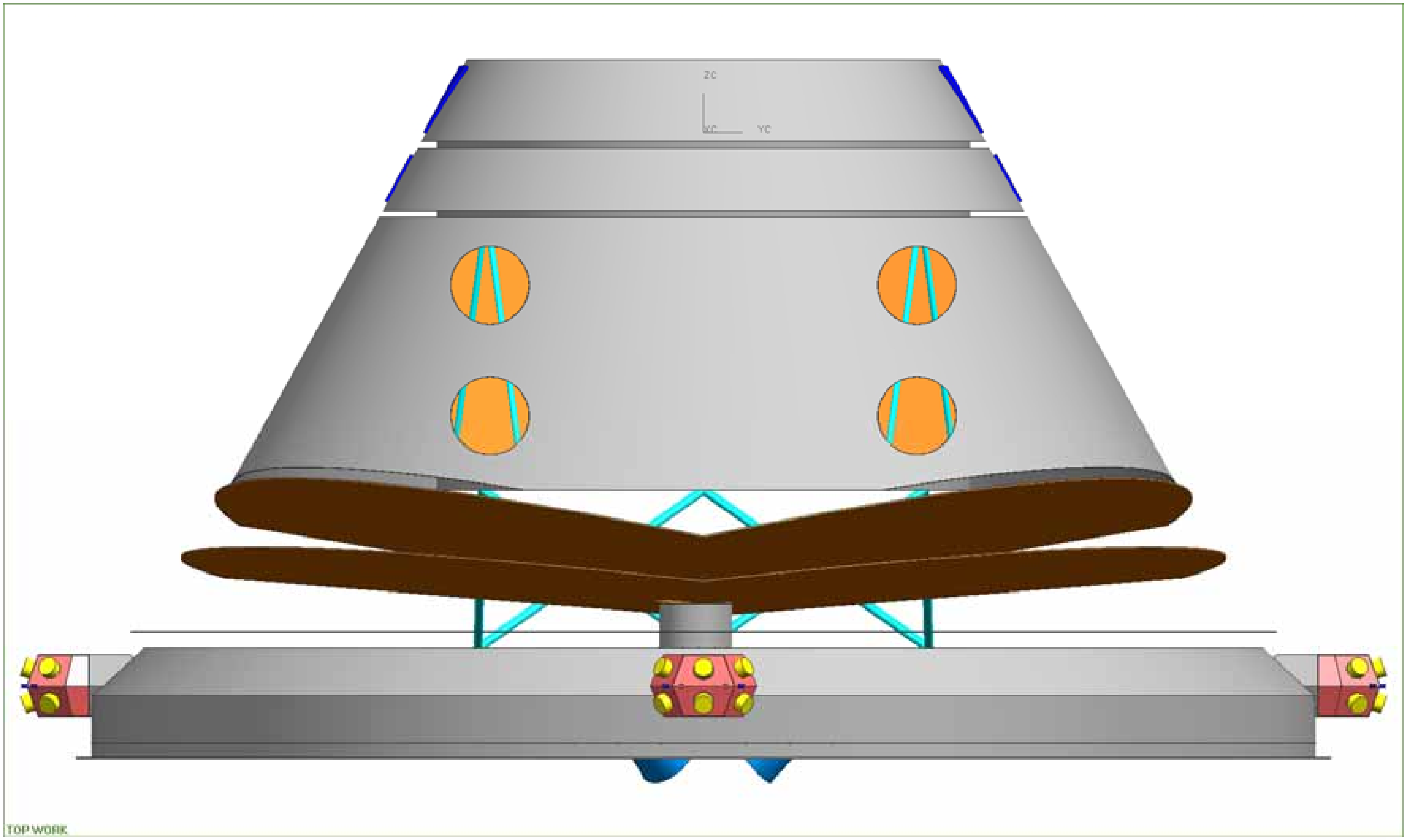
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

BEAM COMBINER-TOP

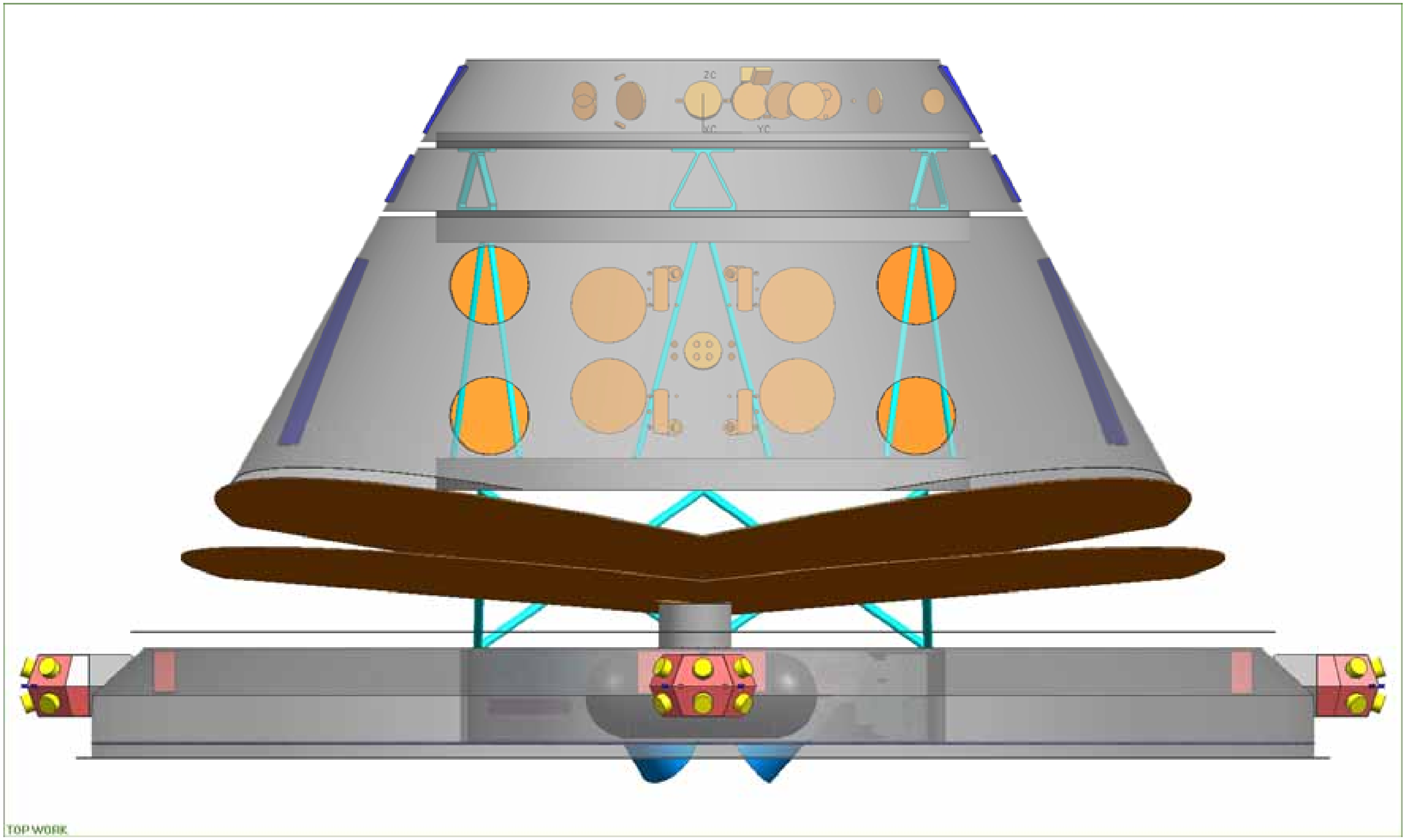


TPF Terrestrial Planet Finder

BEAM COMBINER-SIDE



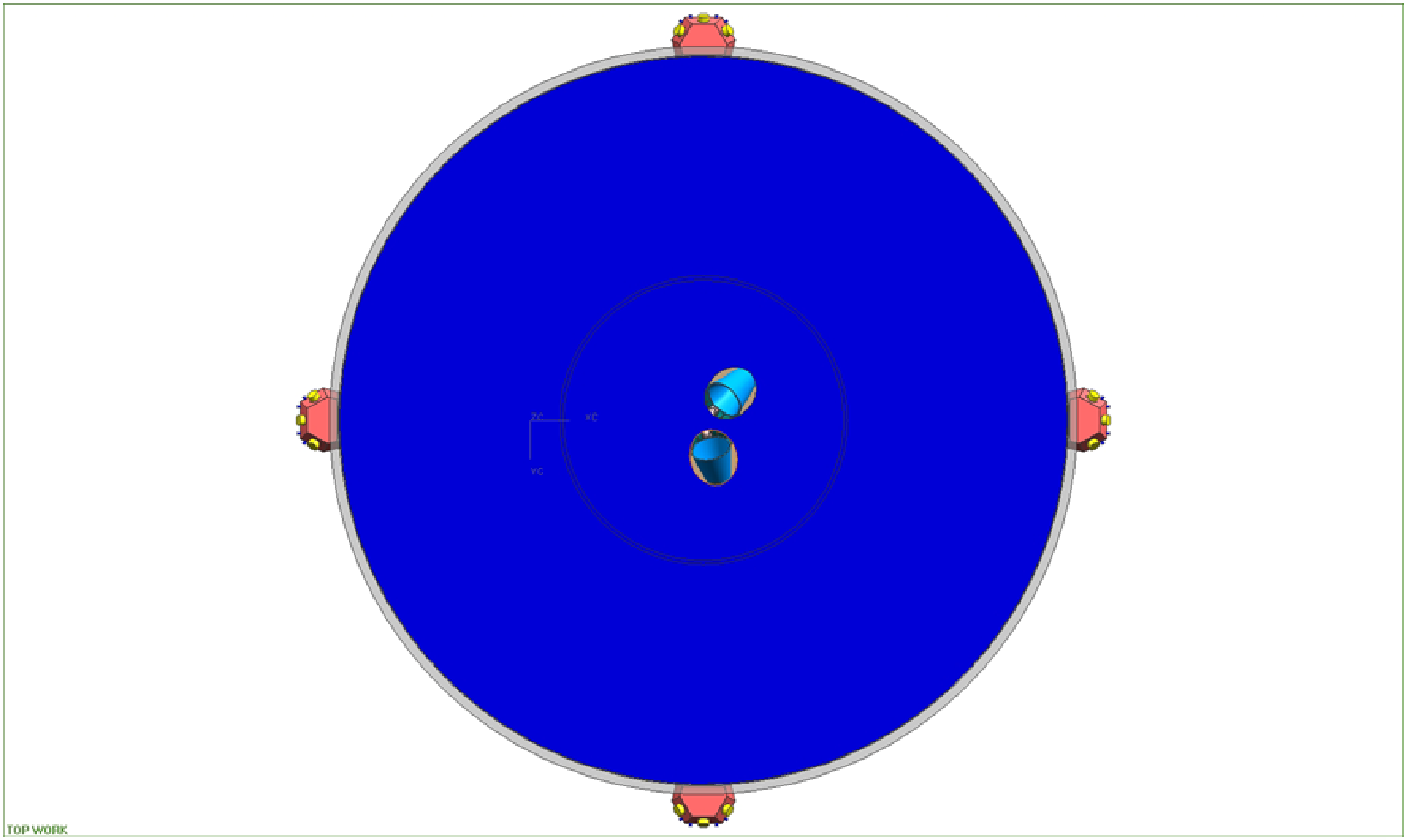
BEAM COMBINER-SIDE (TRANSPARENT)



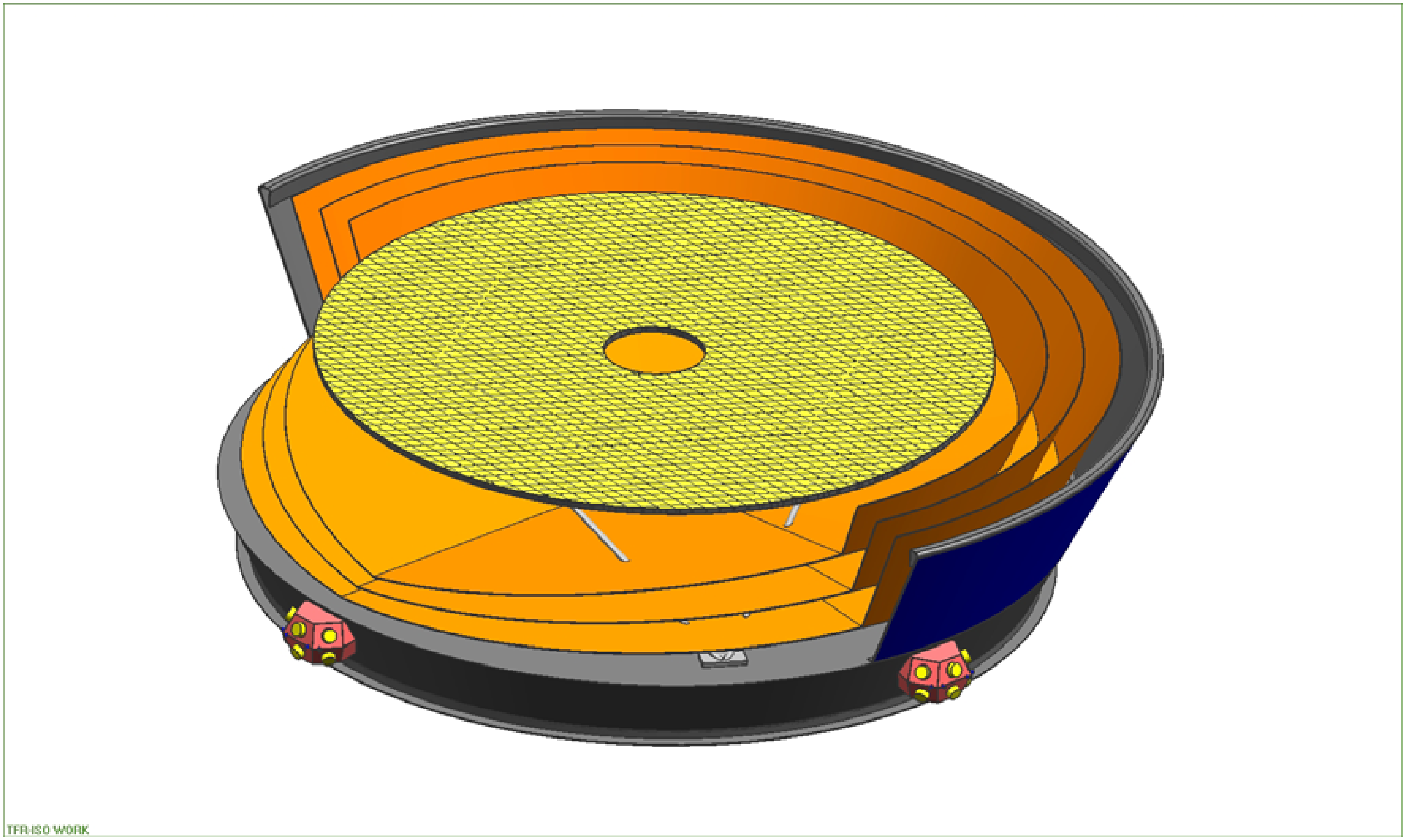
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

BEAM COMBINER-BOTTOM

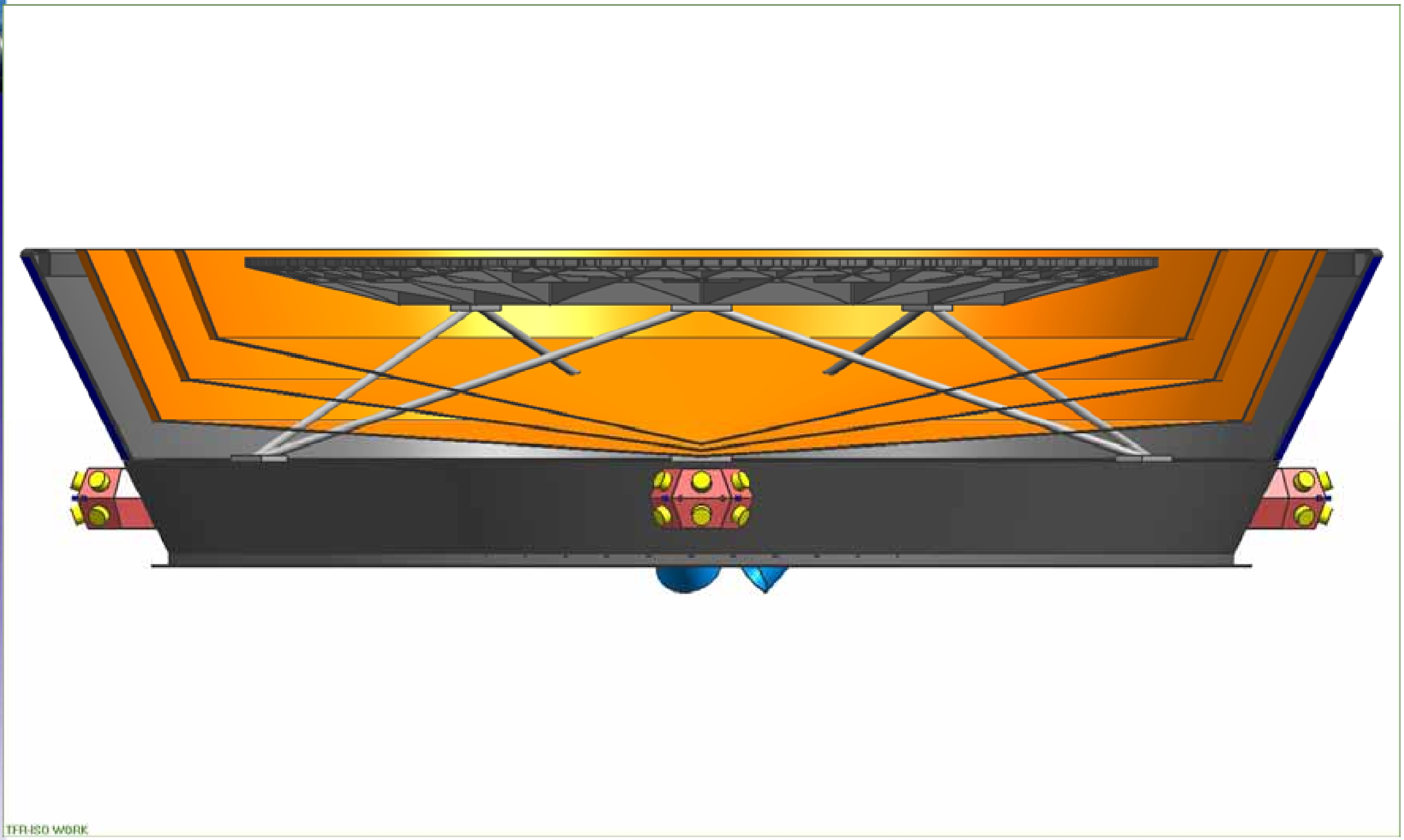
TPF Terrestrial Planet Finder



COLLECTOR SPACECRAFT

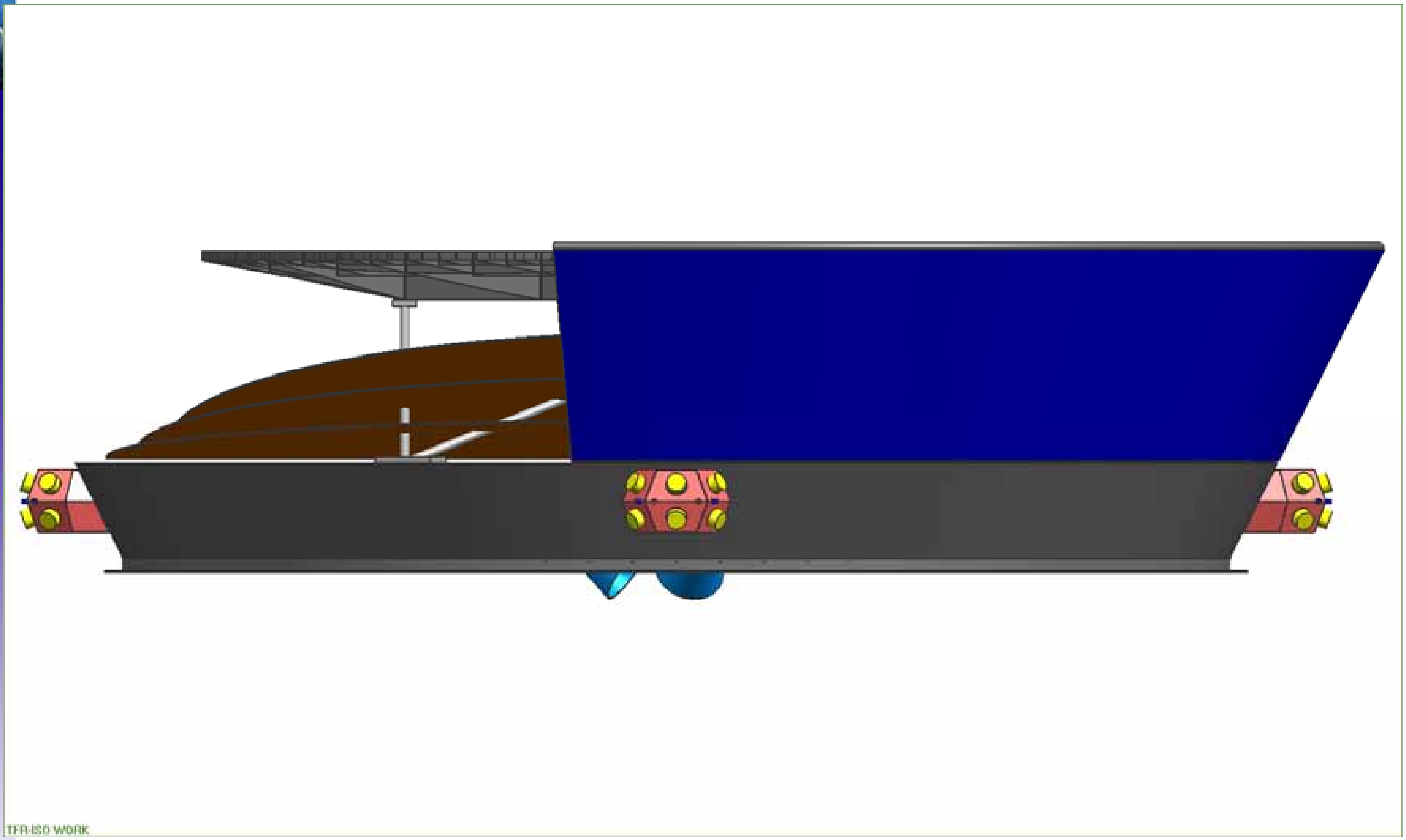


COLLECTOR-FRONT VIEW

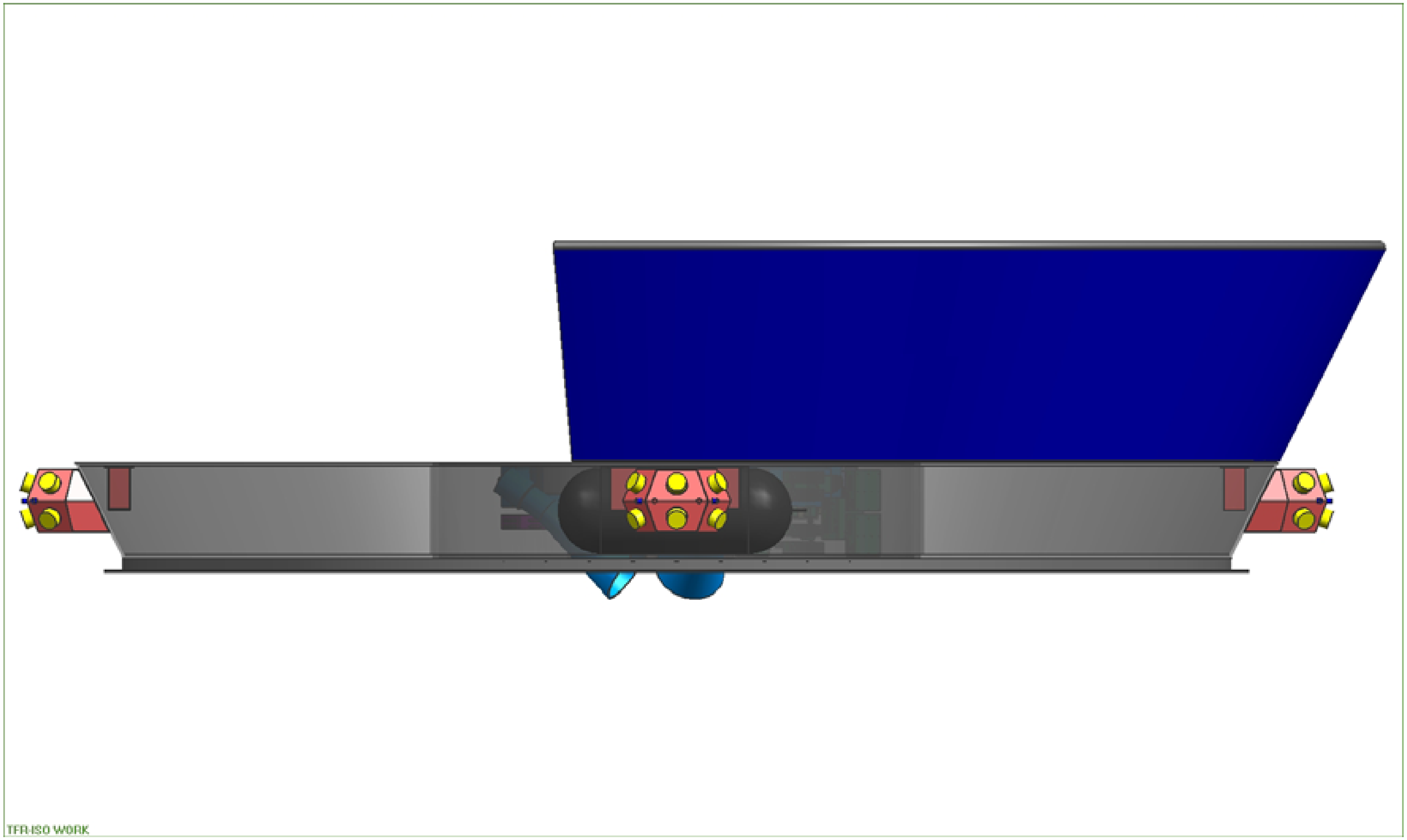


COLLECTOR-FRONT VIEW (TRANSPARENT BUS)

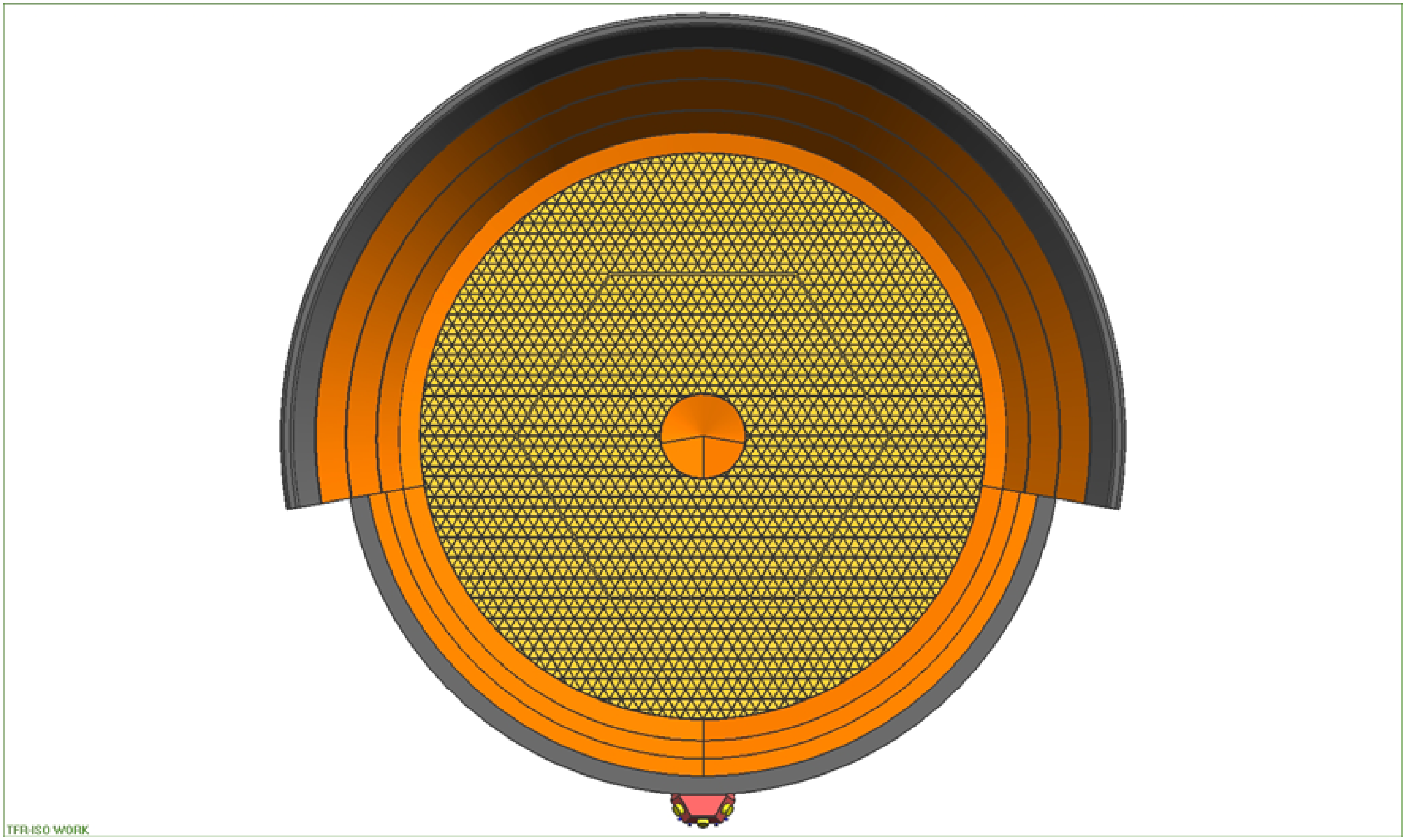
COLLECTOR-RIGHT SIDE VIEW



COLLECTOR-RITGHT SIDE (TRANSPARENT BUS)

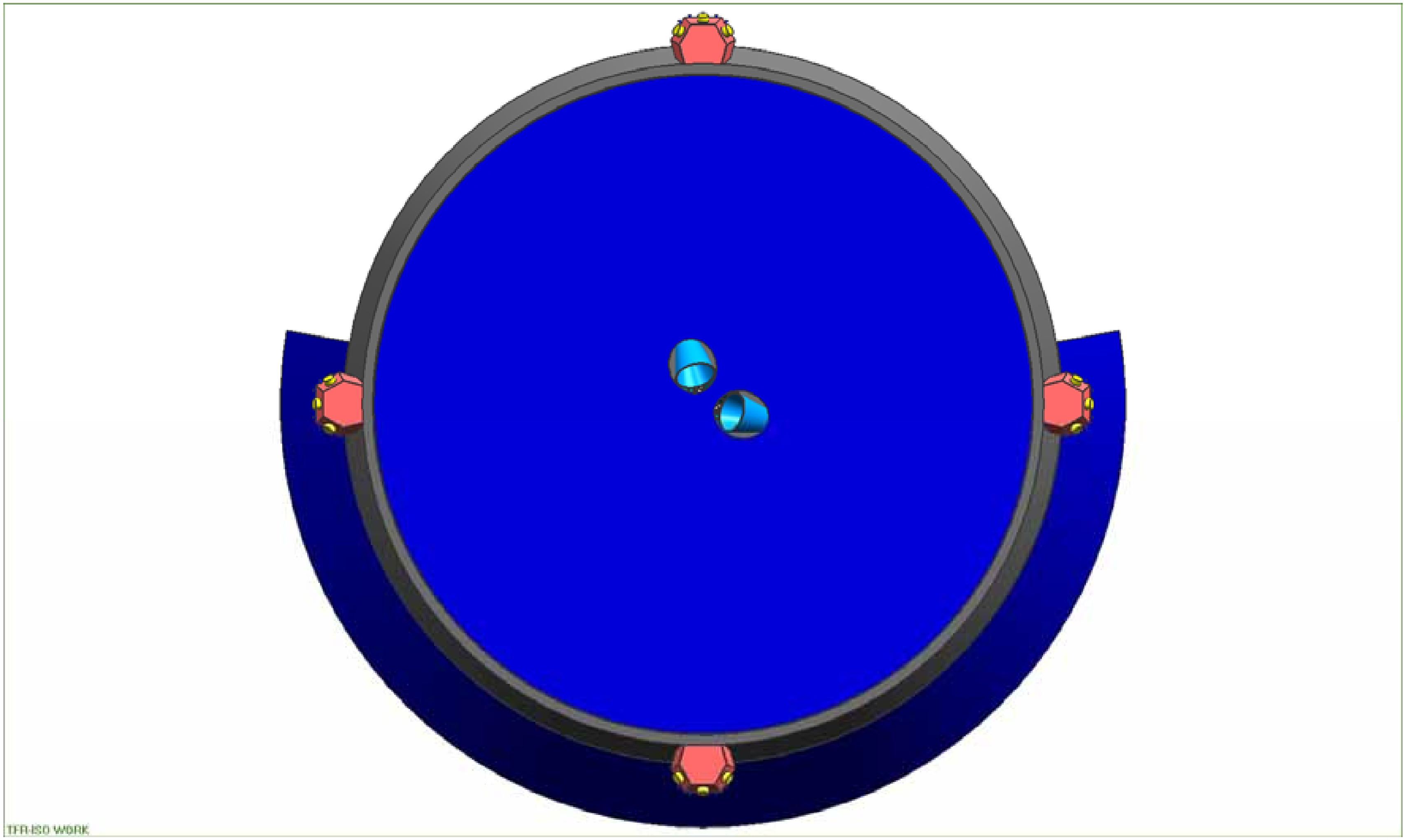


COLLECTOR-TOP VIEW



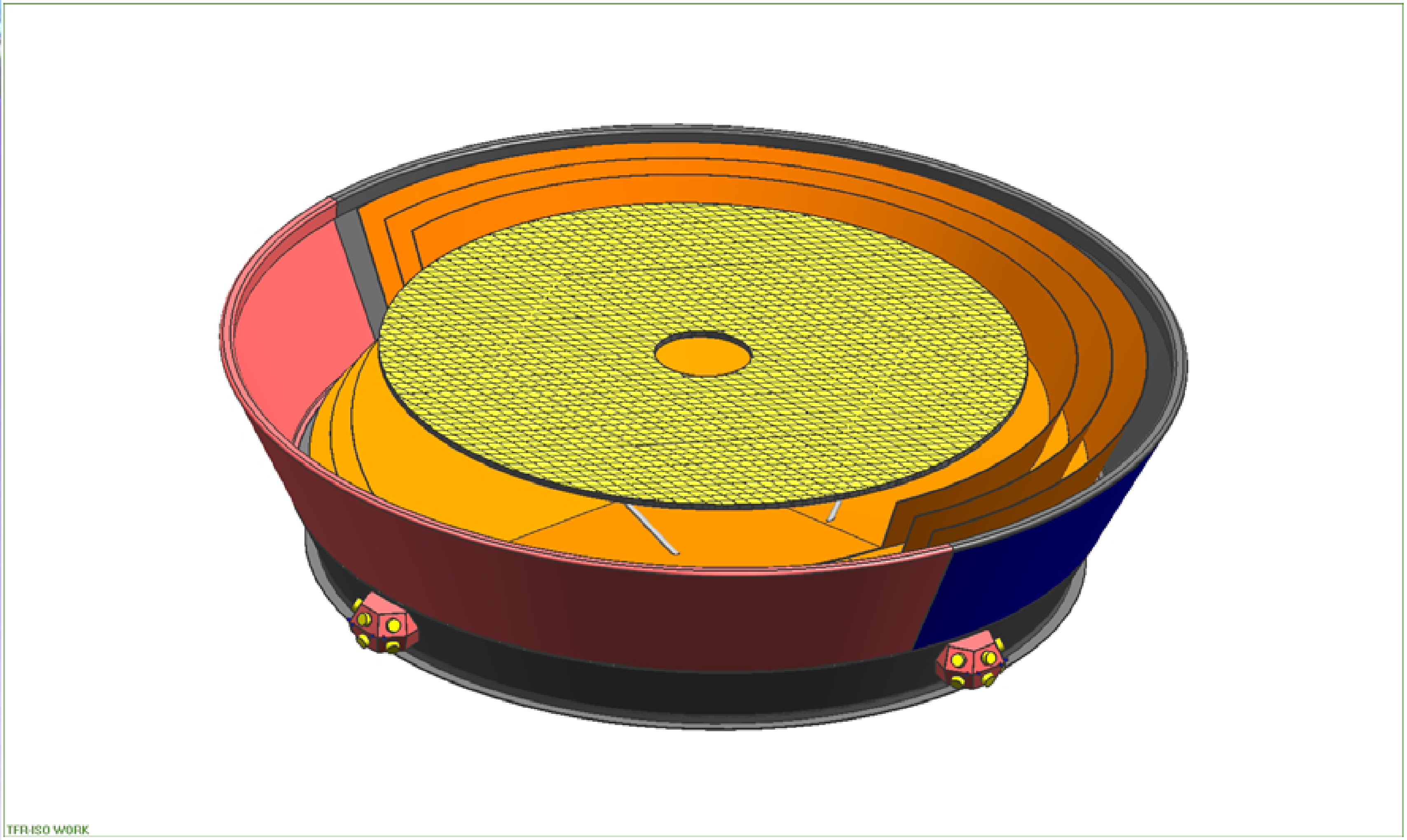
COLLECTOR-TOP VIEW (BUS COMPONENTS)

COLLECTOR-BOTTOM VIEW

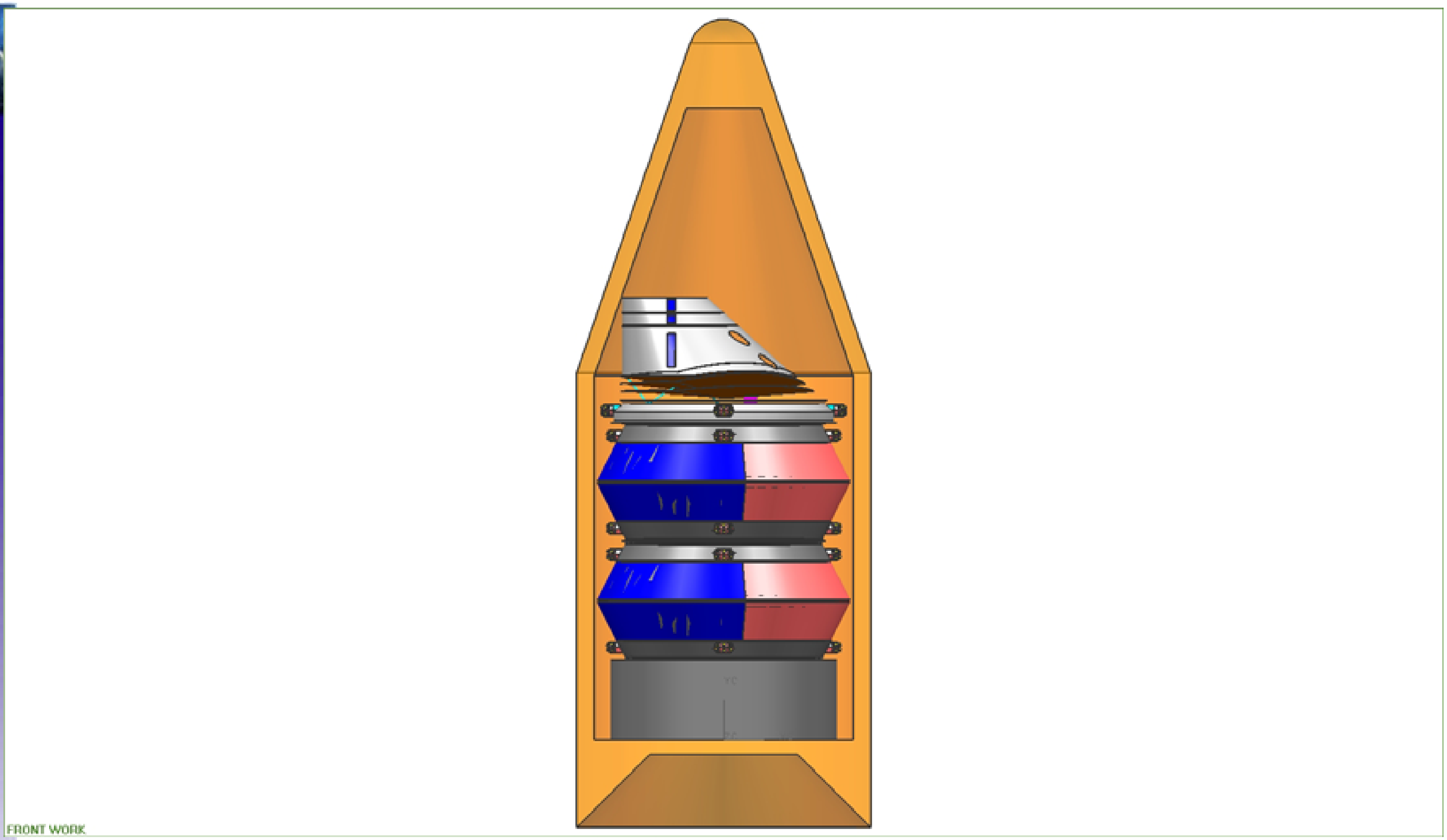


COLLECTOR (TRANSPARNET BUS)

COLLECTOR W/ADDITIONAL SHELL FOR LAUNCH



LAUNCH VEHICLE (DELTA IV M+)



Acknowledgments

- This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

TPF Terrestrial Planet Finder

EMMA DESIGN STUDY
Cryo/Thermal Design and Analysis

Dr. Jose I. Rodriguez

Cryogenic Systems Engineering Group
Jet Propulsion Laboratory
California Institute of Technology

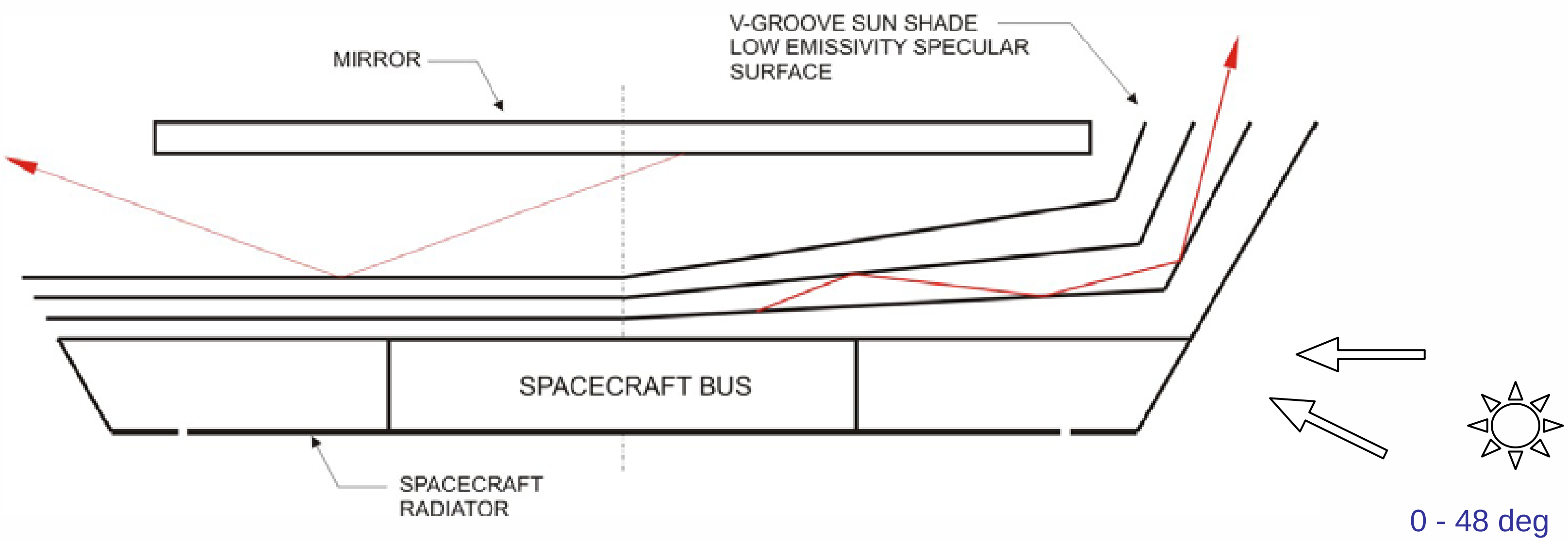
Thermal Design Objectives

Collector Spacecraft

- Primary mirror
  - Temperature < 50K
  - Minimize radial temperature gradient
- Provide waste heat rejection system with ~1000W capacity
- Minimize infrared radiation flux from v-groove sunshade on combiner spacecraft at a distance of 1200m
- Minimize inter-spacecraft infrared heating effects for conditions with minimum spacecraft separation

V-Groove Sunshade Design

Collector Spacecraft



Collector Spacecraft
Thermal Model Assumptions

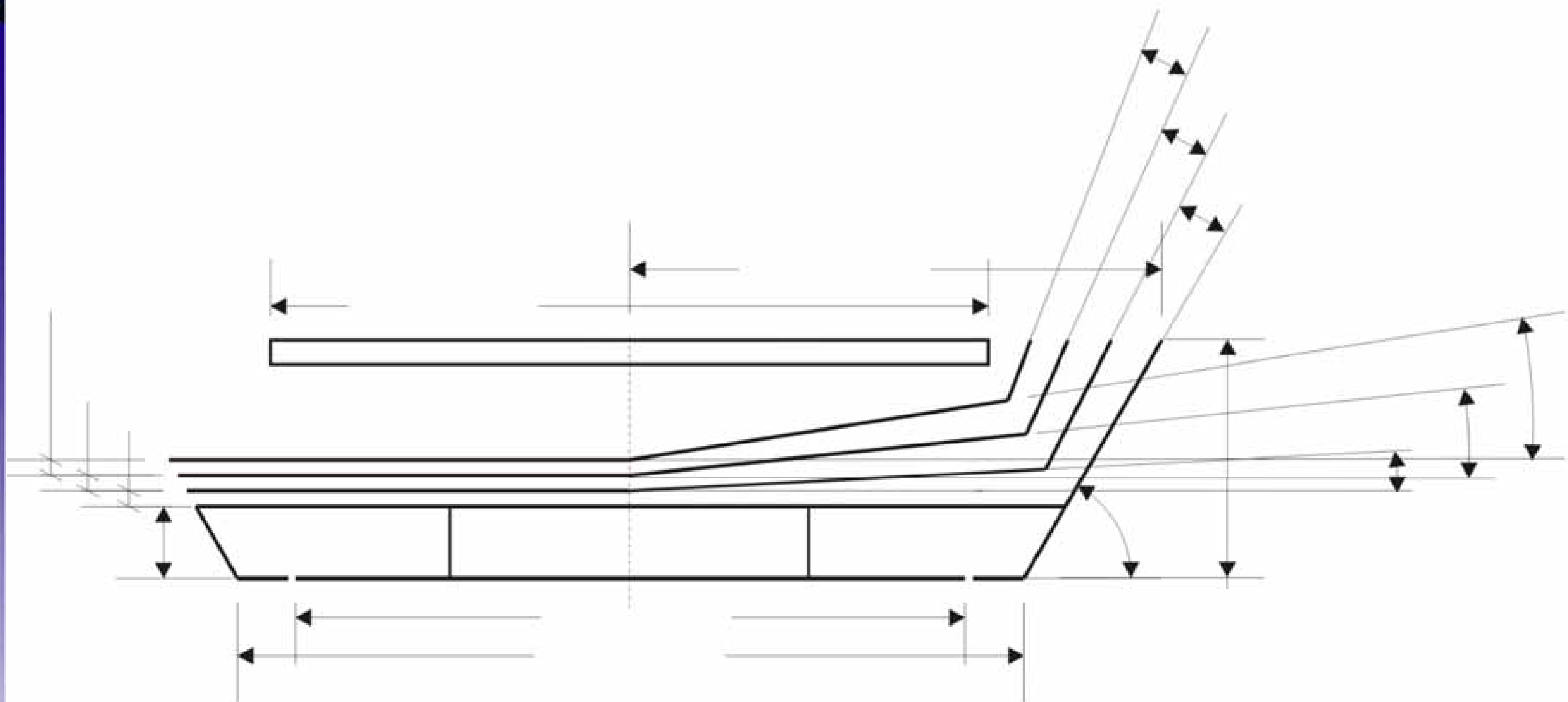
- Primary mirror
  - Dimensions: 3.0m diam
  - Thermo-optical properties:
    - Gold on top surface (α =0.3, ε =0.05)
    - Black on bottom and edge (α =1.0, ε =1.0)
- V-groove sunshade
  - Sunshade with 3 grooved film layers
    - Diverging angle, 3 deg
    - Minimum separation, 65mm
  - Specular vapor deposited aluminum (VDA, ρ_{IR} =0.75)
  - Low emissivity (α =0.05, ε =0.45)
- Spacecraft bus radiator
  - White paint (α =0.21, ε =0.88)
- Solar array
  - Area 5.75m^2
  - Thermo-optical properties (α =0.8, ε =0.94)

Collector Spacecraft
Thermal Model Assumptions (Cont'd)

- Mirror is supported with three gamma-alumina bipods with an A/L ratio of 0.44mm for each bipod
  - Approximate conductive heat load is ~350mW
  - High infrared effective emittance on back side of mirror
- Mirror thermal conductance
  - Assumed material with kt_{eff}=0.15 W/K (i.e. low conductance)
  - Effective mirror thickness (t_{eff}) is a function of the ribbed grid pattern geometry
- All of the spacecraft bus electrical power dissipation is rejected to space via the spacecraft bus radiator at the bottom of the spacecraft
  - Spacecraft bus power dissipation, 1000W
  - Assumed spacecraft radiator is 6.15m^2 (power dissipation flux of 163W/m^2)

Collector Spacecraft

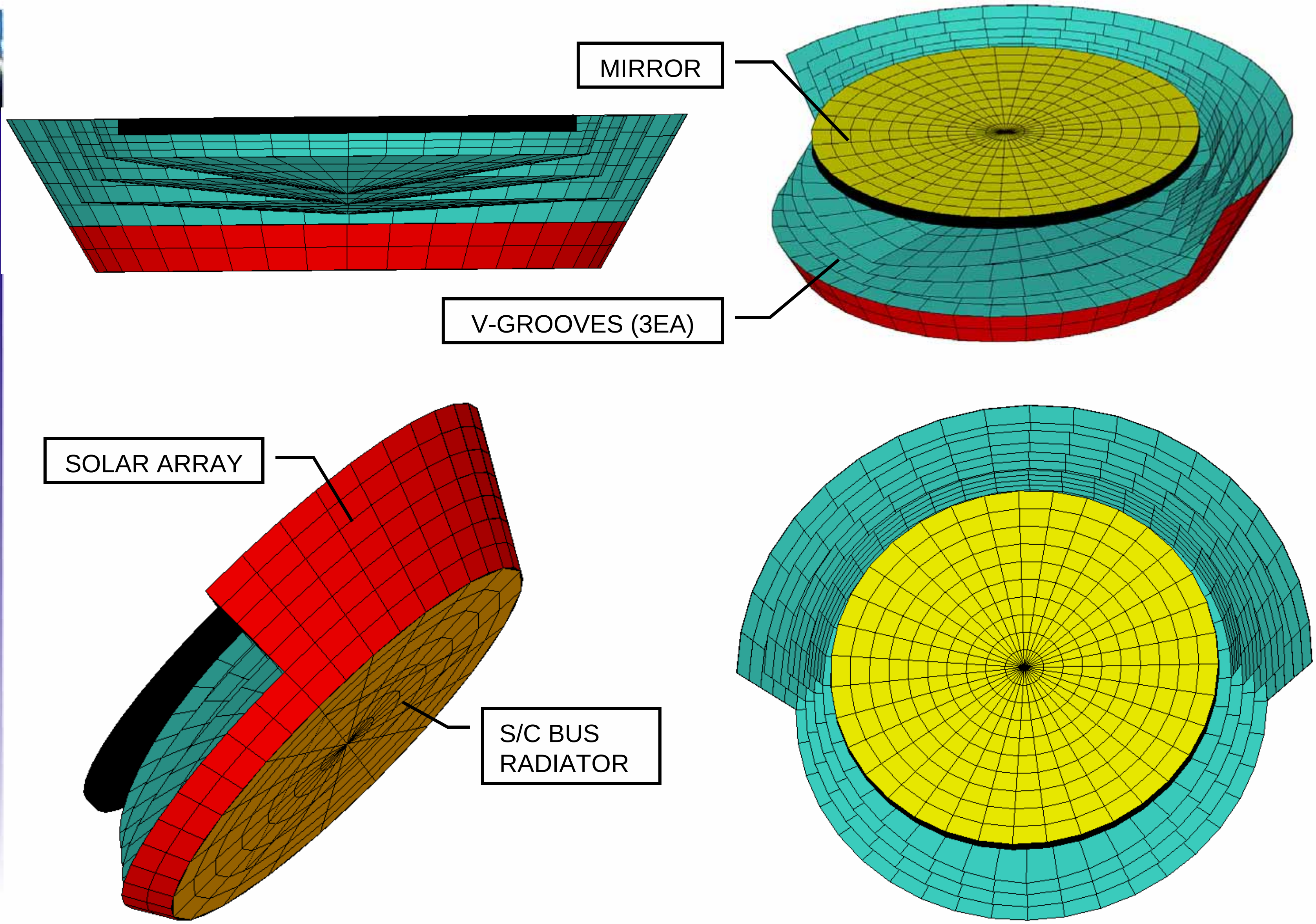
Thermal Model Geometry



Thermal Analysis Tools

- Geometric Mathematical Model (GMM) developed with Thermal Synthesizer System (TSS) ver. 11.01
  - Defines geometry with thermo-optical surface properties
  - Computes IR radiation exchange factors
  - Computes environmental heat loads
- Thermal Mathematical Model (TMM) developed with Sinda/Fluint ver. 5
  - Finite-difference nodal network with boundary conditions
  - Solver uses iterative or matrix inversion to obtain solution
  - Temperature solution is mapped to geometric model in TSS for analysis and review

Collector Spacecraft - GMM

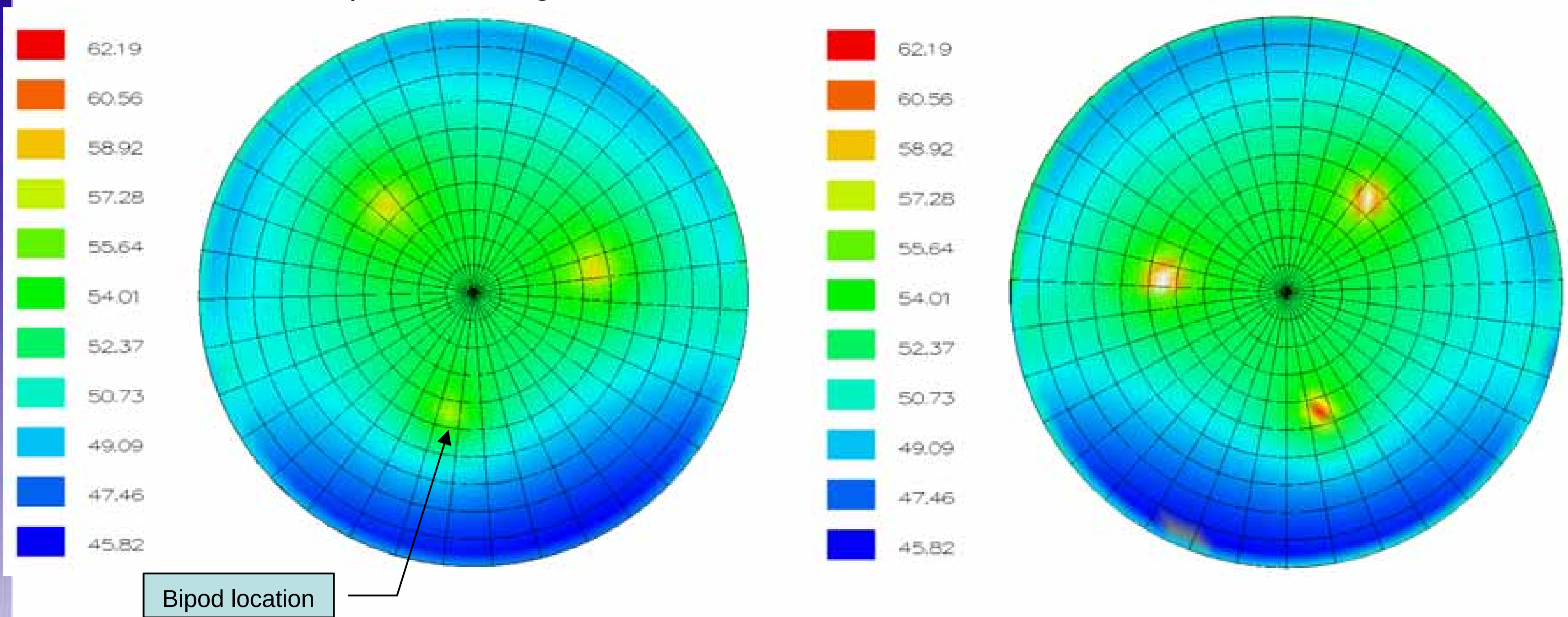


Thermal Analysis
Mirror Temperature Profile

Mirror Support uses 3-bipods with A/L=0.44mm each (i.e.~127mW/bipod)

Space Viewing Side

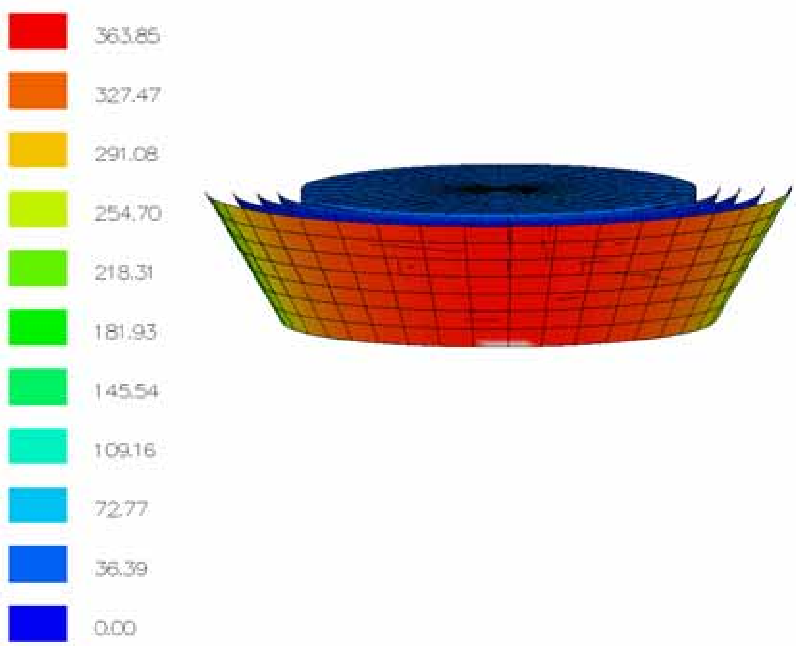
Back Side

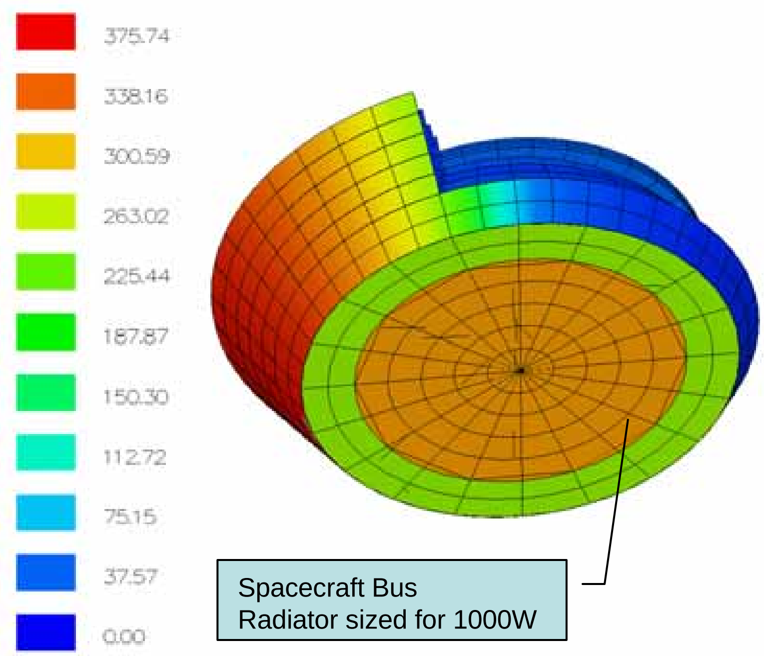


Higher kt_{eff} (i.e. =1.7 W/K) results in $\Delta T<5K$

Degrees in Kelvin

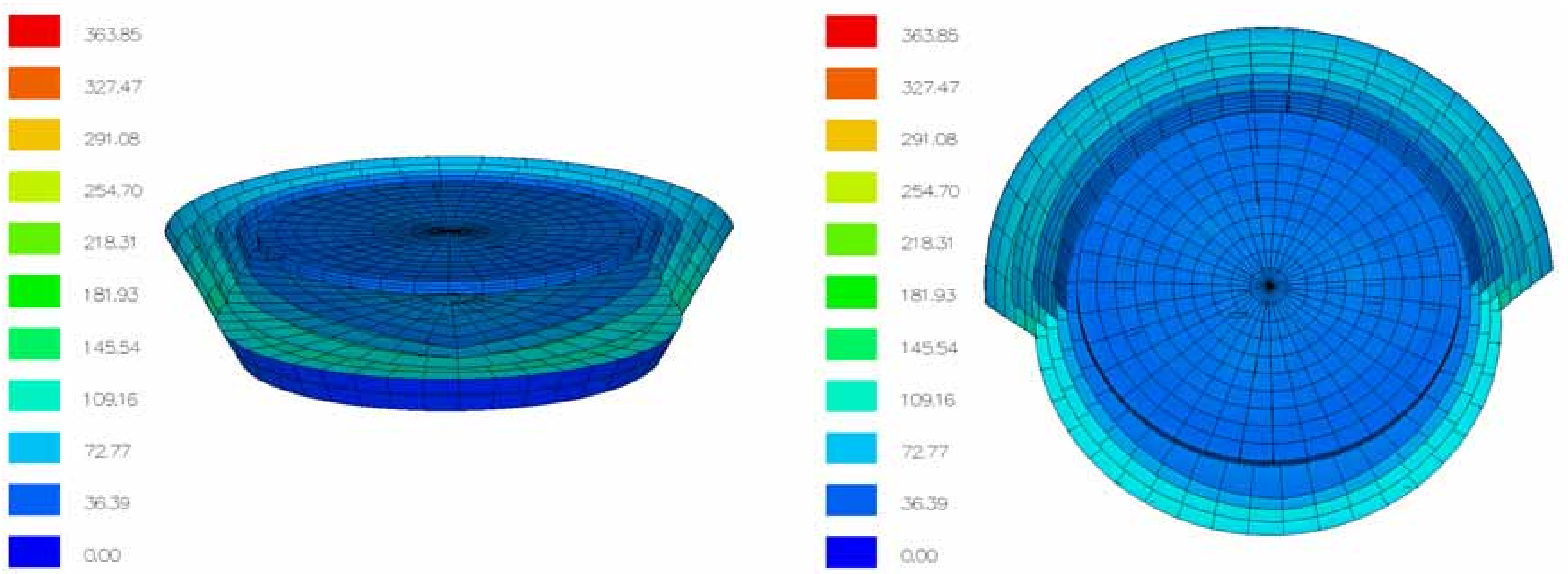
Thermal Analysis Results (Cont'd)





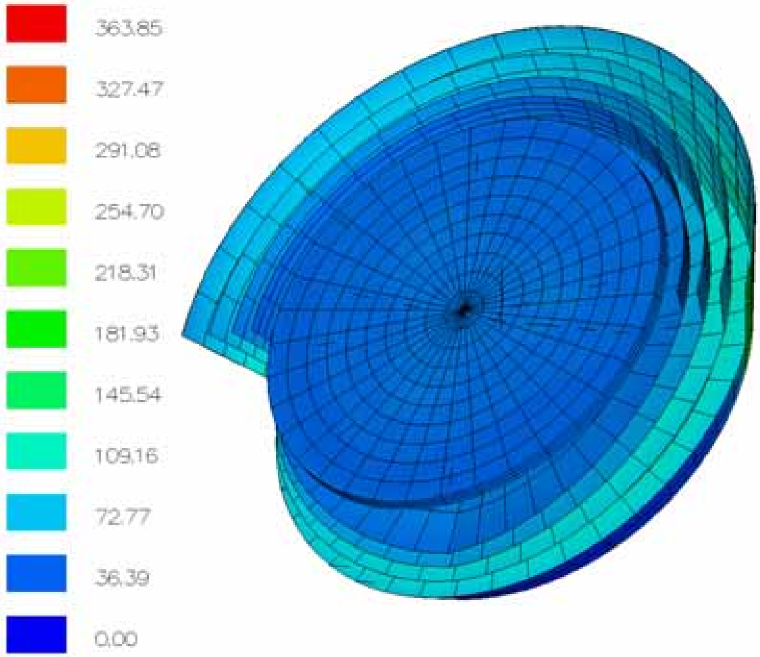
Degrees in Kelvin

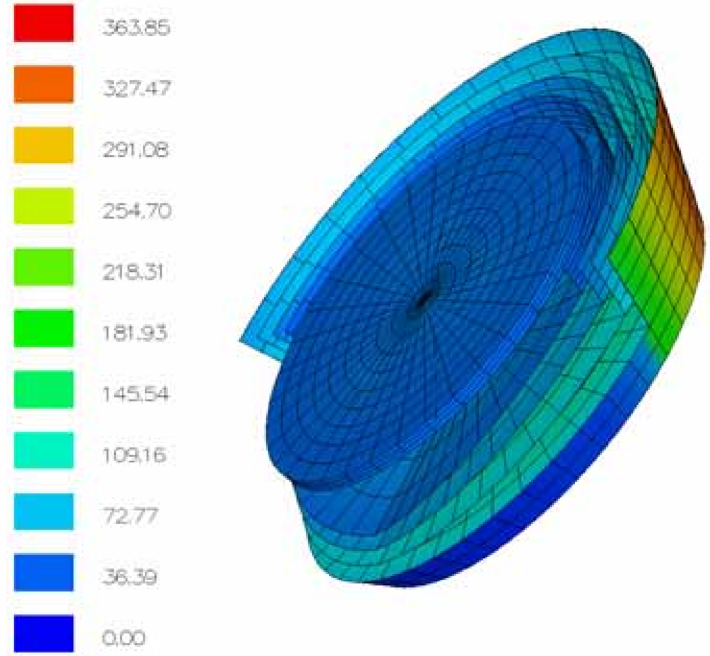
Thermal Analysis Results (Cont'd)



Degrees in Kelvin

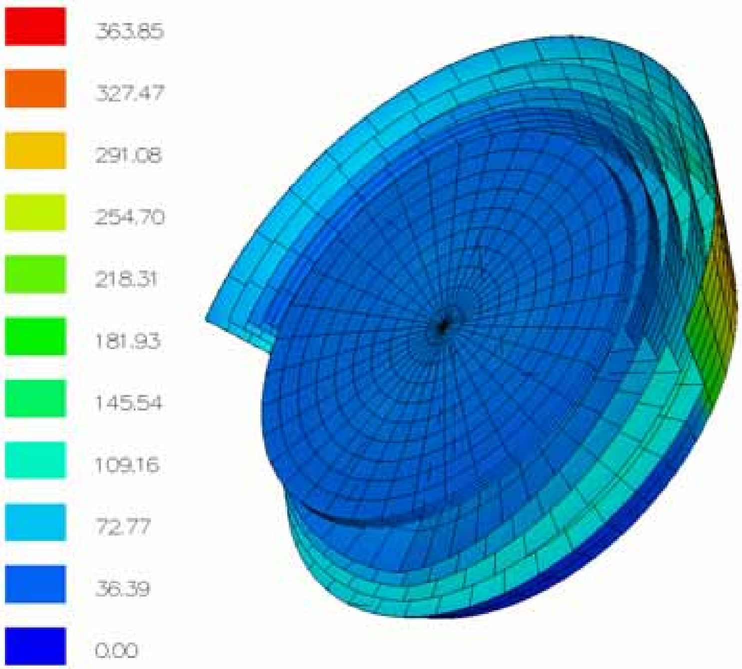
Thermal Analysis Results (Cont'd)

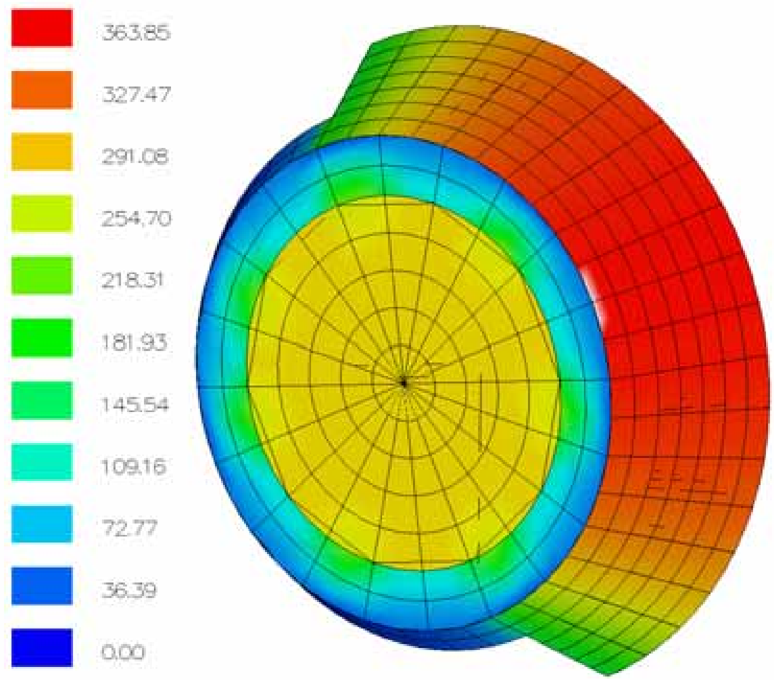




Degrees in Kelvin

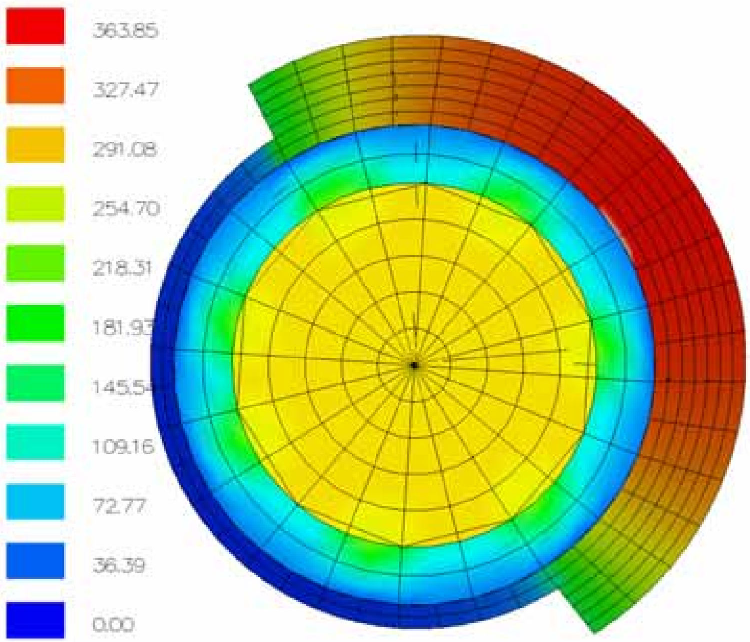
Thermal Analysis Results (Cont'd)

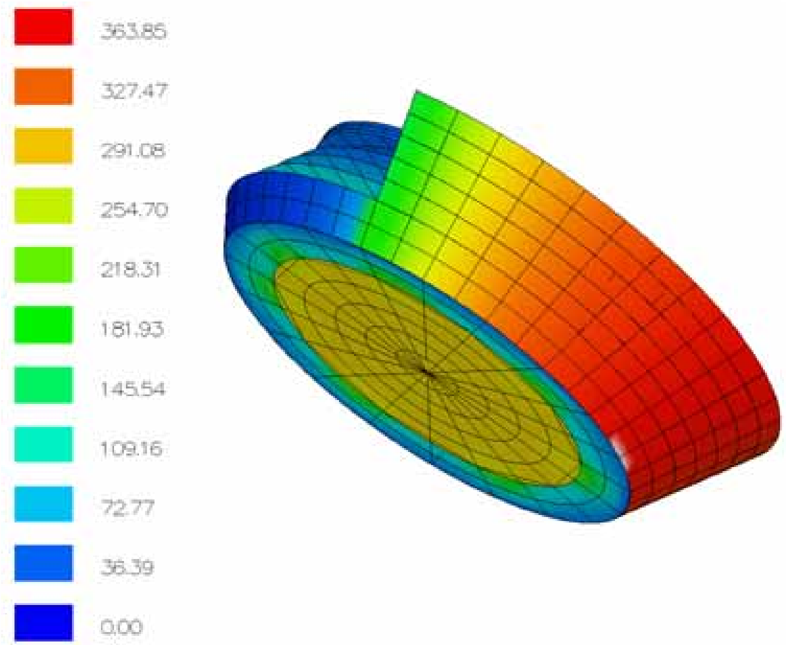




Degrees in Kelvin

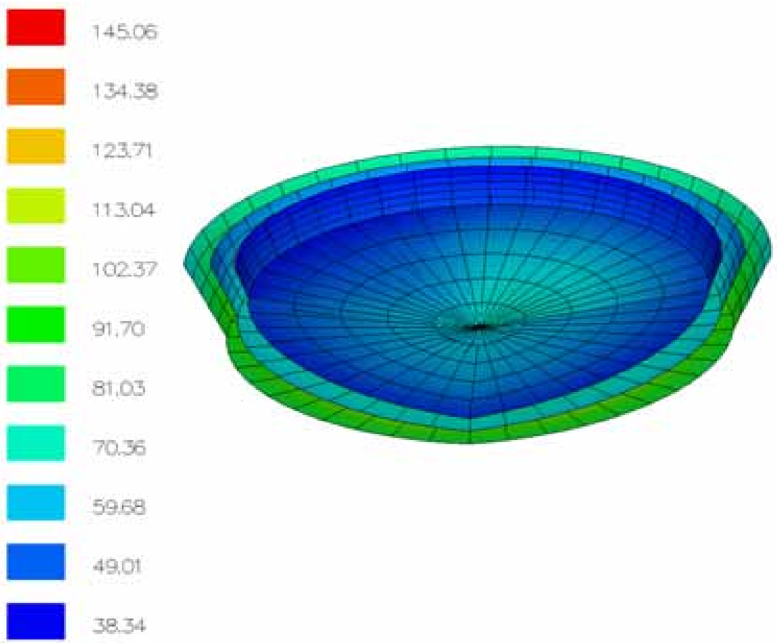
Thermal Analysis Results (Cont'd)

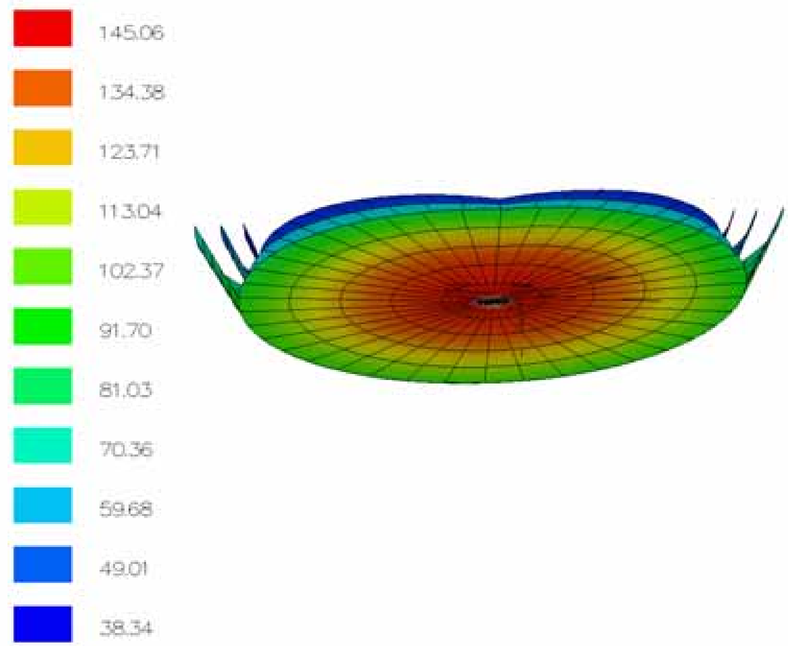




Degrees in Kelvin

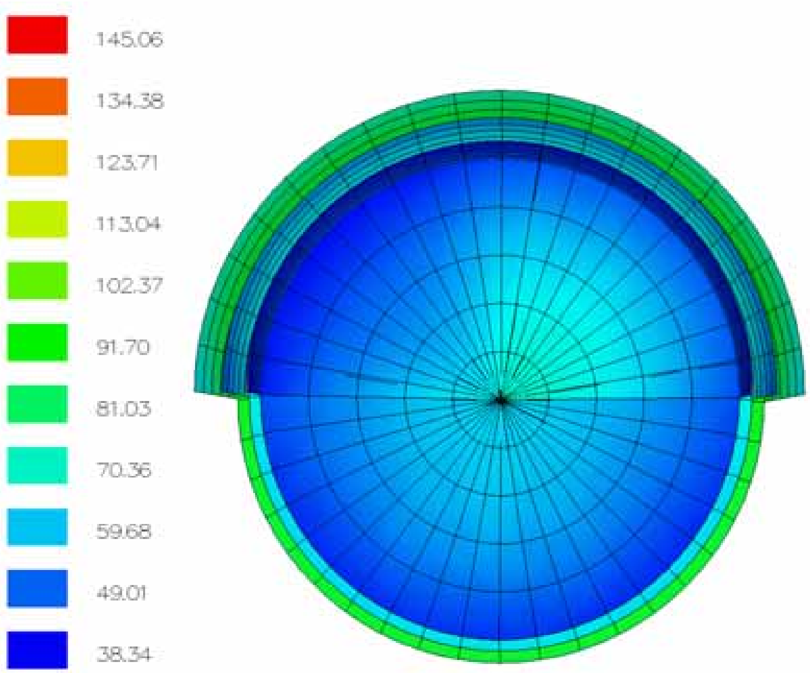
Thermal Analysis Results (Cont'd)

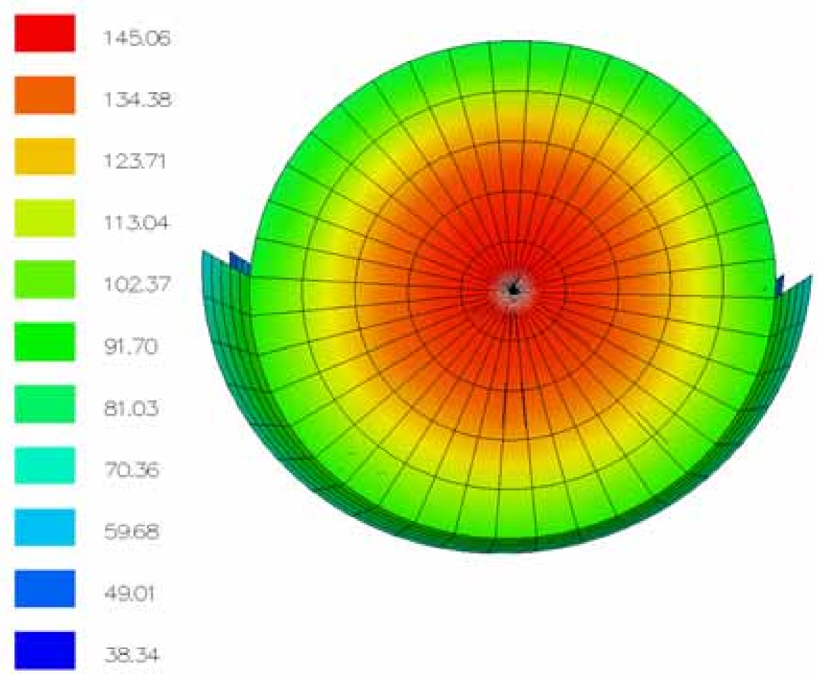




Degrees in Kelvin

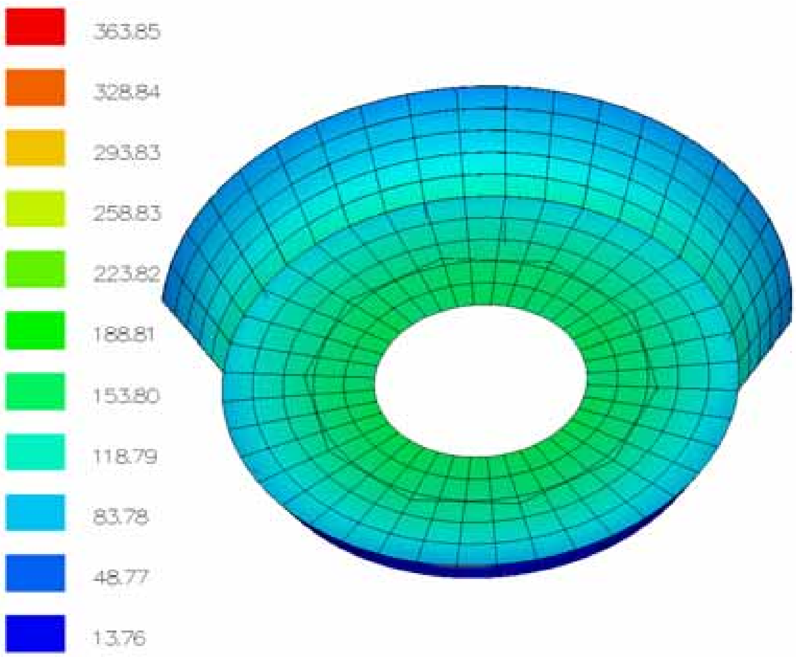
Thermal Analysis Results (Cont'd)

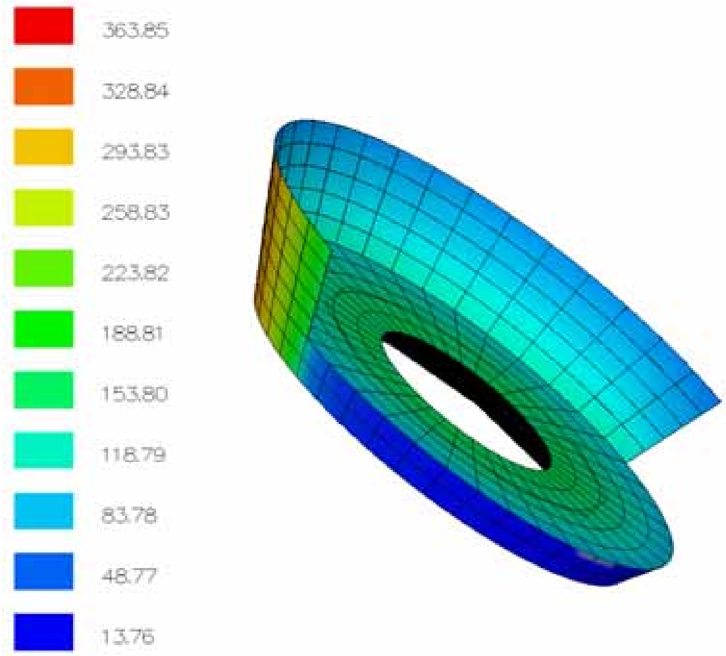




Degrees in Kelvin

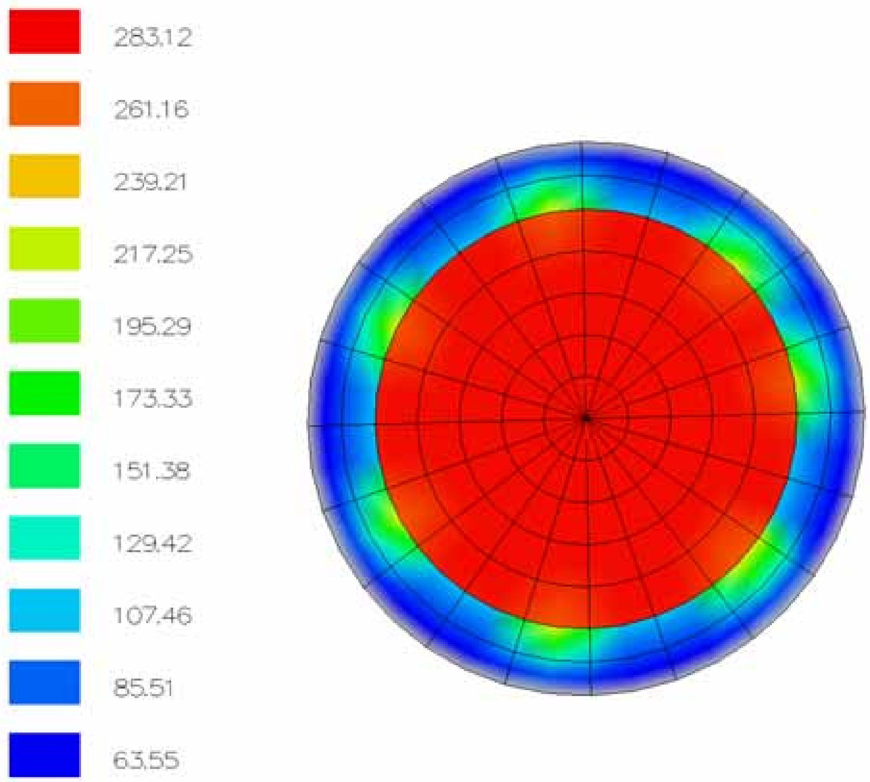
Thermal Analysis Results (Cont'd)





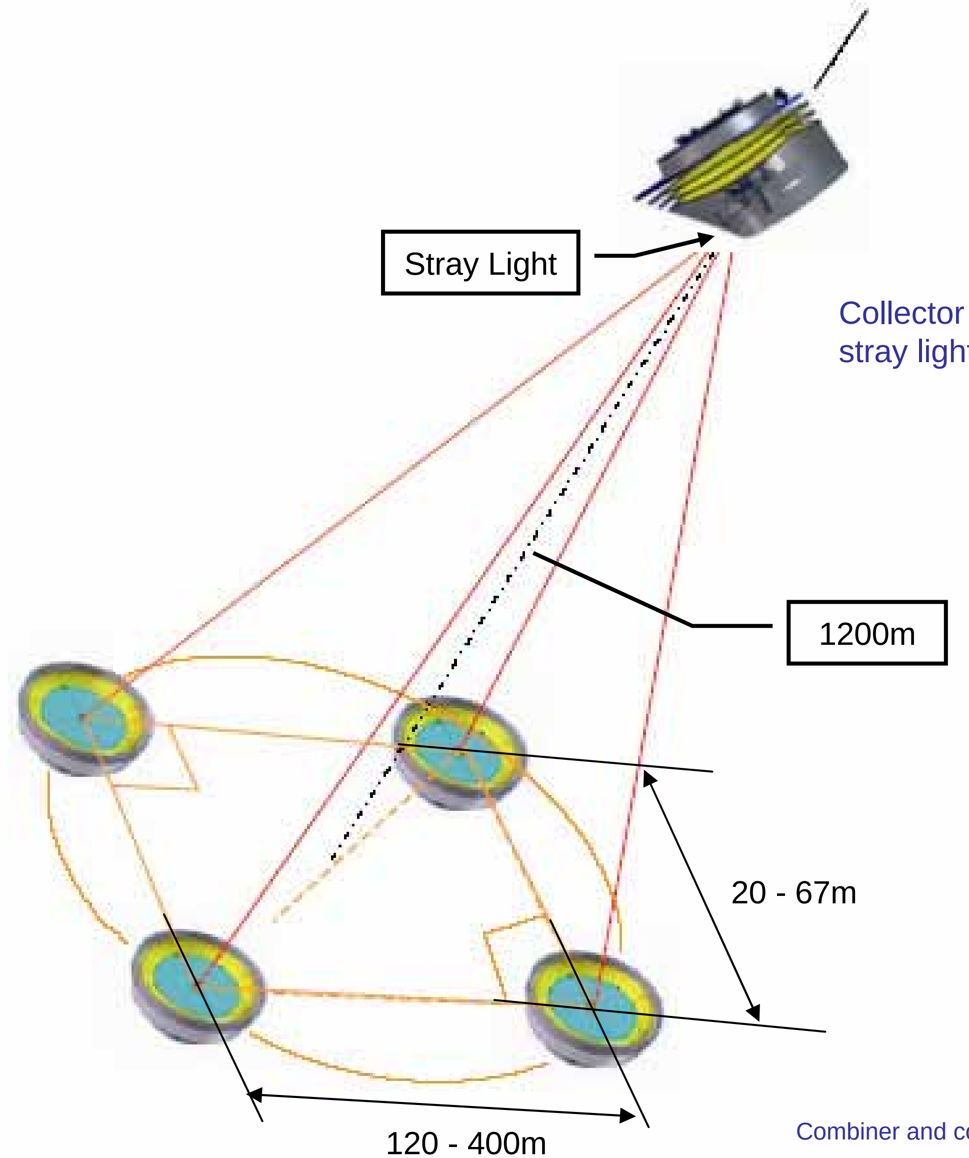
Degrees in Kelvin

Thermal Analysis Results (Cont'd)



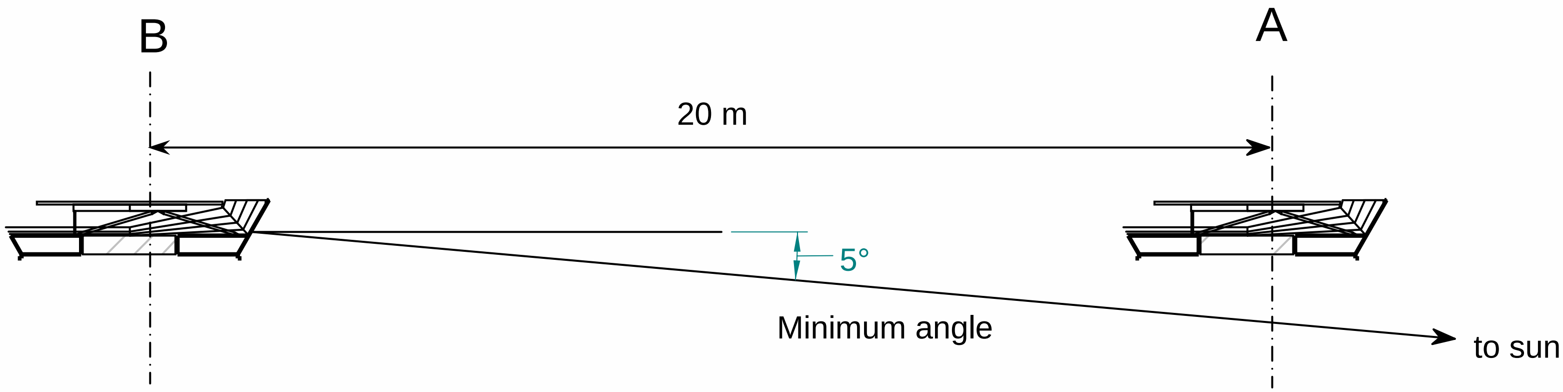
Degrees in Kelvin

Infrared Heating at Combiner Spacecraft



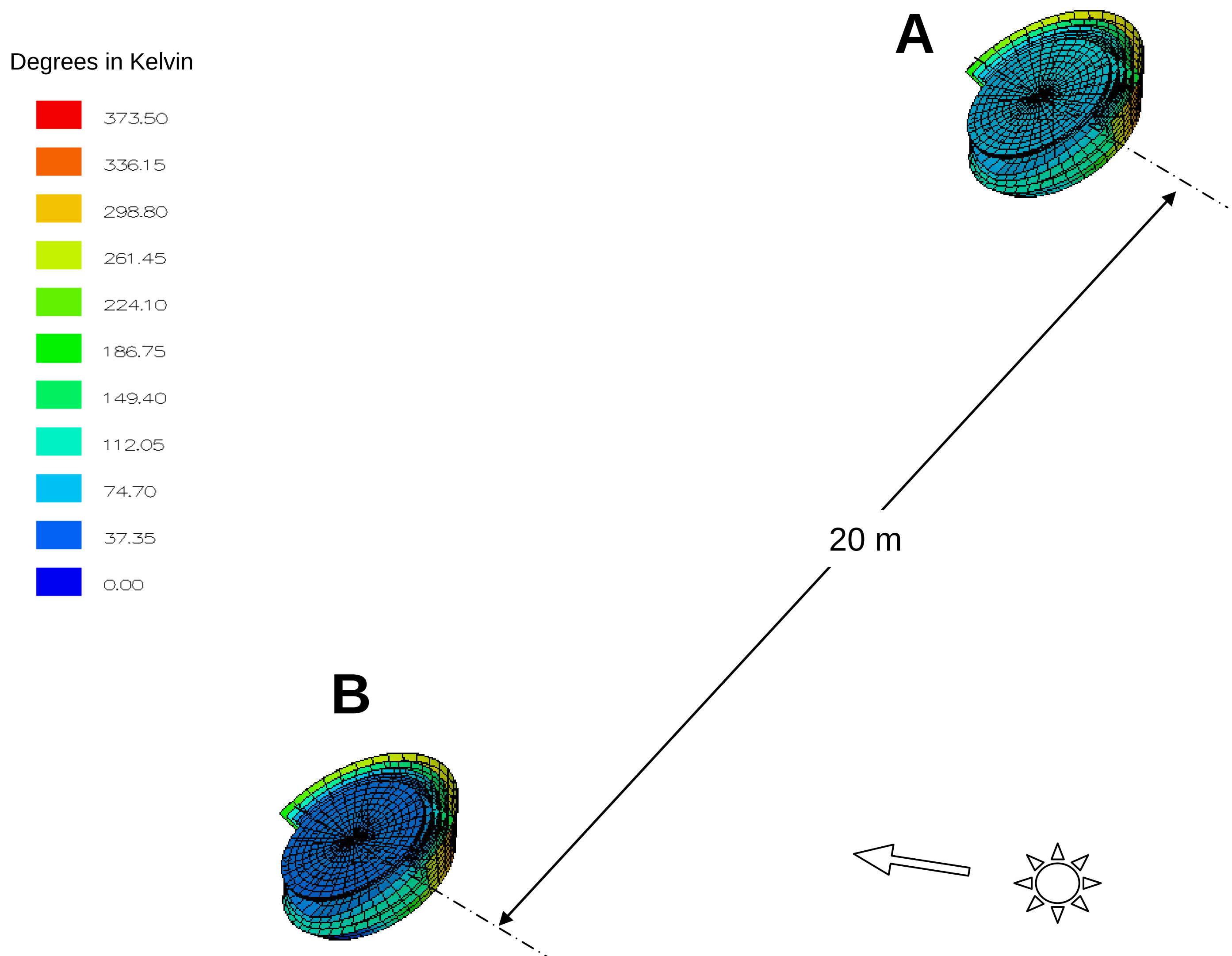
Combiner and collector drawings by Alcatel Alenia Space

Heating from Adjacent Collector S/C



Spacecraft B will heat spacecraft A?
Will vary with angle

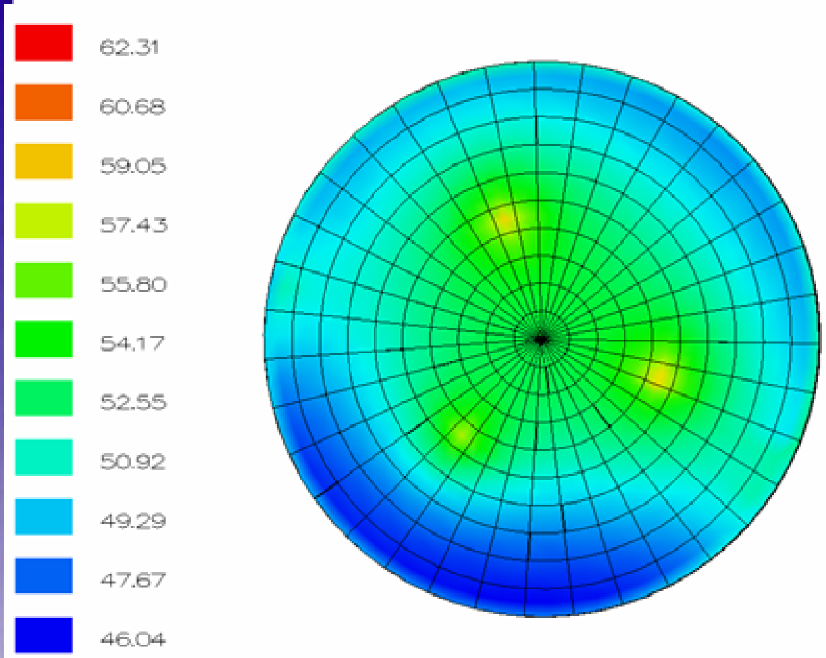
Thermal Analysis – Collectors A/B



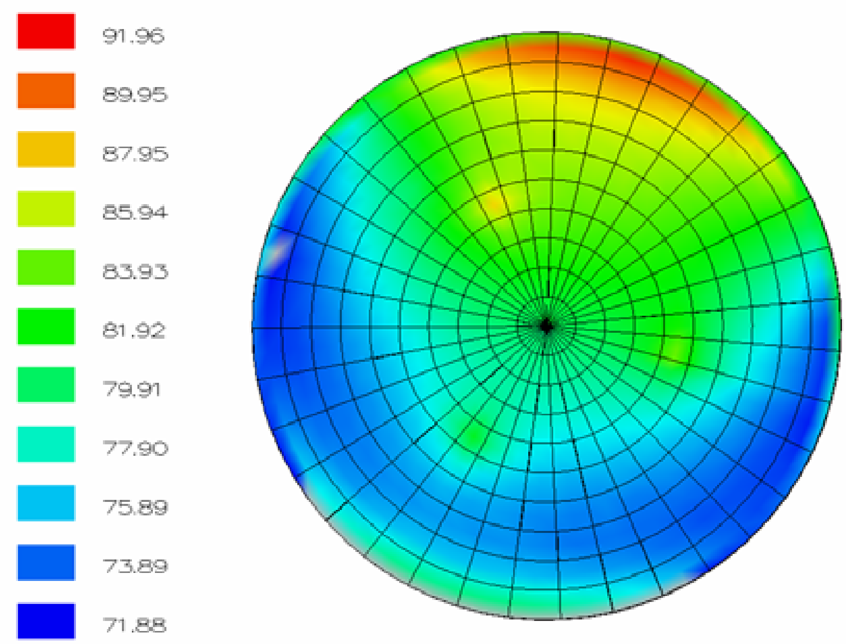
Thermal Analysis – Collectors A/B

TPF Terrestrial Planet Finder

Collector S/C B - Mirror



Collector S/C A - Mirror

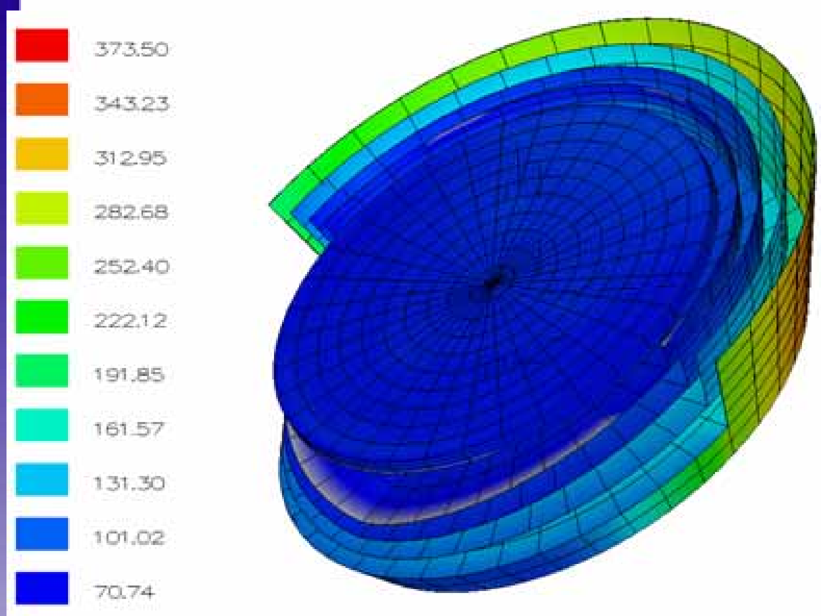


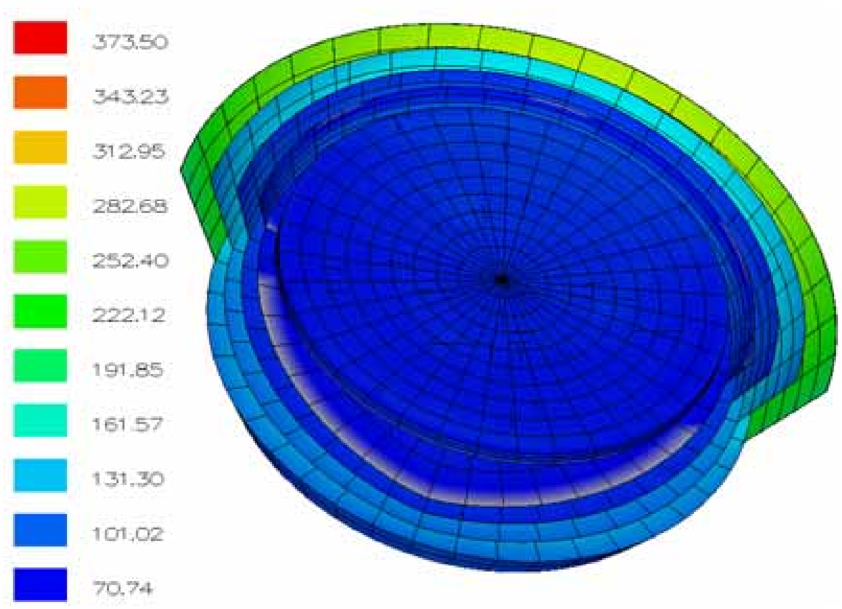
Degrees in Kelvin

Thermal Analysis – Collectors A/B

TPF Terrestrial Planet Finder

Collector Spacecraft A





Degrees in Kelvin

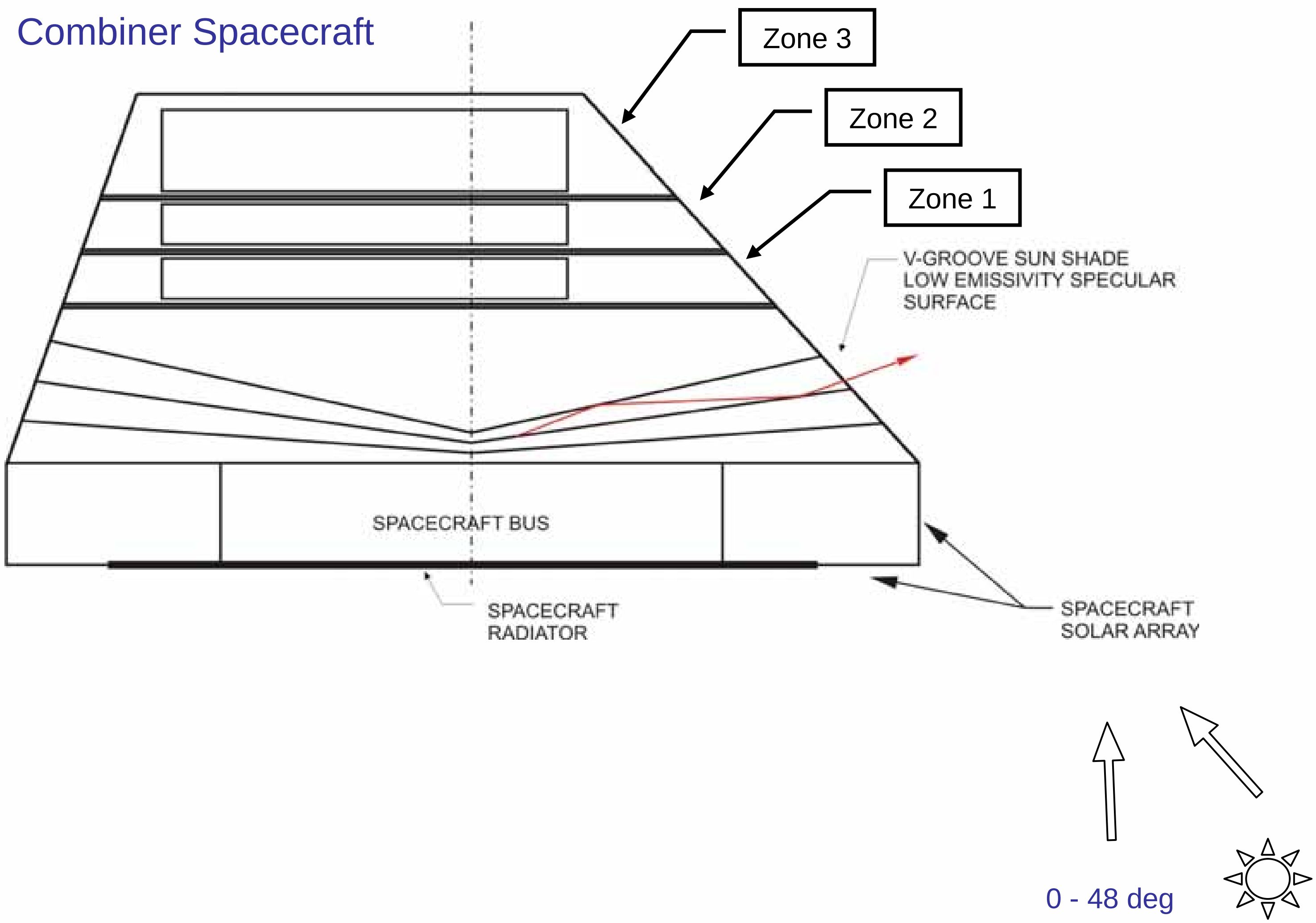
Combiner Spacecraft

Thermal Design Objectives

Combiner Spacecraft

- Provide a waste heat rejection system with ~1800W capacity
- Provide passive cooling means to cool optical bench, thermal shields and other hardware at three temperature stages:
  - 80K temperature for zone 1 with 250mW cooling
  - 60K temperature for zone 2 with 250mW cooling
  - 40K temperature for zone 3 with 250mW cooling
- Provide means to cool detector to 7K with 65mW of cooling

V-Groove Sun Shield Design



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Combiner Spacecraft

Thermal Model Assumptions

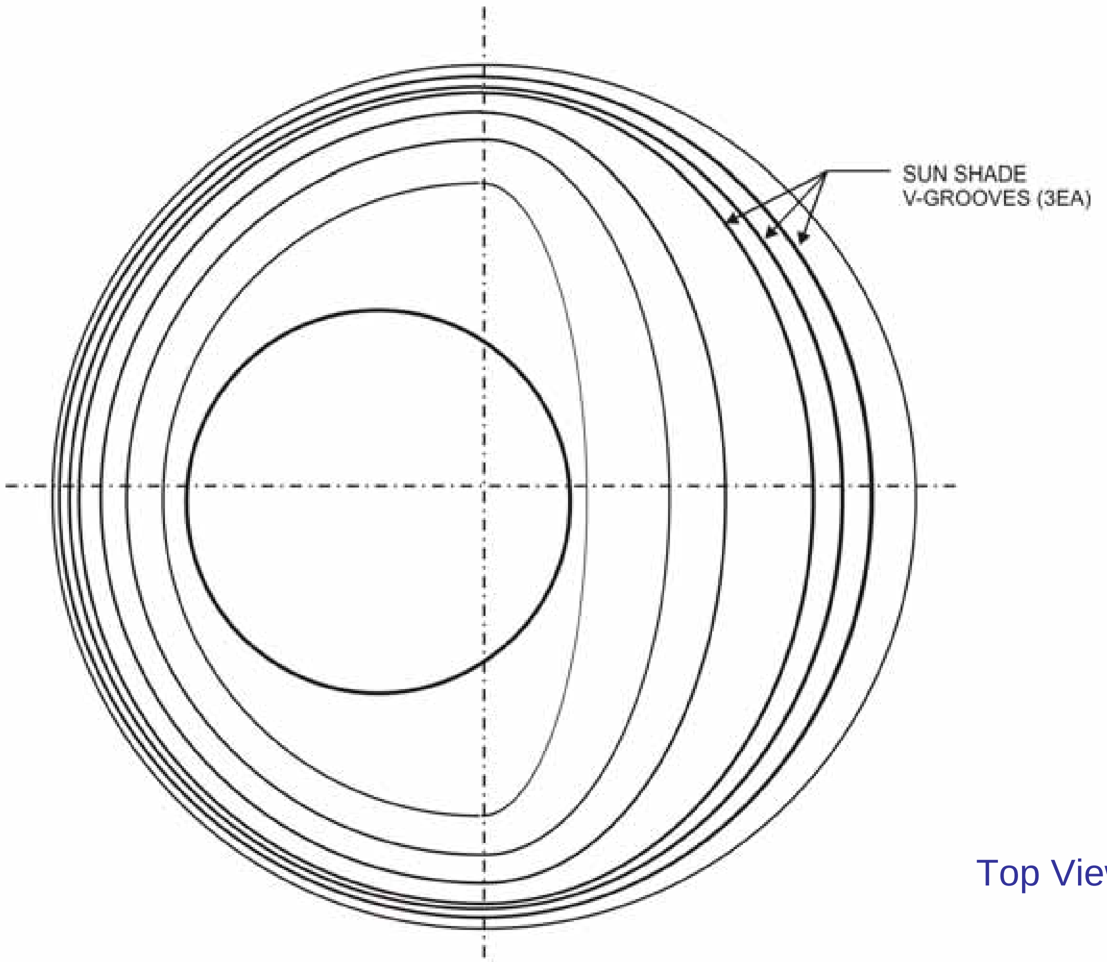
- V-groove sunshade (3ea)
  - Specular vapor deposited aluminum (VDA, ρ_{IR} =0.75)
  - Low emissivity (α =0.45, ε =0.05)
  - Geometry
    - Diverging angle, 4 deg
    - Minimum separation, 50mm
- Spacecraft bus radiator
  - White paint (α =0.21, ε =0.88)
- Solar array
  - Area 13.35m^2
  - Thermo-optical properties (α =0.8, ε =0.94)

Combiner Spacecraft

Thermal Model Assumptions (Cont'd)

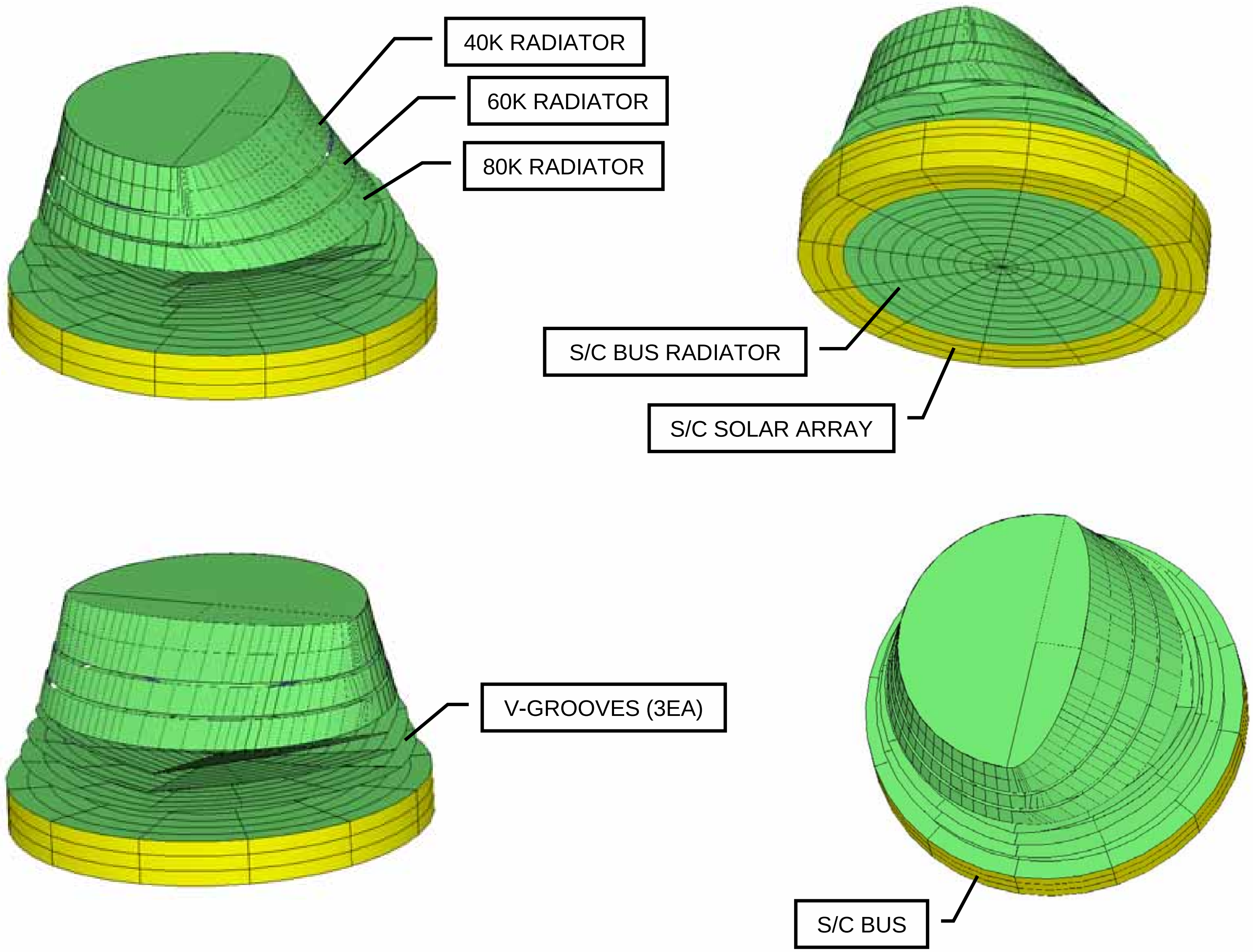
- All of the spacecraft bus electrical power dissipation is rejected to space via the spacecraft bus radiator at the base of the spacecraft
  - Spacecraft bus power dissipation, 1800W
  - Assumed spacecraft radiator is 9.62m^2 (power dissipation flux of 187W/m^2)
- Assumes the JWST MIRI 6K cryocooler is used to cool detector array to 6.7K
  - Cooler uses pulse tube precooler and Joule-Thomson helium circuit to provide 6K cooling at the detector up to a 10m away
  - Electrical input power 400W with 65mW heat load
  - Total mass is 70kg including cooler control electronics and electrical harnesses

Combiner Spacecraft
Thermal Model Geometry (Cont'd)

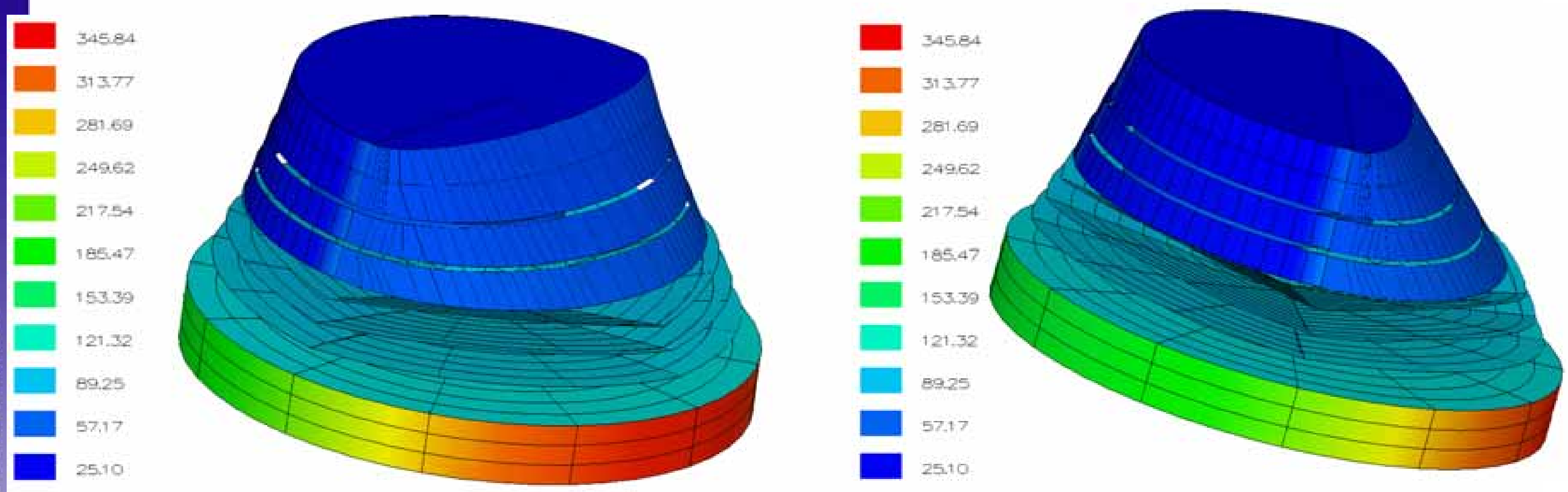


Top View

Combiner Spacecraft - GMM

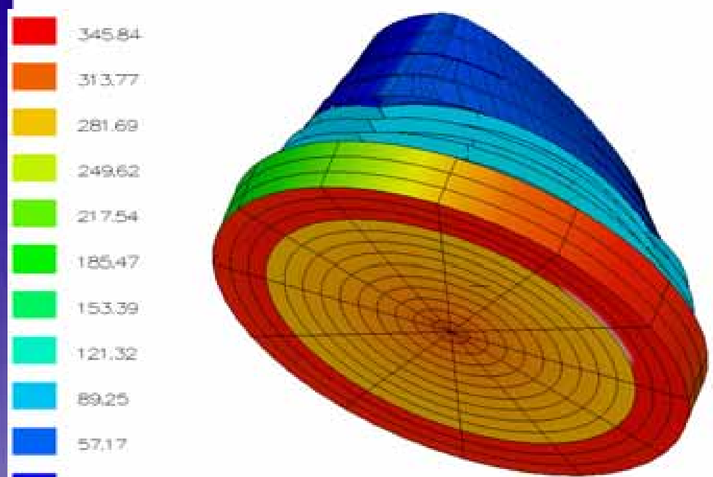


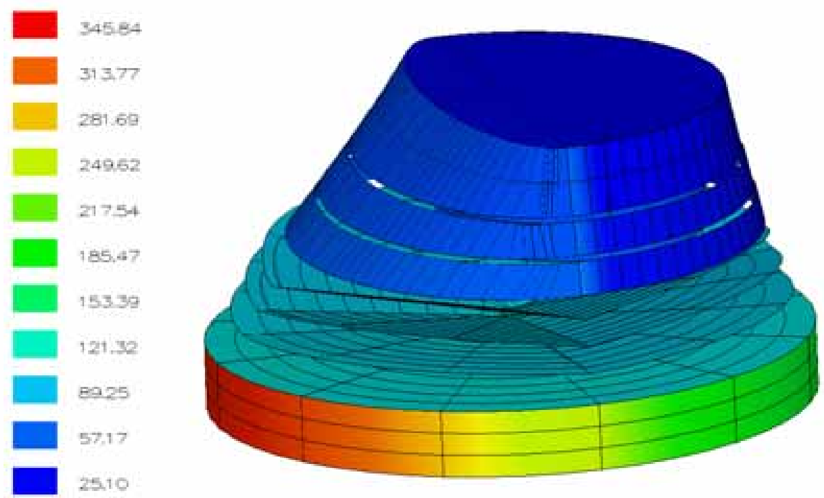
Thermal Analysis Results



Degrees in Kelvin

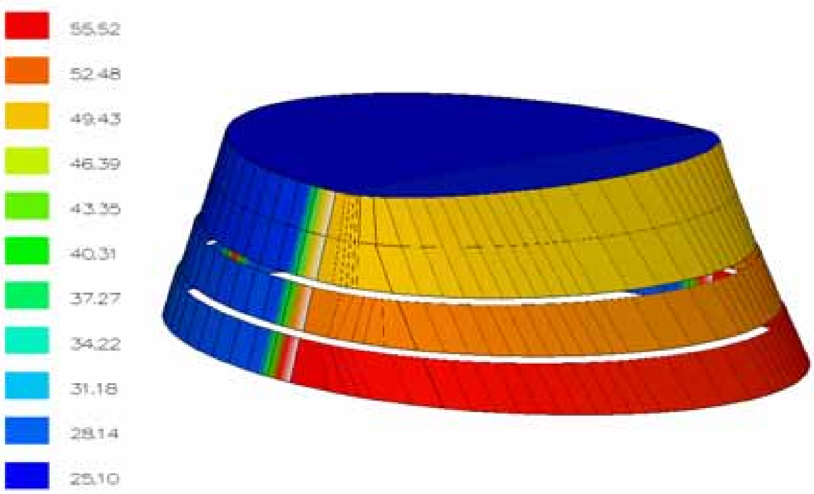
Thermal Analysis Results (Cont'd)

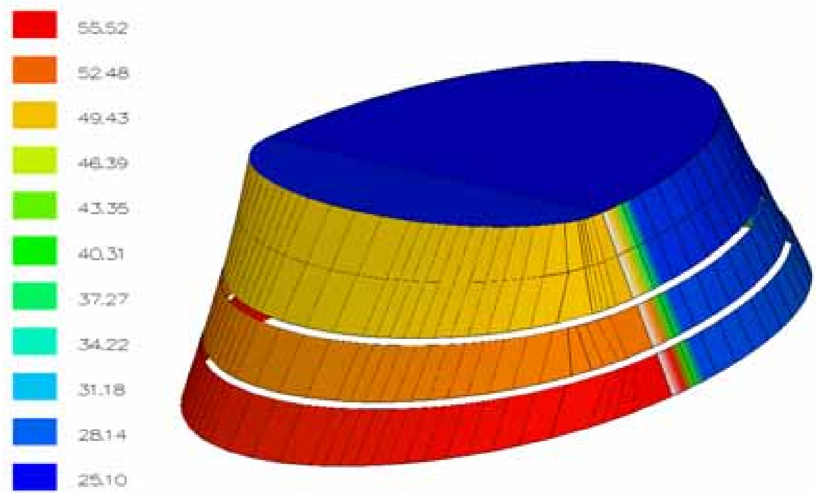




Degrees in Kelvin

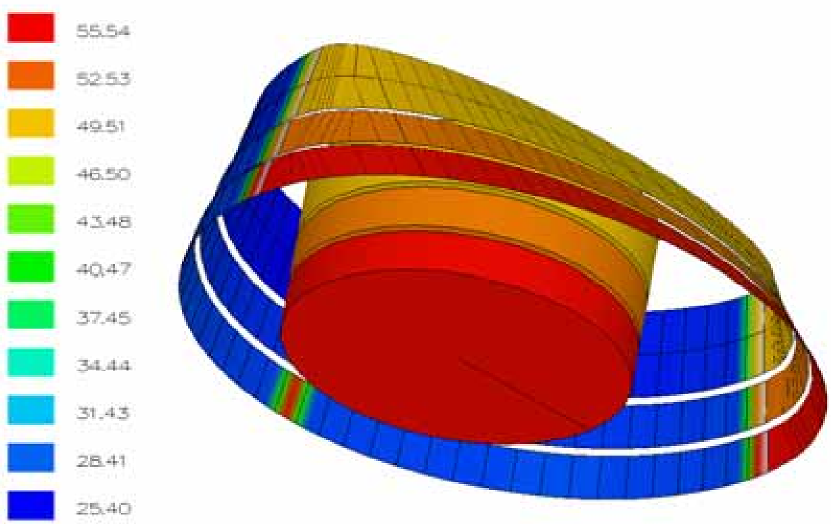
Thermal Analysis Results (Cont'd)

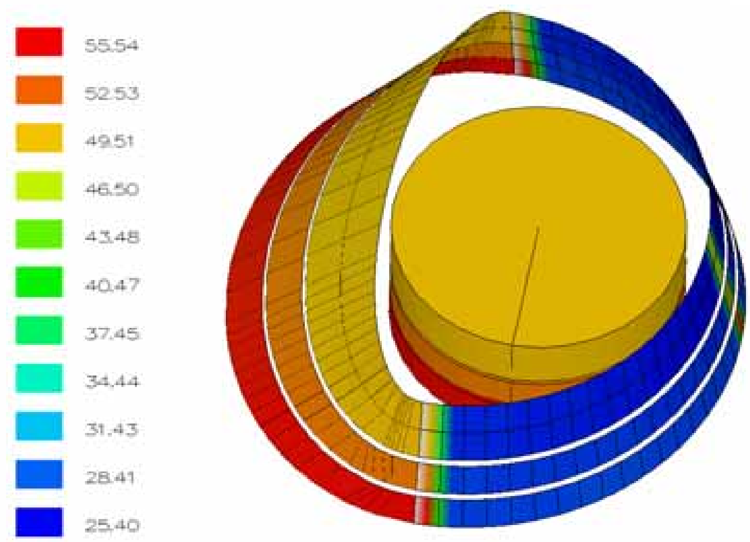




Degrees in Kelvin

Thermal Analysis Results (Cont'd)





Remaining Work - Recommendation

- Modify collector spacecraft v-groove sunshade geometry to reduce infrared heating to an acceptable level on the adjacent spacecraft 20m apart
- Detailed thermal model of collector mirror and bipod supports
  - Develop detailed model of a small section of the mirror with ribbed structure and determine effective thickness and surface emittance for use in the large TMM
  - Develop detailed model of bipods for inclusion in large TMM
- Develop mechanical support structure concept for collector and combiner v-groove sunshades and add to thermal models
- Develop detailed thermal model of combiner optical bench assembly with focal plane array
- Additions to existing spacecraft GMMs and TMMs
  - Course and fine sensor assemblies with power dissipations
  - Thruster assemblies with expected temperature profiles
  - Electronics requiring accommodations outside of the spacecraft bus

Summary

- The thermal design concepts presented for the collector and combiner spacecrafts show promising results with no show-stoppers
- The study trades identified key areas requiring further modeling and analysis before proceeding to develop a preliminary concept

Acknowledgments

- This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Emma FACS:
Formation and Attitude Control System Preliminary Design

Dan Scharf

Jet Propulsion Laboratory
California Institute of Technology

TPF Terrestrial Planet Finder

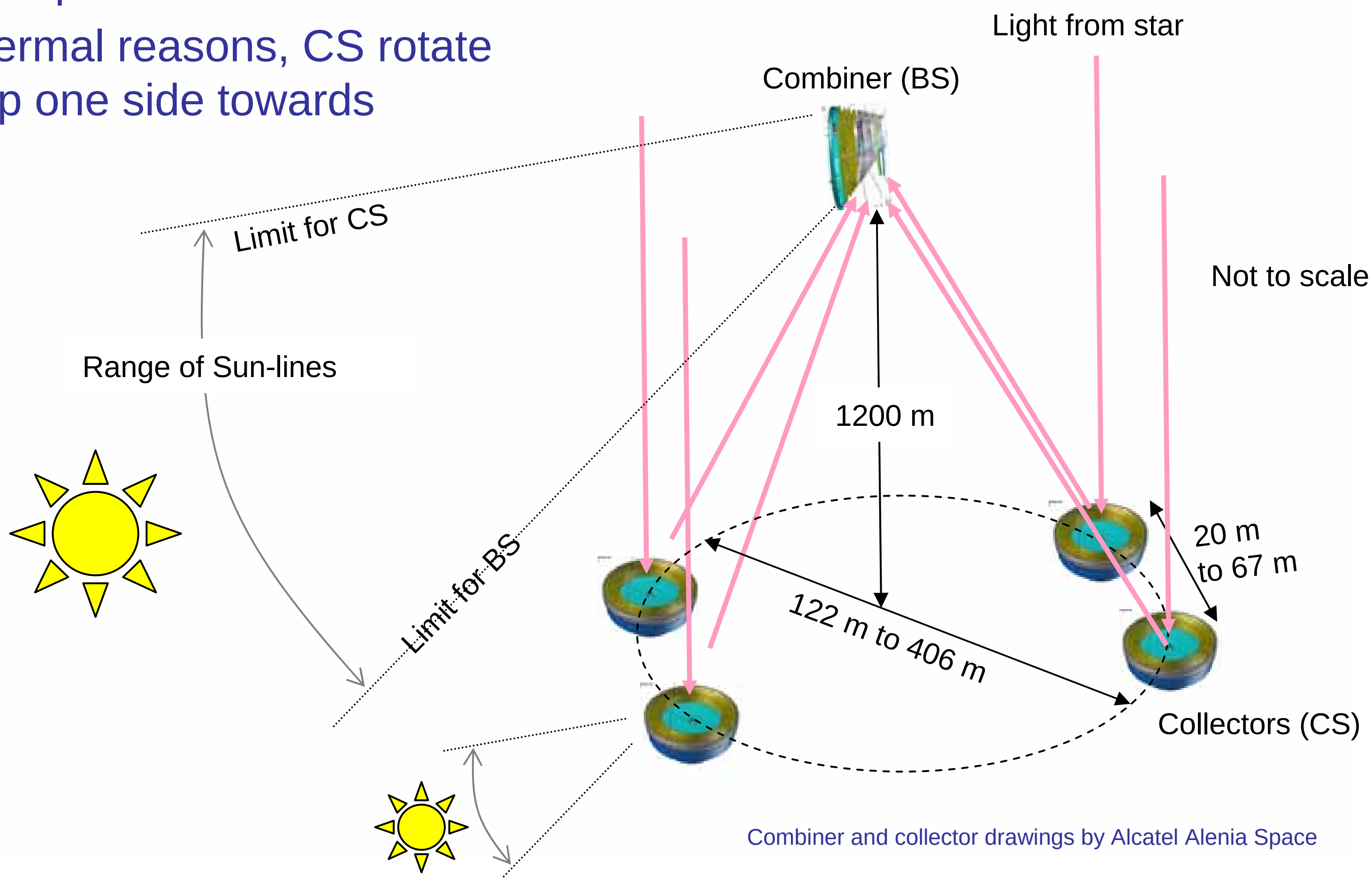
New Acronyms

- BS Beam combiner Spacecraft
- CS Collector Spacecraft

Introduction:
Differences from TPF-I Mk.I

Overall Geometry

- Collectors (CS) form 6:1 rectangle on circle
- CS-circle 1.2 km from Combiner (BS)
- CS-circle diameter varies from 122 m to 405 m
- Rotation period P varies from 10 hrs to 18 hrs
- For thermal reasons, CS rotate to keep one side towards Sun



Combiner and collector drawings by Alcatel Alenia Space

FACS Phases

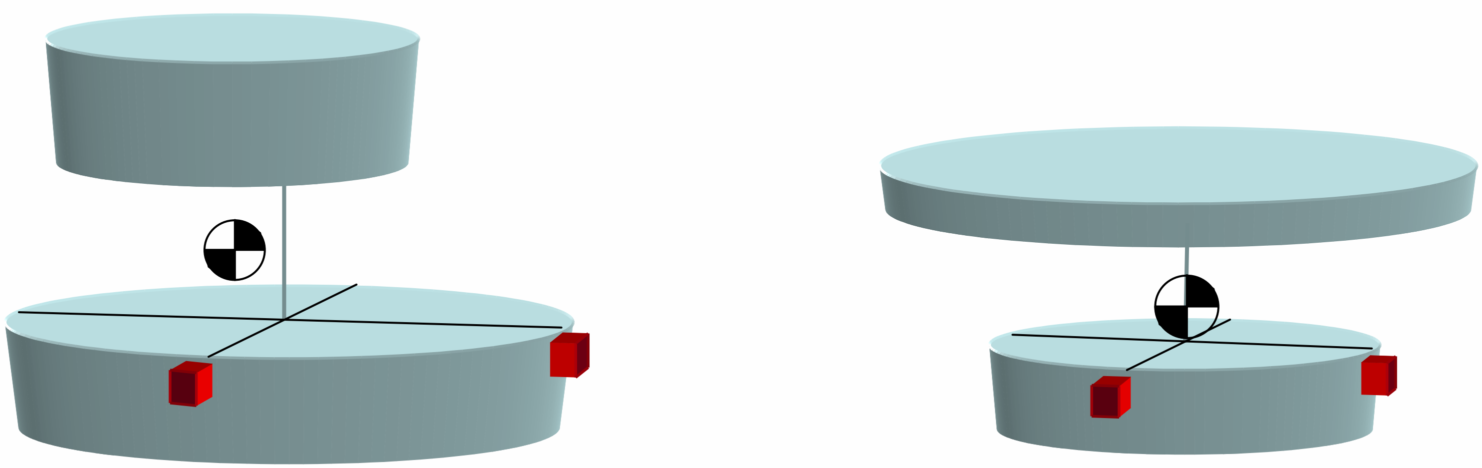
- ***Unlike TPF-I Mk.I, the CS have no fast steering mirror***
  - CS are not telescopes but reflectors!
  - Entire CS must be steered to get starlight onto Combiner's detectors
- Implications
  - Star acquisition on detectors requires the entire CS to be slewed
    - Trying to catch moving target on sky with small, limited-agility beam
  - During science, the BS drifts within the formation control requirements with respect to a CS
    - CS attitudes must be continually controlled to track drifting BS
- Two phases are design drivers
  - Star Acquisition
  - Precision Coupled Formation and Attitude Control for Science

TPF Terrestrial Planet Finder

Spacecraft Specifics for FACS: Mass Properties & Thruster Configuration

Thruster Configuration (1/2)

- Constraints
  - Thrusters on “hot” portion of spacecraft
  - Do not thrust at neighboring spacecraft
  - Perform science maneuvers with at least one thruster failure
- Four pods arranged symmetrically around lower, bus structures
  - Top of pods 2 cm below “lip”
  - Five thrusters per pod (next slide)
  - Thrusters angled so predominantly out-of-collector-plane

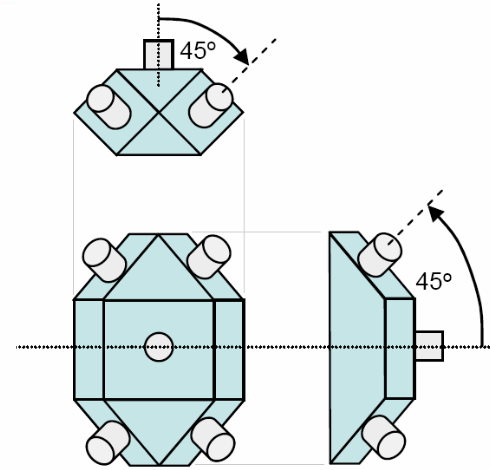


Schematic not to scale

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

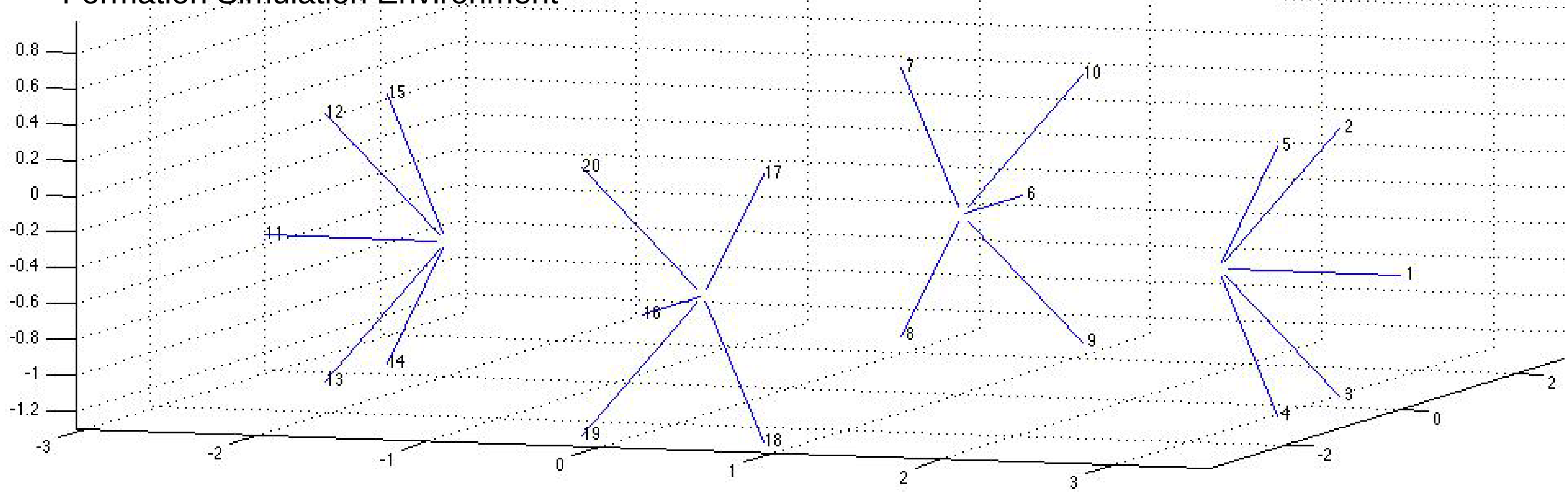
Thruster Configuration (2/2)

- Thrusters in a pod arranged as in TPF-I Mk.I
  - 1 radial, that will be disabled when plume will intersect another CS
  - 4 arranged in 45 deg./45 deg. splay
- Thrusters NOT centered about center of mass



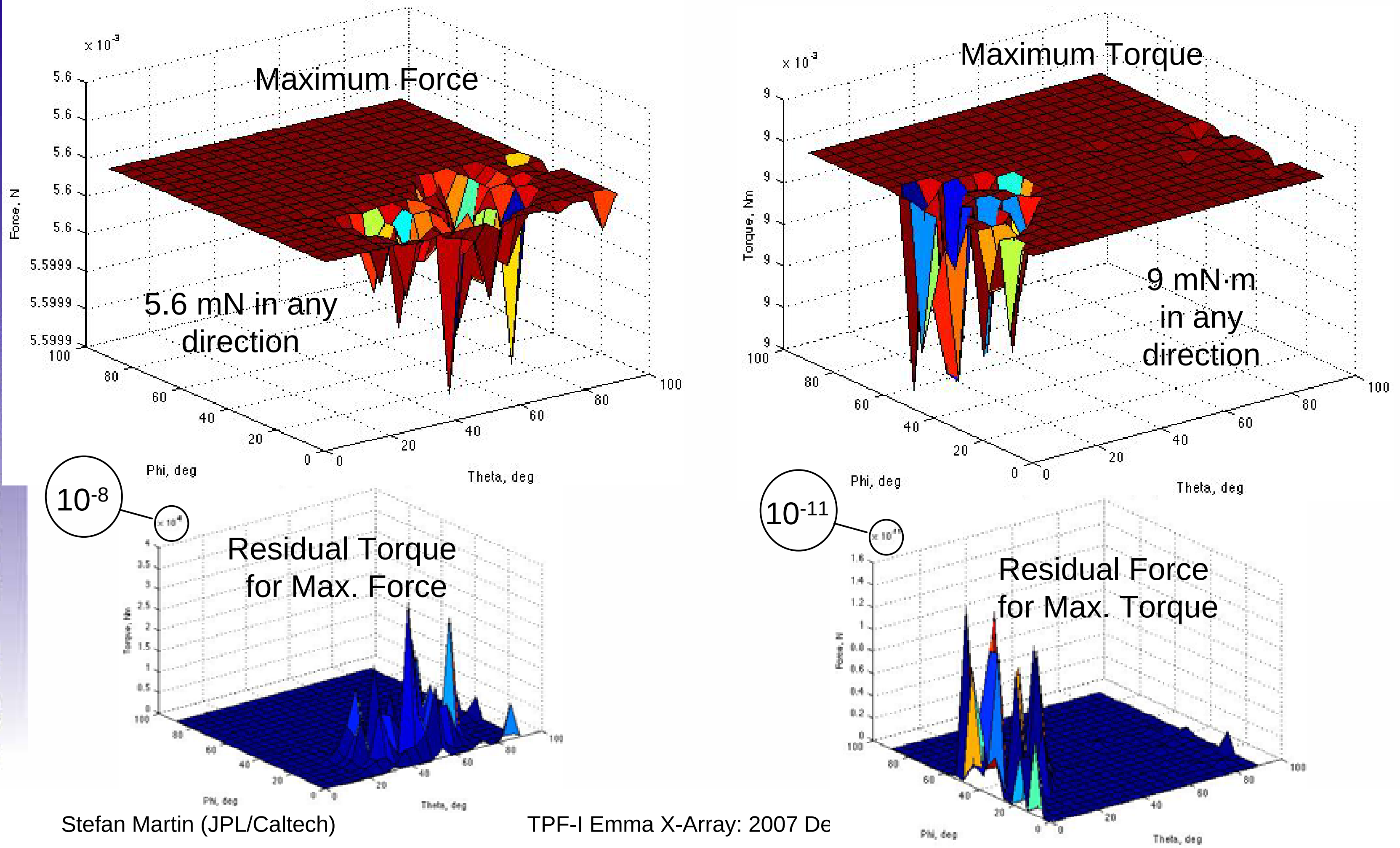
Pod View from
TPF-I Propulsion Study

Thruster Configuration from
Formation Simulation Environment



Spacecraft Agility

- Thruster on-time allocation done via optimization algorithm
  – Developed by G. Singh for formation flying
- Plots show maximum achievable force and torques for BS with near zero residuals as function of (θ,ϕ) = (az,el) despite CM-offset



TPF Terrestrial Planet Finder

Dynamic Requirements

- To execute translational and rotational motion, the feedforward impulses (acceleration * sample period of 1s) required are as follows
  - Feedback and thruster failures will need the additional capability

Science Configuration	Max. Translational Impulse, m/s	Max.Rotational, Acceleration, rad/s
10 hr, 120 m	1.9e-6	5.6e-9
18 hr, 400 m	1.9e-6	3.9e-9
3 DOF Capability	5.9e-6	4.7e-6

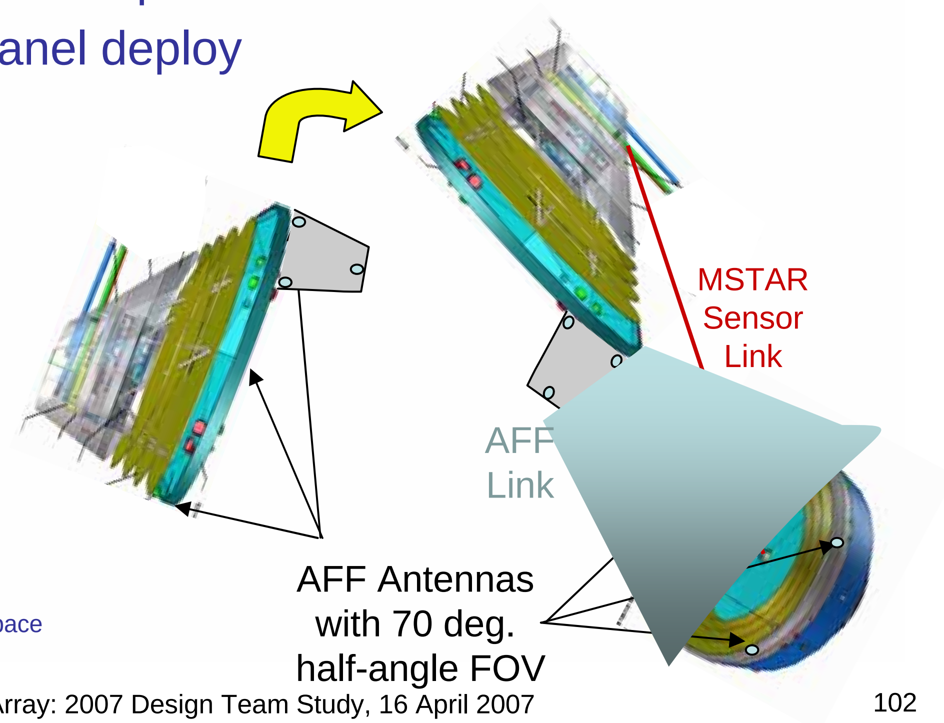
Overview of Specific Formation Phases

Major Mission Phases

- Launch
- Cruise/Insertion
- Deployment/Initialization
- Reconfiguration
- Star Acquisition
- Science Maneuver

Deployment/Initialization

- Deployment similar to TPF-I Mk.I
- Spring-off speeds up to 32 cm/s can be arrested before exceeding range of AFF (10 km)
  - Can be done open loop on accelerometer
- Formation Initialization algorithm already developed for TPF-I Mk.I using limited-FOV version of AFF proposed here
  - Antennas around upper rim of CS and bottom rim of BS
- Implies "blind" moment during Star Acquisition
  - Can be avoided by having panel deploy from bottom of BS

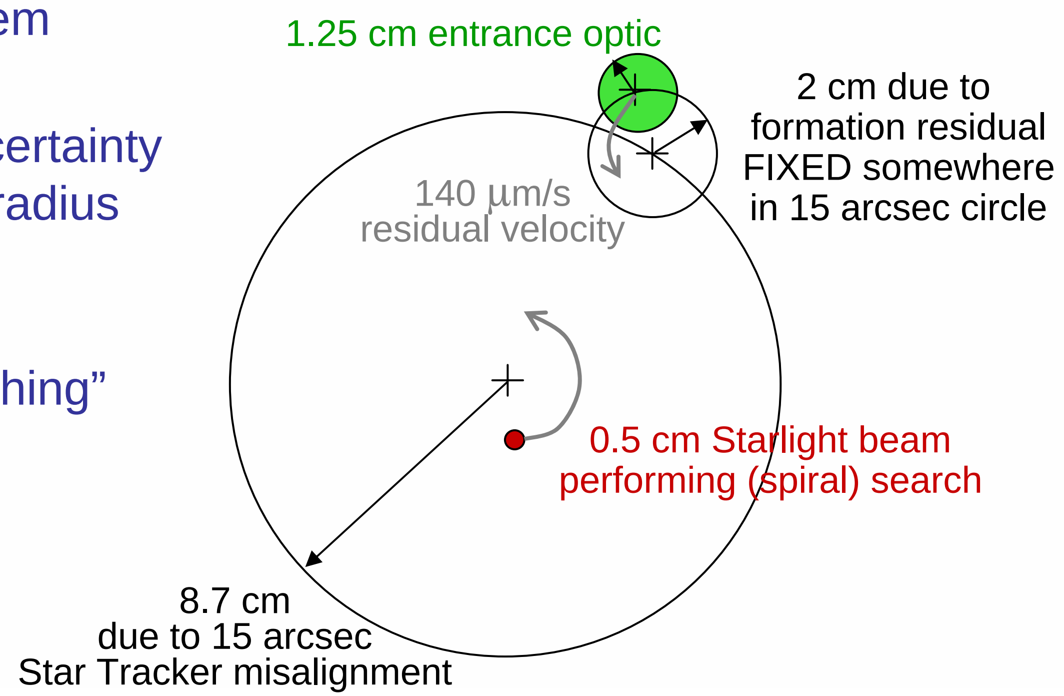


Combiner and collector drawings by Alcatel Alenia Space

Star Acquisition

- Preliminary analysis
  - Requires further study including all misalignments
- Need to steer starlight into BS entrance optic
- Entrance optic only known to Star Tracker misalignment and formation control residual
  - From simulations with a CS stationary w.r.t. the BS, residual position is ±2 cm and residual velocity is 0.014 cm/s

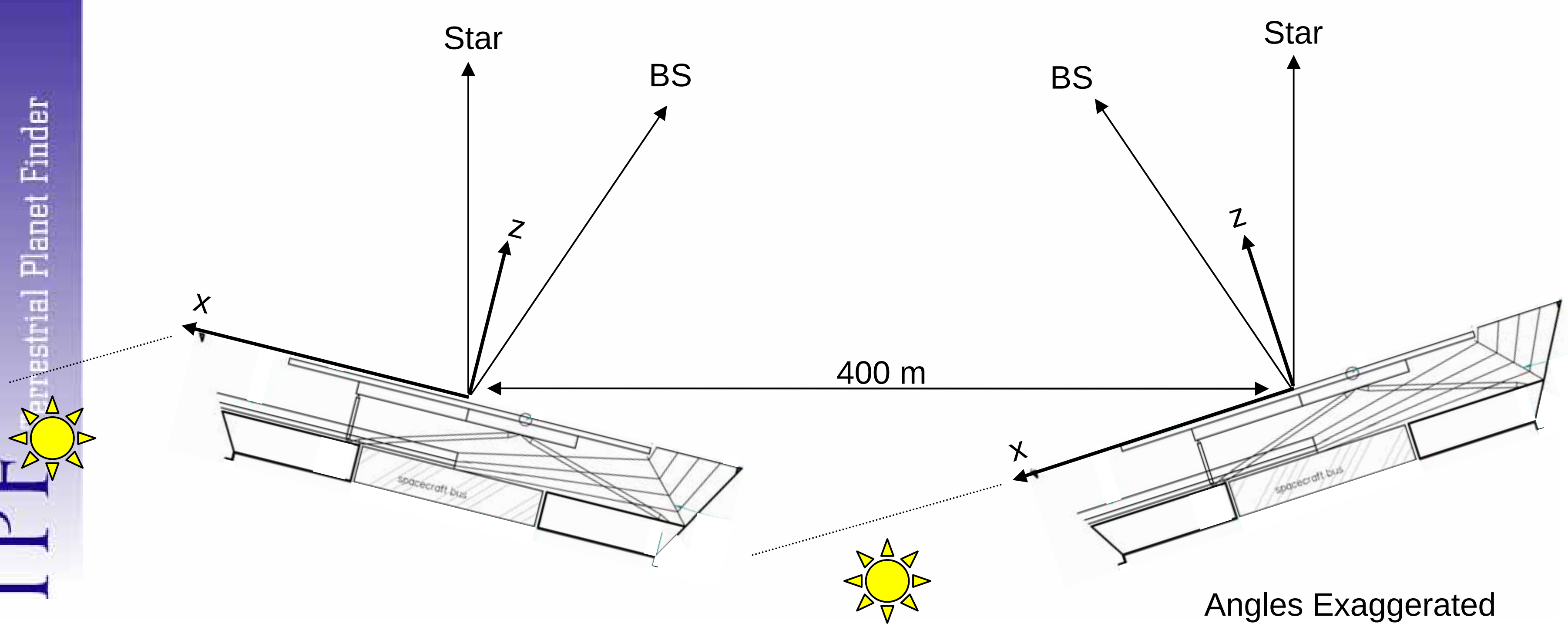
- View acquisition problem "on-the-sky" at the BS
- Given CS agility, a uncertainty region with a 10.7 cm radius can be searched in ~20 minutes
- Need to evaluate "catching" a moving target, but formation residual constrains optic



TPF Terrestrial Planet Finder

Science: CS Attitude (1/2)

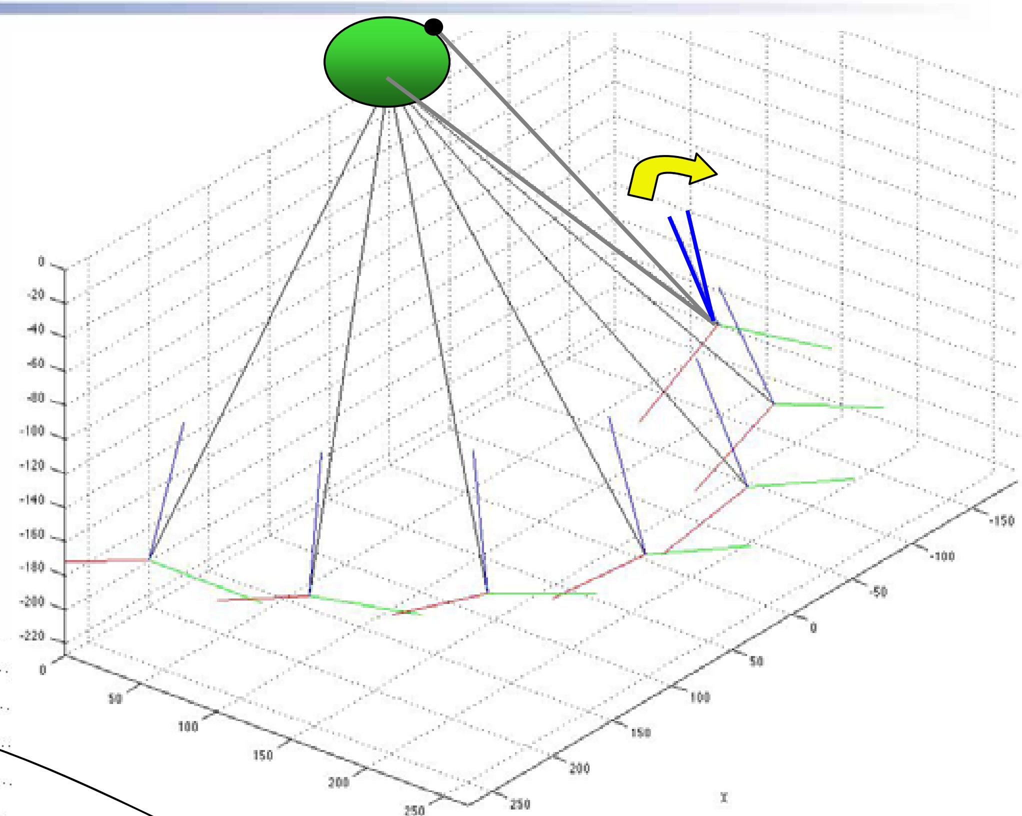
- Recall CS must be steered as a whole to get starlight in BS
- Primary Constraint (must be met):
  - Point telescope boresight (Body z-axis) along bisector of Star and BS
- Secondary Constraint (meet as much as possible):
  - Point "front" (Body x-axis) towards Sun
- Cassini-heritage algorithm (G. Singh)

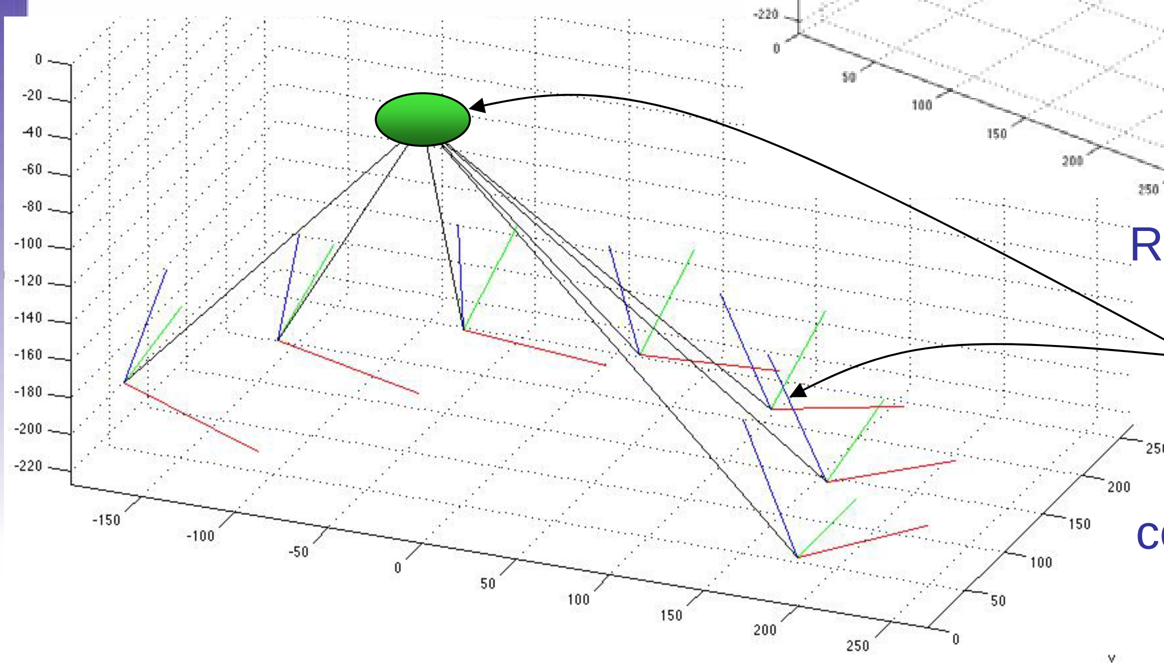


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Science: CS Attitude (2/2)

- Visualization for half-rotation
  – BS only 200 m away to exaggerate angles
- Open-loop attitude command
  – Actual command will is updated in real-time to account for motion of BS
  – BS will only in vicinity of planned apex





Reflector normal will shifted slightly to bisect angle between star and ***actual*** BS position that lies within formation control performance region

TPF Terrestrial Planet Finder

Simulation of Science Maneuver

Assumptions

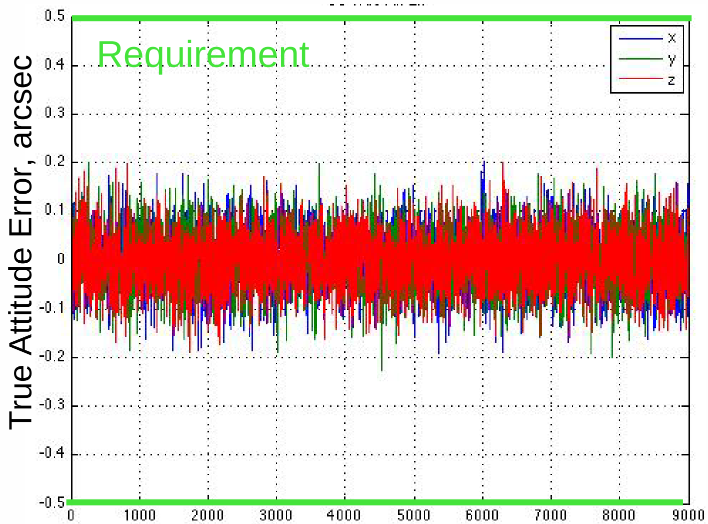
- Showing feasibility of precision, coupled attitude & formation control
- One CS: Each CS controls itself independently w.r.t. the BS
- ***No misalignments or unresolved calibrations***
- Solar pressure forces and torques approximated
- Formation sensor noise included consistent with MSTAR
  - 0.1 mm range, 4.5 arcsec bearing 1σ
- Attitude sensor noise consistent with SIRTF on-orbit performance
  - 0.1 arcsec 1σ (two star trackers assumed so no “bad” axis)
- Mass properties as described
- ***Thrust allocator with minimum on-times***
  - Critical for ensuring performance with saturation
  - Critical for ensuring performance with CM-offset from thrusters that can cause spillover from translational to rotational degrees of freedom
- ***Ideal fine-pointing sensor***
  - BS has CM-offset, 2.5 cm dia. entrance optic (±2 arcsec at 1.2 km)
  - When within 2 arcsec, sensor gives by-axis angular offset between incoming starlight and center of entrance optic
  - Used to keep starlight “locked” during formation maneuvers

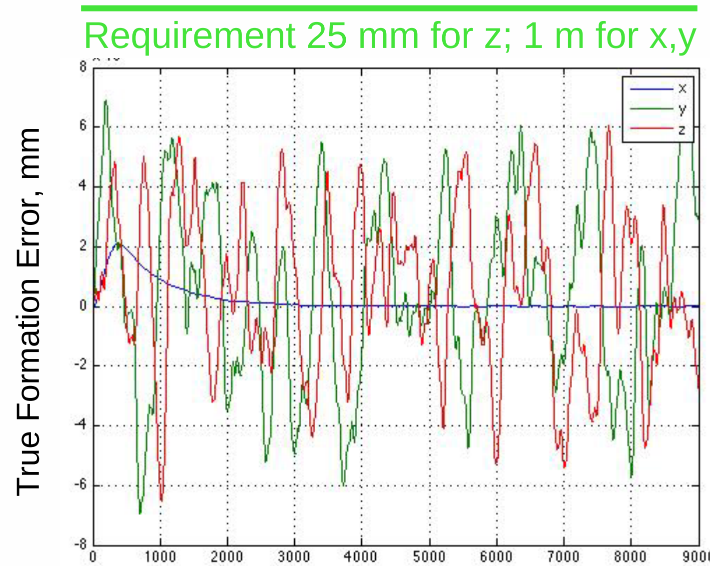
TPF Terrestrial Planet Finder

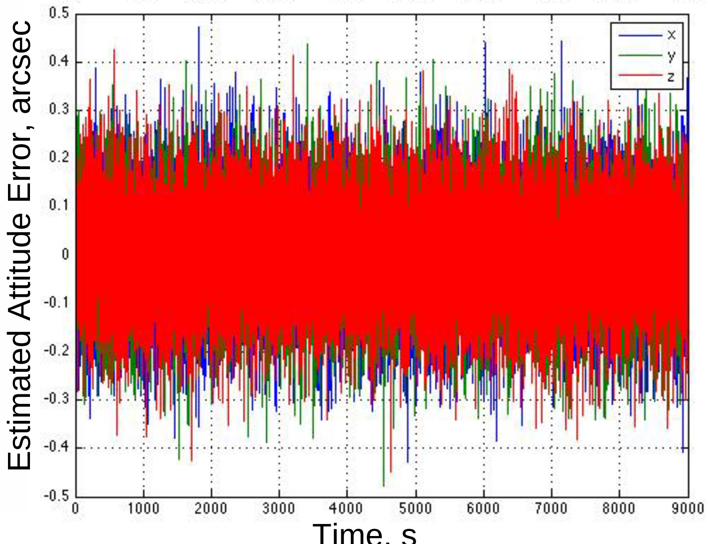
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

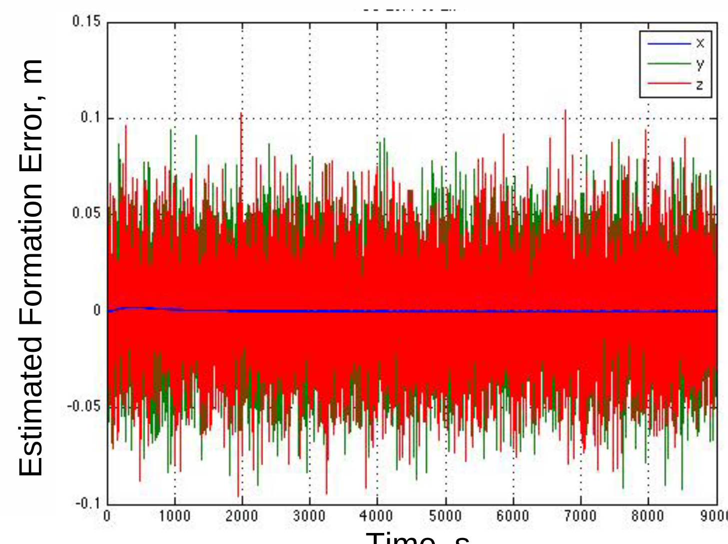
Precision Formation Simulation

- One CS doing a quarter rotation at minimum separation: 9000 s
- It works





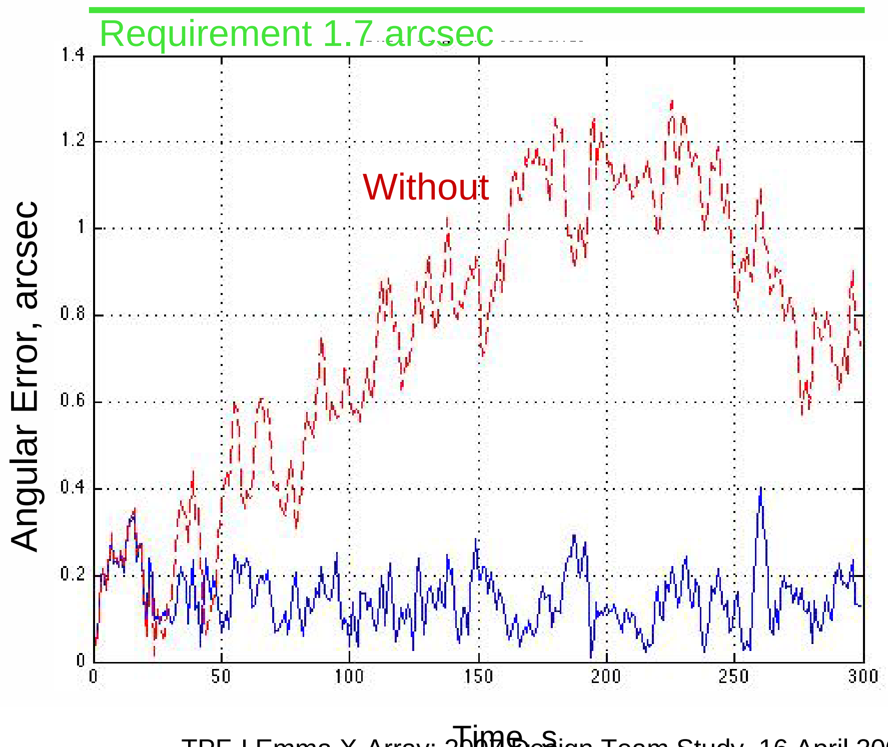




Importance of Pointing Sensor

- Offset angle between starlight and CS-BS beam train with and without fine-pointing sensor (FPS)
- "Without" formation tracking error shows up directly
  - 1.2 arcsec peak in "without" corresponds to 7 mm y-axis formation error
  - 7 mm / 1200 m * 180 / pi * 3600 = 1.2 arcsec
- If x,y-axis performance relaxed to 1 m requirement to conserve fuel, then impossible to keep starlight on detector without FPS

Angle Between Reflected Starlight Beam and CS-BS Beam Train



Summary

- New TPF-I design requires slewing the collectors like steering mirrors
  - Attitude control requirement 120 times tighter than TPF-I Mk.1
  - Attitude coupled to formation performance
  - Formation control requirement slightly relaxed from Mk.1
- Feasibility of coupled, attitude/formation control system shown
  - Requirements met with good starting margin (factor of 4)
  - Initial analysis neglected misalignments in sensing systems, many of which should be able to be calibrated out
- Thruster configuration with CM-offset shown to work for 6-dof precision control
  - (Not Covered) Performance maintained even with a thruster failure
  - And in some cases two failures!
- Fine pointing sensor key to maintaining “starlight lock” despite intra-formation drift
- Future work: lots obviously, but first
  - Including misalignments
  - Star acquisition simulations to confirm preliminary analysis

Acknowledgements

- This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

TPF Terrestrial Planet Finder

Terrestrial Planet Finder - Interferometer / EMMA

Propulsion Subsystem

Design Review

Richie Wirz

Jet Propulsion Laboratory
California Institute of Technology

Mission Overview

- Mission Phases:

1. Launch
   - 200 km parking orbit

   → **Launch Vehicle**

2. Transfer
   - From Earth orbit to L2
3. Insertion
   - Into L2 Halo orbit

   → **Cruise Stage**

4. Science
   - Deployment
   - Formation Flying
     - Up to 1800 observations over 10 year mission

   → **Individual Spacecraft**

Cruise Stage Requirements

- "L" = Launch day
- Transfer Phase (L +1 to L + 100 days)
  - TCM1, 2, and 3 to attain transfer trajectory
  - TCM4 (optional) into desired L2 orbit
- Insertion Phase (L + 100 to L + 107 days)
  - Halo Orbit Insertion (HOI) maneuver
  - TCM5 to correct Halo orbit

Event Schedule	Maneuver	ΔV (m/s)
L + 1 day	TCM1	50
L + 7 + 28 + 75 days	TCM2,3,4	8.29
L + 100 days	HOI	5
L + 104 days	TCM5	0.4
	Total	**63.69**

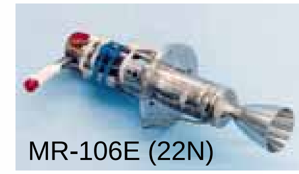
TCM –Trajectory Correction Maneuver

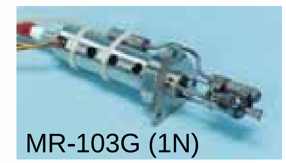
- Cruise stage propellant requirement
  - Assume:
    - Isp = 230 s
    - Total mass ~ 5720 kg
      - Includes Combiner (wet), 4 Collectors (wet), Cruise Stage (dry)
    - ΔV = 63.69 m/s
  - **164 kg of hydrazine propellant required for Cruise Stage**

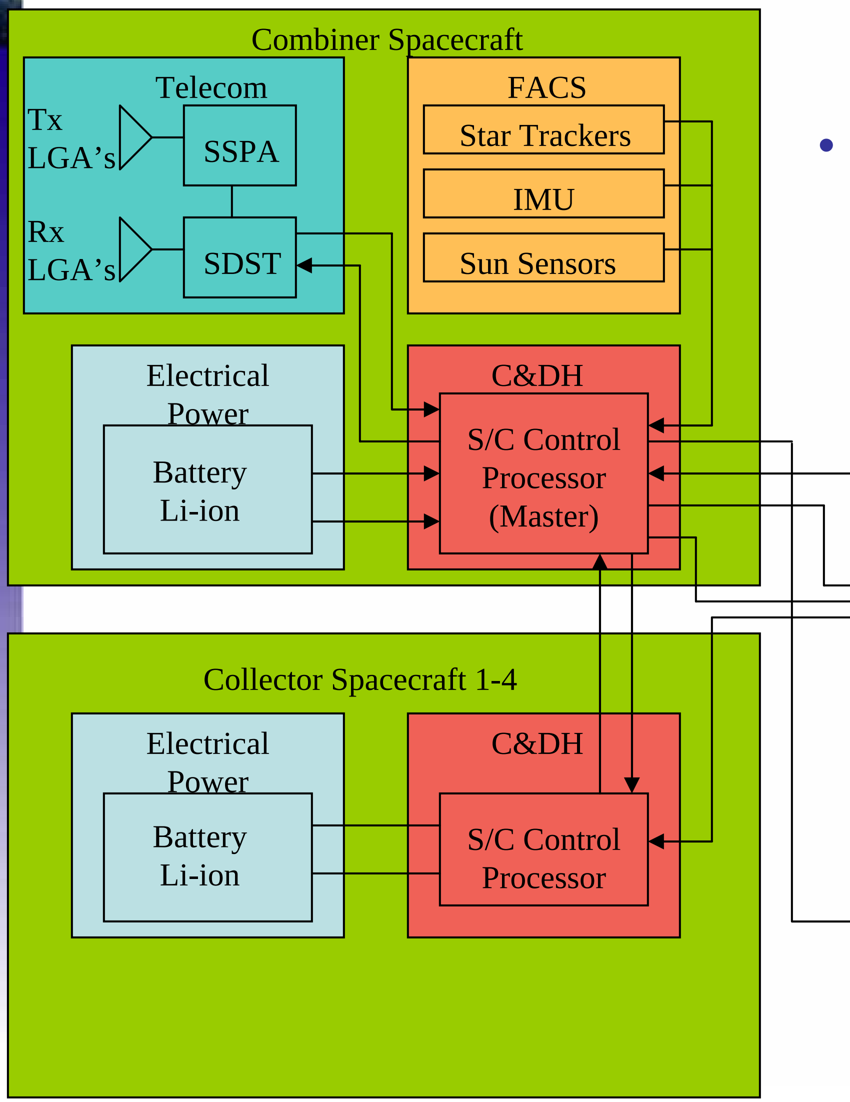
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

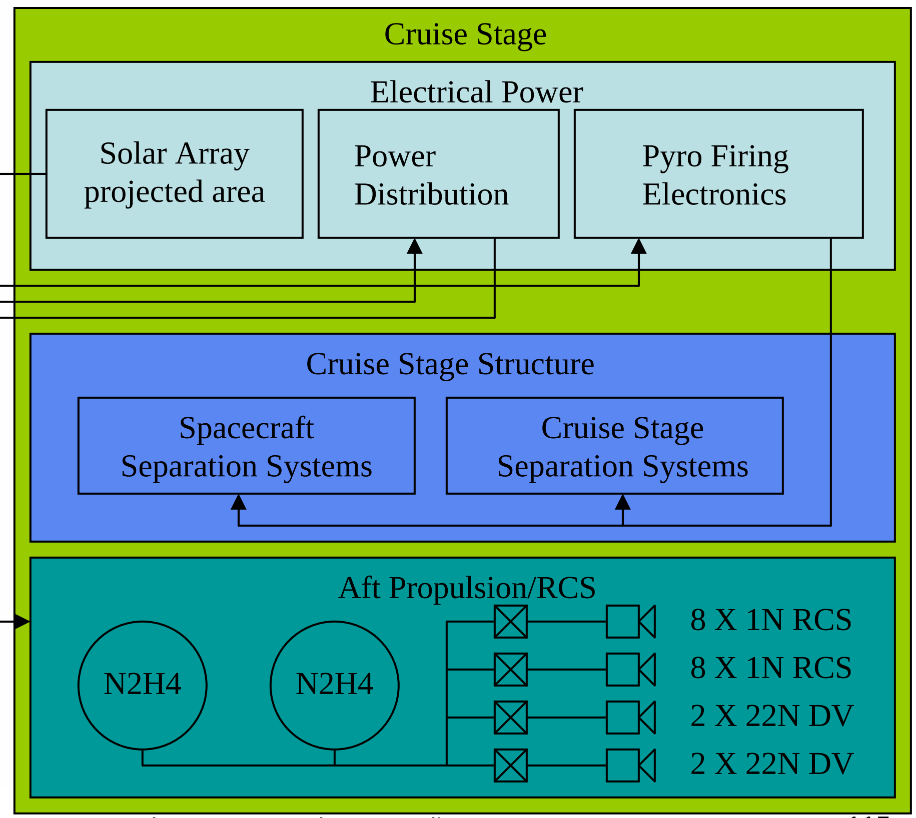
Cruise Stage Diagram

- Cruise stage uses its own solar array and propulsion system
- Controlled by Combiner flight system



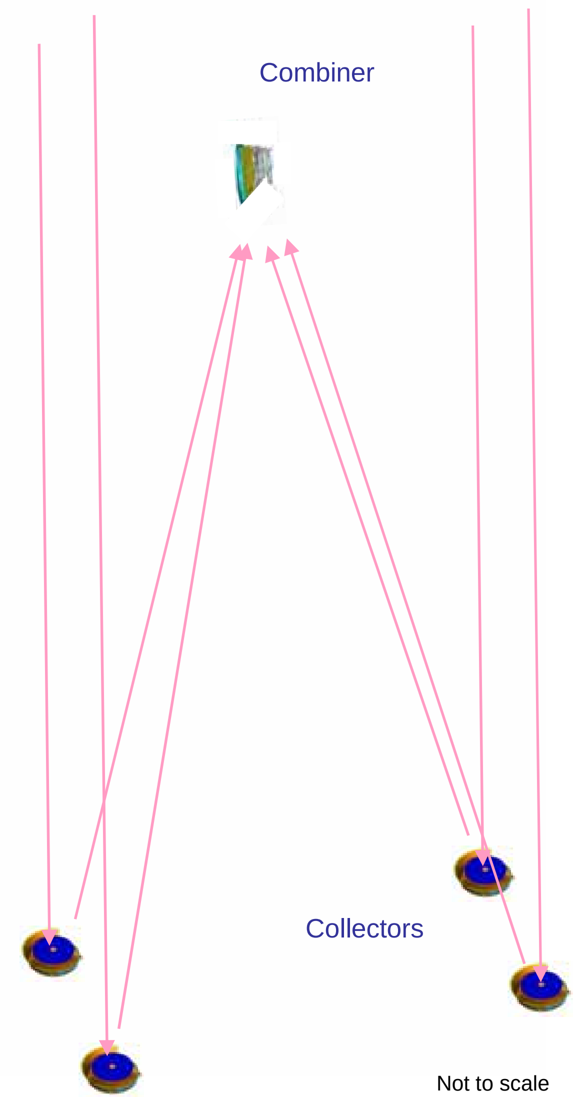






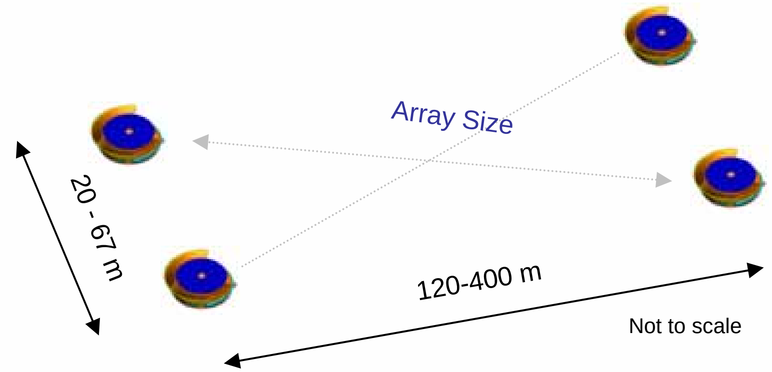
Science Phase Propulsion

- Deployment
  - Initial deployment of spacecraft into science formation from cruise stage “stacked” configuration
  - Minor one-time ΔV
- Formation Flying
  - Retargeting
    - Position formation to view target
    - Acquire desired formation baseline
  - Spin-up
    - Initiate formation rotation
  - Fine Target Acquisition
    - Perform precise pointing maneuvers to attain target interferometer
  - Observation
    - Formation rotation
    - Maintain precise pointing



Collector Thrust Level and ΔV Requirement

- **Assumptions:**
  - 1000 kg collectors (> 30% margin on dry mass)
  - Rotation period 10 – 18 hrs
  - Circular 360º rotation
  - Rectangular collector orientation (as shown)
  - Linear Spin-Up trajectory
  - Retarget = 3 x Spin-Up ΔV



- **ΔV and Thrust requirements:**

Config #	P [hrs]	Array Size [m]	ΔV Requirements [m/s/observation]				Thrust [mN] Requirement
			Rotation	Spin-Up / Fine Acq	Retarget	**Total**	Rotation
1	10	122	0.067	0.011	0.032	**0.109**	1.85
2	12	193	0.088	0.014	0.042	**0.144**	2.04
3	14	264	0.103	0.016	0.049	**0.169**	2.05
4	16	335	0.115	0.018	0.055	**0.188**	1.99
5	18	406	0.124	0.020	0.059	**0.202**	1.91

Thrust required pre s/c to maintain circular rotation

- **Total ΔV for 1800 observations = 265 m/s**
  - Assuming 50% at Config #1, 25% at Config #3, and 25% at Config # 5
  - 1800 observations for 10-year mission
- **Nominal thrust level per thruster ~ 1 – 2 mN**
  - Precise thrust level depends on thruster #/orientation/location
  - Ideal thrust level for rotation maneuvers
  - Retarget time under 5 hours for these thrust levels
    - See additional slides

Observation ΔV Summary (per Collector)

Config	Mission Allocation	ΔV per Observation	Observations	ΔV (m/s)
1	50%	0.109	900	98
2	0%	0.144	0	0
3	25%	0.169	450	76
4	0%	0.188	0	0
5	25%	0.202	450	91
		Total	**1800**	**265**

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Collector Propellant Mass vs. Specific Impulse (Isp)

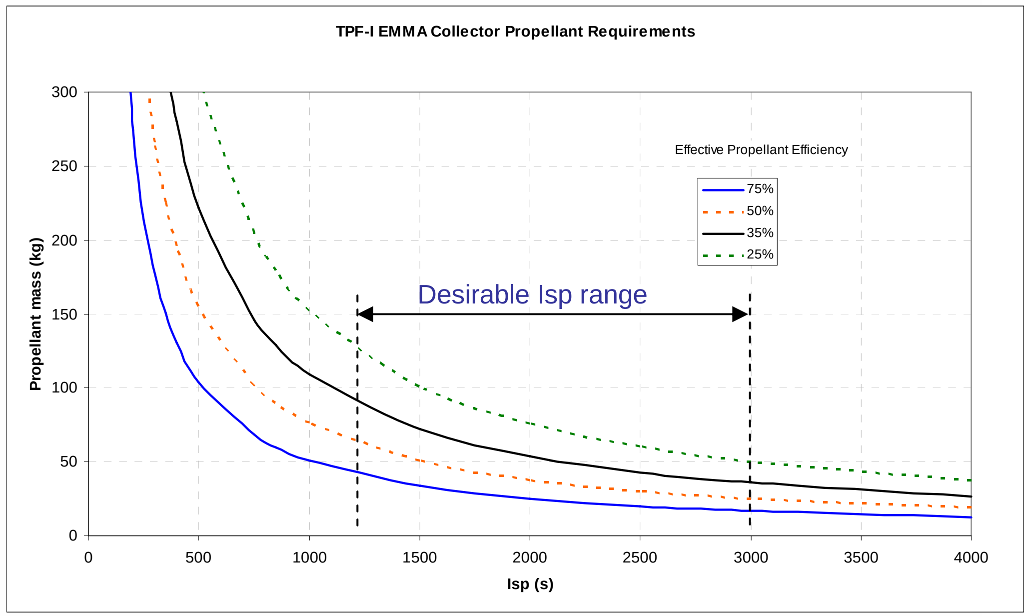
TPF Terrestrial Planet Finder

- **Total Mission ΔV ~ 367 m/s**
- Contributors (per TPF-I values)
  - Deployment < 0.1 m/s
  - Observations 265 m/s
  - Solar Radiation Forces ~ 50 m/s
    - Using solar optimal orbit location
  - Angular Momentum ~ 7 m/s
  - Station Keeping ~ 30 m/s
  - Z-axis control ~ 15 m/s

Mission ΔV Summary (per Collector)

Maneuver	ΔV (m/s)
Deployment	0.1
Observations	265
Solar Radiation	50
Angular Momentum	7
Station Keeping	30
Z-axis control	15
Total Mission	**367**

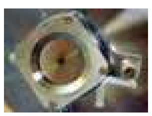
- Propellant Mass vs. Isp
  - Collector dry mass 1000 kg
  - Effective Propellant Efficiency
    - reflects losses due to factors such as cant angle, neutralizer, and thrust mode (should not double-account for Isp)
    - 35 – 50% for current propulsion system
- **Isp > 1200 s requires < 100 kg of propellant**
  - Isp >> 3000 s does not provide significant benefit-to-risk
- **Combiner requirements are less than Collector**
  - see additional slides



Key Propulsion Subsystem Requirements

- Collectors and Combiner command thrusters by the Formation and Attitude Control System (FACS)
- Thrusters shall be located and aligned on each Collector/Combiner to:
  - Provide 3-axis attitude control authority
  - Provide 3-axis translation capability (without reorientation of the S/C)
  - Minimize plume/thermal interaction with source spacecraft and adjacent spacecraft in the formation
  - Minimize contamination to scientific instruments or other sensitive components
- S/C Thrusters shall be capable of operating in the milli-Newton (mN) range (rotation and coarse control) and micro-Newton (μN) range (fine control)
- S/C will be capable of performing all mission functions with the loss of any single thruster
- Thrusters will cause minimal s/c vibration
  - Amplitude modulated control provides minimal s/c disturbance

Thruster Trade-off

	Thruster Technology	Thrust Range (mN)	Primary Thrust Control	Isp (sec)	Plume Divergence Half-Angle (°)	Propellant	Contamination Potential	TRL
	Cold Gas	4.5 - 1000	Pulse Width Modulated	65	45	Nitrogen	Low	9
	Colloid	0.001-0.1	Amplitude Modulated	100-500	18	Ionic Liquids Glycerol	High	5
	Cs- FEEP	0.001 - 1	Amplitude Modulated	6,000 - 10,000	30-45	Cesium	Very High	4-5
	In-FEEP	0.001 - 0.1	Amplitude Modulated	8,000 - 12,000	30-45	Indium	High	4-5
	Hall (BHT-200)	4-17	Amplitude Modulated	1,200 - 1,600	60-75	Xenon	Low (except for beam divergence)	5-9
	Ion (MiXI)	0.1 - 1.5	Amplitude Modulated	2,500 - 3,500	5-15	Xenon	Low	4
	Teflon PPT	~ 1 @ 1 Hz	Pulse Width Modulated	650-1400	30-45	Teflon	High	9

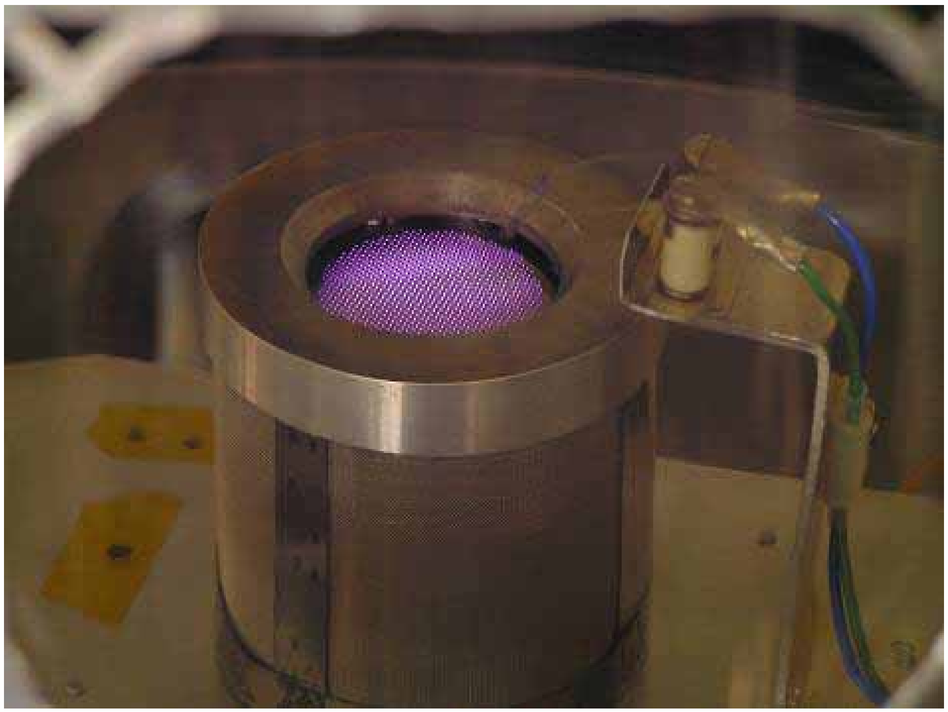
Not desirable for PFF (red) — Desired for PFF (green)

PFF = Precision Formation Flying

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Miniature Xenon Ion (MiXI) Thruster

- JPL developed technology
  - Miniature version of dc ion thruster such as the NASA's DS-1 NSTAR or Boeing's XIPS thrusters
- Large thrust range and control envelope:
- Requires neutralizer to maintain spacecraft charge



TPF Terrestrial Planet Finder

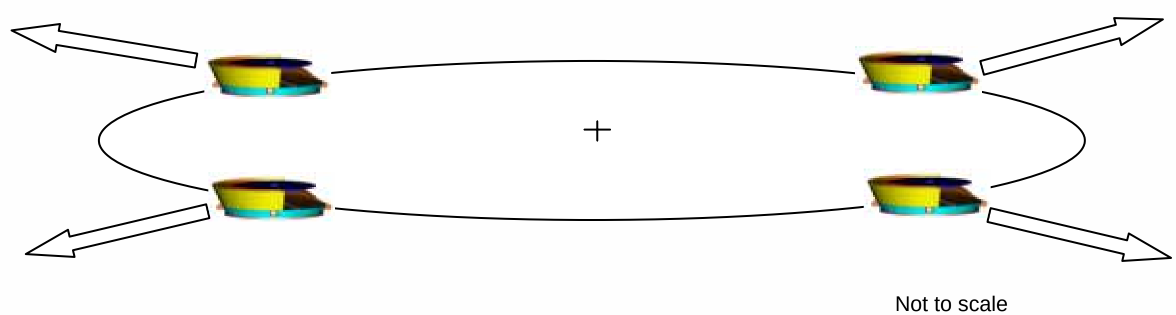
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Spacecraft Plume Interaction

Overview

- During observations thrusters will supply a continuous centripetal force to maintain formations circular rotation
- Inter-spacecraft plume interaction is minimized since **majority of thruster force (plumes) are directed away from rotation center** and, hence, other spacecraft; however
  - **Some thrust to formation interior will be required to maintain spacecraft attitude, orientation, and z-axis position**
    - Thrust assignments that result in direct plume interaction will not be used

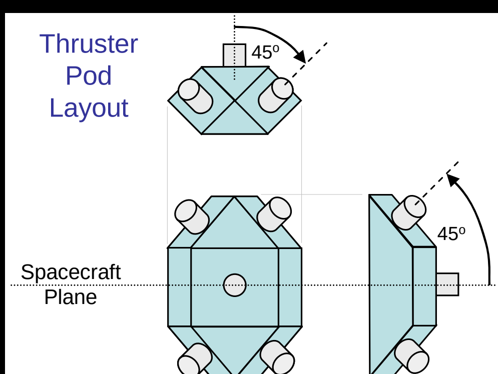
Spacecraft thrust vectors necessary to maintain formation rotation

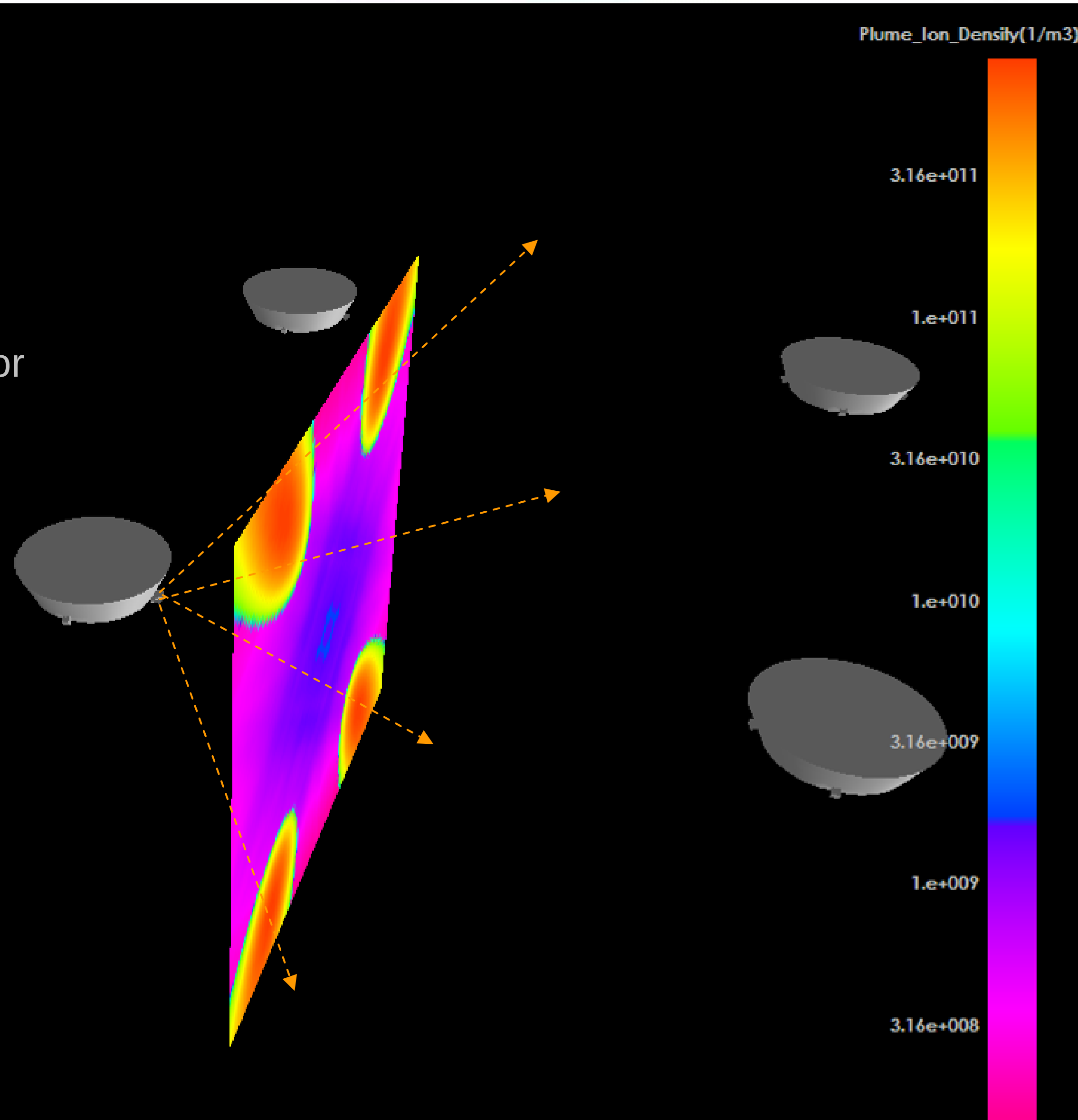


Spacecraft Plume Interaction

Thrust Direction

- Minimize interaction by only firing 45º canted thrusters into formation interior
  - Combiner ~ 1200 m away, must investigate optical contamination
- In-plane thruster is used only for centripetal force thrust
  - thus minimizing inter-spacecraft plume interaction



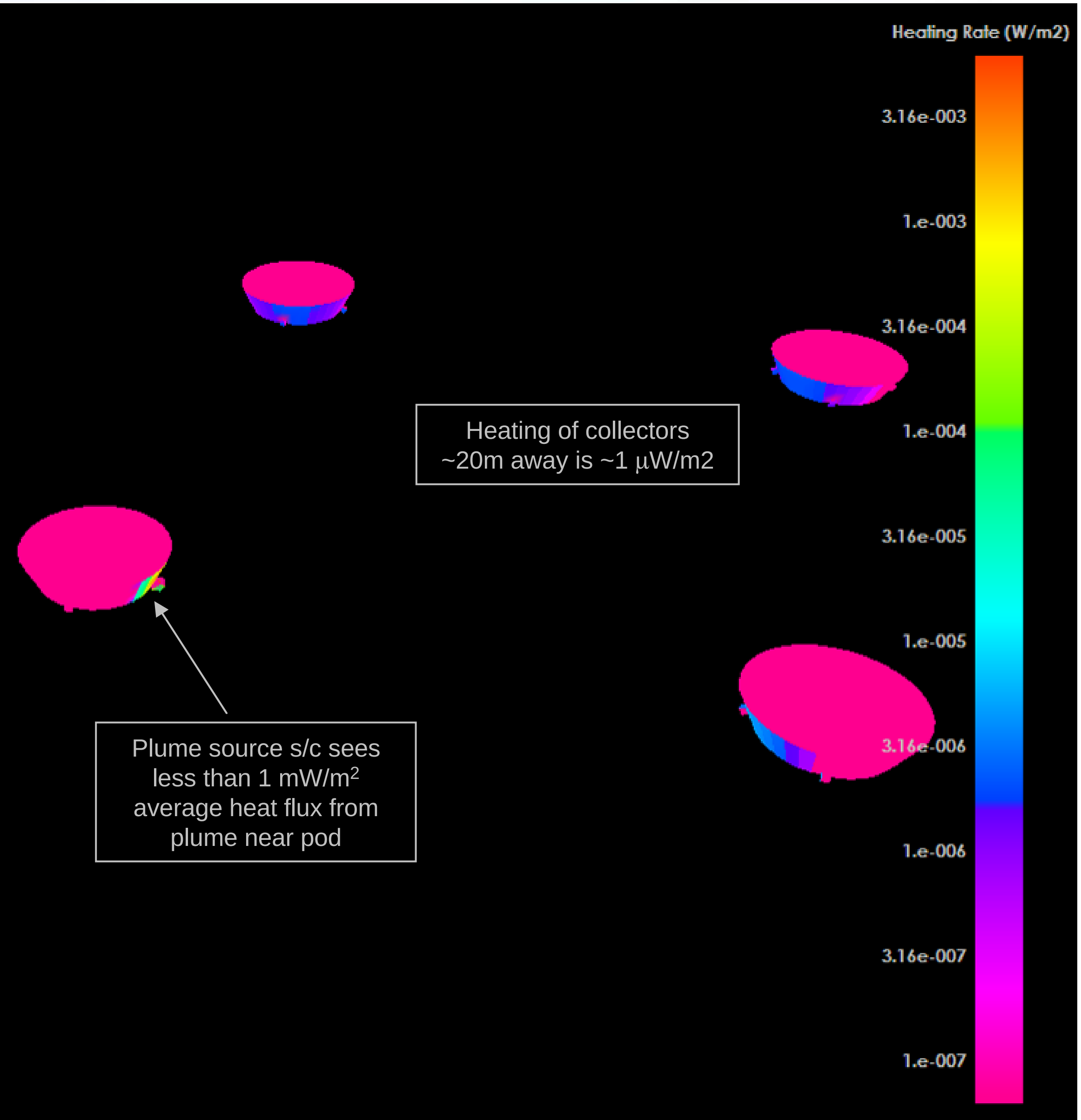


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Spacecraft Plume Interaction

Inter-Spacecraft Heating

- Spacecraft receives heat from thruster plumes due to:
  - Direct impingement
  - Radiation
- Spacecraft/plume interaction predictions show
  - Self heating of s/c due to plume is several orders of magnitude less than solar heating
    - L2 Solar Flux ~ 1325 W/m^2
  - Thruster pod on cold side needs a “backboard” to avoid line-of-sight heating of sensitive surfaces (e.g. mirrors)
  - Heating of closest collector is on order of 1 $\mu W/m^2$



Propulsion Subsystem Conclusions and Remaining Work

- Conclusions
  - Existing propulsion subsystem design meets mission requirements
  - Cruise stage propulsion is COTS
  - Development required for propulsion system used in science phase
  - Exact thrust orientation will require trade between FACS performance and plume/spacecraft interaction

- Remaining Work
  - Perform detailed plume/spacecraft interaction analysis
    - Local and inter-spacecraft (collector-collector, collector-combiner)
    - Surface and optical contamination
      - Consider argon propellant for lower condensation temperature
      - Plume data required to assess optical contamination (e.g. IR radiation)
      - Combiner must effectively reject plume radiation
    - Erosion/deposition
  - Trade all-thruster versus thruster/RWA configuration
    - If necessary a thruster/RWA configuration may minimize thruster firing events inside formation rotation circle, thus minimizing optical contamination
  - Develop propulsion technology to ensure mission readiness

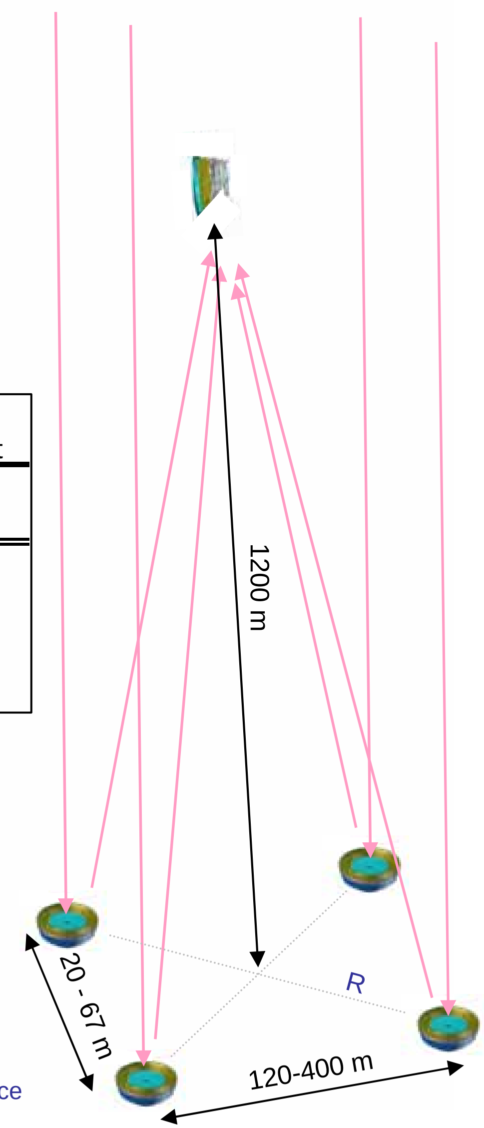
Appendix

Combiner Thrust Level and ΔV Requirement

- Assumptions
  - Combiner will perform only station keeping maneuvers during observations and spin-up
    - Conservatively assume Spin-Up / Fine Acq ΔV during rotation and spin-up of collectors
  - Combiner will primarily perform retarget maneuvers approximately equal to rest of formation

Config #	P [hrs]	Array Size [m]	ΔV Requirements [m/s/observation]				Thrust [mN] Requirement
			Rotation	Spin-Up/ Fine Acq	Retarget	**Total**	Rotation
1	10	122	0.011	0.011	0.032	**0.053**	1.85
2	12	193	0.014	0.014	0.042	**0.070**	2.04
3	14	264	0.016	0.016	0.049	**0.082**	2.05
4	16	335	0.018	0.018	0.055	**0.091**	1.99
5	18	406	0.020	0.020	0.059	**0.098**	1.91

- Total ΔV for 1800 observations = 129 m/s
  - Assuming 50% at Config #1, 25% at Config #3, and 25% at Config # 5
- Nominal thrust level per s/c thruster ~0.5 – 2 mN
  - Maintain similar requirements to collector if possible

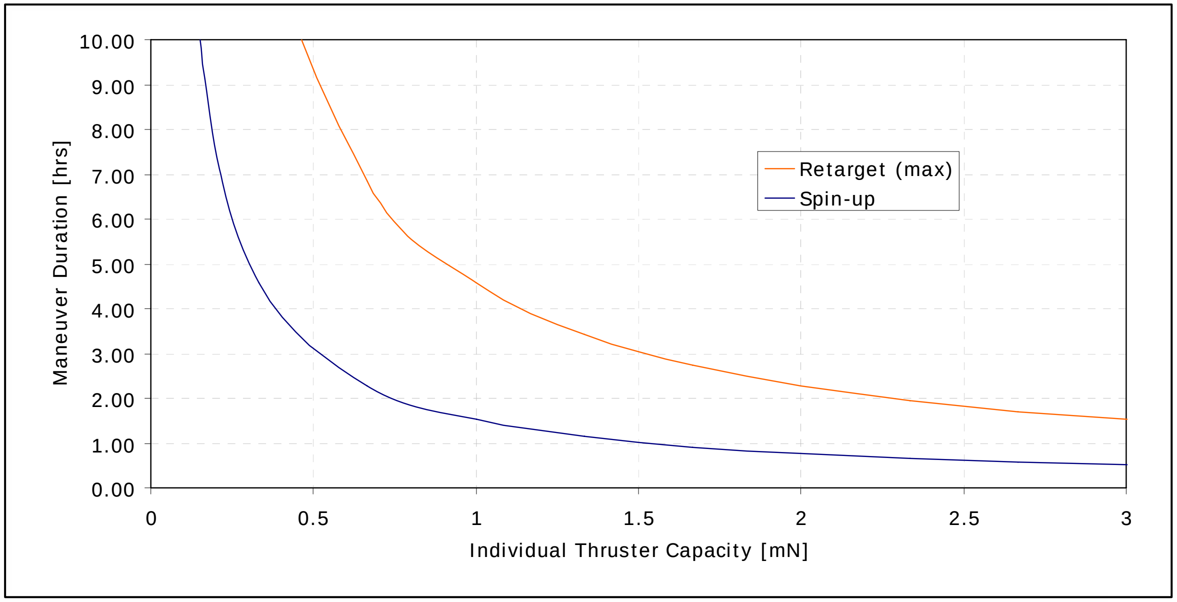


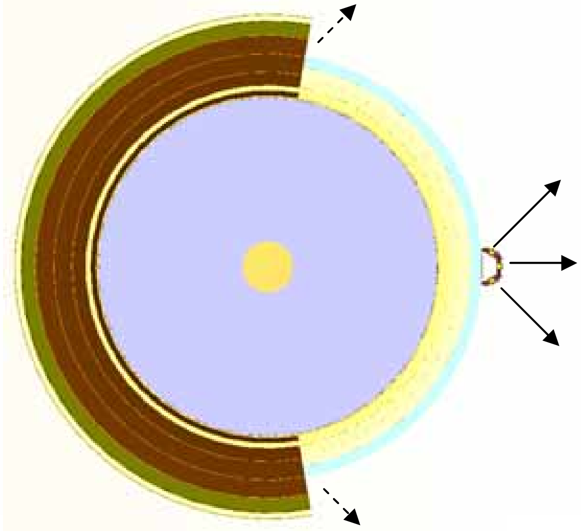
Combiner and collector drawings by Alcatel Alenia Space

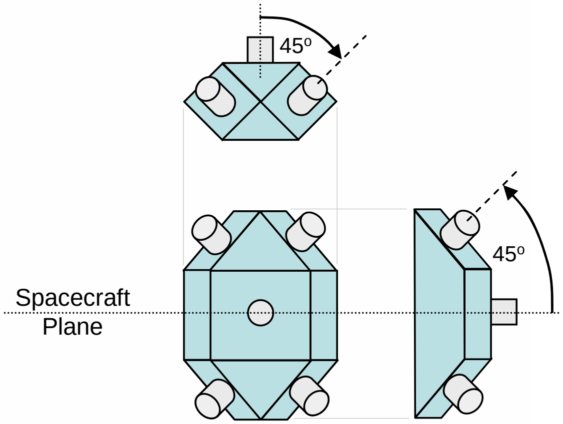
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Estimated Retarget and Spin-up Time

- Assume 5 thrusters firing
  - 4 canted thrusters
    - $45^0 - 45^0$
  - 1 in-line thruster
  - Can use 8 canted thrusters
    - 40% reduction in time
- Nominal thrust of 1 – 1.5 mN yields desirable maneuver times (< 5 hrs)







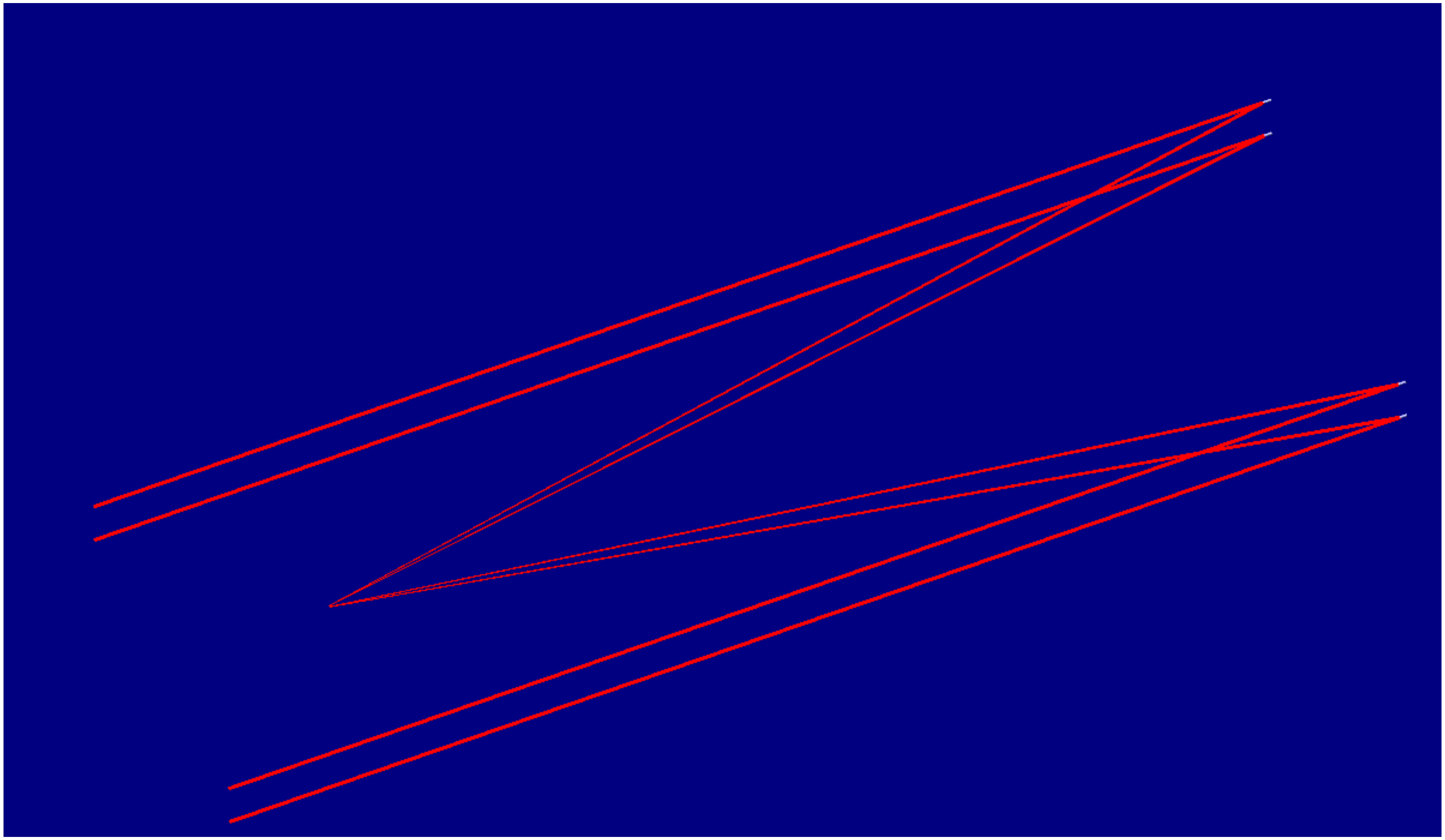
TPF Terrestrial Planet Finder

TPF-Emma
Optical Layout

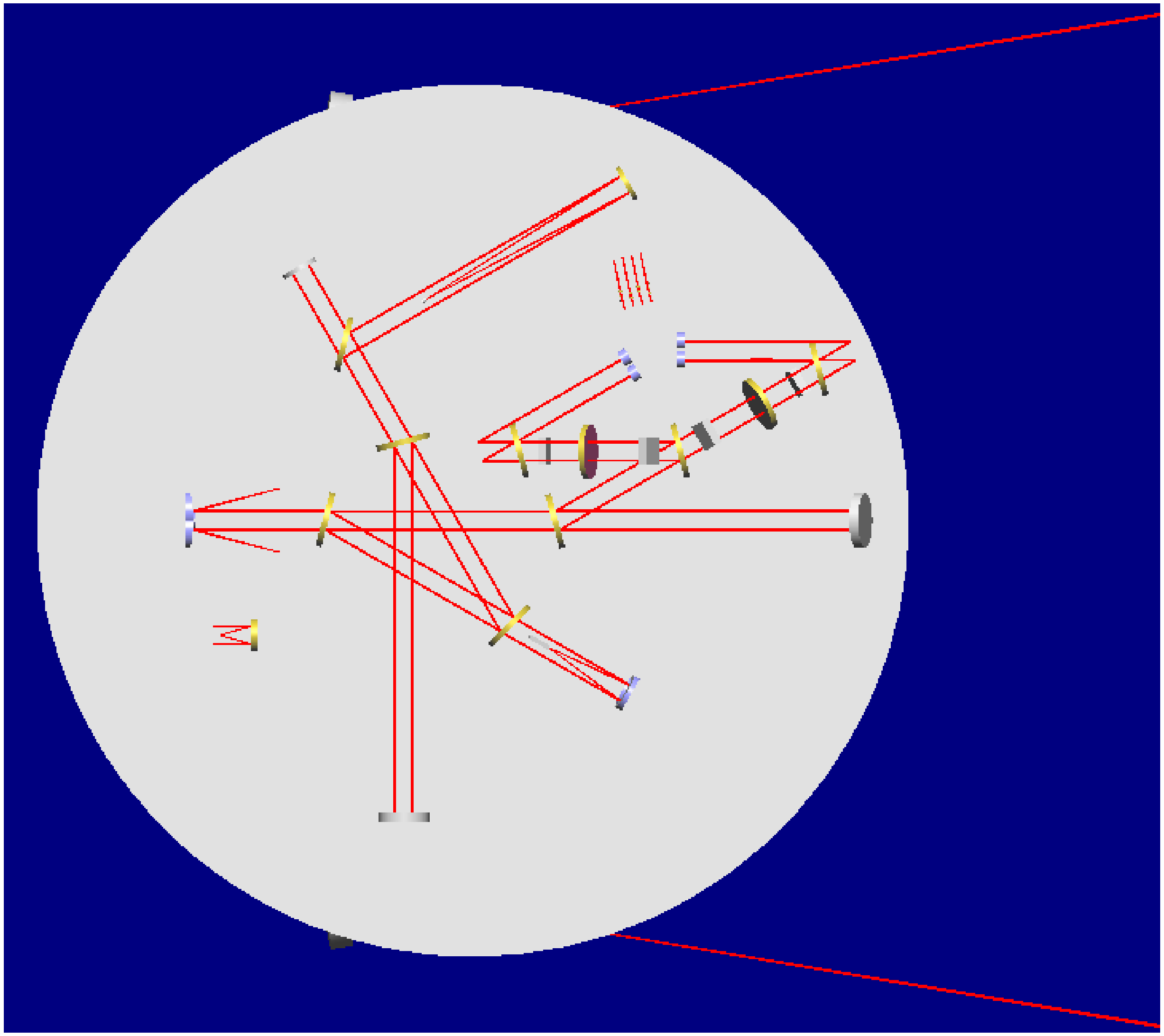
Leonard Wayne

Jet Propulsion Laboratory
California Institute of Technology

The Big Picture

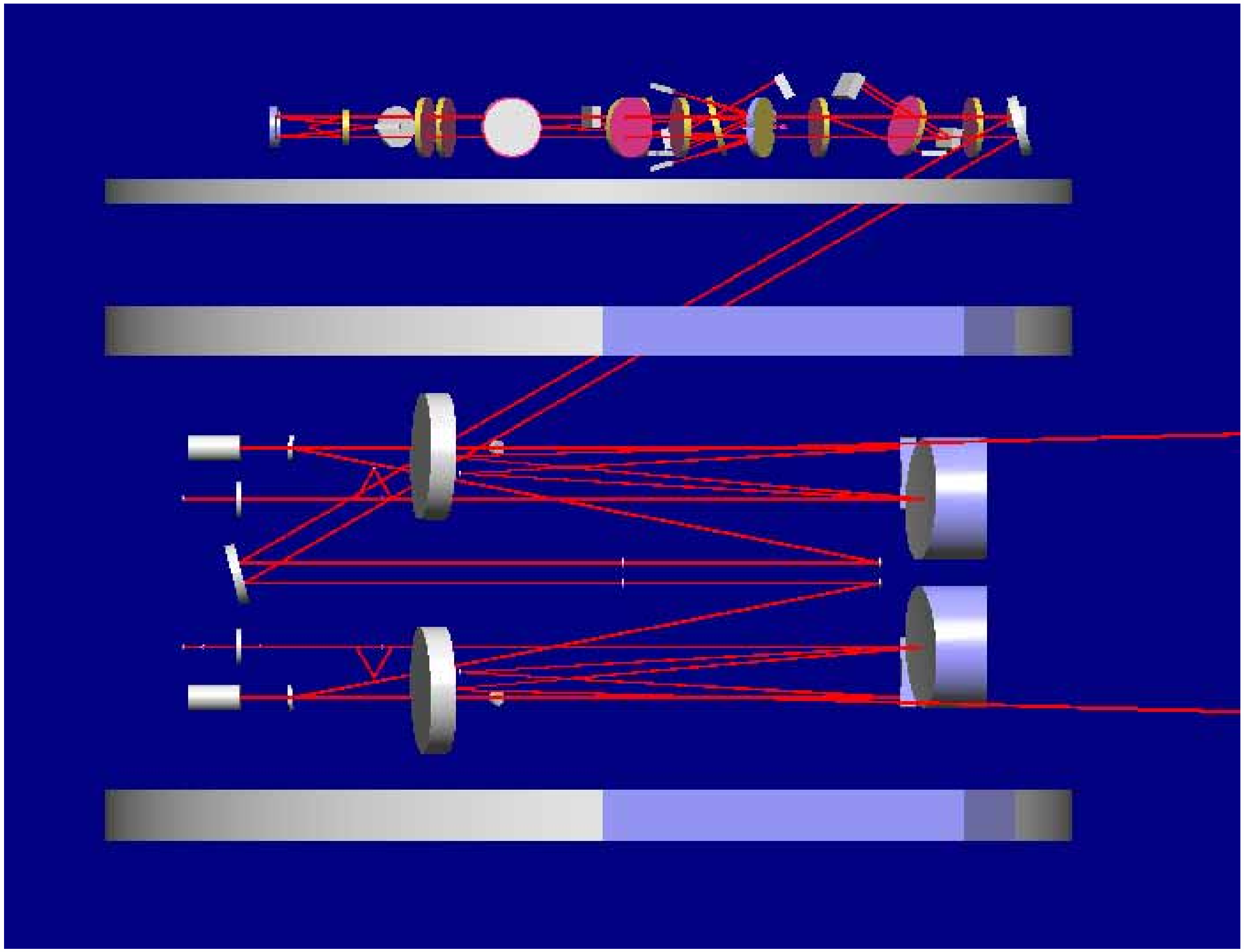


Top View of Combiner

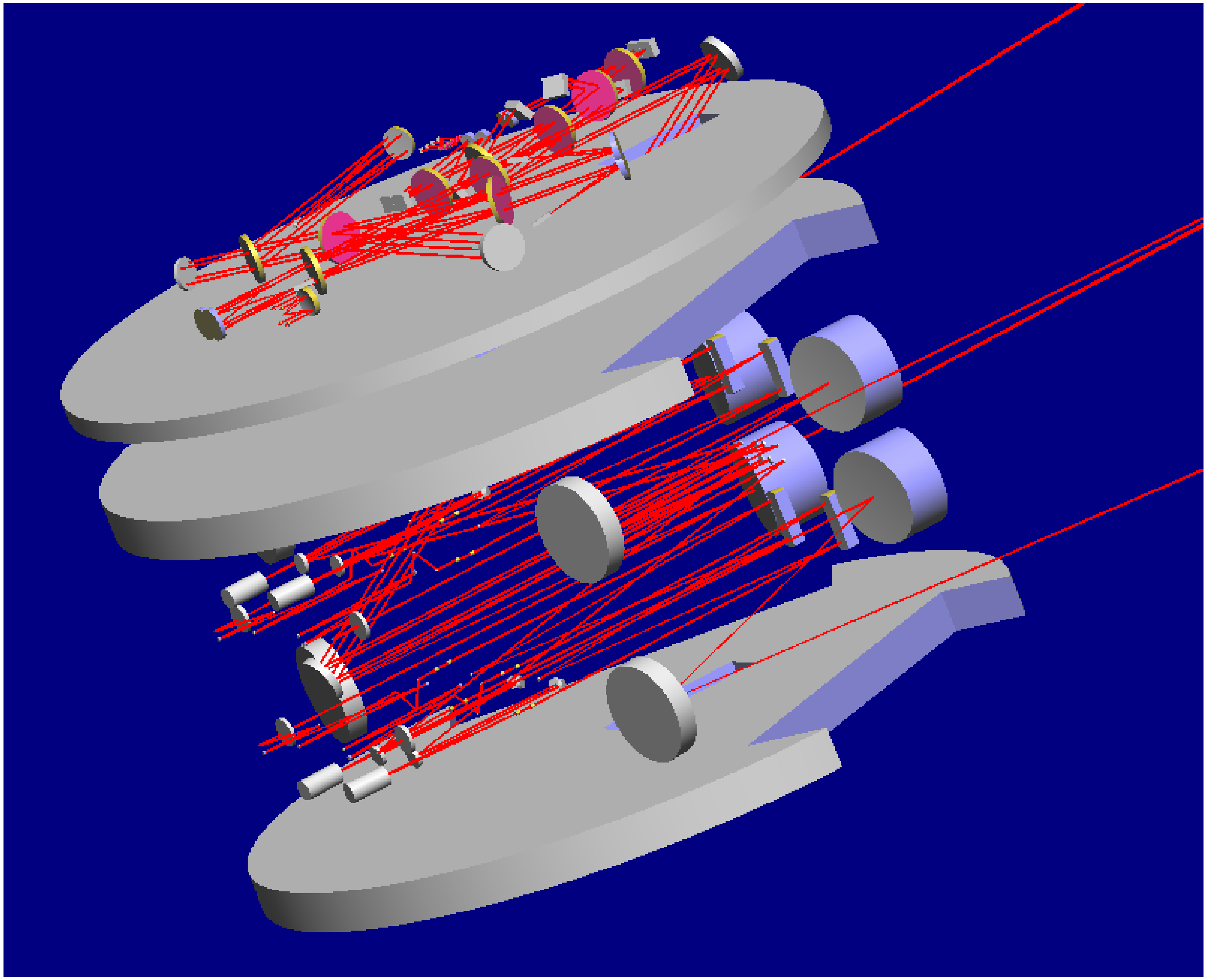


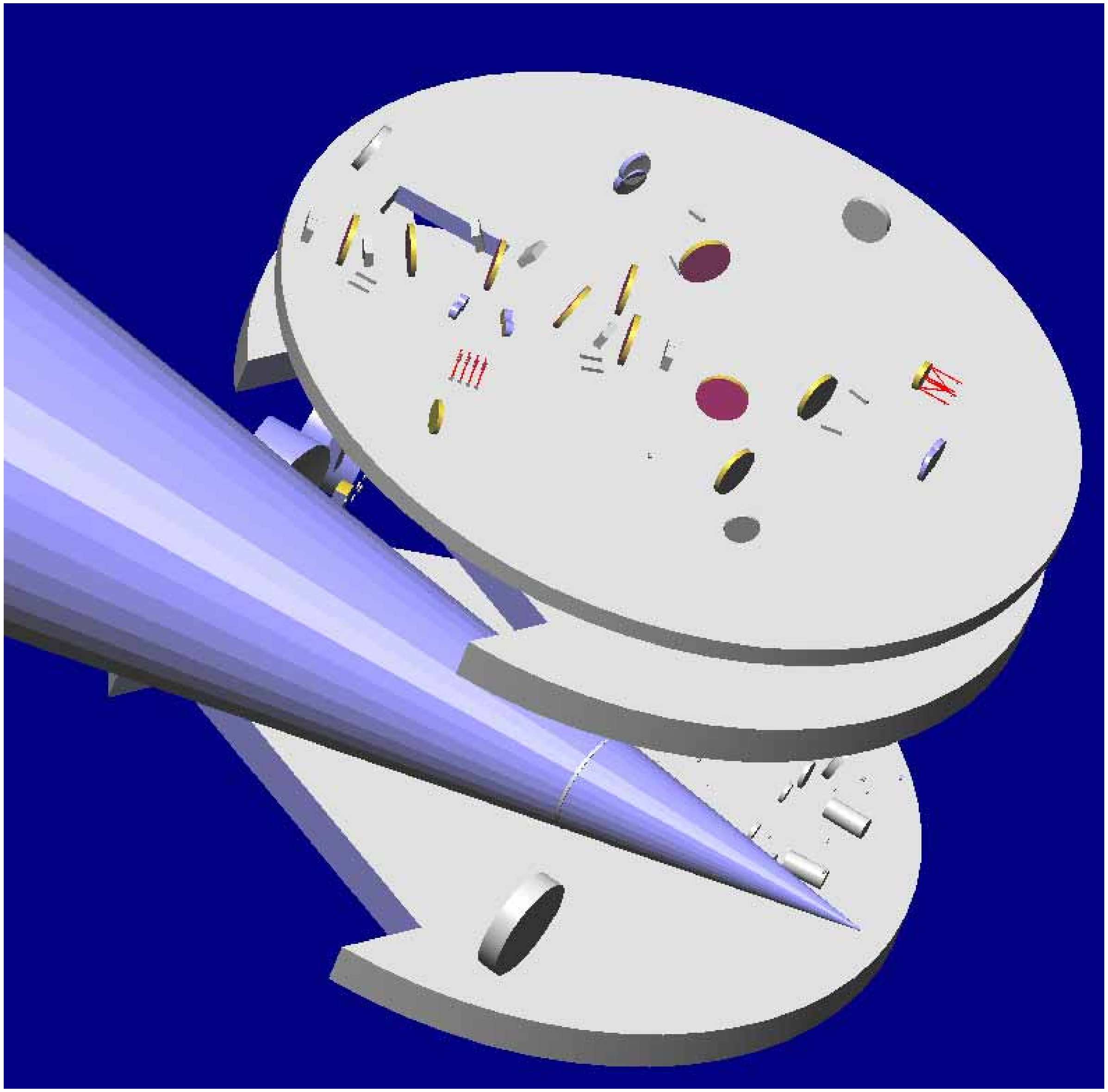
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Side View of Combiner



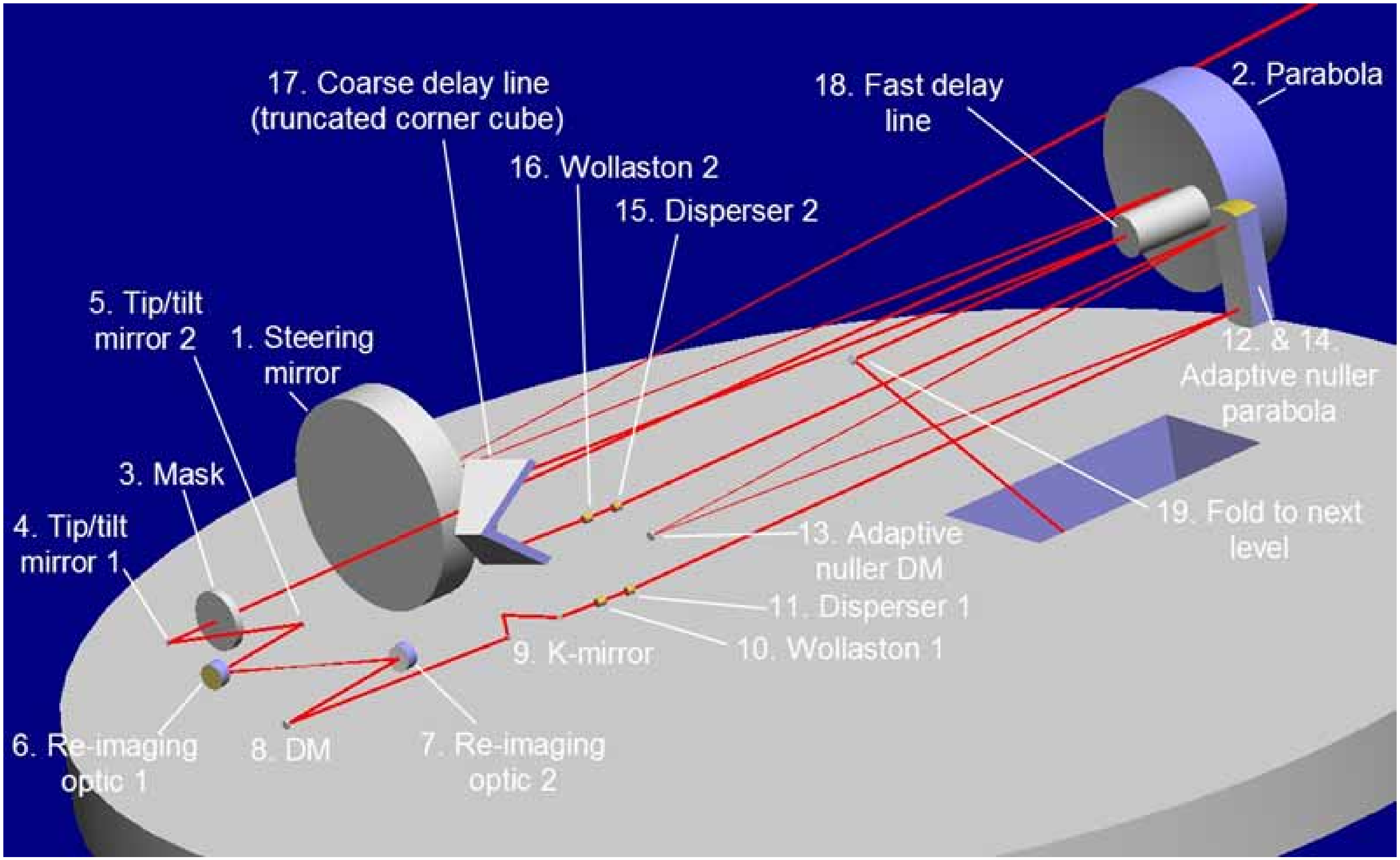
Oblique View of Combiner





The baseplates were carved out to keep the collector spacecraft in view

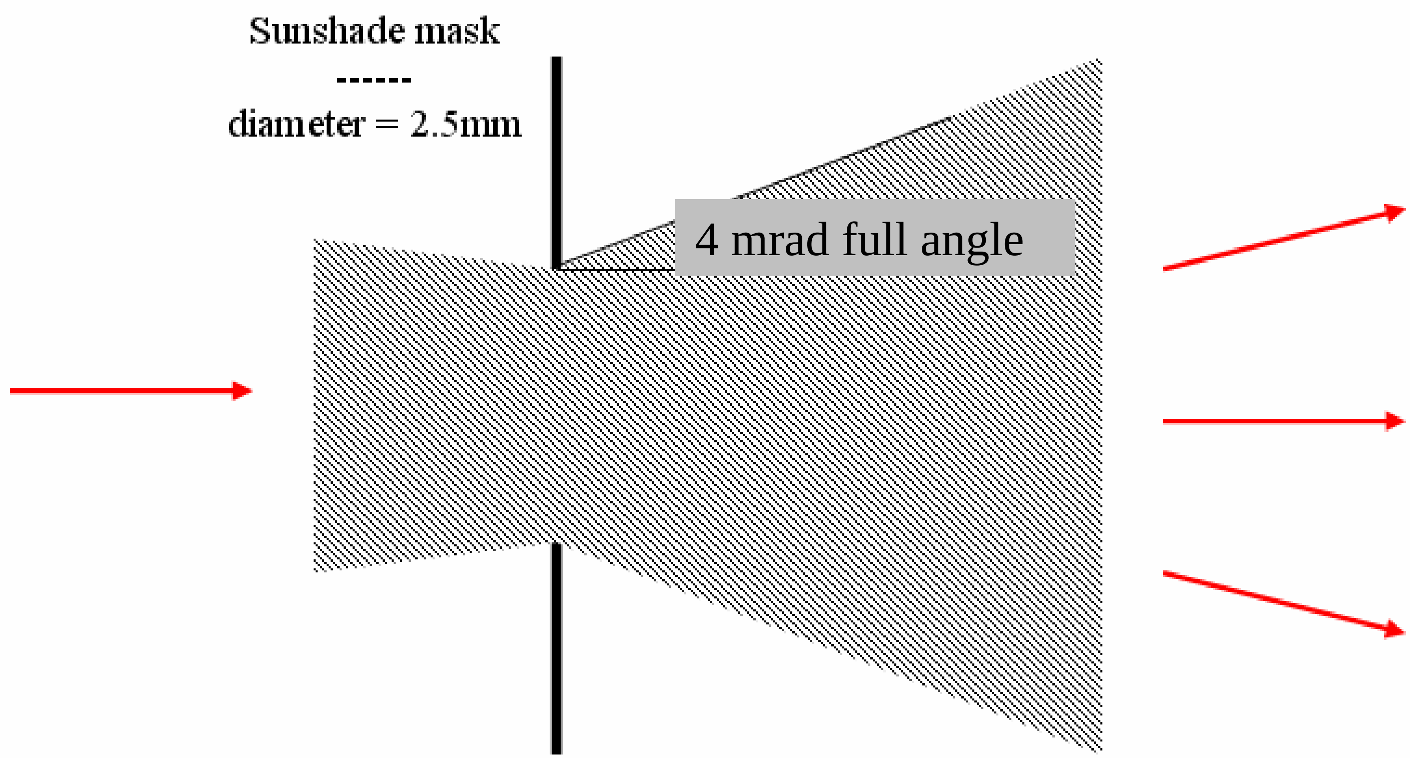
Close-up of Single Beam



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Optics Size Estimate

- Optic size estimates include diffraction calculations



TPF Terrestrial Planet Finder

Illustration of Beam Densification

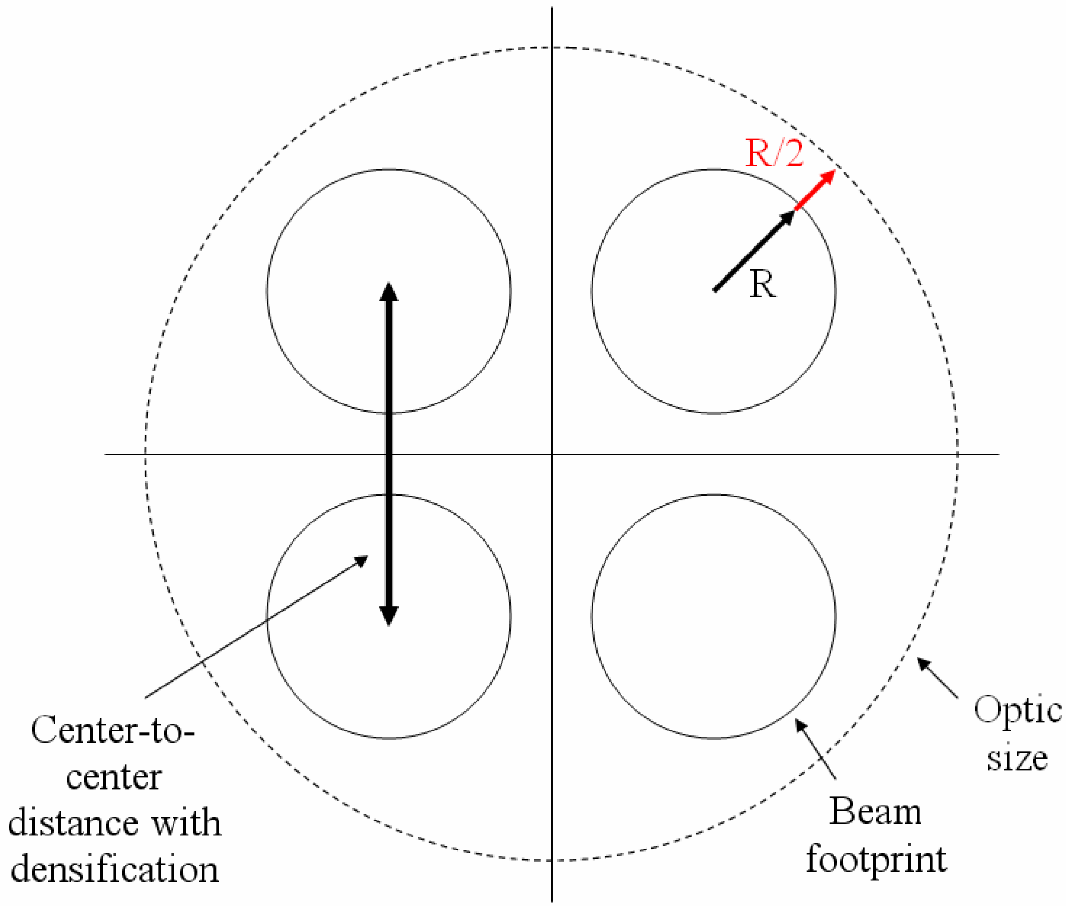


Illustration of (1) beam densification, and (2) oversizing of common-mode optics

Acknowledgments

- This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Terrestrial Planet Finder Primary Mirror Structural Analysis

James R. Smith

Jet Propulsion Laboratory
California Institute of Technology

TPF Primary Mirror FEM Analysis Conclusions and Work Remaining

- Modal frequencies are acceptable at 77 HZ
- Maximum stress levels of 389 PSI suggest 200 G capability based on 80 KSI ultimate, compression loading probably critical on ribs lowering G level capability for the silicon carbide
- Supports
  - The design of the bipod attachments to the mirror will be of concern, limiting acceleration capabilities
  - An attachment design configuration used on another program should be considered for use here

Work remaining

- Mirror support design
- Duplicating the same analysis with support structure
- Random loads analysis
- Thermal analysis with gradients mapped onto FEM
- Margin summaries
- Optical concerns – Pointing accuracy, etc...

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

TPF Primary Mirror FEM Analysis Summary

- Mirror Diameter = 3 m (118.11 in), Curvature = 2400 m
- Material Silicon Carbide
  - Elastic Modulus = 59.5e6 psi, Poisson's Ratio = 0.14, Flexural Strength = 80 ksi
  - Coefficient of Thermal Expansion = 2.2e-6/^{o}F, Density = 2.9e-4 lbm/in^3
- Summary of Results

MAX DEFLECTIONS 1 G X, 1 G Y, 1 G Z					
NODE		X	Y	Z	TOTAL
ID	ACCEL	IN	IN	IN	IN
30238	1 G X	2.64E-04	0	-1.50E-03	1.52E-03
16168	1 G Y	8.45E-06	2.57E-04	2.57E-04	1.45E-03
18740	1 G Z	6.98E-06	1.21E-04	1.21E-04	5.33E-04
MAX STRESS IN MIRROR - 1 G X, 1 G Y, 1 G Z ACCELERATIONS					
MISES STRESS			**MAX PRIN**	**MIN PRIN**	**MAX SHEAR**
ELEMENT	ACCEL	PSI	PSI	PSI	PSI
43356	1 G X	253	389	-376	226
43164	1 G Y	263	366	-366	214
42539	1 G Z	193	121	-250	145
MODAL ANALYSIS SUMMARY					
MODES	Hz				
1	77	BENDING			
2	77	BENDING			
3	168	BENDING			
4	188	BENDING			

TPF Terrestrial Planet Finder

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

TPF Terrestrial Planet Finder

Emma System Budgets

George Purcell

Jet Propulsion Laboratory
California Institute of Technology

Introduction to Budgets

- Budgets have been assembled for mass, power, and volume for the collectors, combiner, and cruise stage.
- For some systems, budgets have been estimated from scratch for Emma. For example,
  - Propulsion
  - Attitude Control System
  - Payload (interferometer and support equipment)
- For other systems, budgets have been borrowed or extrapolated from TPF or ST-9. For example,
  - Power
  - Relative Sensors
  - Flight Computer
- Numbers are estimates of the actual values. 30% margin is added explicitly at the end.
- Volume budgets are very incomplete and of questionable value; they are not presented here.

Total Mass

- Total mass for 4 Collectors, 1 Combiner, and 1 Cruise Stage

ELEMENT	NUMBER	TOTAL MASS (kg)
Collectors	4	3107.2
Combiner	1	1175.6
Cruise Stage	1	953.6
TOTAL		5236.3
TOTAL + 30%		6807.2

- Capacity of Delta IV M+ vehicle:
  - To an Earth-trailing orbit: 7850 kg
  - To a geostationary transfer orbit: 4350 kg

Acknowledgements

- This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.