SPECTRE

Spectral **P**hotovoltaic **E**nergy **C**ollection & **Tr**ansmission to **E**arth

2018-2019 ISSP Student Competition
Semi finals at ISDC 2019 in Arlington, VA

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SPECTRE

Contents

- Introduction
- Problem statement
- Solution
- Design
- Sustainability
- SPS-Alpha comparison
- Conclusion
- Recommendations

LR: Jamie – Lars – Chris – Berend
Joshua – Dylan – Bart – Kasper - Rik

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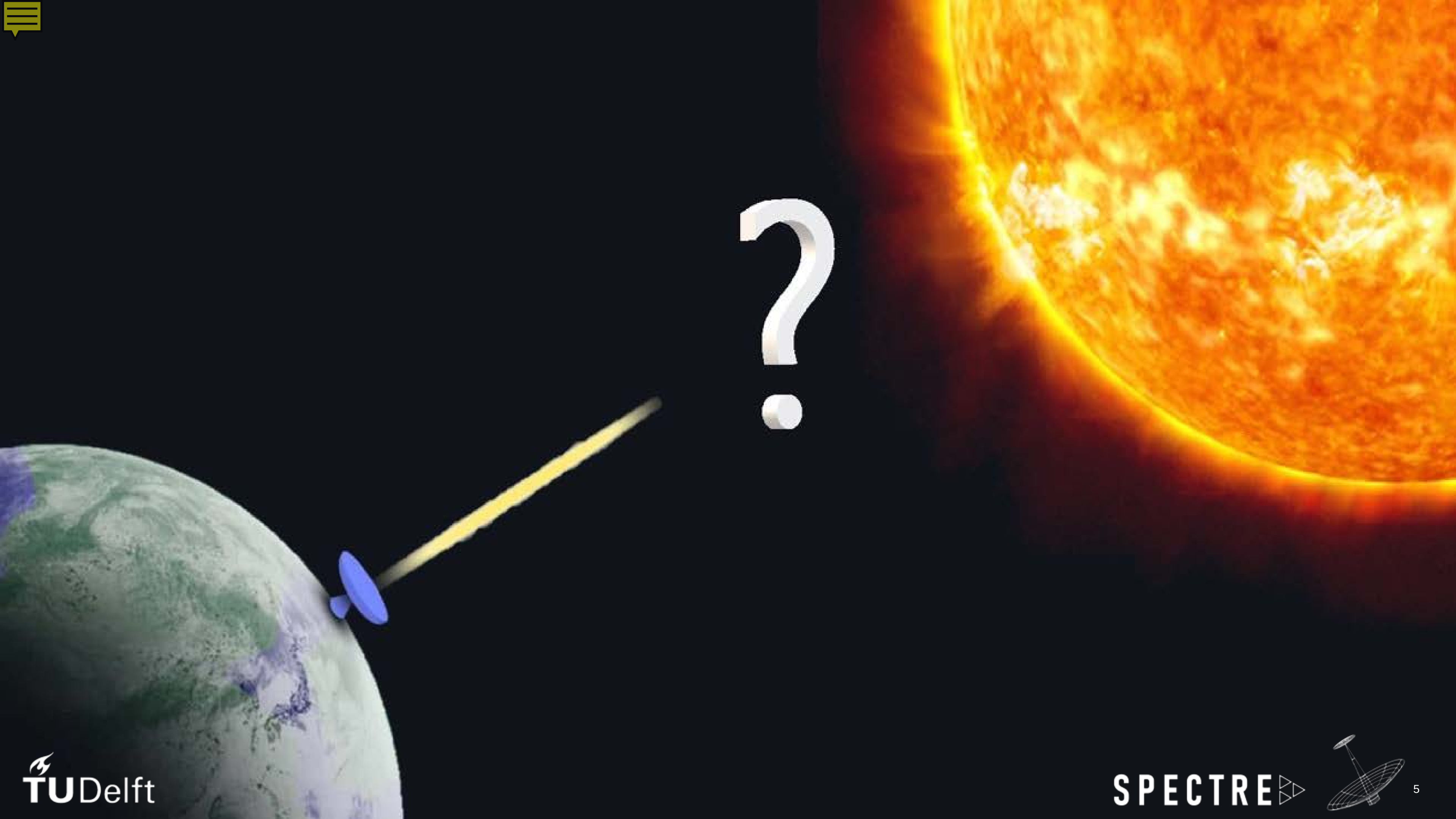
Problem Statement

Source: Natural Resources Council of Maine



Design Case

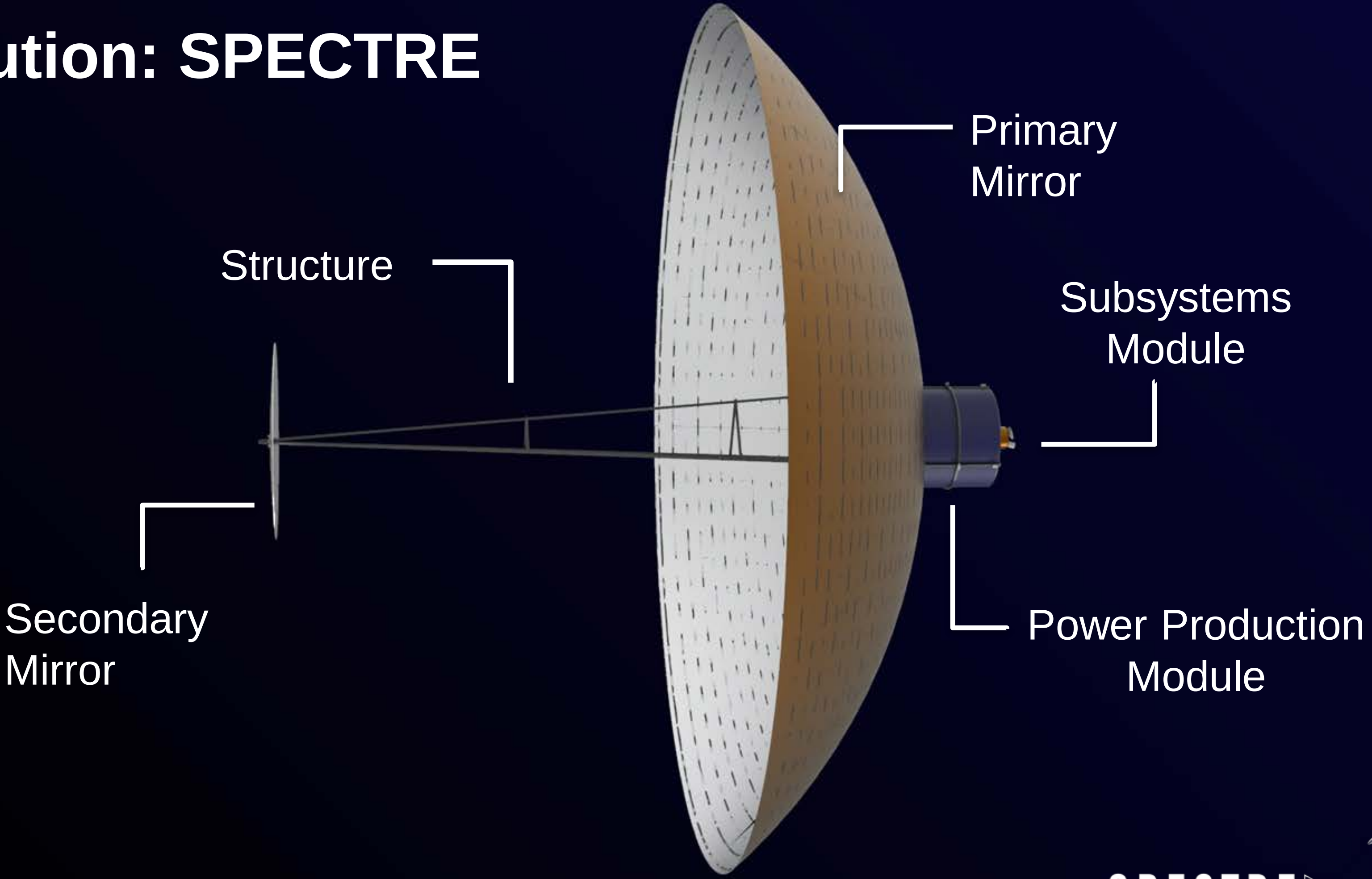
1 Gigawatt
of power

30
years

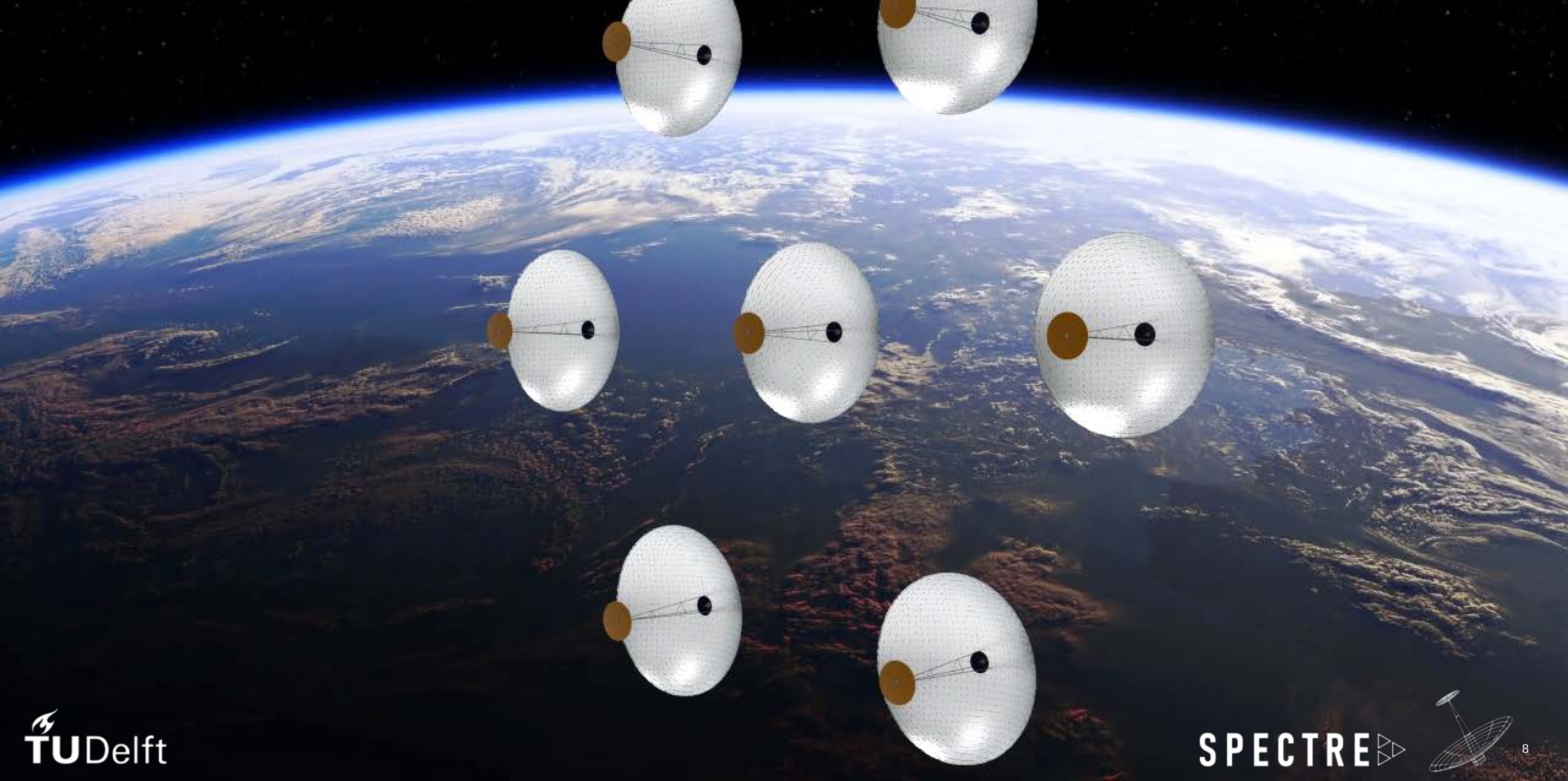
Economically
Viable

Environmentally
Sustainable

Solution: SPECTRE



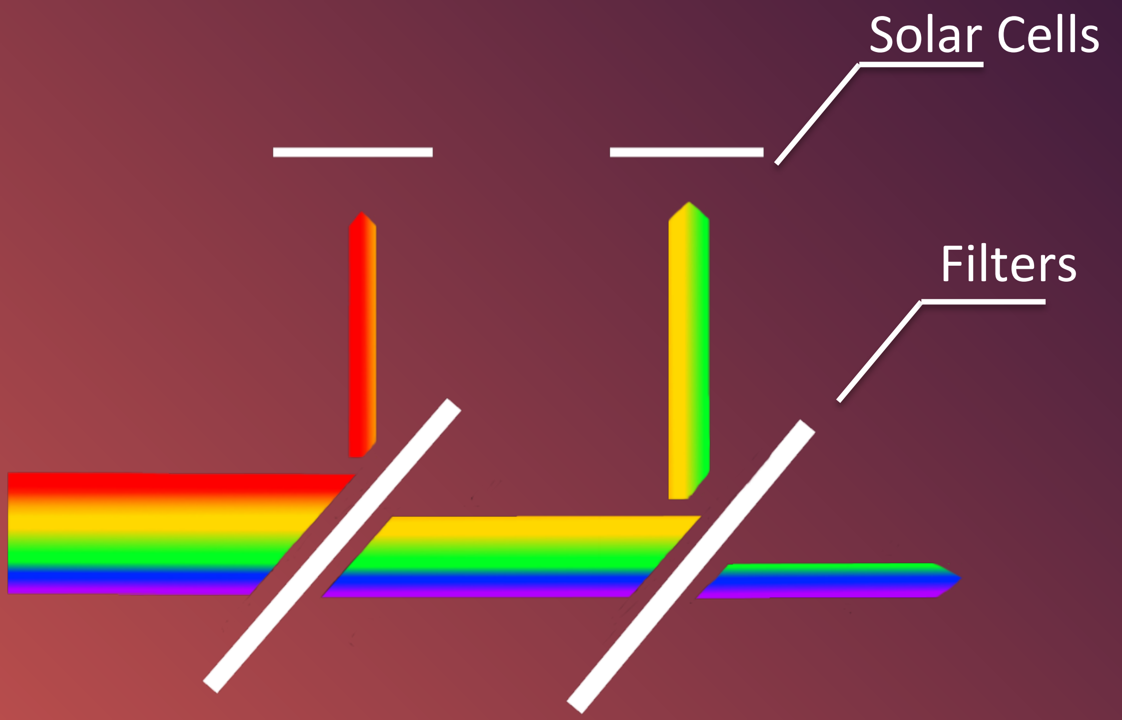
SPECTRE Cluster



Power Collection

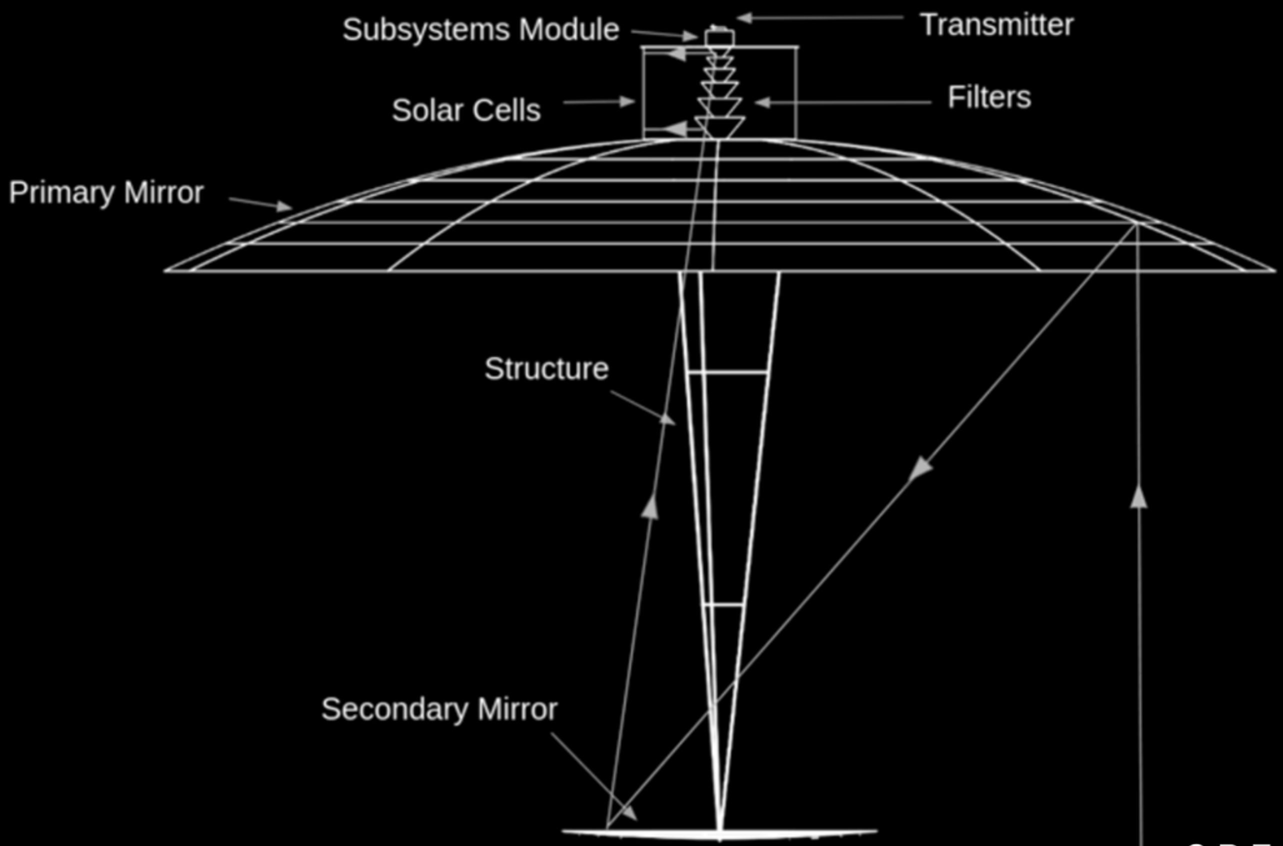
Source: NASA

Spectral Splitting

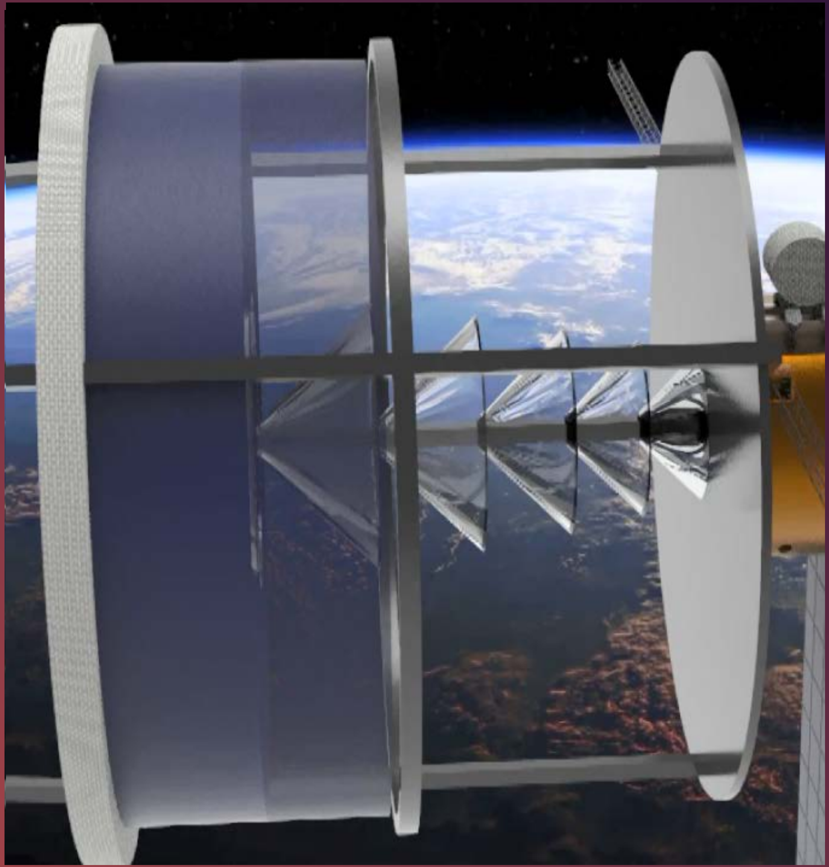


70% Efficiency

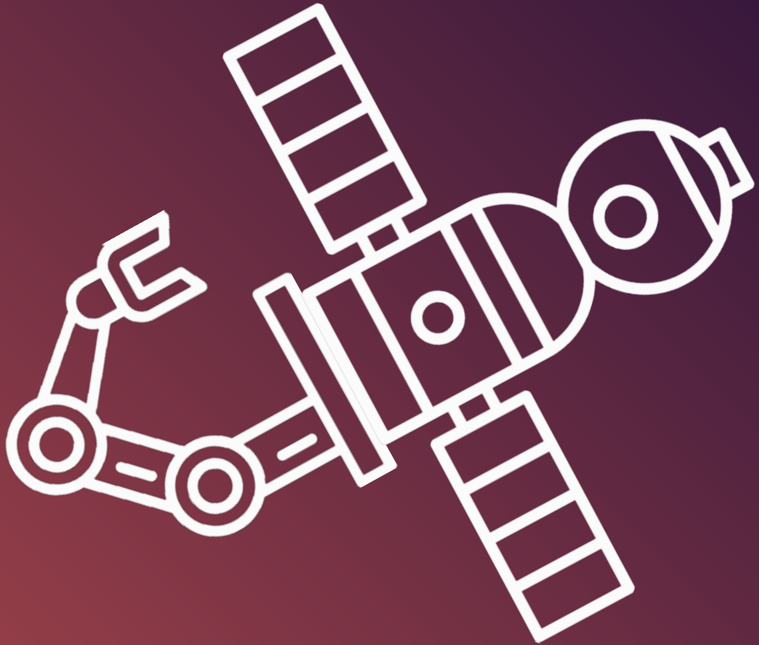
Power Collection



Power Collection

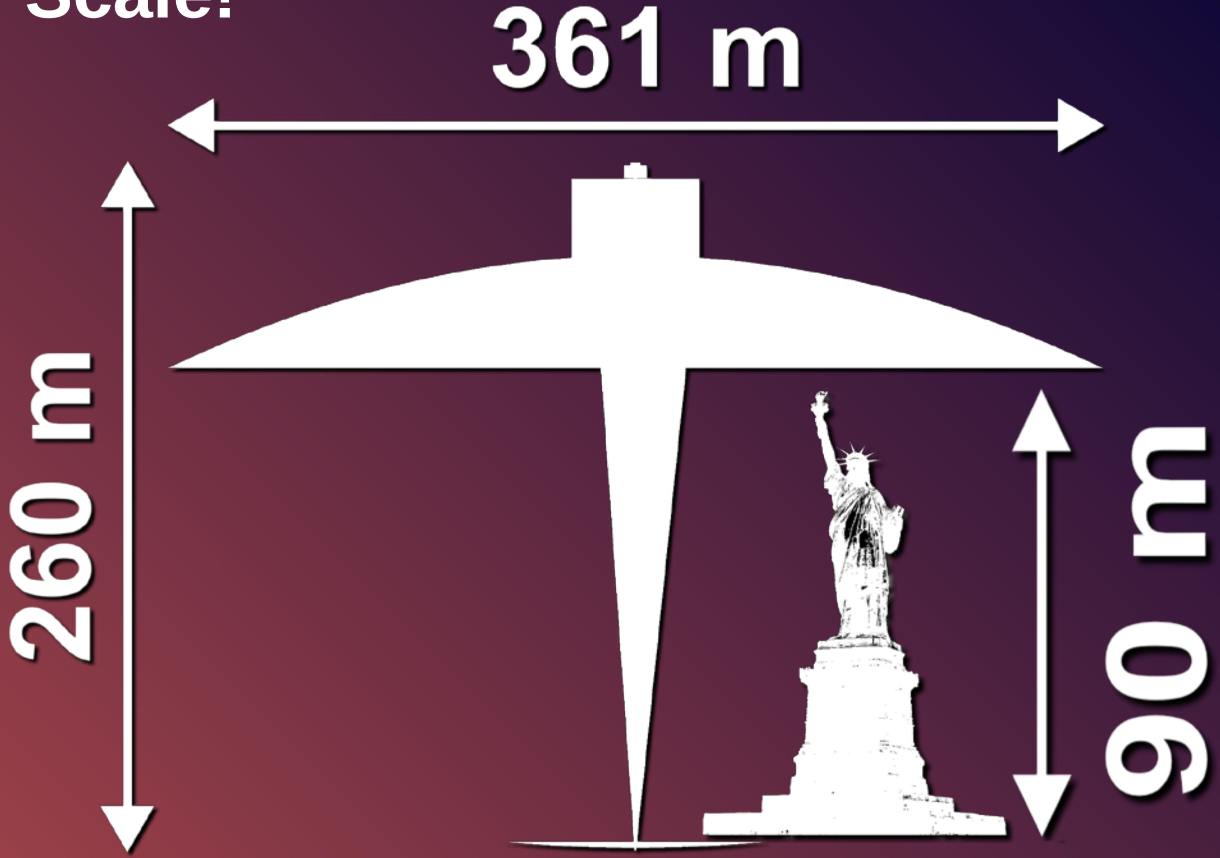


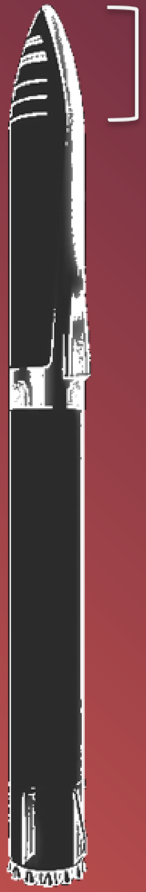
Production



Scale!

20x





In-orbit construction:

- High packing efficiency
- No launch loads on structure

> Large and light S/C

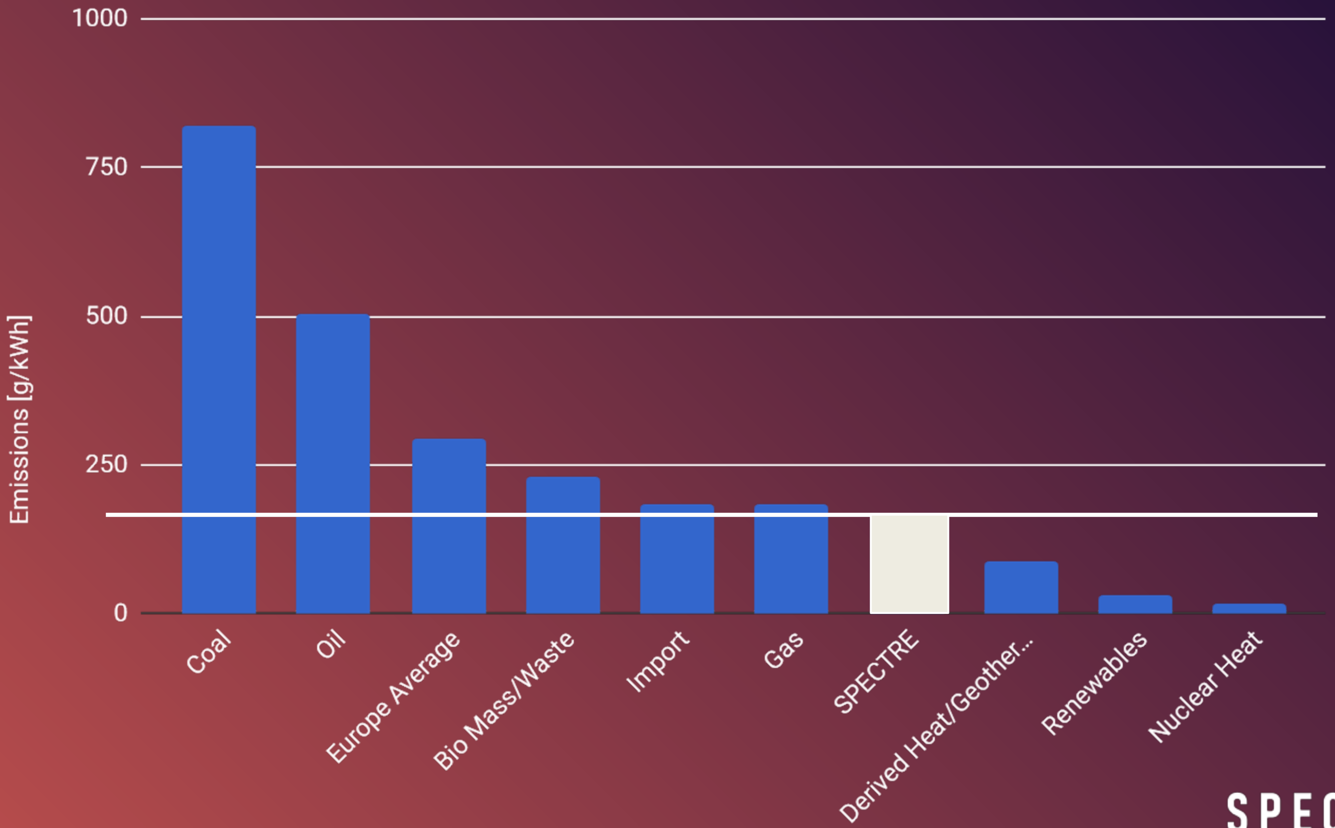
Integration Animation

Sustainability

Environmental

Economical

Environmental Sustainability



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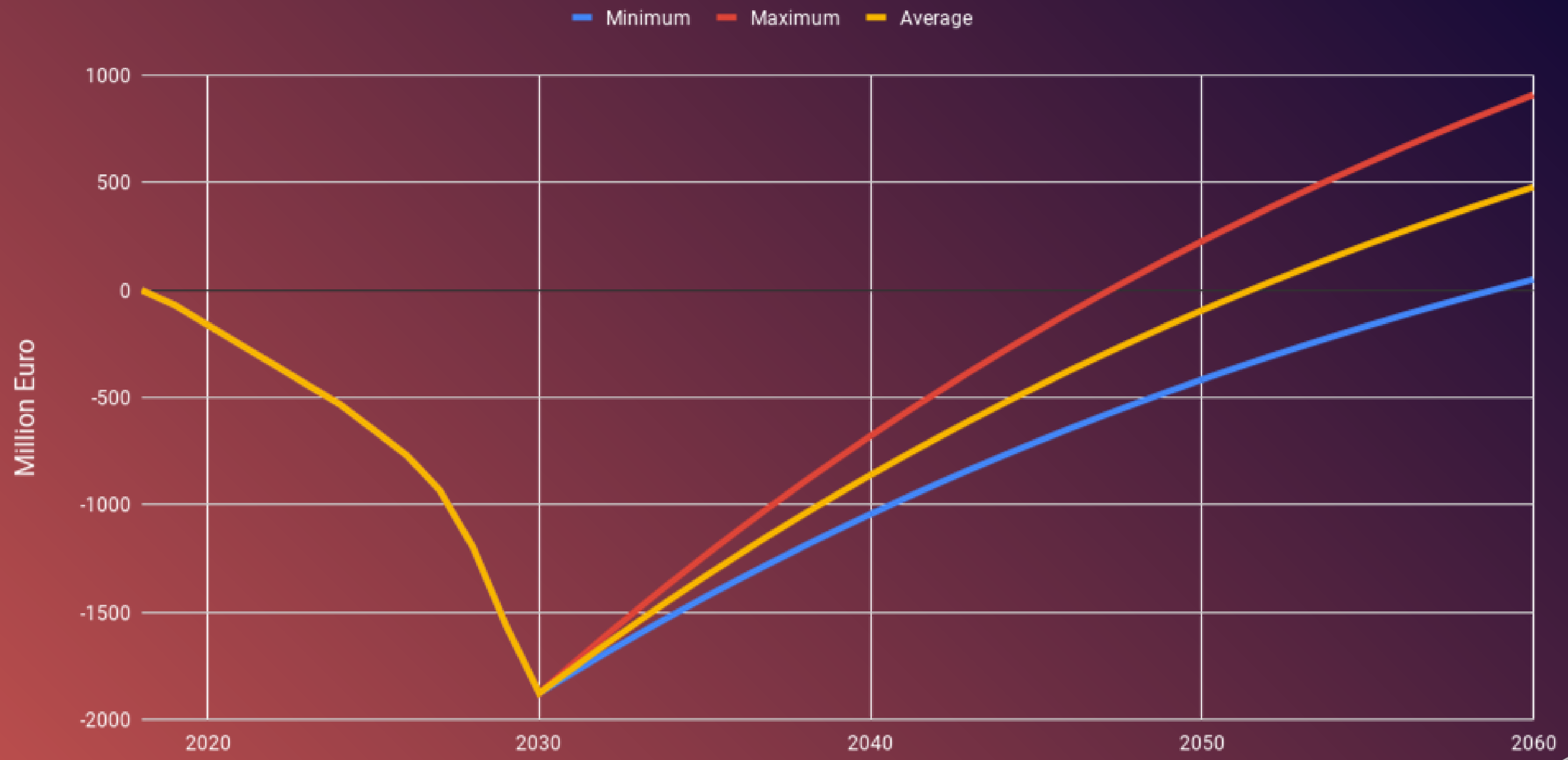
Economical Sustainability



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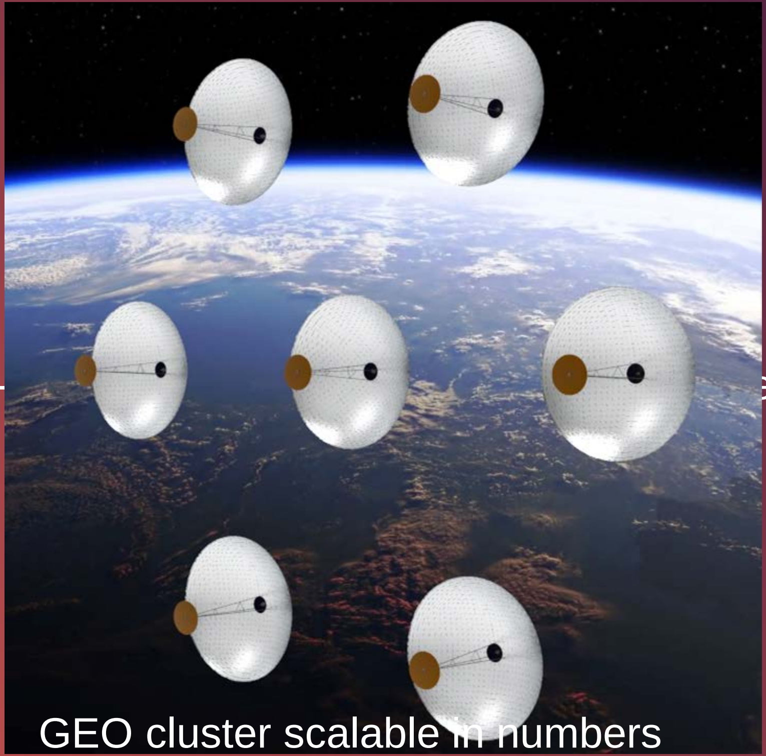
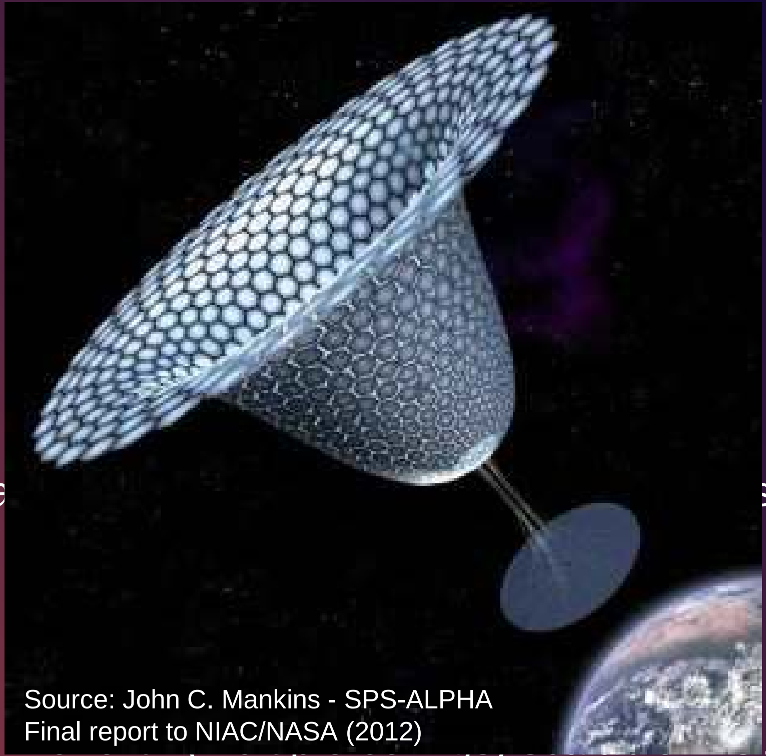
SPECTRE vs. SPS-ALPHA



In-

GEO cluster scalable in numbers

200 gr. CO_2/kWh



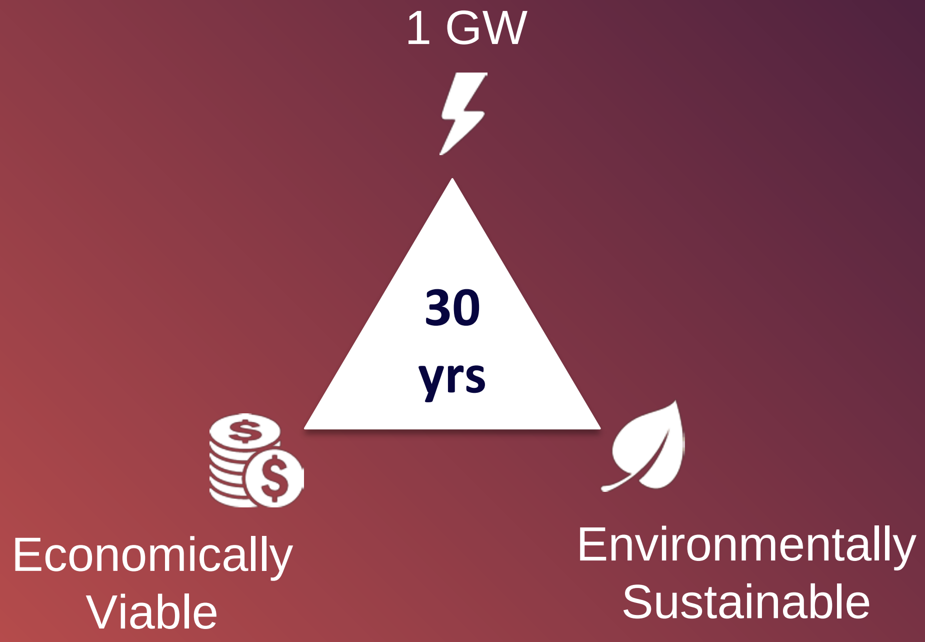
Source: John C. Mankins - SPS-ALPHA
Final report to NIAC/NASA (2012)

Ha

GEO ... ze

??? gr. CO_2/kWh (likely higher than 200)

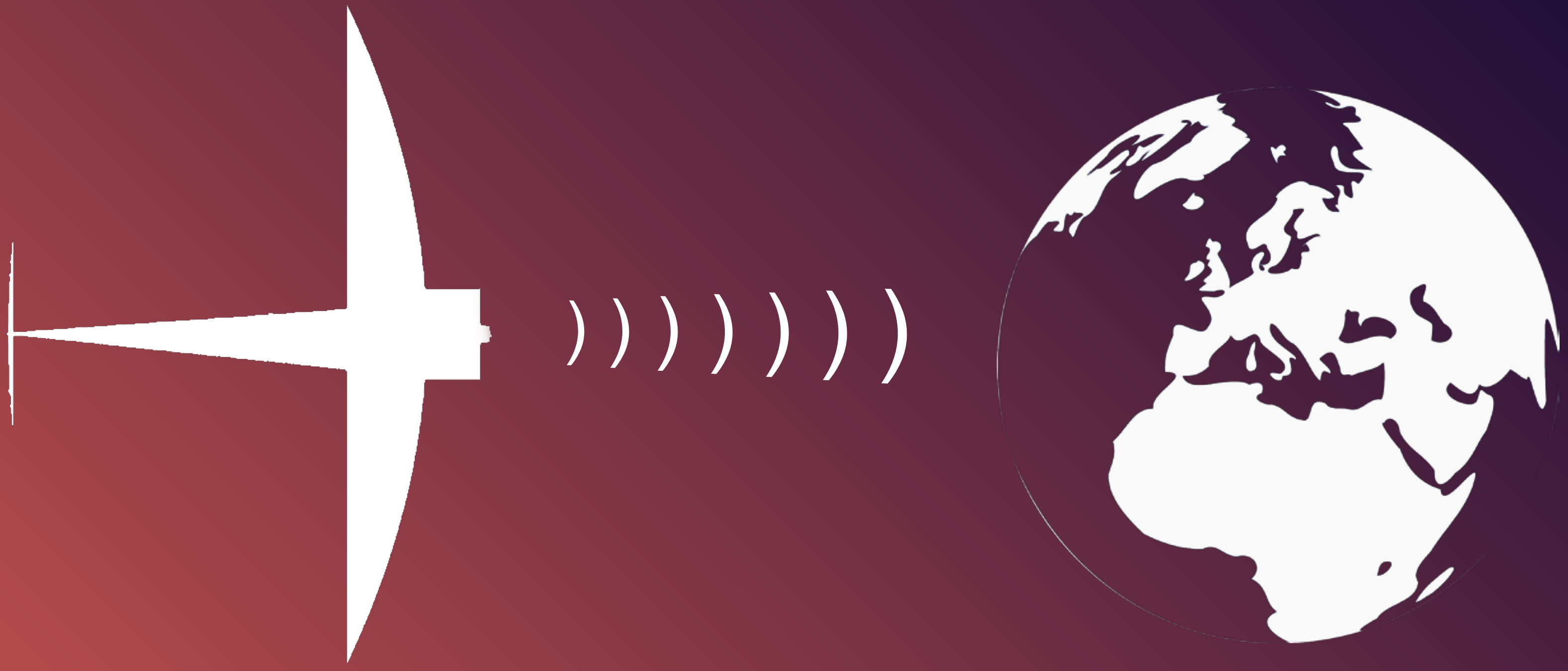
Conclusion



- ✓ 1 GW
- ✓ 30 Years
- ✓ Environmentally Sustainable
- ✓ Economically Feasible

Recommendations

Transmission Module

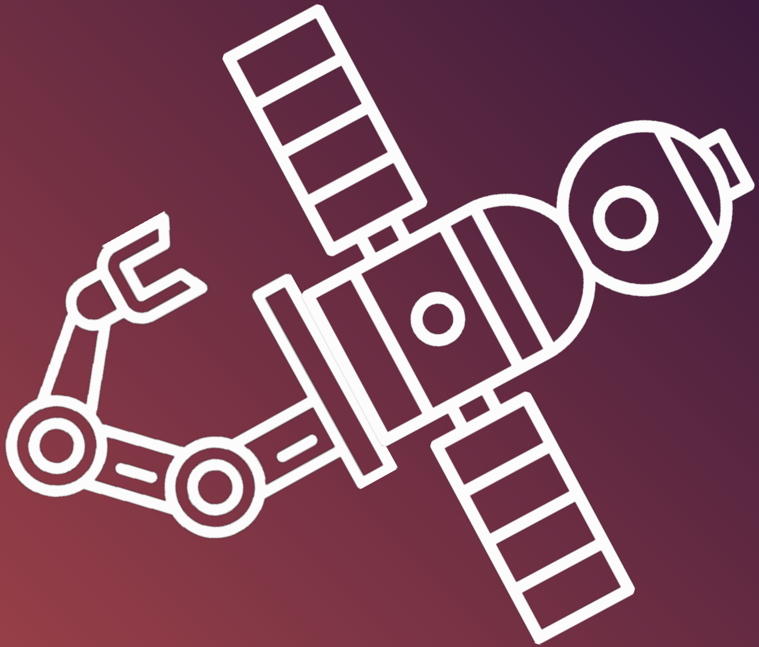


Recommendations

Filter Development

Recommendations

In-Orbit Production



Thank You!

Contact:

J.J.Spaander@student.tudelft.nl

Backup Slides

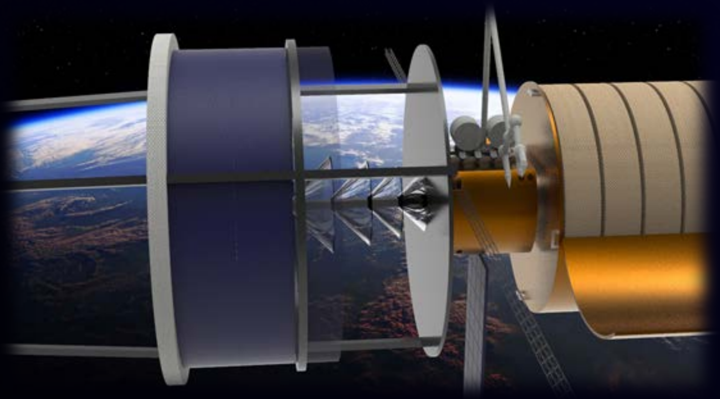
General Backup Slides

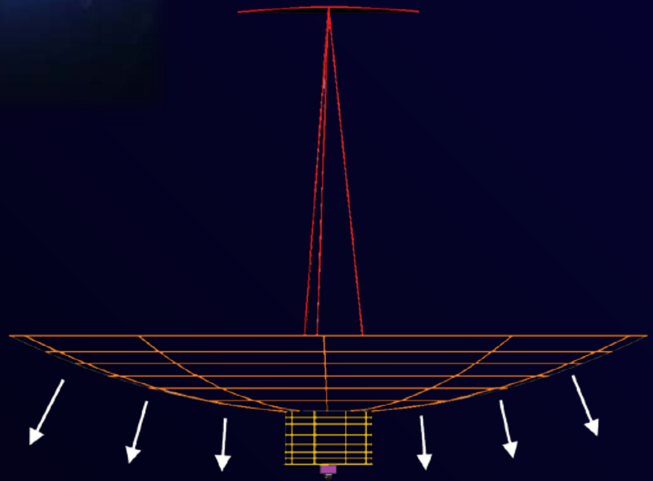
Further Recommendations

- Power transmitter

- Thermal control

- In-orbit production





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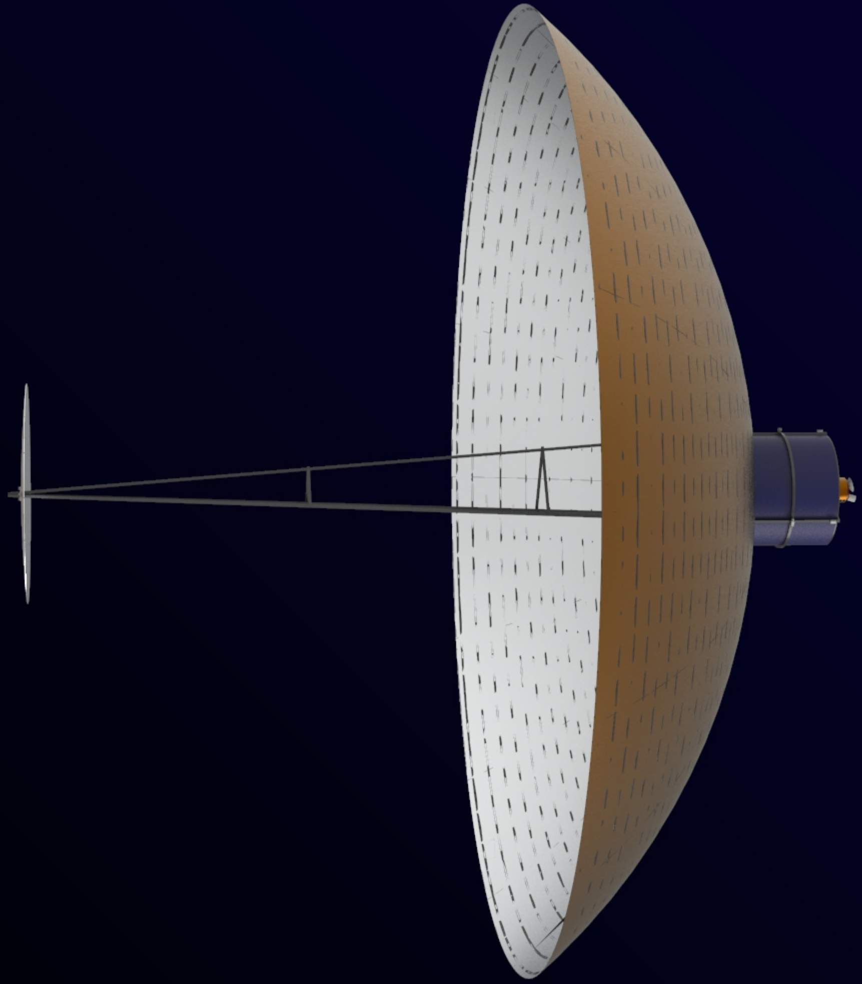
Conclusion

1 GW

20 S/C

2 km²

289 Tonnes



Spectral Splitting

In-Orbit Production

70% Efficiency

90%+ Availability

€1B Profit

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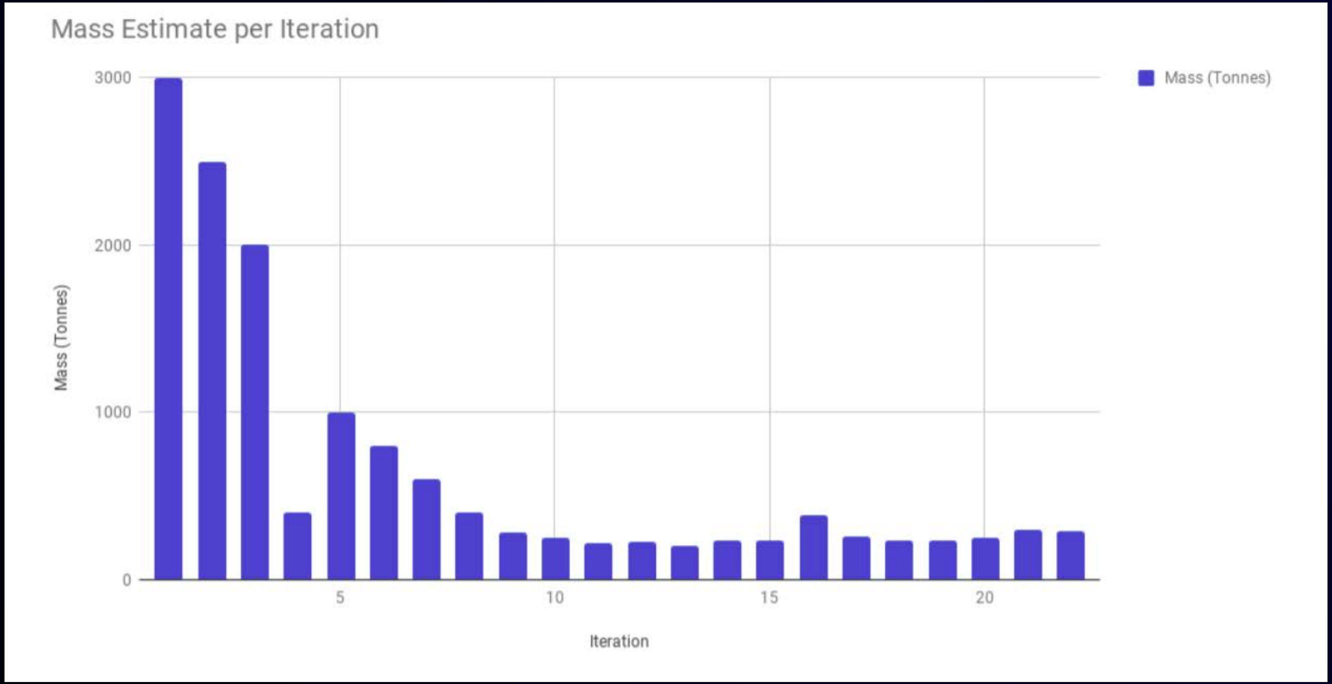
Mass Budget Overview

Subsystem	Total SPECTRE Mass Breakdown [tonnes]	Mass Breakdown per Spacecraft [tonnes]	Mass Breakdown (%)
Propulsion	35	1.8	12.11
ADCS	49	2.4	16.96
Thermal Control	60	3.0	20.76
TT&C	0.3	0.01	0.10
Power Collection	64	3.2	22.15
Power Storage	8	0.4	2.77
EPSY	26	1.3	9.00
Maintenance	20	1.0	6.92
Structure	26	1.3	9.00
Total	**289**	**14.4**	**100.0**

Mass Iterations



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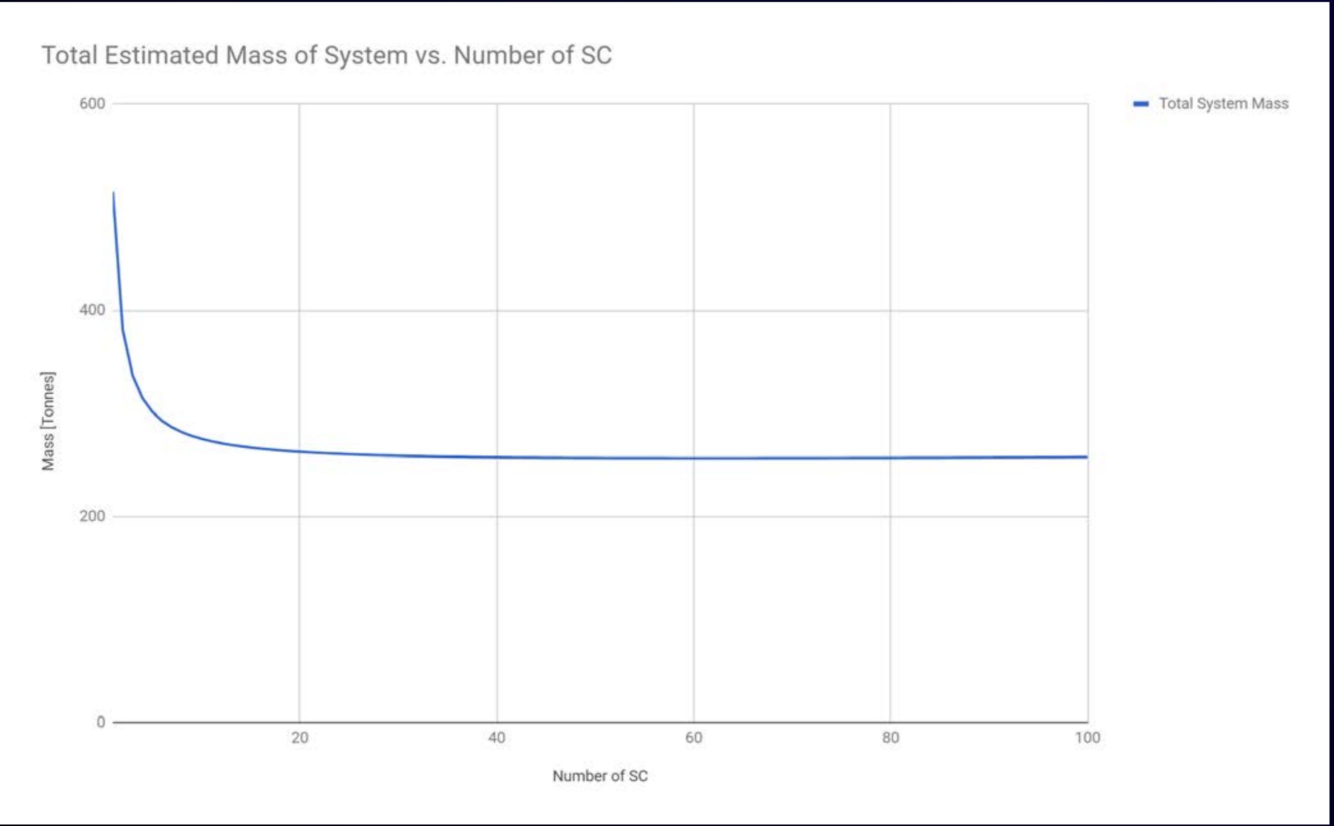
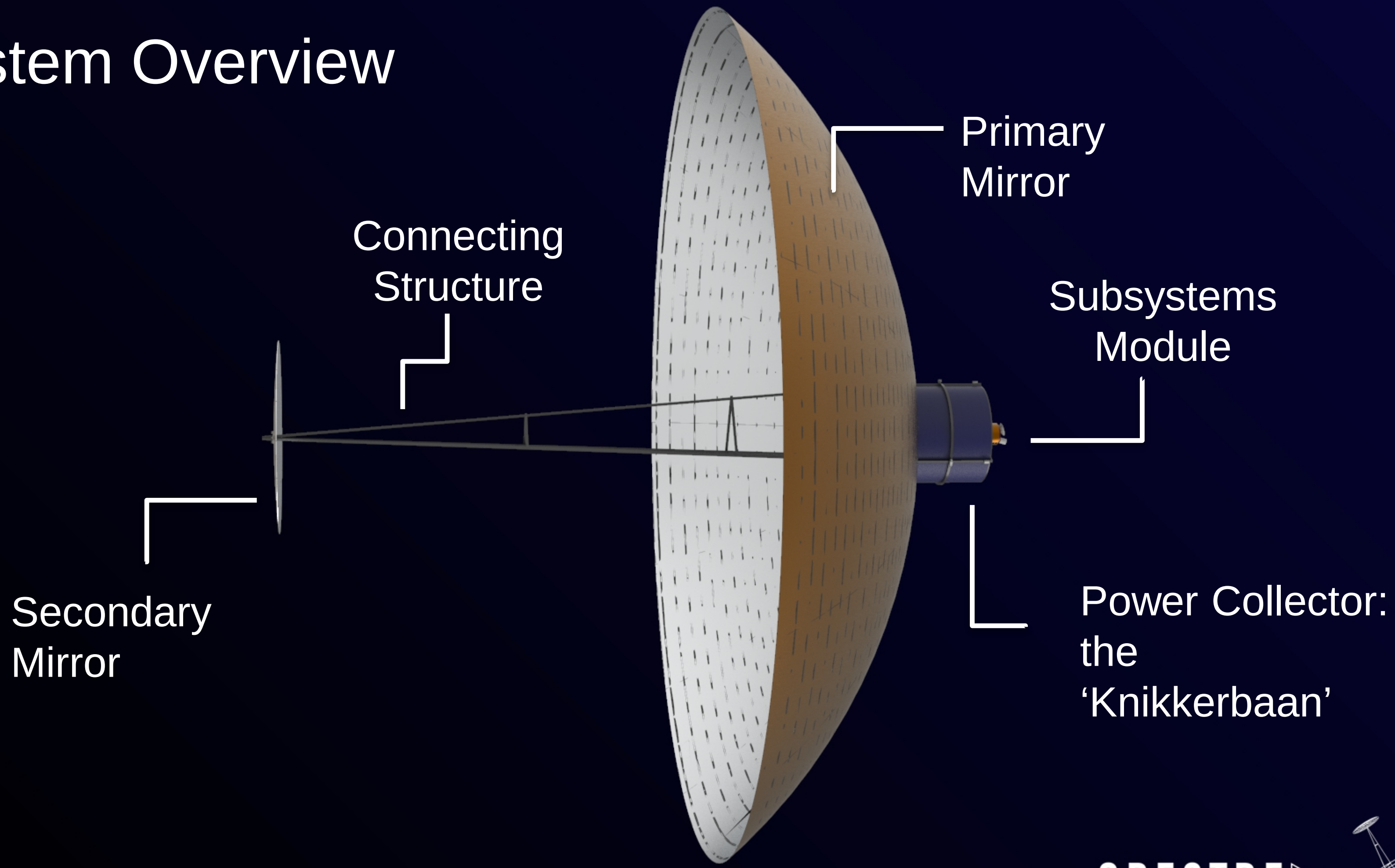
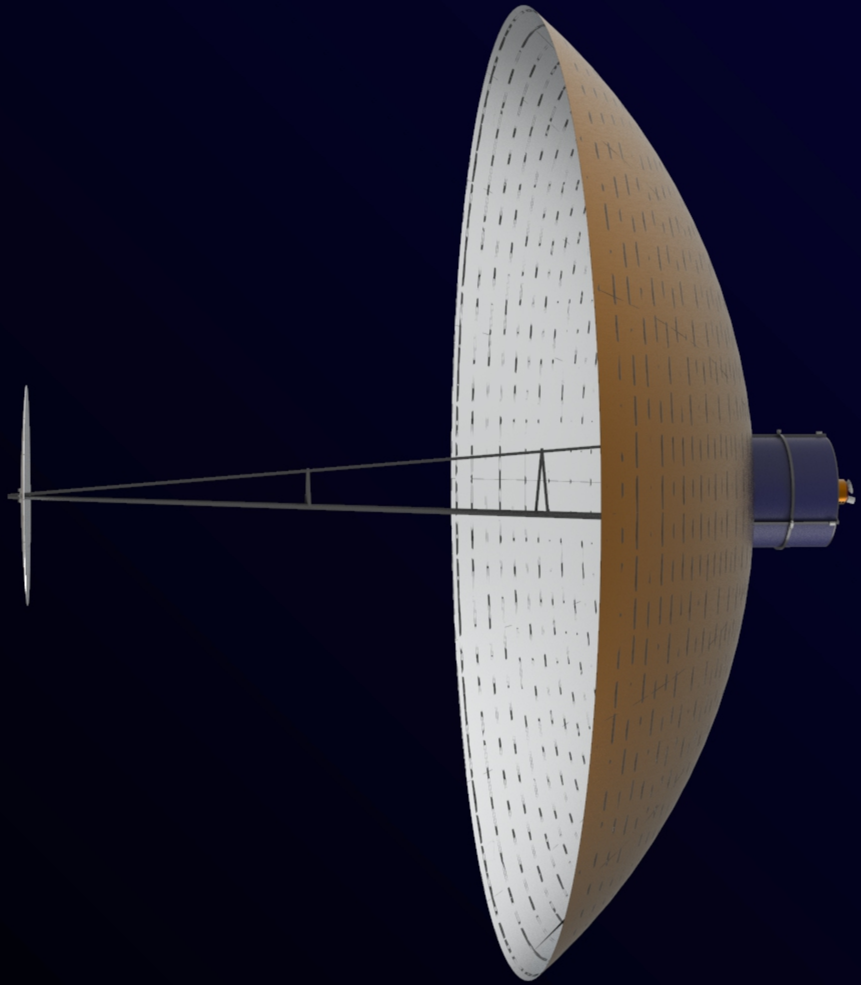
Optimal Number of Spacecraft

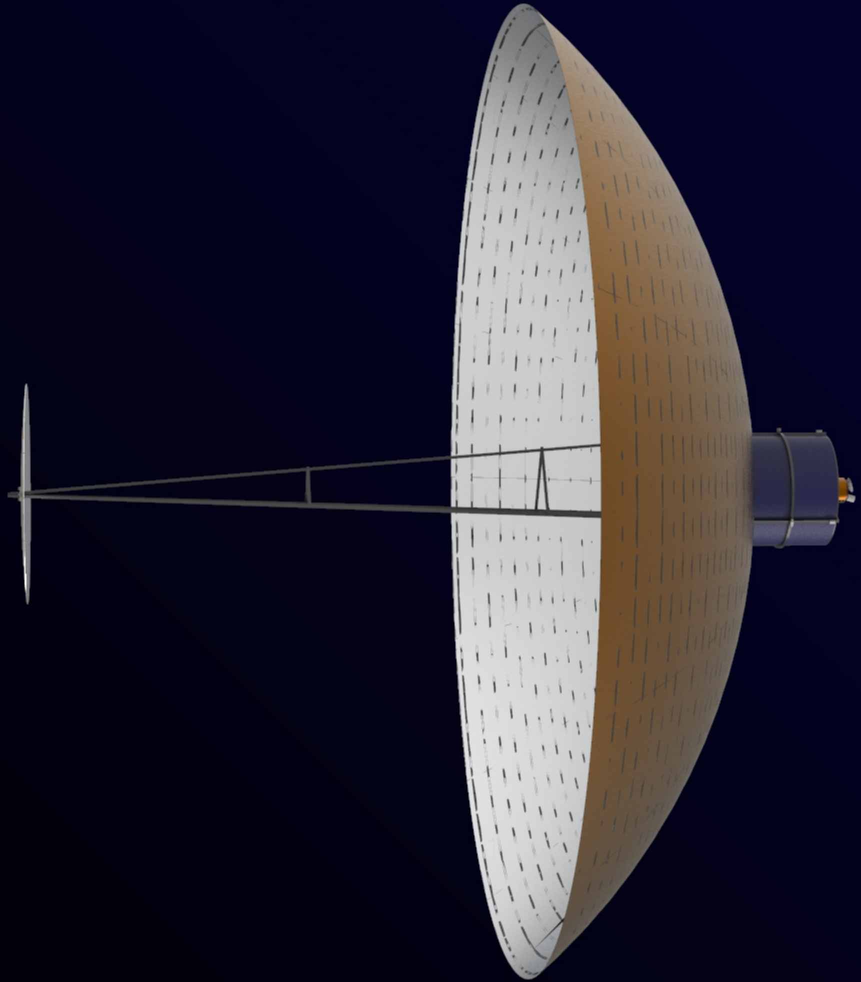


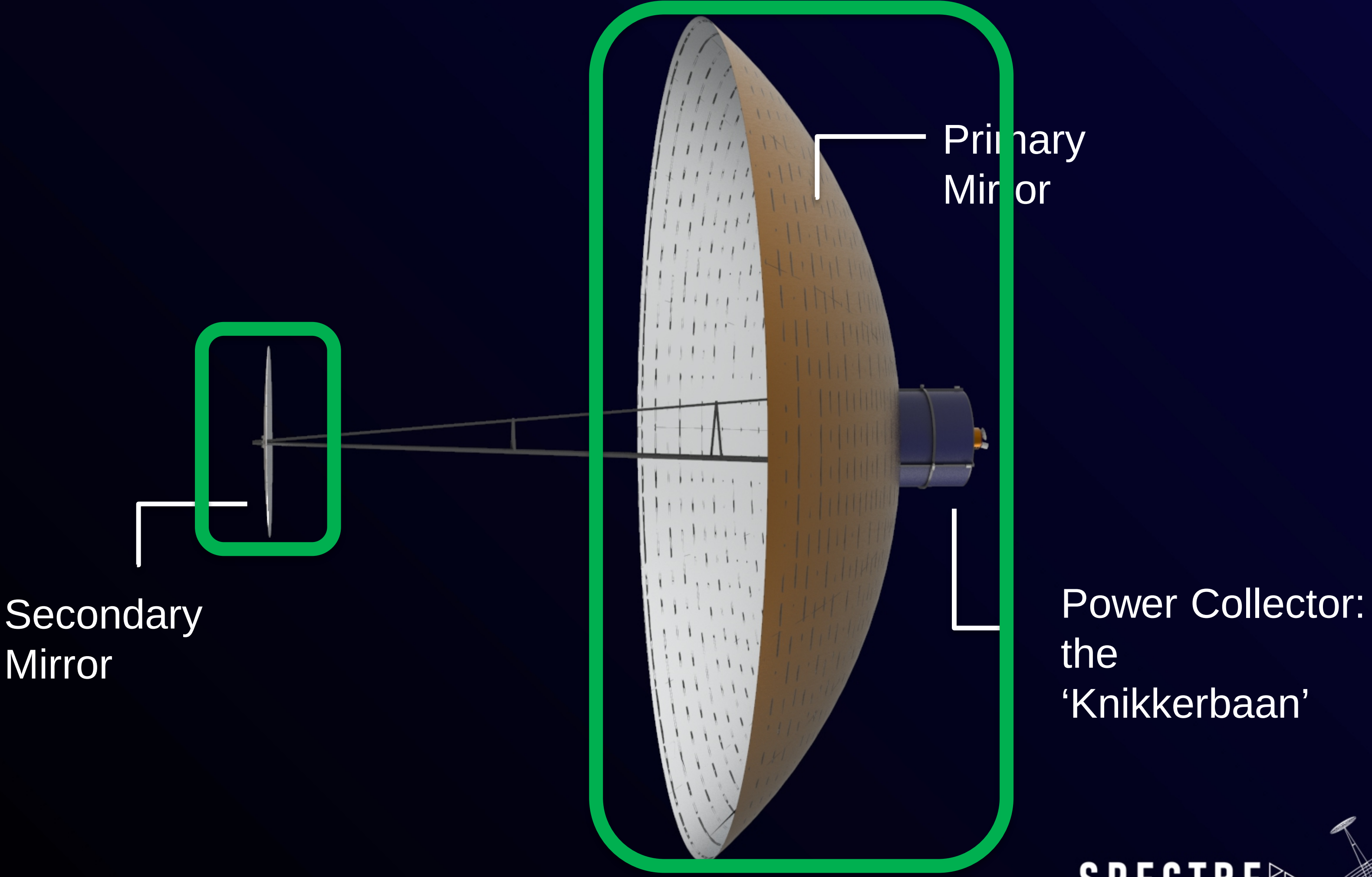
Concept Overview Backup Slides

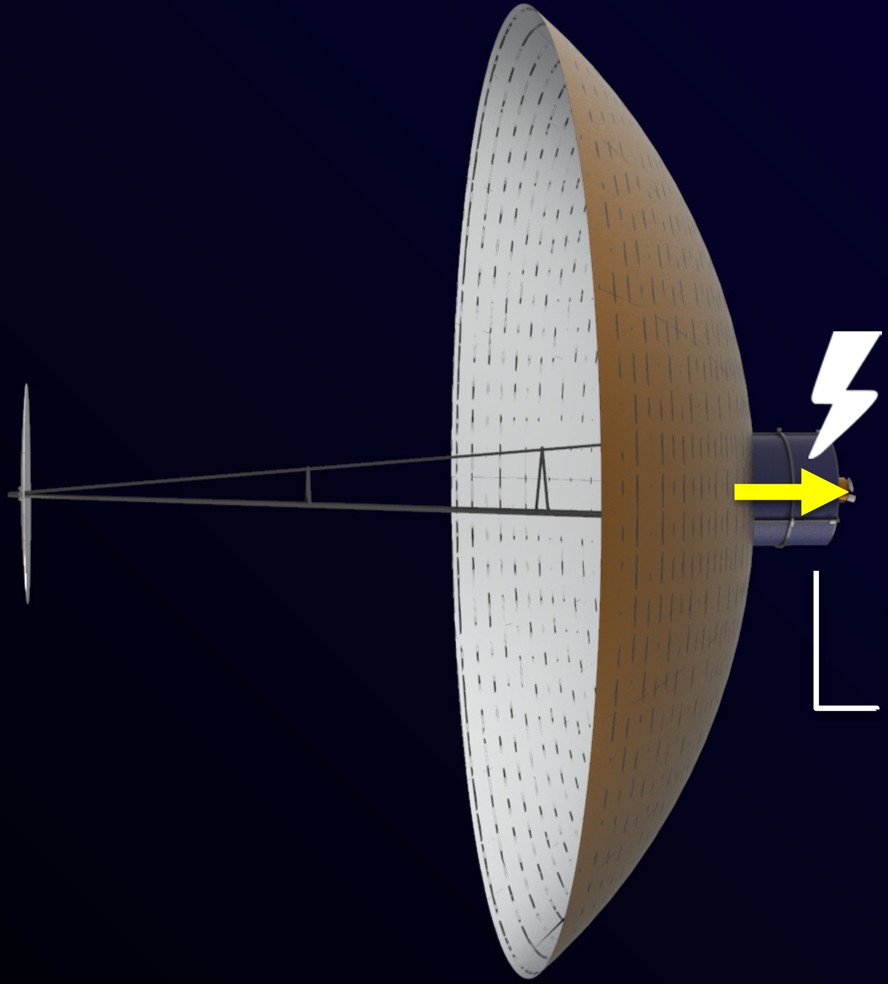
System Overview








Primary
Mirror
Secondary
Mirror
Power Collector:
the
‘Knikkerbaan’



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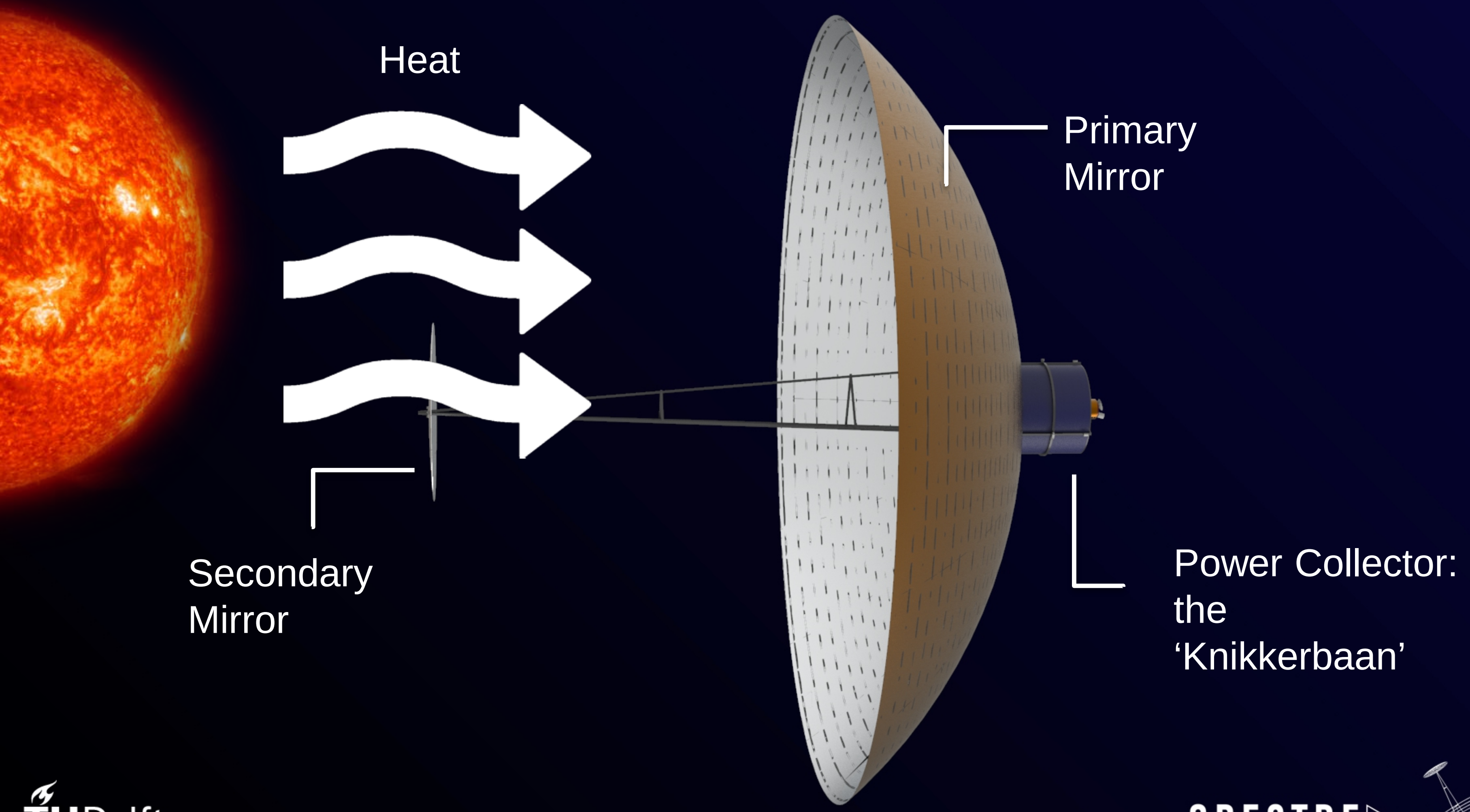
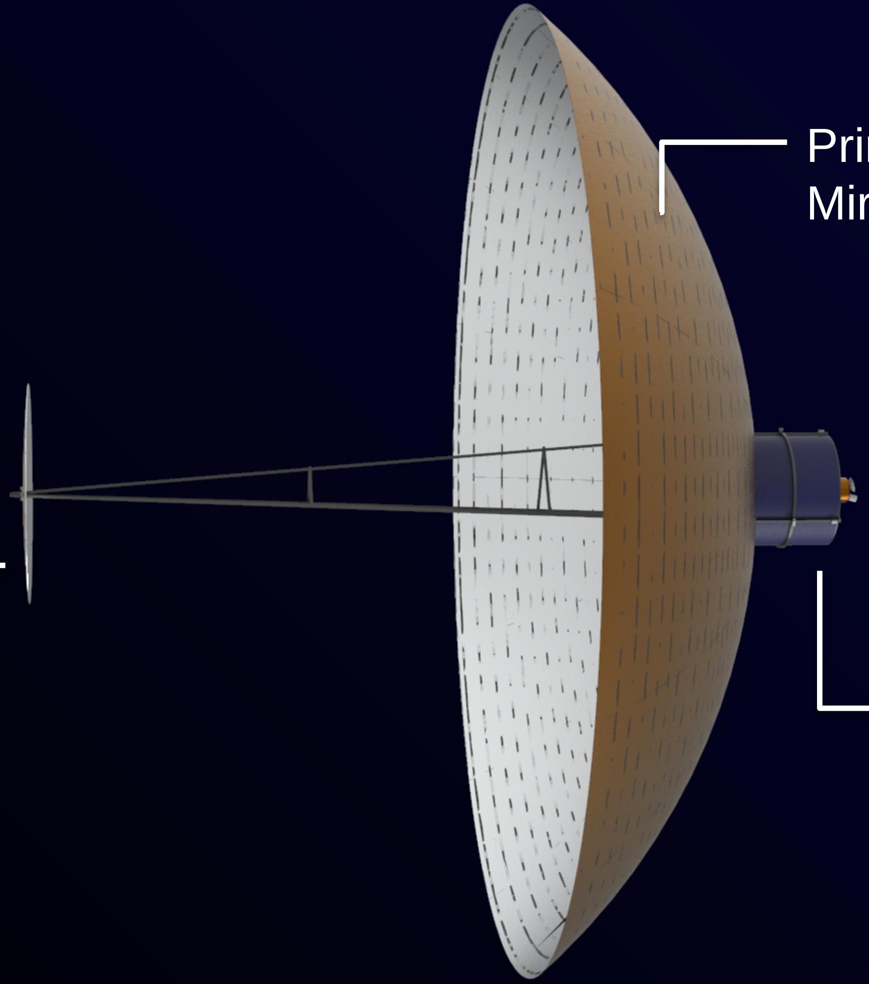
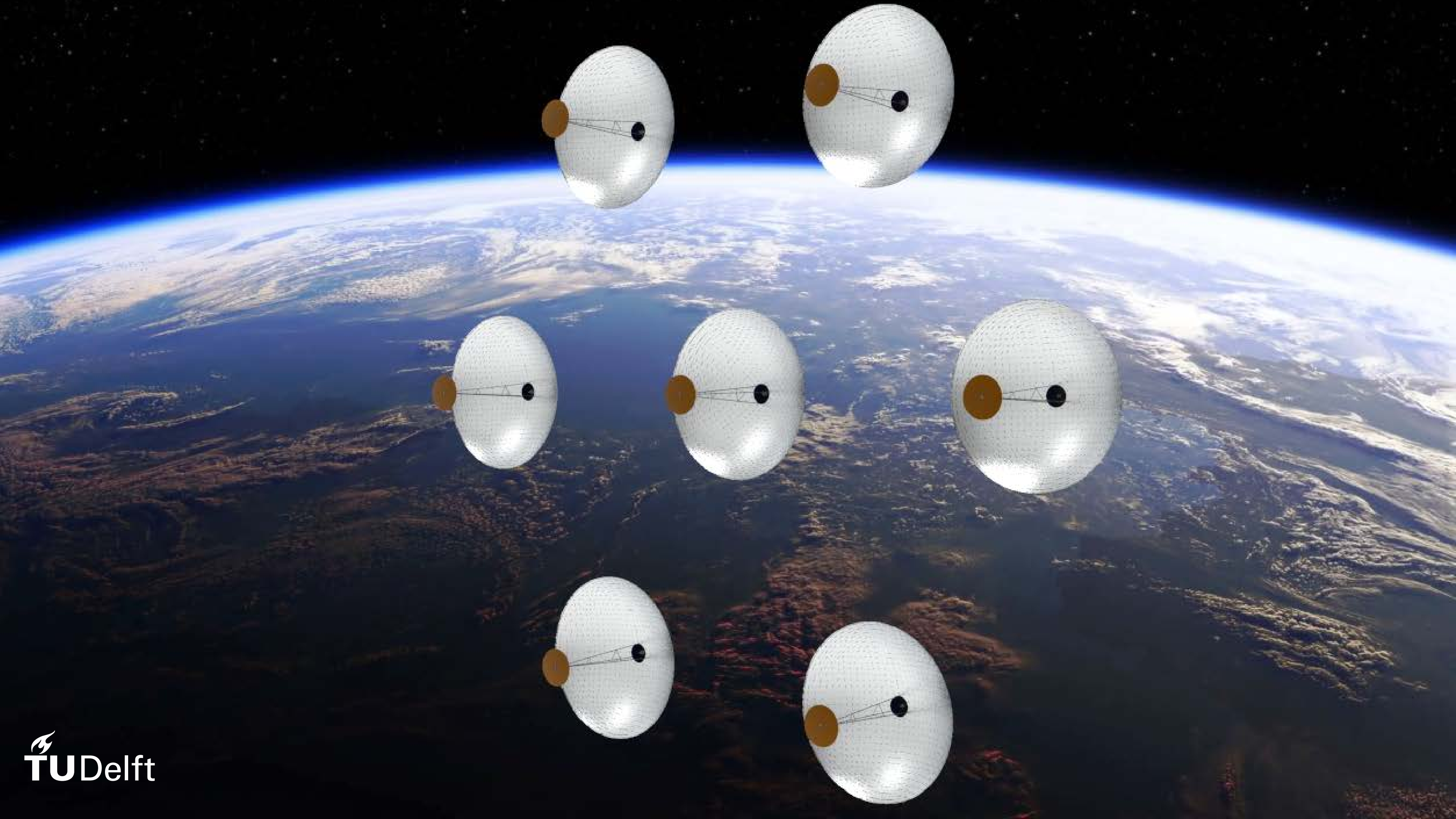

Heat
Primary Mirror
Secondary Mirror
Power Collector: the ‘Knikkerbaan’


Primary Mirror
Secondary Mirror
Power Collector: the ‘Knikkerbaan’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Bandgaps Backup Slides

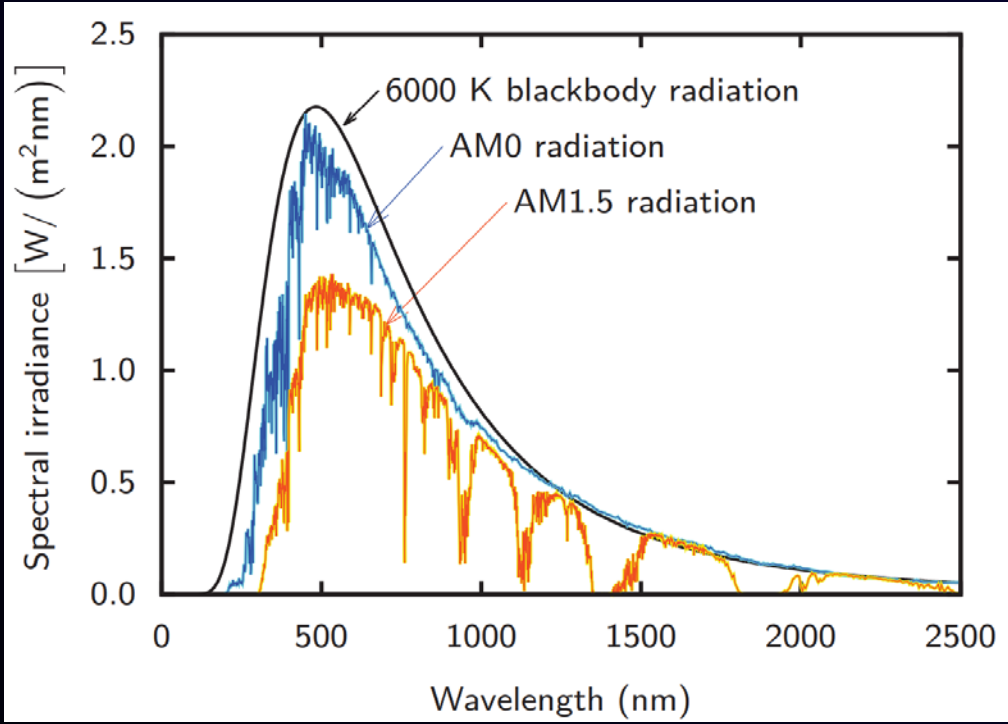
Power Collection Efficiency

Choices:

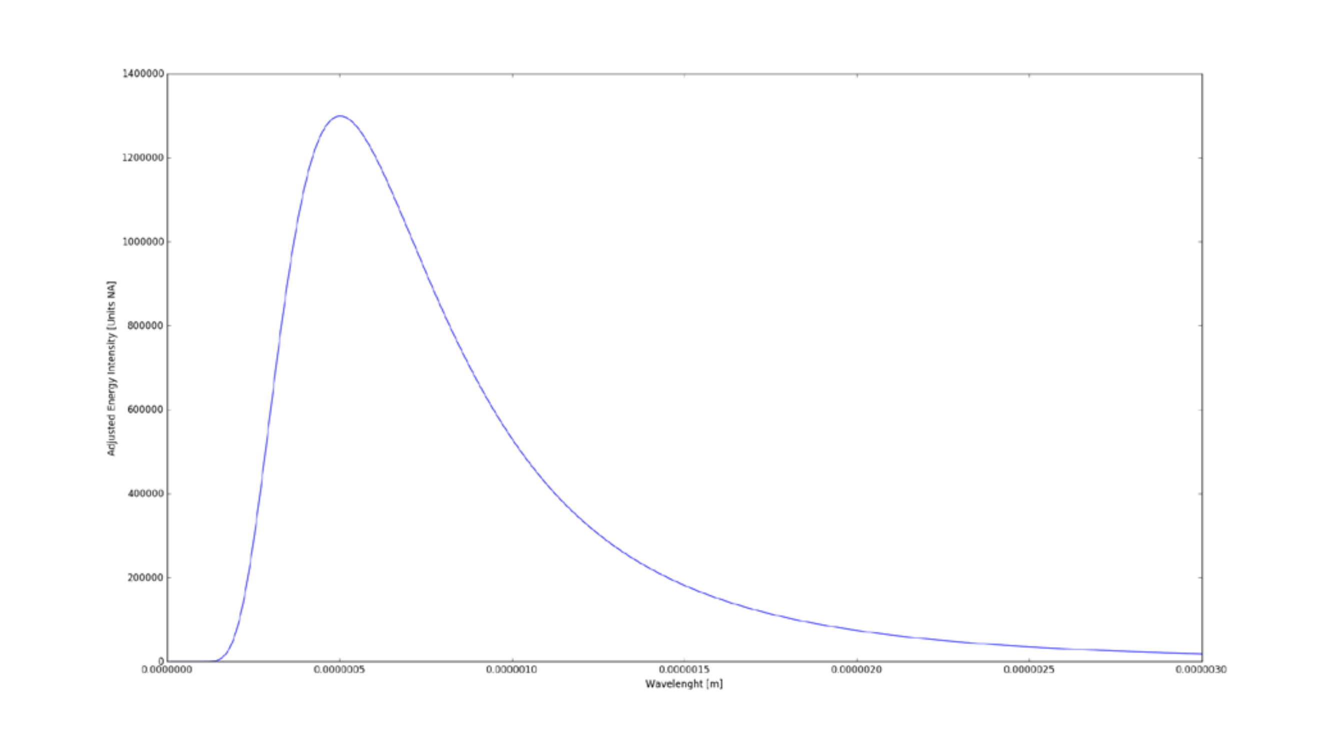
	Spectral Splitting	Photovoltaic Cells	Thermoelectric Generators
Mass	✓		
Cost	✓		
Area	✓		
Technology Readiness Level		✓	
Efficiency	✓		

Source: Solar Energy (Book)

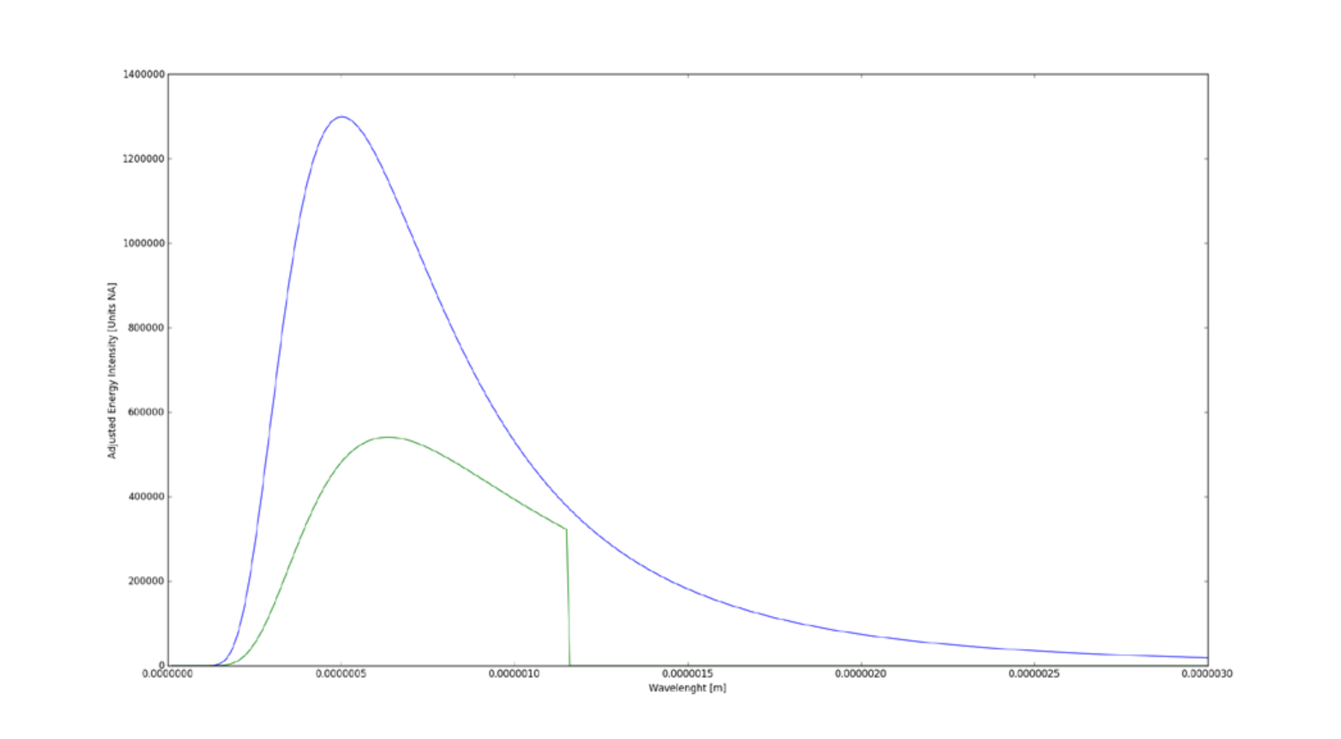
BANDGAP: SOLAR SPECTRUM



BANDGAP: SUN MODEL



BANDGAP: OPTIMISED SINGLE GAP



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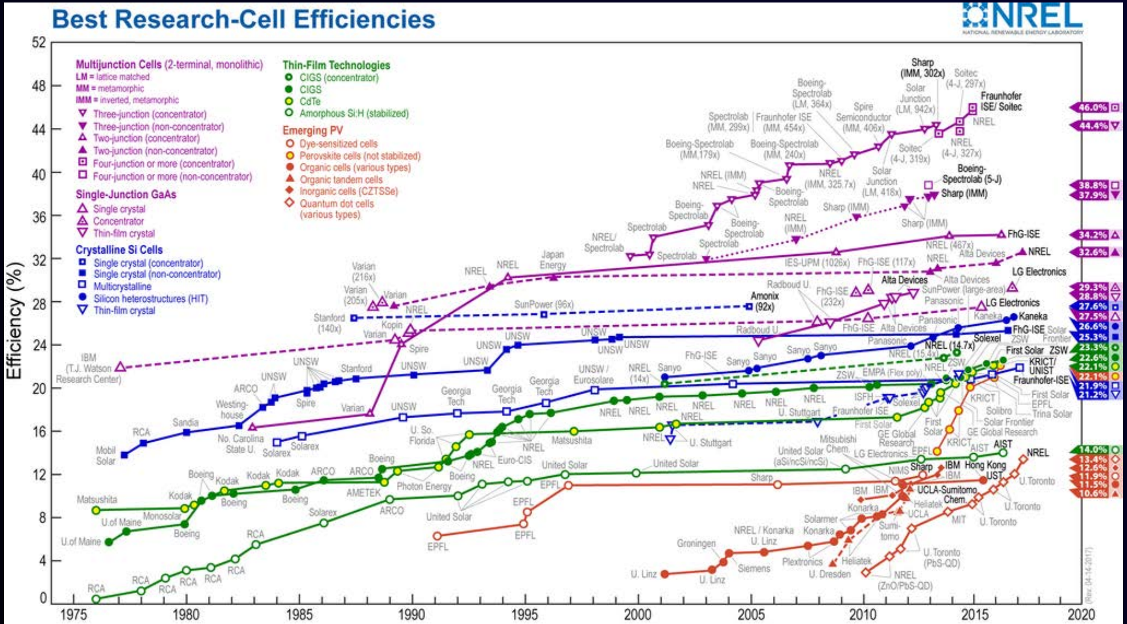
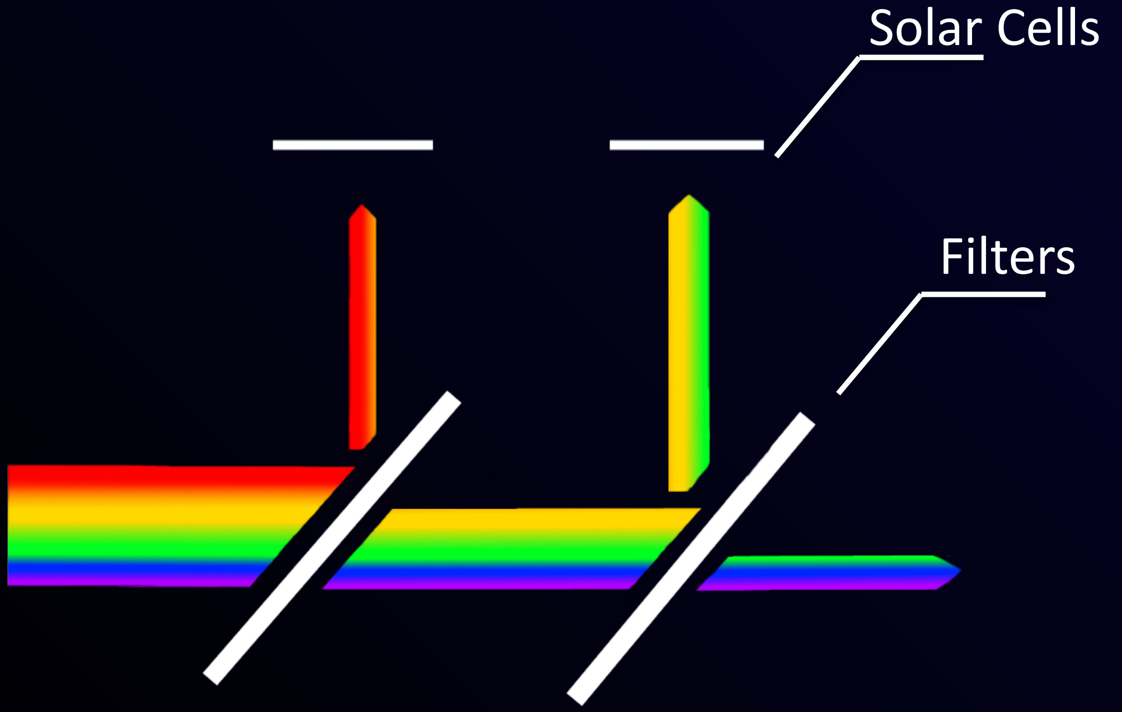
BANDGAP: ADVANCEMENTS IN SOLAR TECHNOLOGY

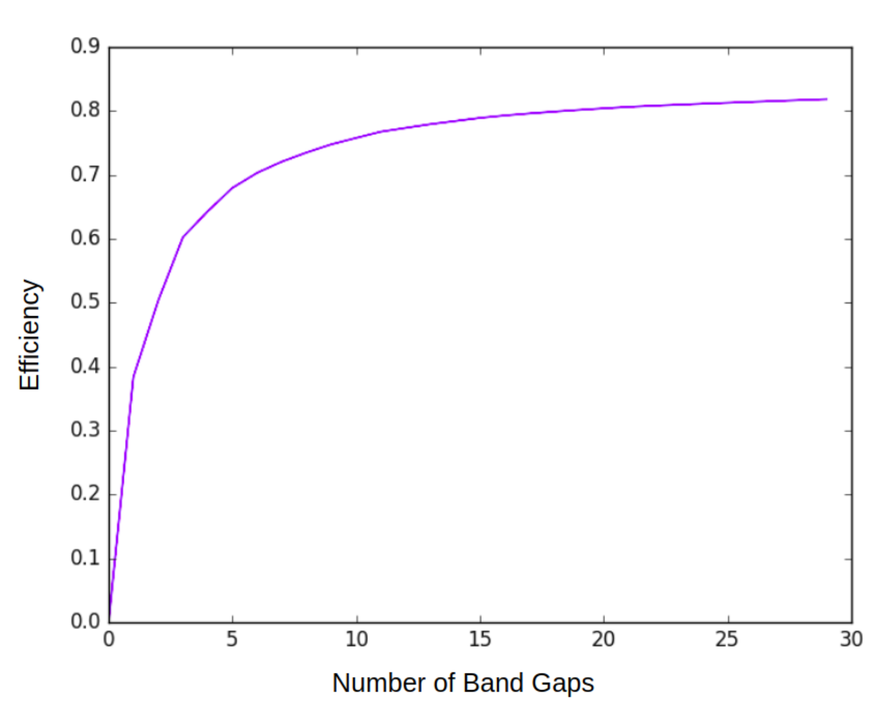


Spectral Splitting

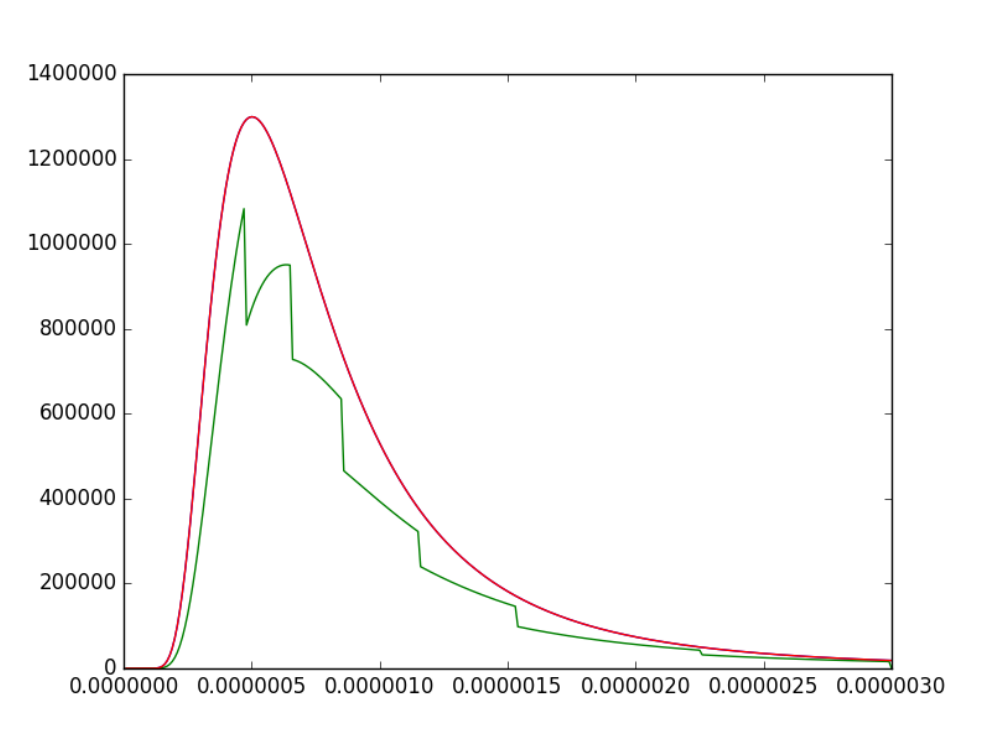


70% Efficiency

BANDGAP: GAPS OPTIMISATION



BANDGAP: CHOSEN GAPS

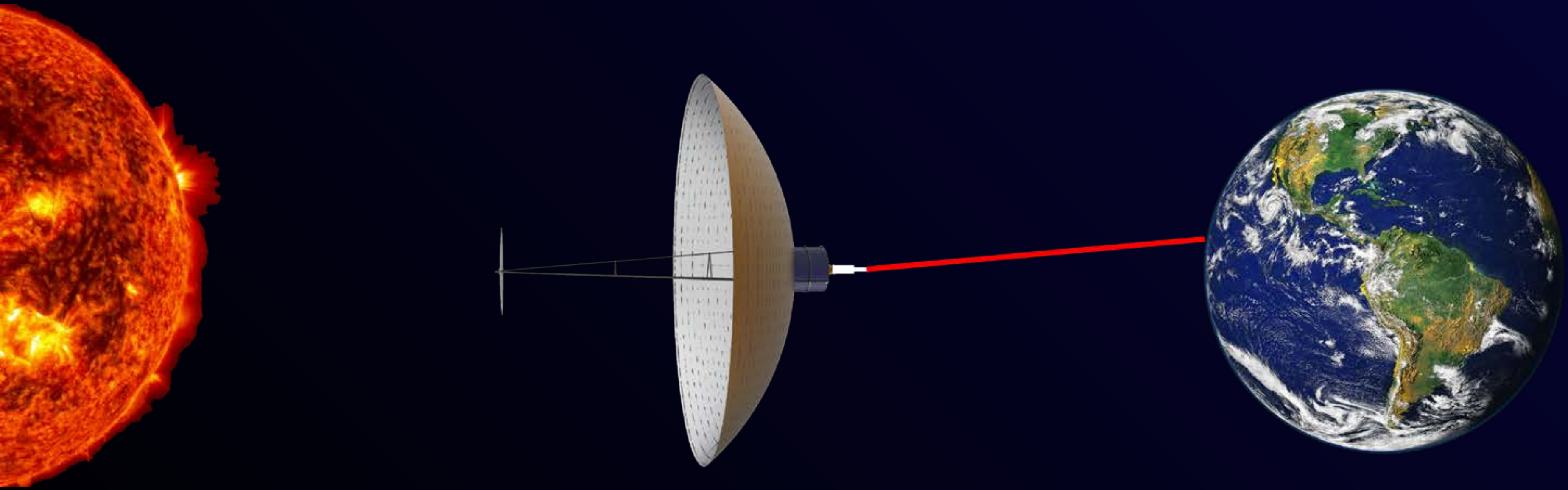


BANDGAP: BANDGAP DESIGN

Solar Array Stage	1	2	3	4	5	6
Solar Array Stage Length	7.127	6.190	5.254	4.450	3.767	3.181
Radius [m]	24.25					
Area [m^2]	1086.8	943.2	800.5	678.1	574.0	484.6
Bandgap [eV]	2.64	1.91	1.45	1.08	0.81	0.55
Solar Cell Material	$In_{0.2}Ga_{0.8}N$	$In_{0.42}Ga_{0.58}N$	GaAs	$In_{0.25}Ga_{0.75}As$	$In_{0.45}Ga_{0.55}As$	$In_{0.75}Ga_{0.25}As$

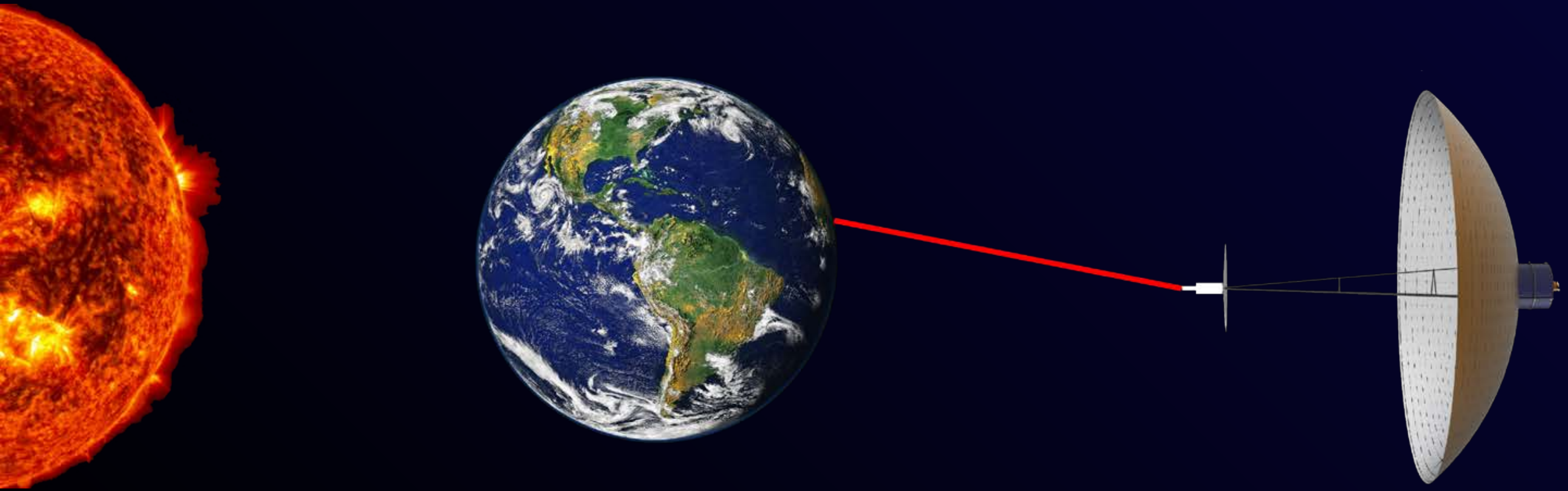
Transmitter Backup Slides

Laser Transmission: Possible Configuration 1



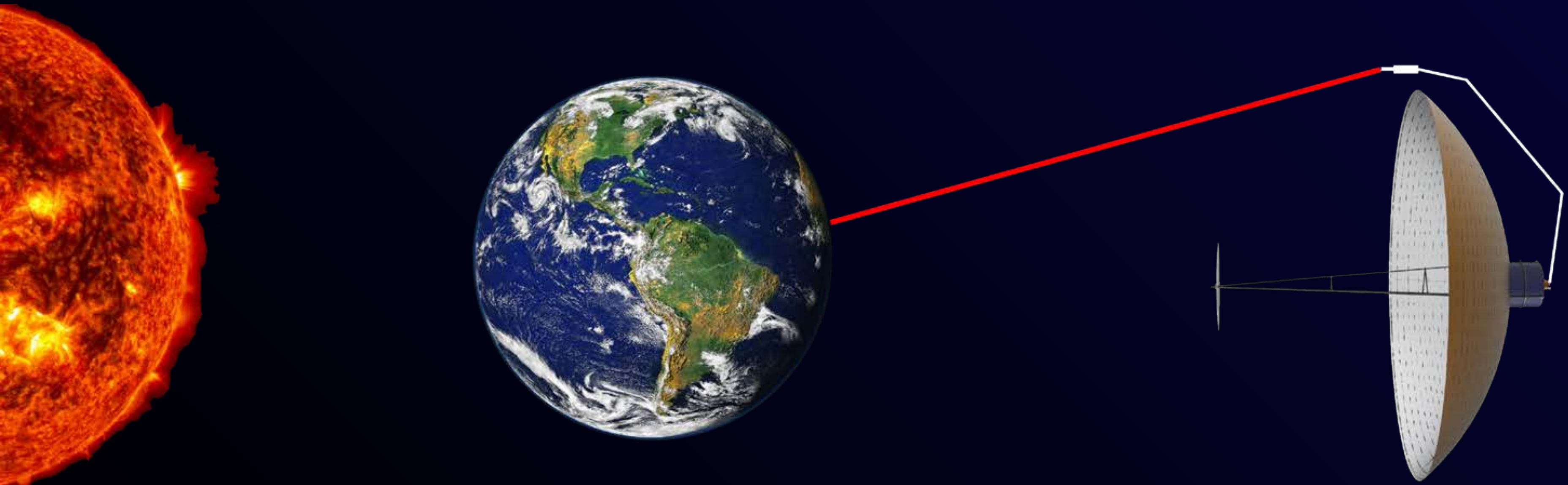
2 transmitters

Laser Transmission: Possible Configuration 1



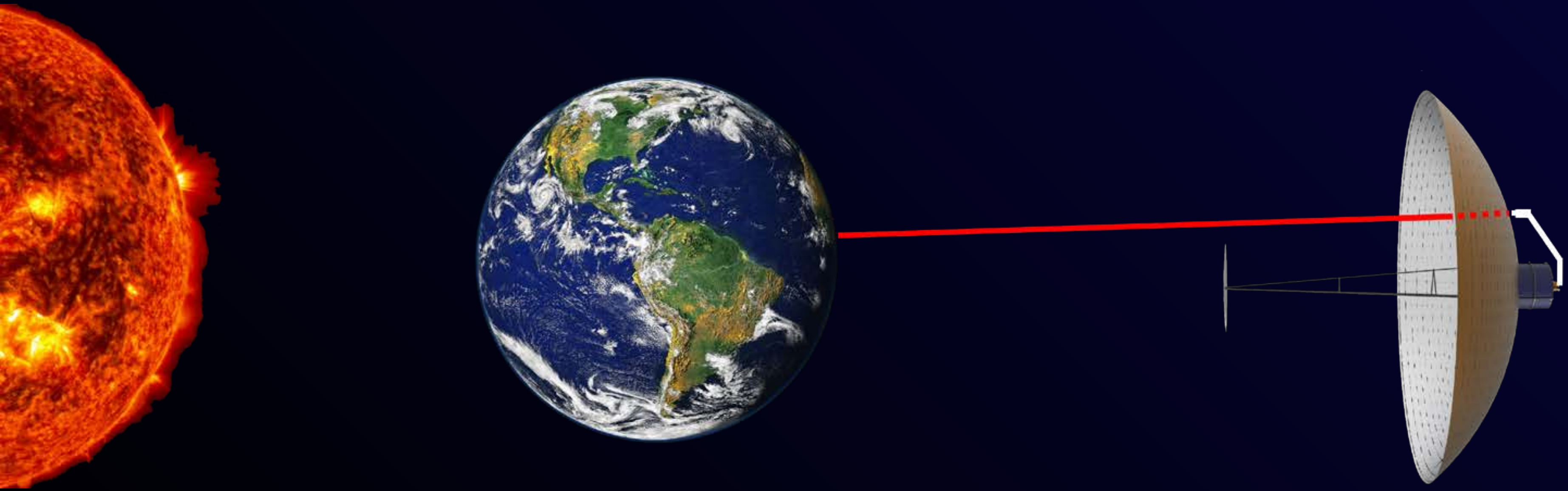
2 transmitters

Laser Transmission: Possible Configuration 2



1 transmitter on boom

Laser Transmission: Possible Configuration 3

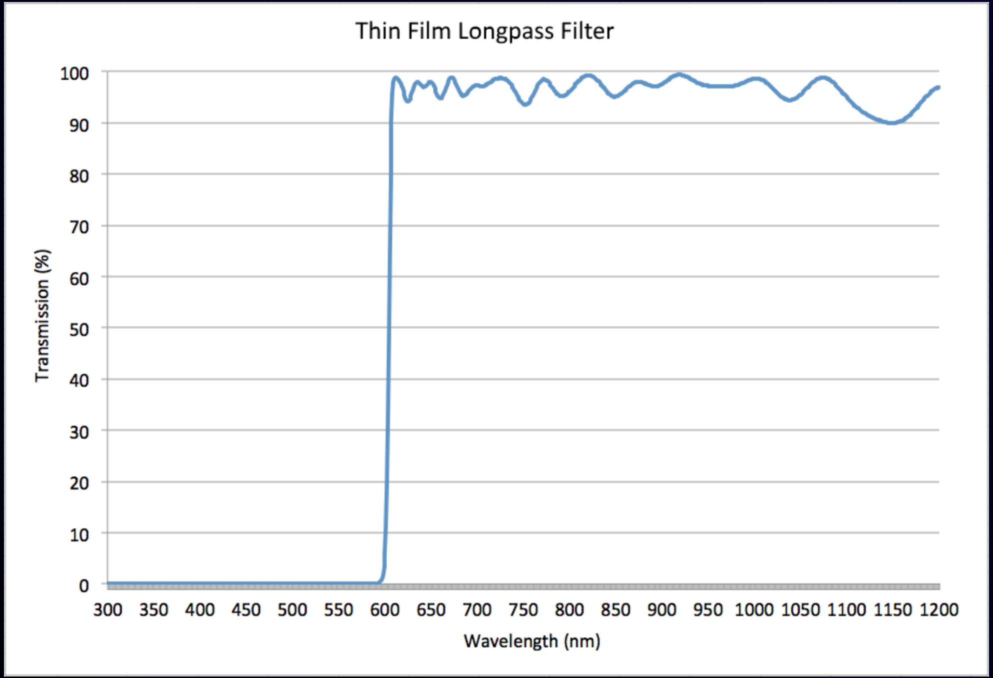


High wavelength transmitter

Filters Backup Slides

Filters

Filters



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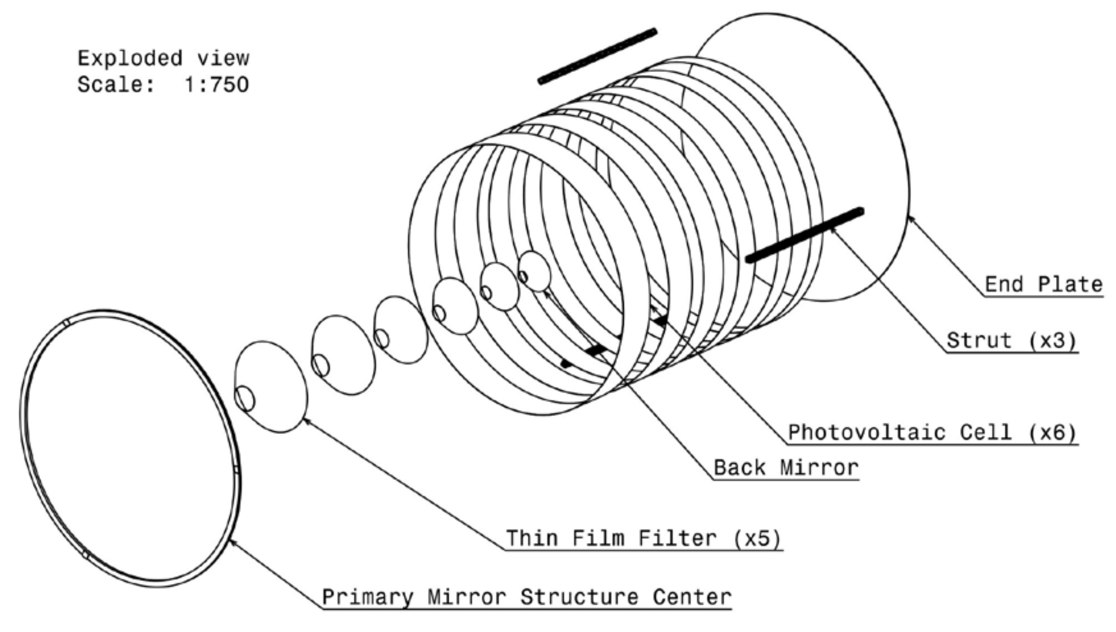
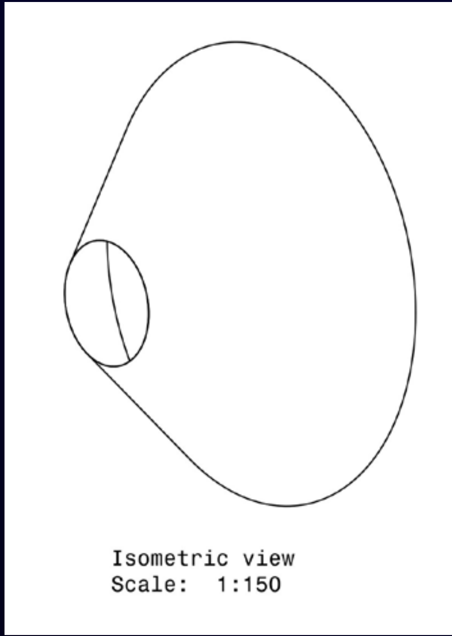
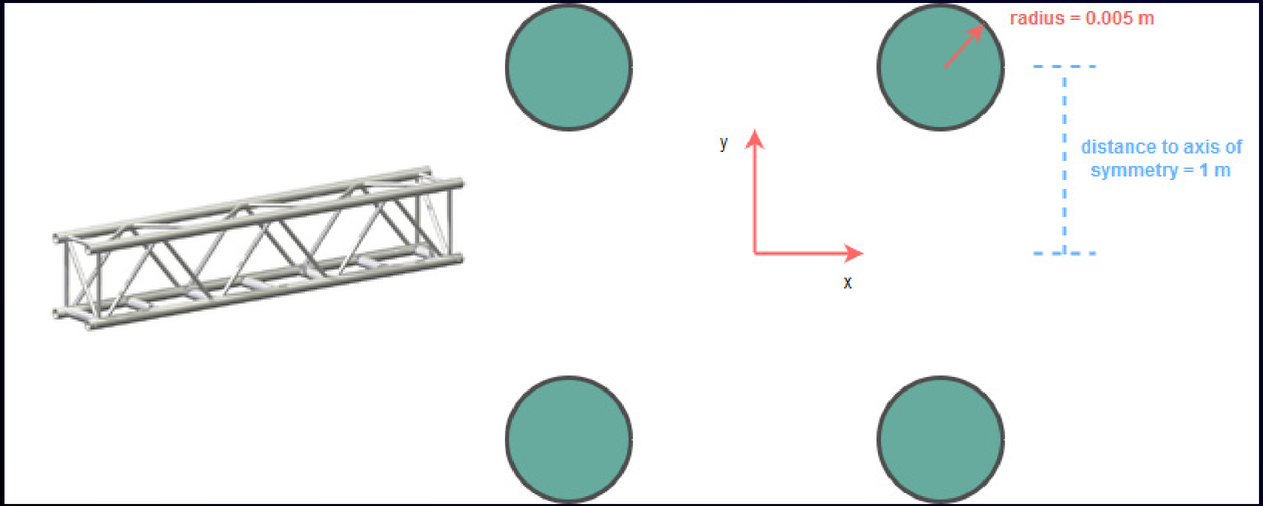
Filters


Exploded view
Scale: 1:750
End Plate
Strut (x3)
Photovoltaic Cell (x6)
Back Mirror
Thin Film Filter (x5)
Primary Mirror Structure Center


Isometric view
Scale: 1:150

Truss cross section



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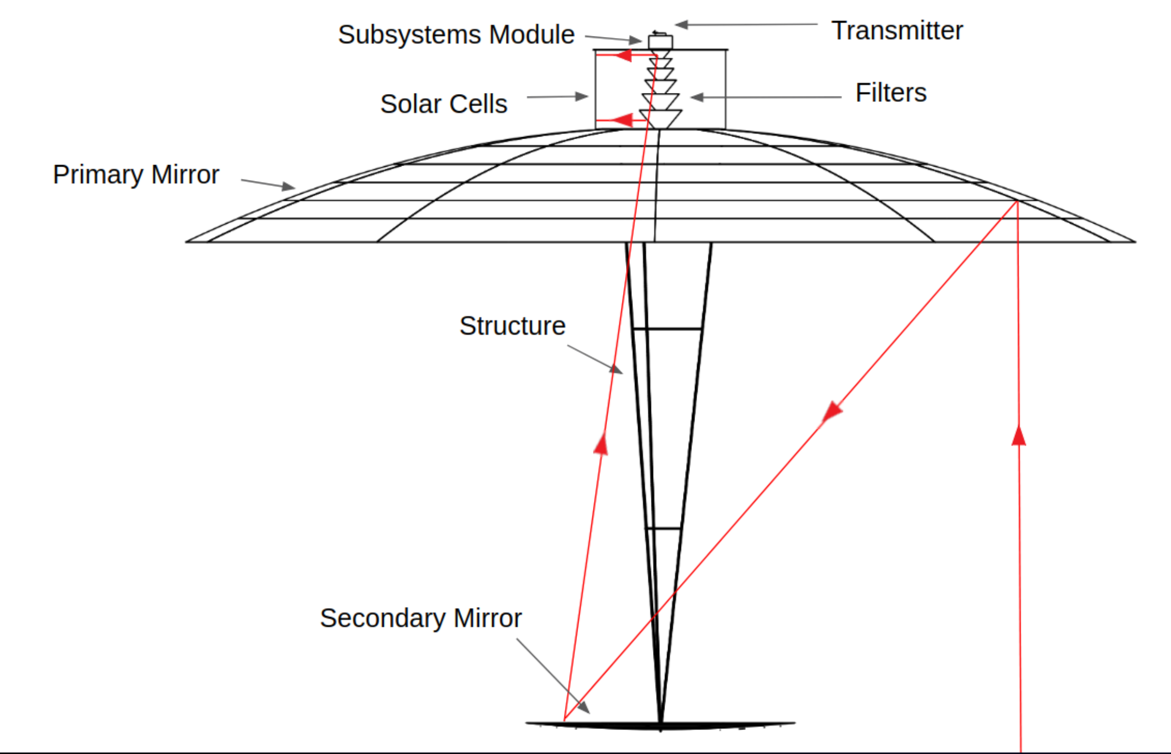
Mirrors



Subsystems Module
Transmitter
Solar Cells
Filters
Primary Mirror
Structure
Secondary Mirror

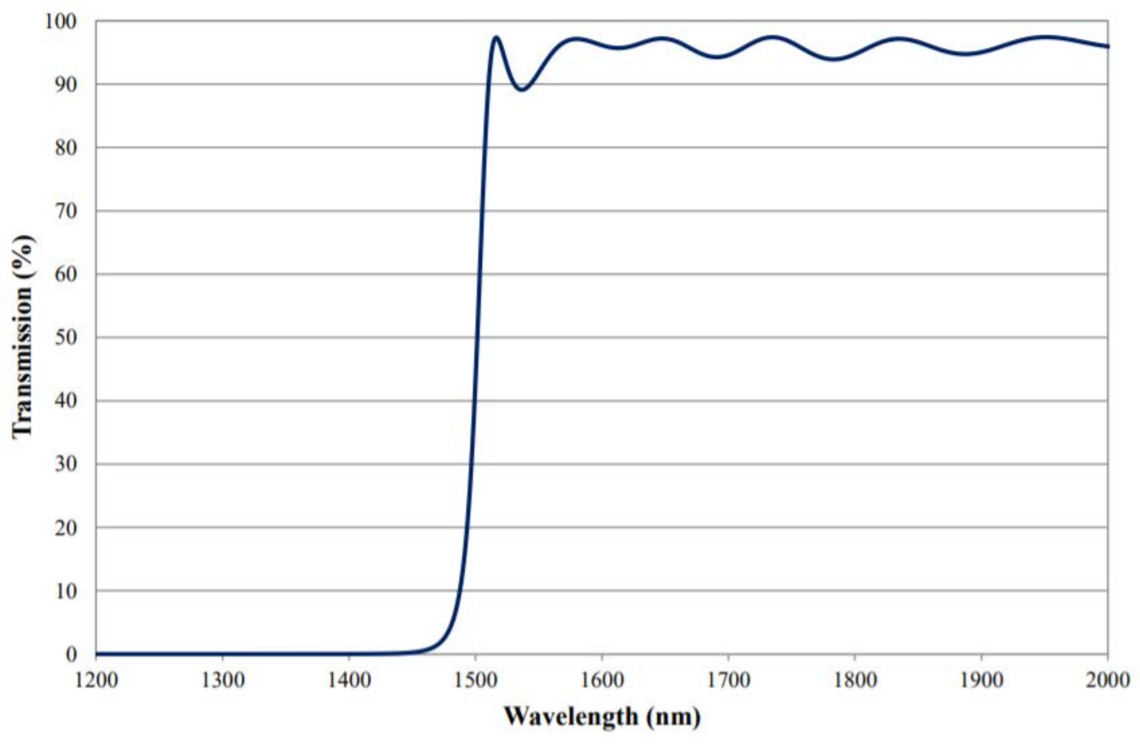
Power Collection System: Dimensions

Dimension	Primary	Secondary
Focal Length [m]	187.42	275.52
X parameter [1/m]	0.001334	0.000907
Y max [m]	37.89	2.37
Radius [m]	180.80	51.15
Frontal Area [m²]	102695	8219
Parabolic Area [m²]	117944	8469
Black Spot Frontal Area [m²]	8219	658
Black Spot parabolic Area [m²]	8584	663
Mirror Frontal Area [m²]	94475	7562
Mirror Parabolic Area [m²]	109360	7806

Component	Concentration Factor
Solar Cells	17
Filters	384
Seconndary Mirror	10
Primary Mirror	1

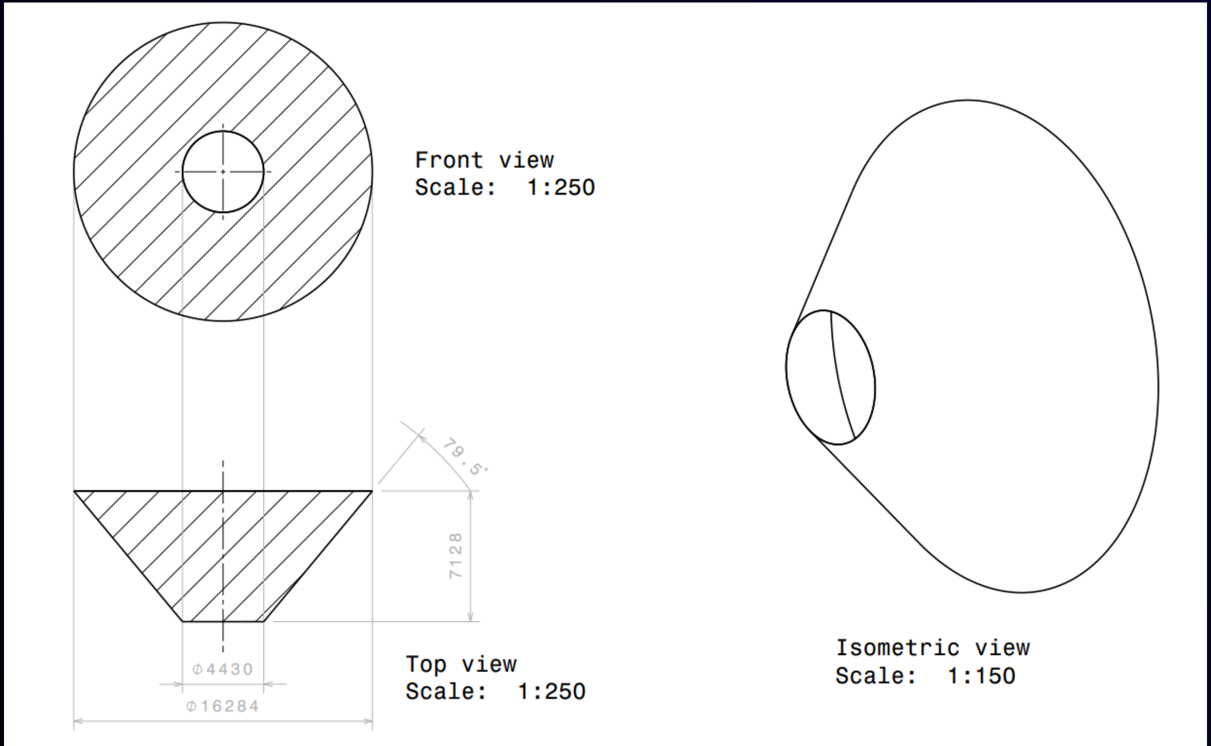
bandgap	1	2	3	4	5	6
Area [m²]	1086	943	801	678	574	485
Length [m]	7.127	6.190	5.424	4.450	3.767	3.181
Radius [m]	24.25	24.25	24.25	24.25	24.25	24.25

Filter #5

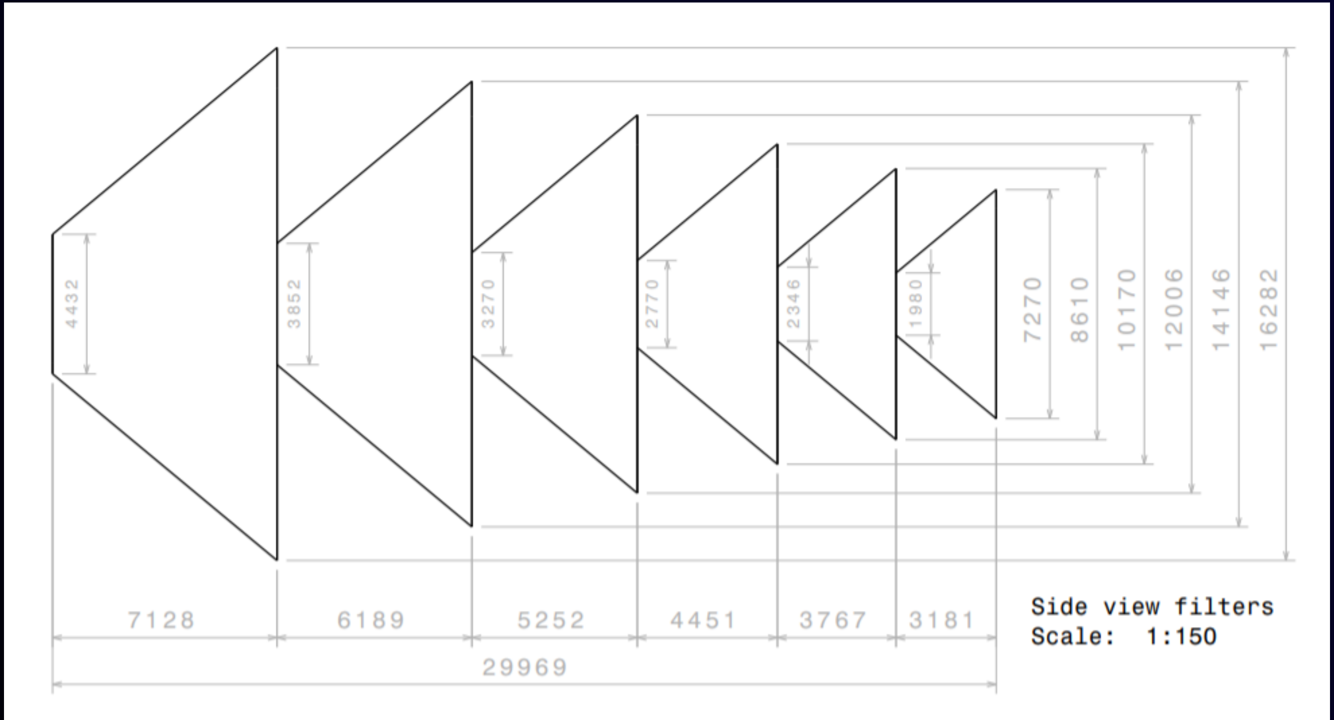


Transmission (%)
100
90
80
70
60
50
40
30
20
10
0
1200
1300
1400
1500
1600
1700
1800
1900
2000
Wavelength (nm)

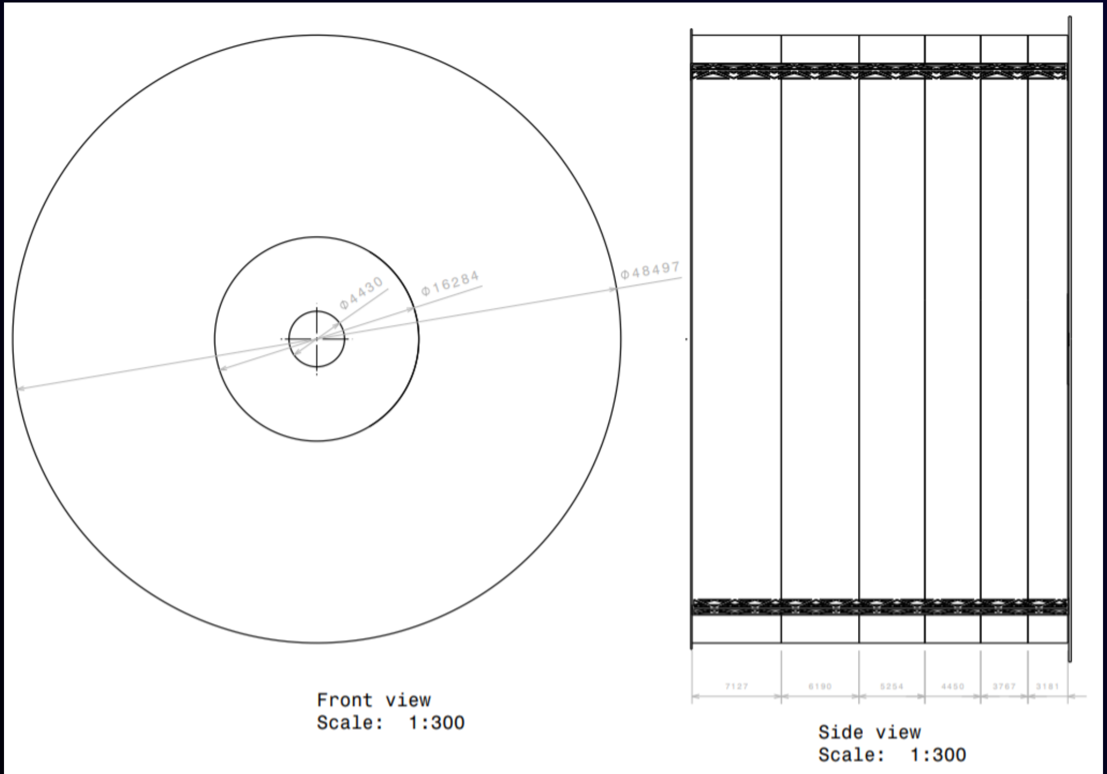
Filter Schematic View #1



Filter Schematic View #2

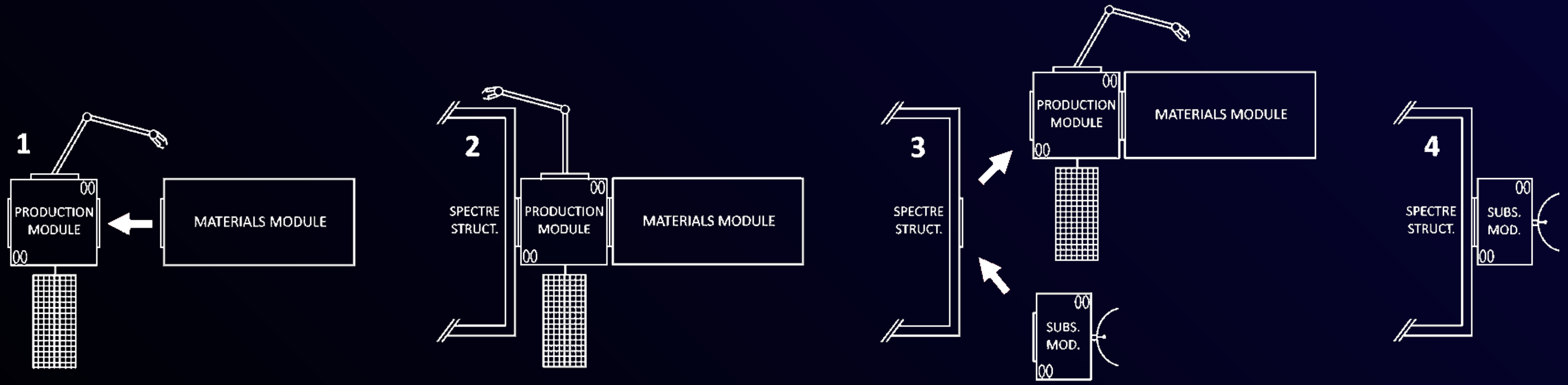


Solar Array and Filter Schematic

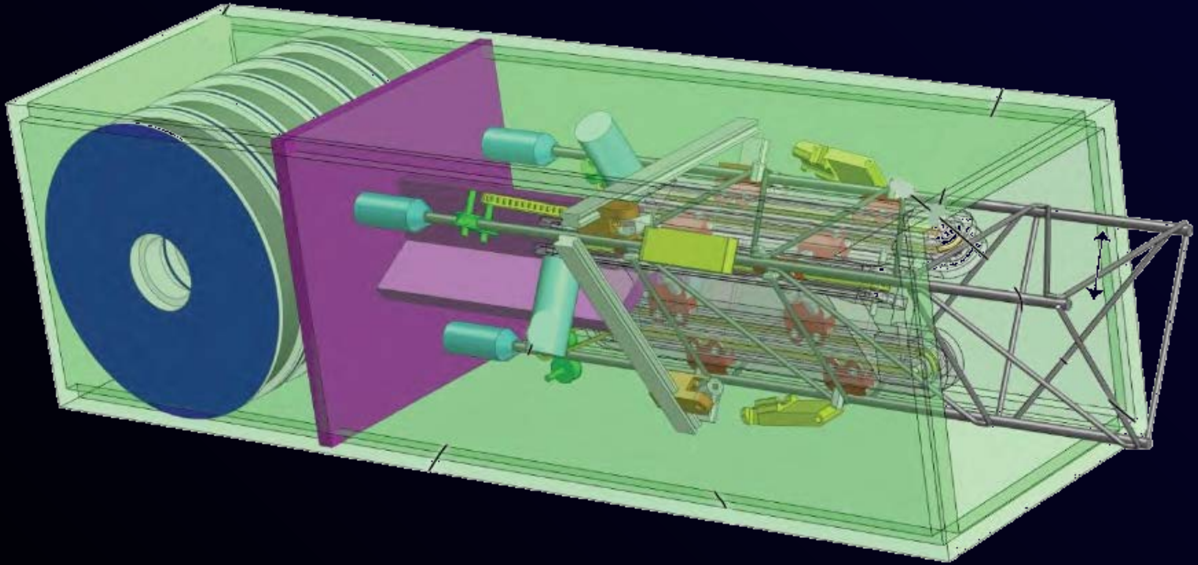


Production Backup Slides

Modular Production



Additive Manufacturing of Trusses



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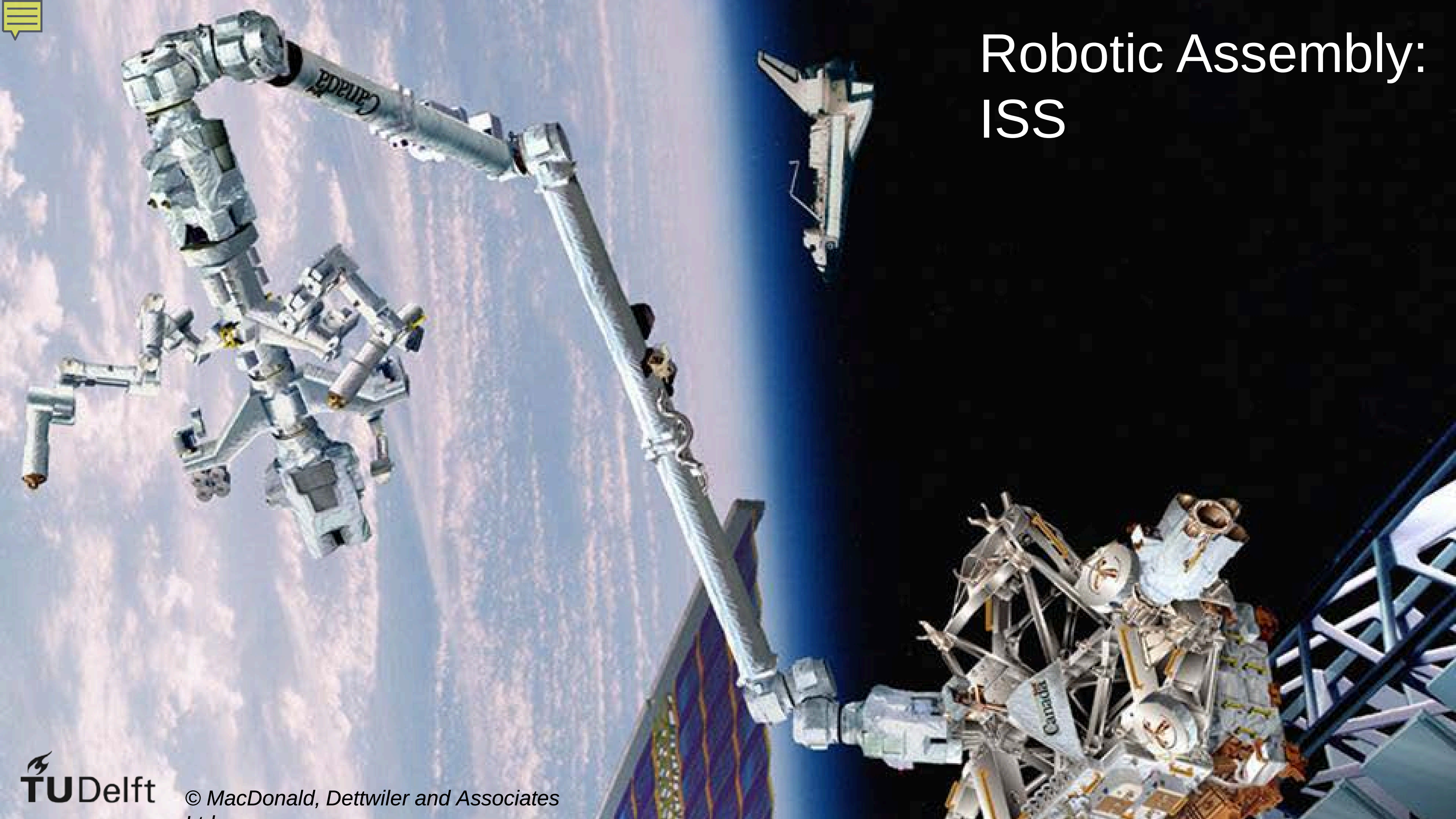
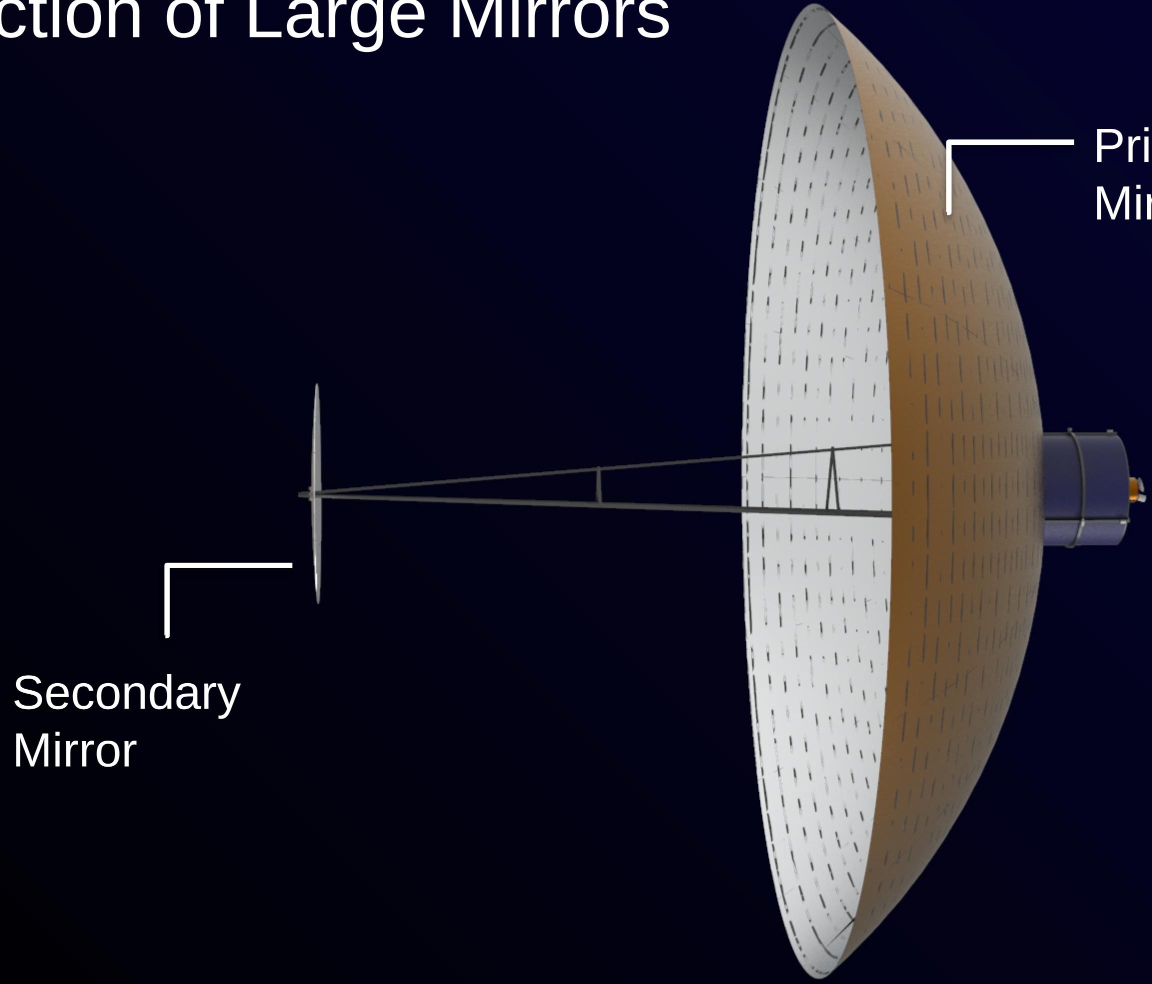
Robotic Assembly: ISS

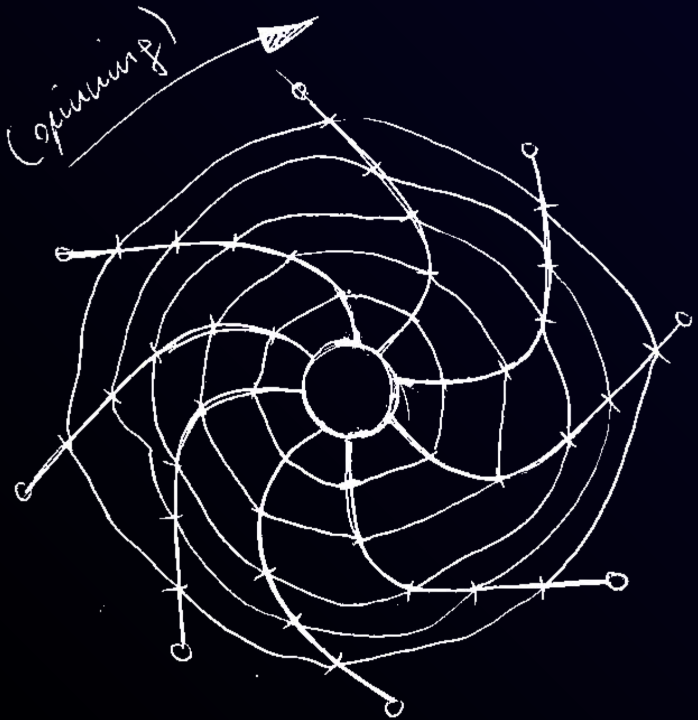


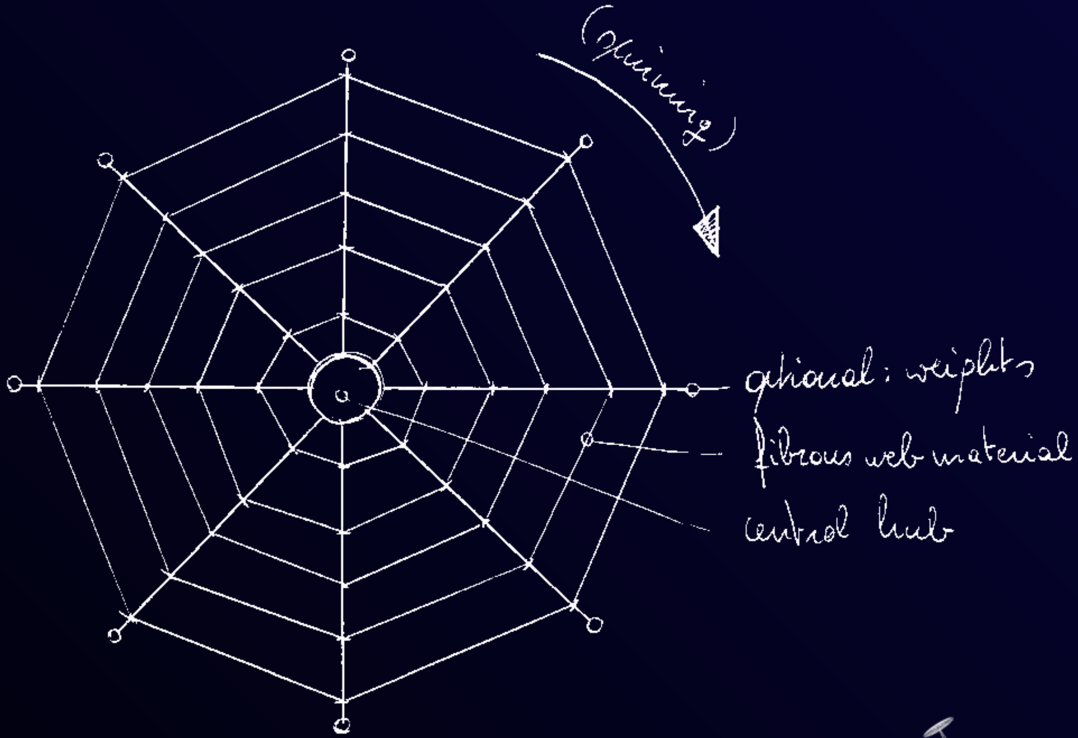
Robotic Assembly: Joining Trusses

Production of Large Mirrors

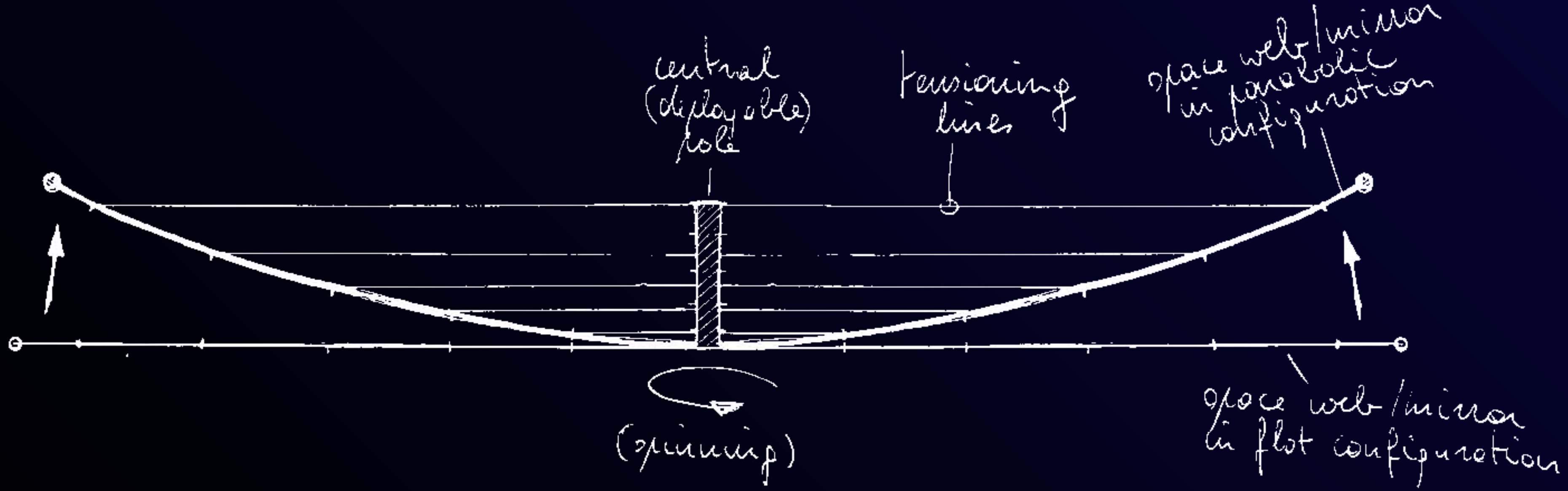


Production of Large Mirrors (1/4)
Centrifugal Space Web

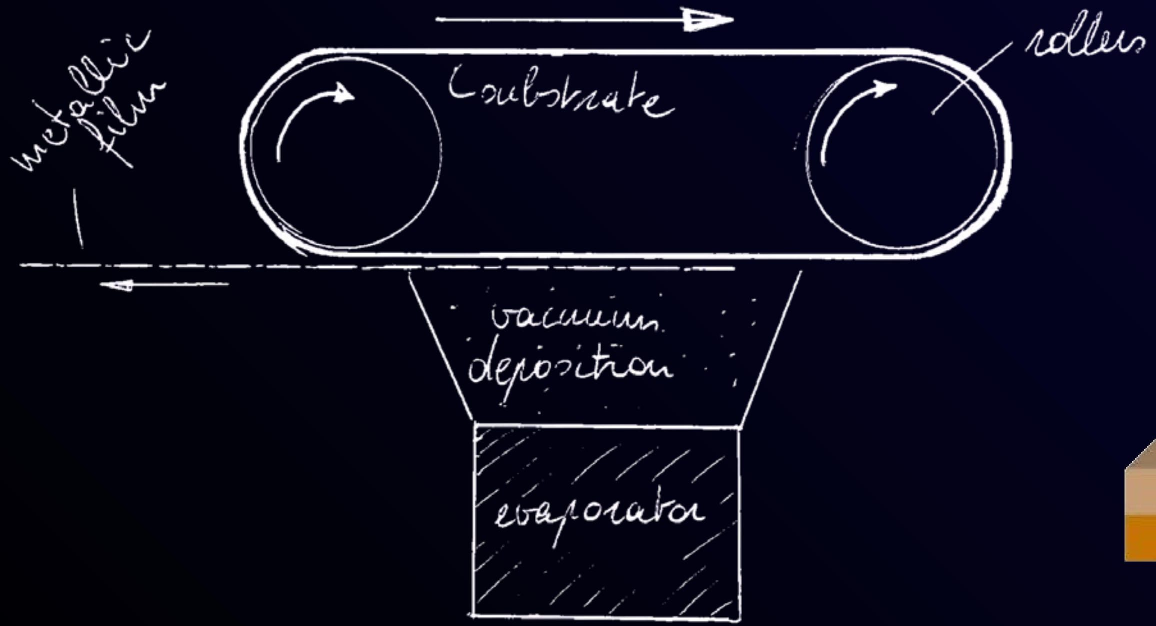


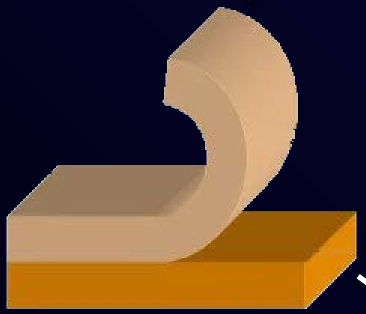


Production of Large Mirrors (2/4) Tensioning of Guy-Wires

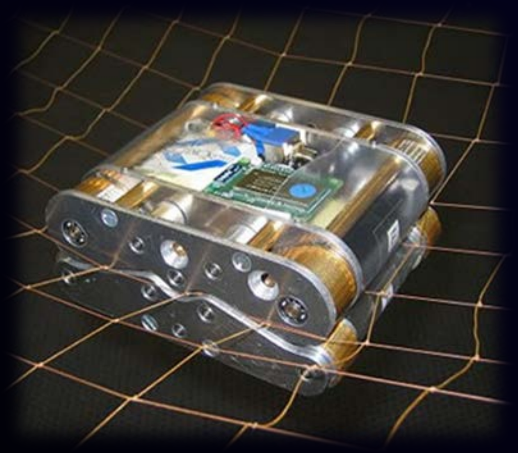


Production of Large Mirrors (3/4)
Chemical Vapor Deposition

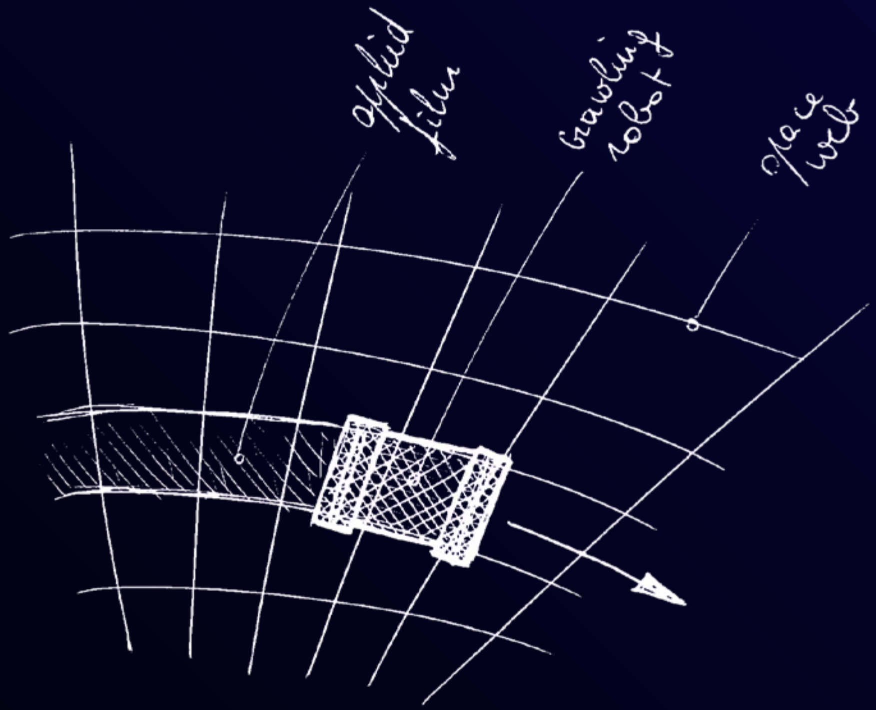




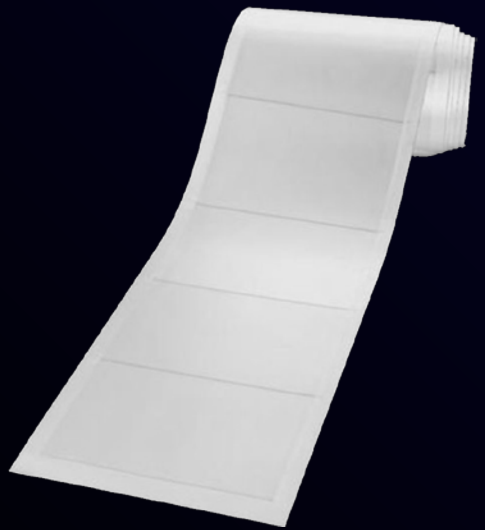
Production of Large Mirrors (4/4)
Robotic Web Crawlers



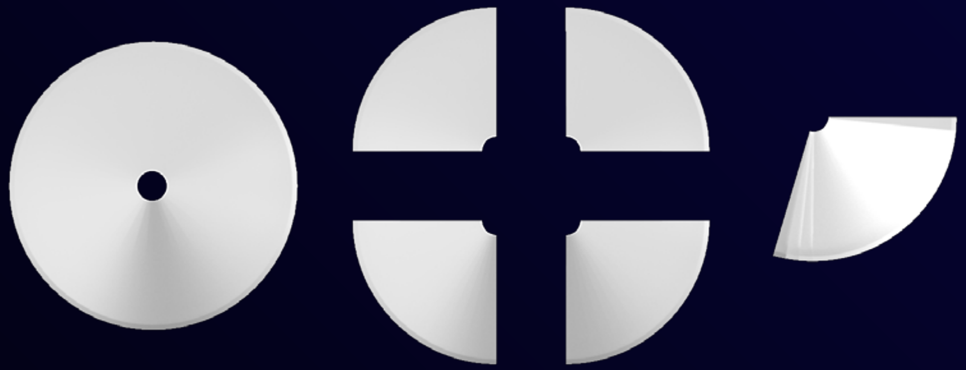
© ESA



Large Earth Produced Parts



Photovoltaics



Filters

Robotics specs

	Canadarm2	Dextre	Mobile Base System
Length	17.6 m	3.5 m	-
Mass	1641 kg	1662 kg	1500 kg
Handling Capacity	116,000 kg	600 kg	20,900 kg
Degrees of Freedom	7	15	Fixed
Peak Power	2000 W	2000 W	825 W
Average Power	1200 W	600 W	365 W

Web crawlers:
- 0.5 years of application time
- Speed: 3.22 mm/s (primary crawlers); 0.528 mm/s (secondary crawler)
- CVD power: 6.2 W (each); 0.88 W
- Crawler power: 19 W (each); 2.6 W
- Lifetime aluminium: 147.6 kg (each); 10.5 kg

Aluminium/Zylon characteristics

	Aluminium 1199-O (reflective thin film)
Specific gravity	2.70 g/cm^3
Hardness (Brinell)	12
Tensile strength (ulimate)	45.0 MPa
Tensile strength (yield)	10.0 MPa
Elongation at break	50%
Modulus of Elasticity	62.0 GPa
Poissons ratio	0.33
Shear modulus	25.0 GPa
Shear strength	34.0 MPa
Thermal exp. coeff. (linear)	21.8 μm/m °C (@-50 - 20 °C) 23.6 μm/m °C (@20 - 100 °C) 24.5 μm/m °C (@20 - 200 °C) 25.5 μm/m °C (@20 - 300 °C)
Specific heat	0.900 J/g-°C
Thermal conductivity	243 W/m-K
Melting point	660 °C
Reflection coeff.	0.9
Thermal conductivity	237 W/m-K
Emissivity	0.04

	Zylon™ high performance fibre (space webs)
Type	Toyobo Co., Ltd. Zylon™ HM PBO fibre
Specific gravity	1.56 g/cm^3
Tensile strength	37 cN/dtex 5.8 GPa 590 kg/mm^2
Tensile modulus	1720 cN/dtex 270 GPa 28000 kg/mm^2
Elongation at break	2.5%
Decomposition temp.	650 °C
Thermal exp. coeff.	$-6 * 10^{-6}$
Creep parameter (50% of breaking load)	$1.1 * 10^{-4}$
Thermal conductivity	42.9 W/m-K
Specific heat	1500 W/kg-K
Emissivity	0.8
Hardness	941 MPa

PEEK characteristics

	PEEK/CF composite (trusses)	PEEK thermoplastic (joints)
Type	Victrex™ PEEK 90HMF40 (40% carbon fibre)	Victrex™ PEEK 450FC30
Specific gravity	1.45 g/cm^3	1.45 g/cm^3
Hardness (shore D)	88.5	83
Tensile strength at break	85.0 MPa (@275 °C) 145 MPa (@180 °C) 220 MPa (@120 °C) 330 MPa (@23 °C)	35.0 MPa (@275 °C) 45.0 MPa (@225 °C) 55.0 MPa (@175 °C) 95.0 MPa (@125 °C) 150 MPa (@23 °C)
Elongation	1.2% (at yield)	2.3% (at break)
Tensile modulus	43.3 GPa	13.0 GPa
Flexural strength	120 MPa (@275 °C) 220 MPa (@180 °C) 350 MPa (@120 °C) 475 MPa (@23 °C)	45.0 MPa (@275 °C) 80.0 MPa (@175 °C) 160 MPa (@125 °C) 230 MPa (@23 °C)
Flexural modulus	37.0 GPa	11.5 GPa
Compressive strength	120 MPa (@200 °C) 250 MPa (@120 °C) 310 MPa (@23 °C)	45.0 MPa (@200 °C) 110 MPa (@120 °C) 170 MPa (@23 °C)
Thermal exp. coeff. (linear)	35.0 μm/m °C (below glass transition) 80.0 μm/m °C (above glass transition)	45.0 μm/m °C (below glass trans.) 115 μm/m °C (above glass trans.)
Thermal exp. coeff., (parallel to flow)	1.00 μm/m °C (above glass transition) 3.00 μm/m °C (below glass transition)	15.0 μm/m °C (above glass trans.) 20.0 μm/m °C (below glass trans.)
Thermal conductivity	2.00 W/m-K (average) 4.30 W/m-K (along flow)	0.850 W/m-K (average) 1.70 W/m-K (along flow)
Melting point	343 °C	343 °C
Glass transition temp.	143 °C	143 °C
Processing nozzle temp.	385 °C	385 °C
Specific heat	1390 Watt/kg-K	1390 Watt/kg-K
Emissivity	0.75	0.75

Parts produced on earth

Cable harness (incl. connections)
Web crawling robots
Primary space web
Secondary space web
Docking interface
Filter parts
Furled photovoltaics
Sensors and cameras
Thrusters, fuel lines, valves, filters
Heat pipes
EPS parts (capacitators, inductors, controllers, switches etc.)
Raw materials (PEEK/CF and PEEK filament, aluminium powder, adhesives)

Sustainability Backup Slides

Sustainability

Challenge:

Low Scrap

Non-Toxic

Sustainability: Scrap

Additive Manufacturing

On Earth vs. In Space:

No Scrap!

Sustainability: Toxicity

Raptor Engines

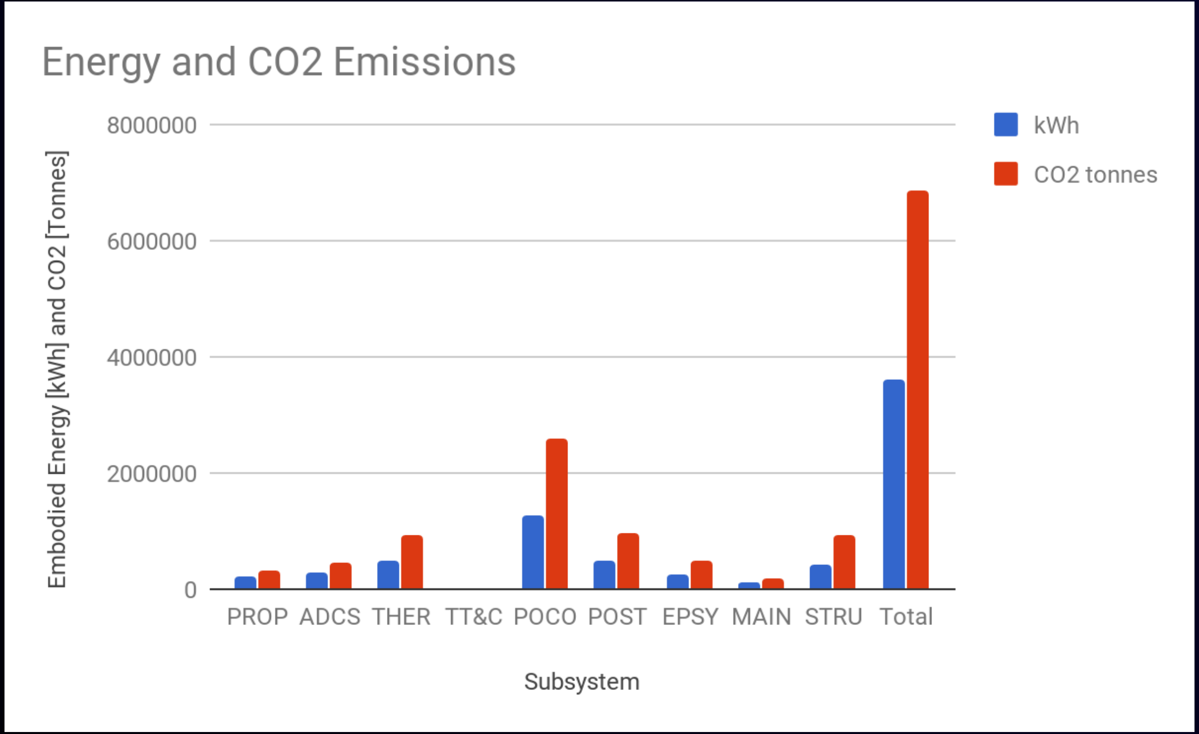
European Union

Sustainability: Toxicity

Source: trumpf

(Mostly) Non-Toxic Materials

SUSTAINABILITY: SUBSYSTEM



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SPECTRE

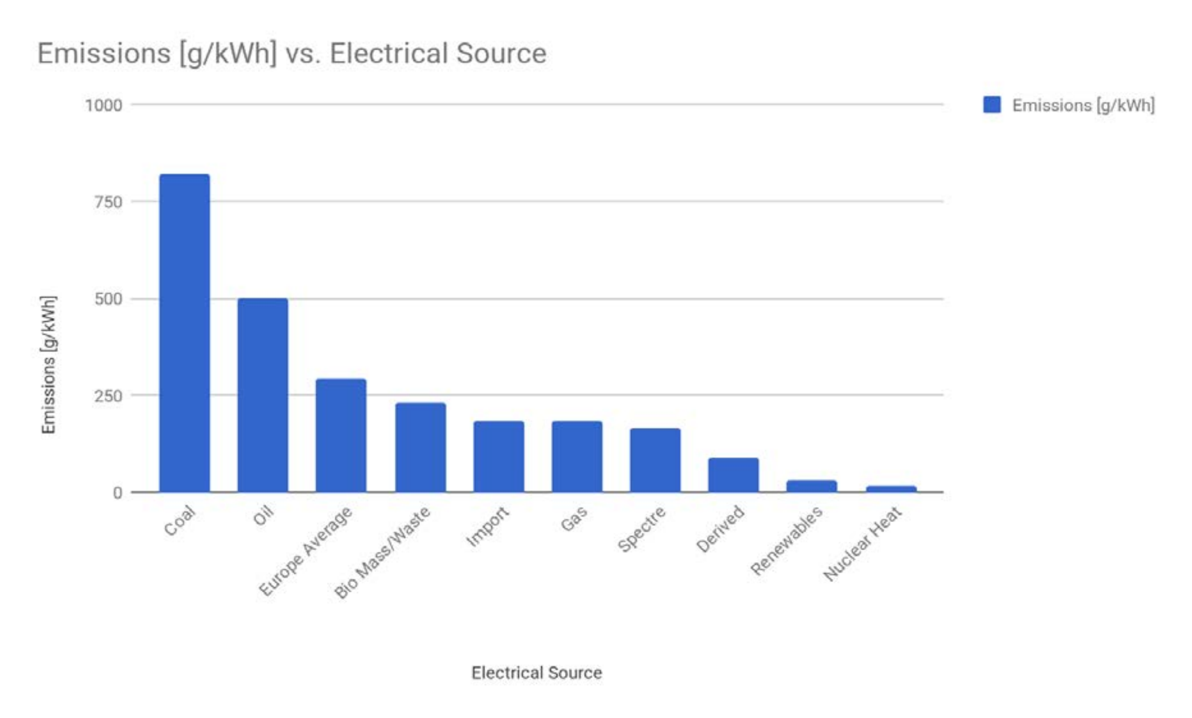
SUSTAINABILITY: ENERGY BALANCE

Energy Production in Space	286276869803	kWh
Estimated Transmitter Efficiency	0.15	
Energy Production on Earth	42941530470	kWh
EOL Energy balance	42937916472	kWh
CO_2 tonnes/kWh	0.000160	Tonne/kWh
CO_2 kg/kWh	0.160	kg/kWh
CO_2 g/kWh	160	g/kWh
Europe average	293	g/kWh

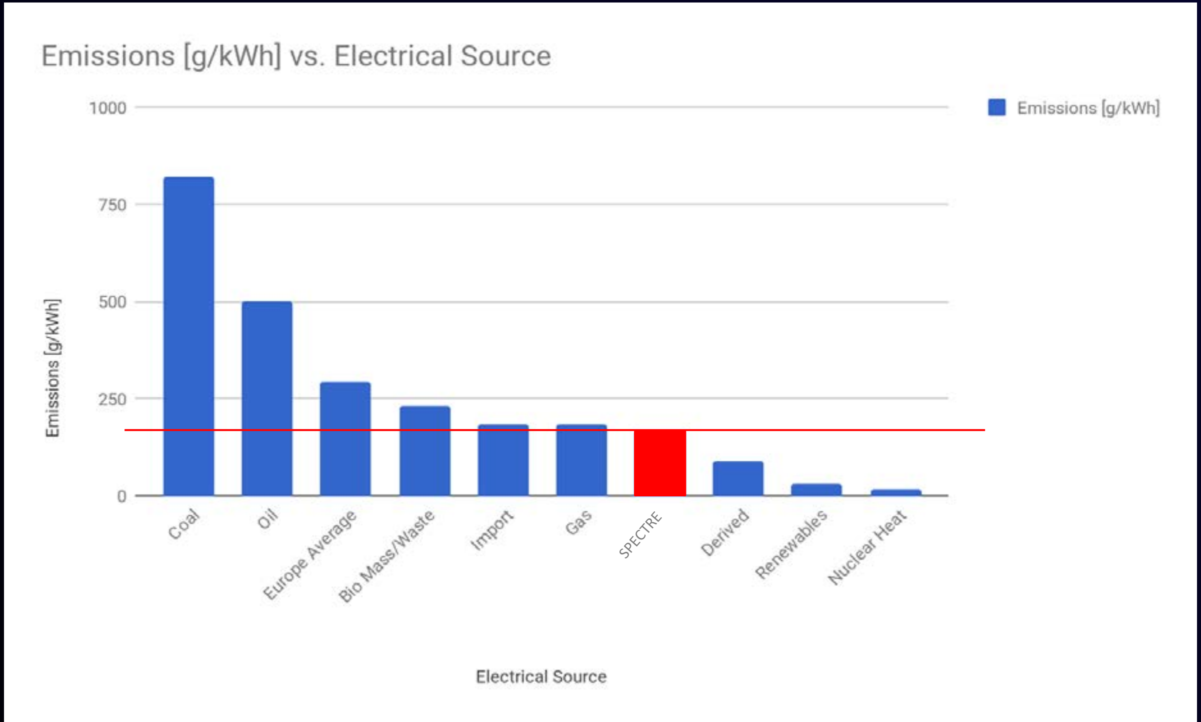
SUSTAINABILITY: SUMMARY

- Net energy produced in space: 286 TWh
  - Net energy on Earth: 42.9 TWh
  - Net energy adjusted: 42.8 TWh

SUSTAINABILITY: ENERGY SOURCE COMPARISON



SUSTAINABILITY: ENERGY SOURCE COMPARISON



Sustainability: Approach

Principles:

- What goes in goes out
  - Mass conservation
  - Energy conservation
- High level
  - Country and continent level
- Detailed
  - Different energy sources

Source: Ausenco

Sustainability: Approach

Source: Stiavelli Irio

Sustainability: Approach

Source: The New Economy

Sustainability: Approach

Sustainability: Approach

Energy in

Conversion Consumption

Energy After Transformation

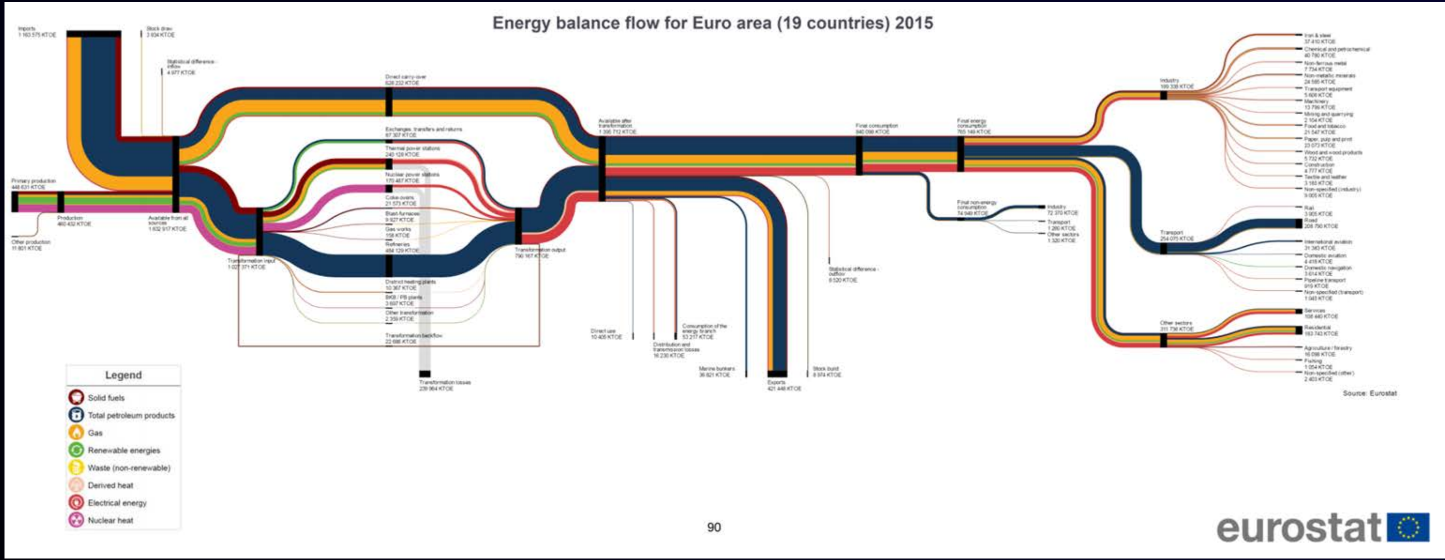
Distribution Losses

Total Available Energy for the Economy

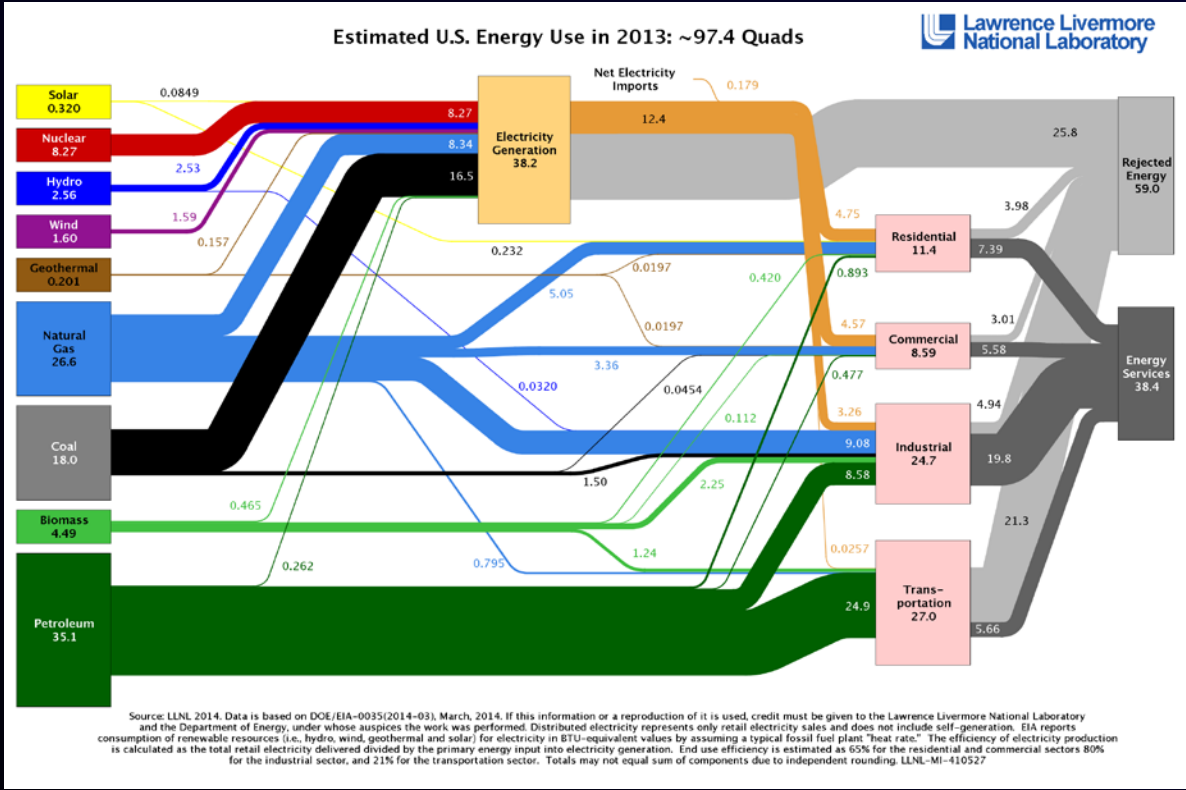
Energy Available for Industry

Energy used to produce product or transport product

Sustainability: Approach



Sustainability: Approach



Sustainability: Approach

Potential CO_2 in

CO_2 from Conversion Consumption

CO_2 After Transformation (Re-distributed)

CO_2 from Distribution Losses

Total CO_2 produced by economy

CO_2 produced by industry

Emissions used to produce product or transport product

Sustainability: Approach

Material:	kWh/tonne	CO2tonne/tonne	kWh/m³	CO2tonne/m³
Steel	2713	4629	21784	37173
Non ferous metals	29199	59665	133736	273272
Aluminium	4632	9465	12243	25017
Copper	4632	9465	41254	84297
Composites (CFRP based)	15278	32660	35139	75118
Plastics	2706	5785	6224	13306
Non-ferrous minerals	1386	3490	3866	9733
Cement and lime	1386	3490	3881	9771
Ceramics	1386	3490	2953	7433
Quartz assumed same as glass	1386	3490	3881	9771

Sustainability: Approach

STRUCTURAL SUSTAINABILITY					
Material:	Coefficient	Production Energy Coef	Production Scrap Coef	Production Viability	Final Score
Steel	2	0.2	0.1	1	0.04
Non ferous metals	0	0.3	0.1	1	0.00
Aluminium	6	0.4	0.2	1	0.48
Copper	0	0.2	0.1	0.5	0.00
Composites (CFRP based)	2	1	1	1	1.52
Plastics	1	1	1	1	0.62
Non-ferrous minerals	26	1	1	0	0.00
Cement and lime	21	1	0.9	0	0.00
Ceramics	585	0	0.2	0	0.00
Quartz assumed same as glass	40	0	0.9	0	0.00

Sustainability: Approach

EPSY		
Material:	Resistivity [Ohmm]	Loss Adjusted Coef
Steel	0.00000016	0.06
Aluminium	0.000000029	0.34
Copper	0.0000000172	0.58

Sustainability: Approach

POCO			
Material:	Coefficient	Reflective Performance	Final Score
Steel	1.78	0.4	0.71
Aluminium	4.71	1	4.71
Copper	0.42	0.2	0.08

Sustainability: Launcher

- Toxicity
- Re-usability
- Specific fuel consumption
- Total tonnage
- Specific cost
- Reliability

Sustainability: Launcher

	Payload to LEO (kg)	Cost total (million EUR)	Cost per kg (EUR/kg)	Reusability	Specific Impulse (s)	Thrust (N)	Toxic Elements	Availability	Reliability	Burn time thrust adjusted (s)	Derived Prop mass(kg)	Derived Prop mass per payload (kg/kg)
BFR	150000	7	46.67	Fully	330	52700000	CH4	Not Developed	-	-	2850450	19
Falcon Heavy	63800	76.5	1199.06	First Stage	285	22827380	RP-1	Developed	1	162	1322687	21
Falcon 9	22800	52.7	2311.40	First Stage	285	8299260	RP-1	Developed	0.97	162	480884	21
Proton K	19760	65	3289.47	None	285	8829000	UDMH-N2O4	Developed	0.9	120	378947	19
Proton M	21600	65	3009.26	None	285	9535320	UDMH-N2O4	Developed	0.9	120	409263	19
Proton M/Briz-m Enhanced	23000	65	2826.09	None	285	10016010	UDMH-N2O4	Developed	0.9	123	440642	19
Delta IV-M+(4,2)	11920	400	33557.05	None	321	5171538	HTPB	Developed	0.82	220	361390	30
Delta IV-M+(4,2) (RS-68A)	12000	400	33333.33	None	321	5171538	HTPB	Developed	0.82	220	361390	30
Delta IV-M+(5,2) (RS-68A)	10220	400	39138.94	None	321	5171538	HTPB	Developed	0.82	220	361390	35
Delta IV-M+(5,4)	13450	400	29739.78	None	321	5171538	HTPB	Developed	0.82	220	361390	27
Delta IV-M+(5,4) (RS-68A)	12820	400	31201.25	None	321	5171538	HTPB	Developed	0.82	220	361390	28
Delta IV-H	22980	400	17406.44	None	321	5171538	HTPB	Developed	0.82	220	361390	16
Delta IV-HU (RS-68A)	25980	400	15396.46	None	321	5171538	HTPB	Developed	0.82	220	361390	14
Atlas V 401/402	12500	137	10960.00	None	312	3827862	HTPB-RP-1	Developed	0.99	240	300250	24
Atlas V 501/502	10300	137	13300.97	None	312	3827862	HTPB-RP-1	Developed	0.99	240	300250	29
Atlas V 521/522	15080	154	10198.94	None	246	7206426	HTPB-RP-1	Developed	0.99	170	506392	34
Atlas V 531/532	17250	162	9402.90	None	274	8895708	HTPB-RP-1	Developed	0.99	155	511864	30
Atlas V 541/542	18960	171	8997.89	None	290	10584990	HTPB-RP-1	Developed	0.99	144	536216	28
Atlas V 551/552	20520	179	8723.20	None	284	12274272	HTPB-RP-1	Developed	0.99	137	603423	29
Zenit 2	13740	35	2547.31	None	311	7259400	Kerosene	Developed	0.83	143	340257	25
Zenit 2SLB	13920	50	3591.95	None	309.5	7259400	Kerosene	Developed	0.83	143	341906	25
Ariane 5 ES(V)	19300	178	9222.80	None	293	11354702	none	Developed	0.89	179	705852	37
Angara A3	14600	95	6506.85	None	309.5	1922760	potentially RP-1-	Developed	0.67	236	149454	10
Angera A5	24500	105	4285.71	None	309.5	1922760	potentially RP-1-	Developed	0.67	236	149454	6
Angara A5/KVRB	24500	105	4285.71	None	309.5	1922760	potentially RP-1-	Developed	0.67	236	149454	6

Launcher Backup Slides

So… How do we get this into space?

- Launcher

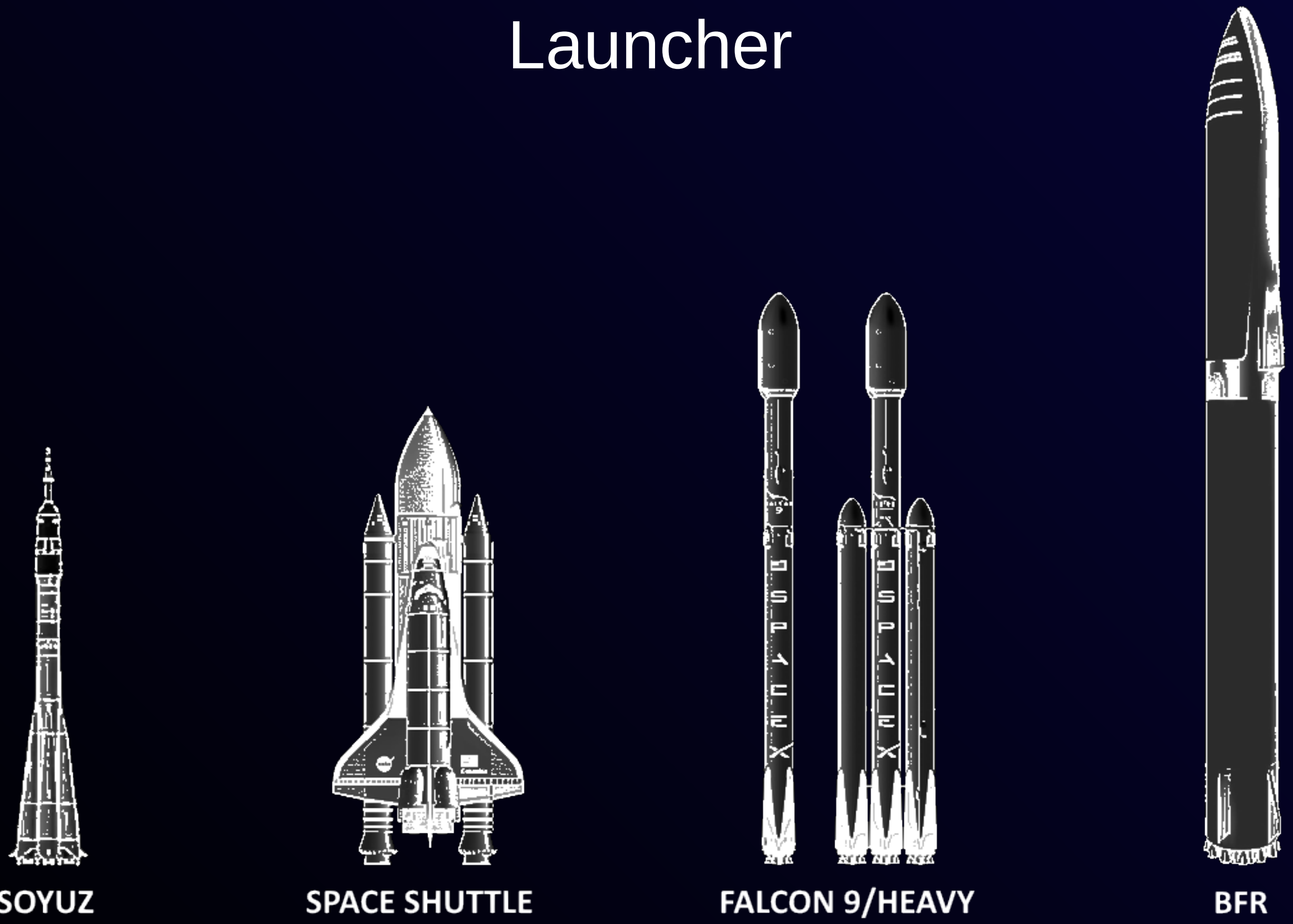
- Focus on In-Orbit Production:
  - Modular production
  - Additive manufacturing of trusses
  - Robotic assembly
  - Production of large mirrors
  - Large earth produced parts

- Integration (animation)

Conclusion

Q&A

Launcher



On Earth vs. In-Orbit

Launching = limits on volume and mass

In-orbit construction:
- High packing efficiency
- No launch loads on structure
> Large and light S/C

But… In-orbit production = complex!

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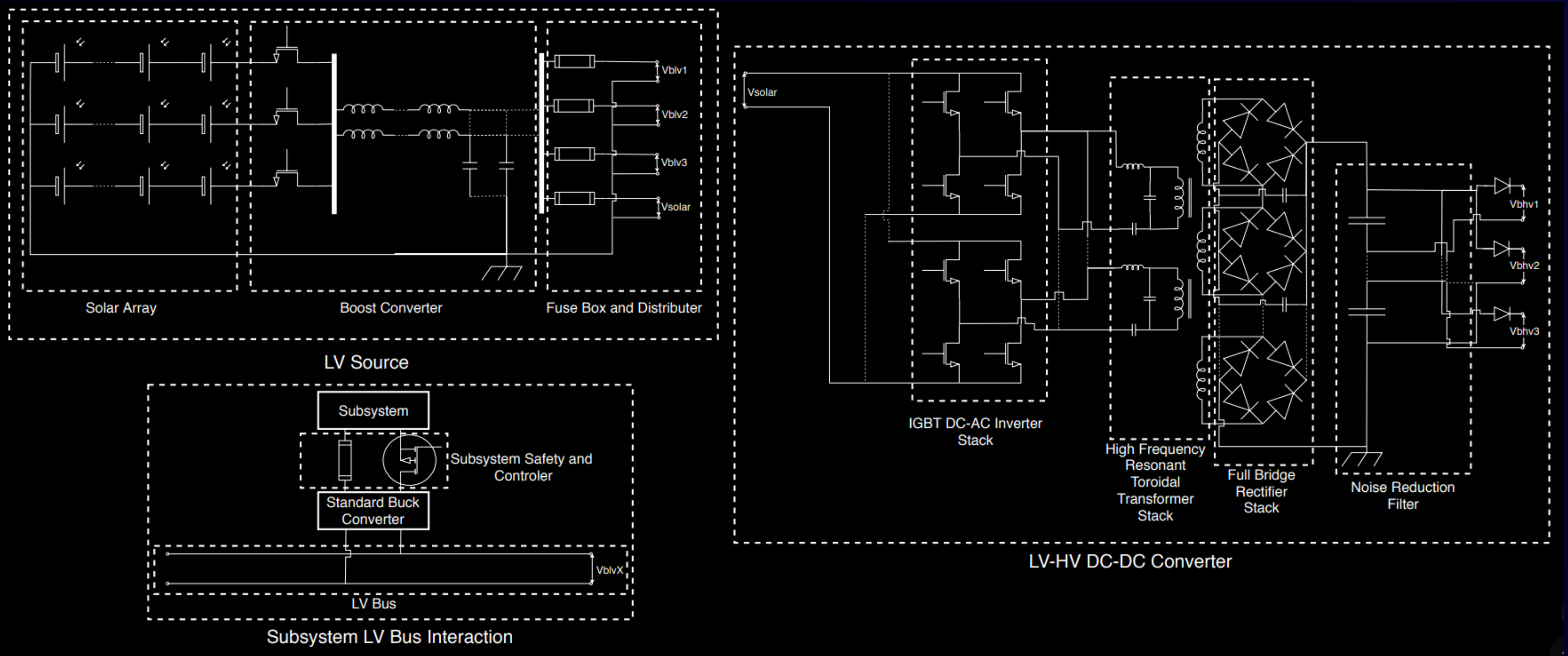
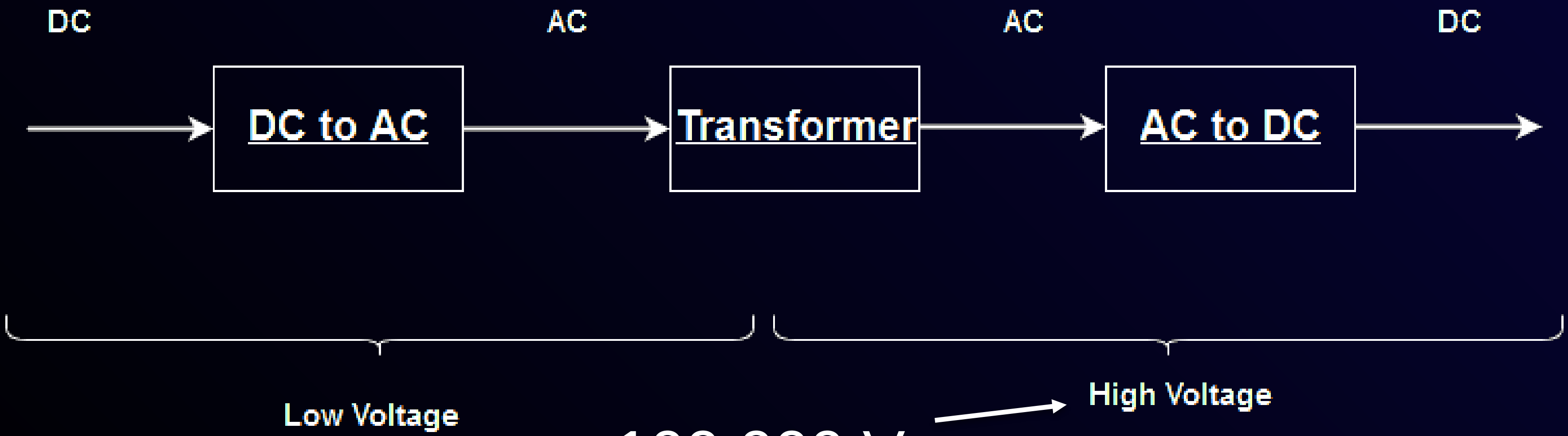
SPECTRE

EPS
Backup Slides

Electric Power System



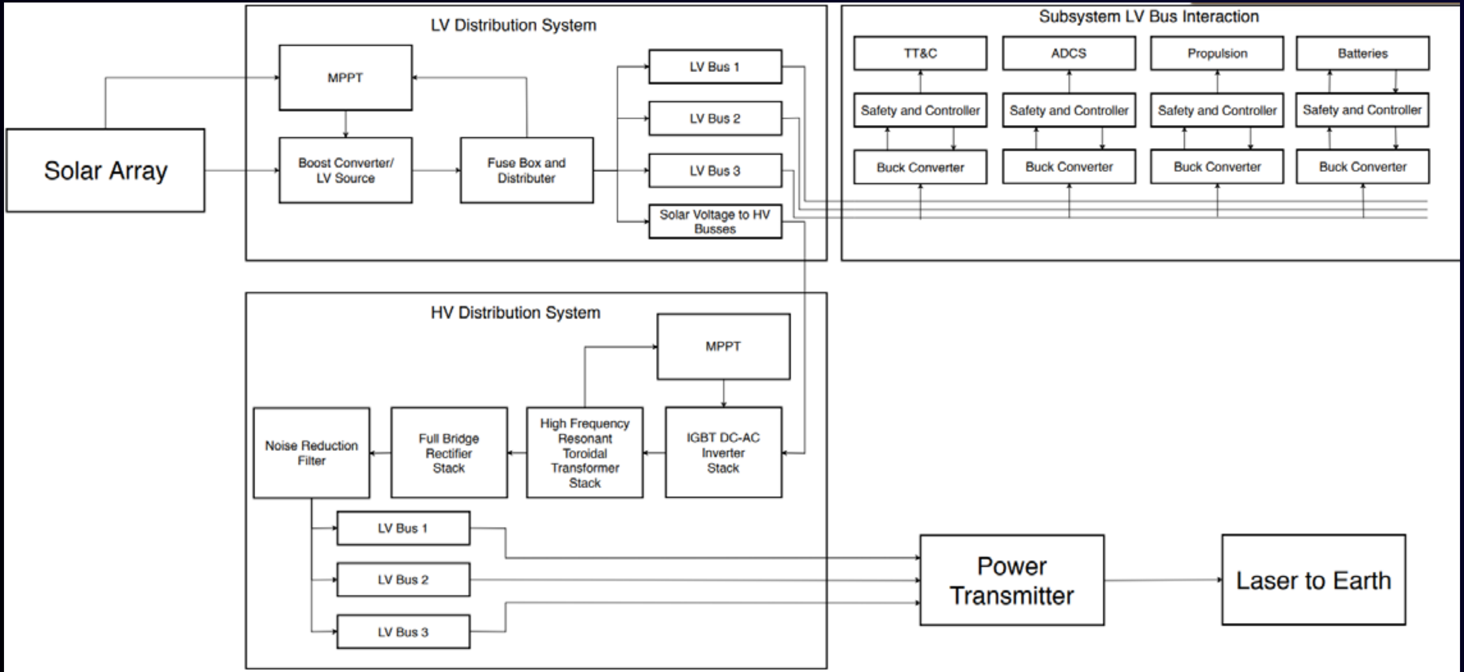
Electric Power System



100,000 V

Only 1300 kg

EPS: BLOCK DIAGRAM



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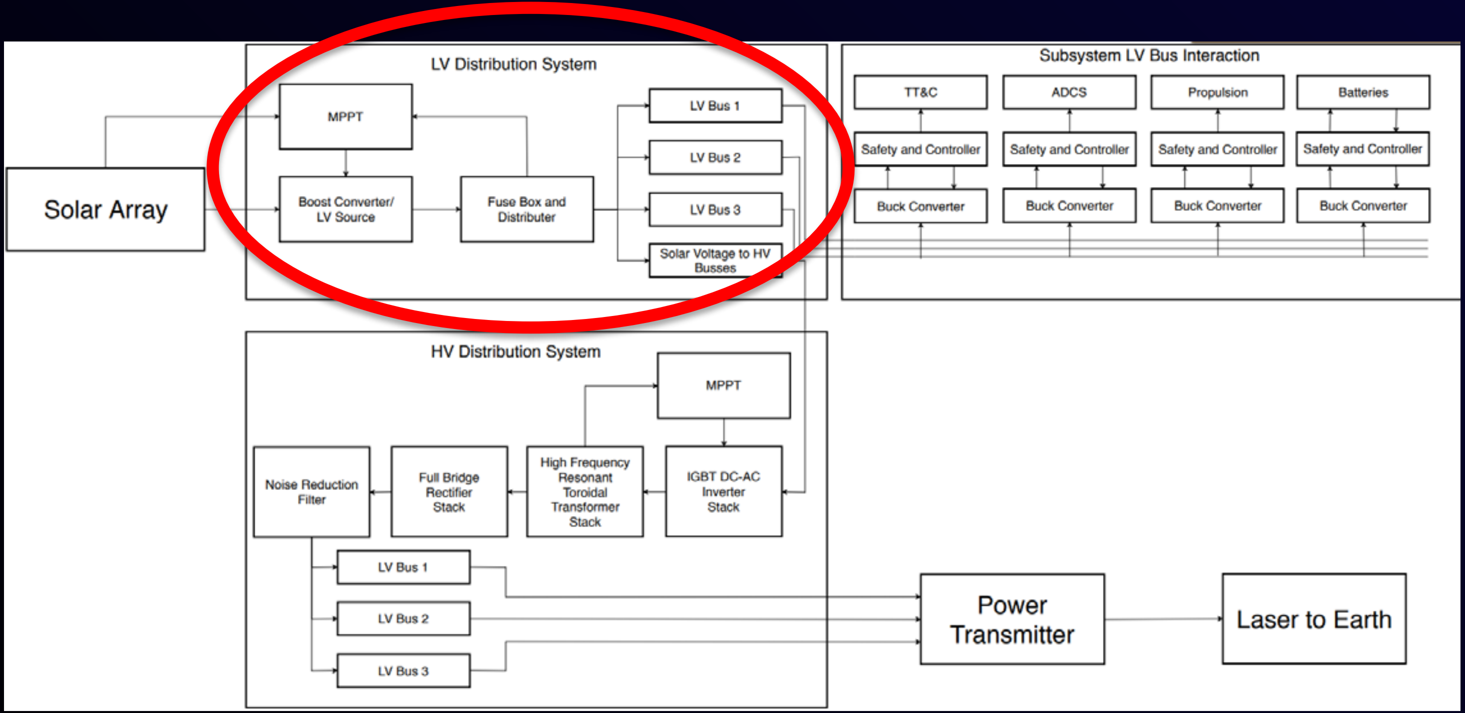
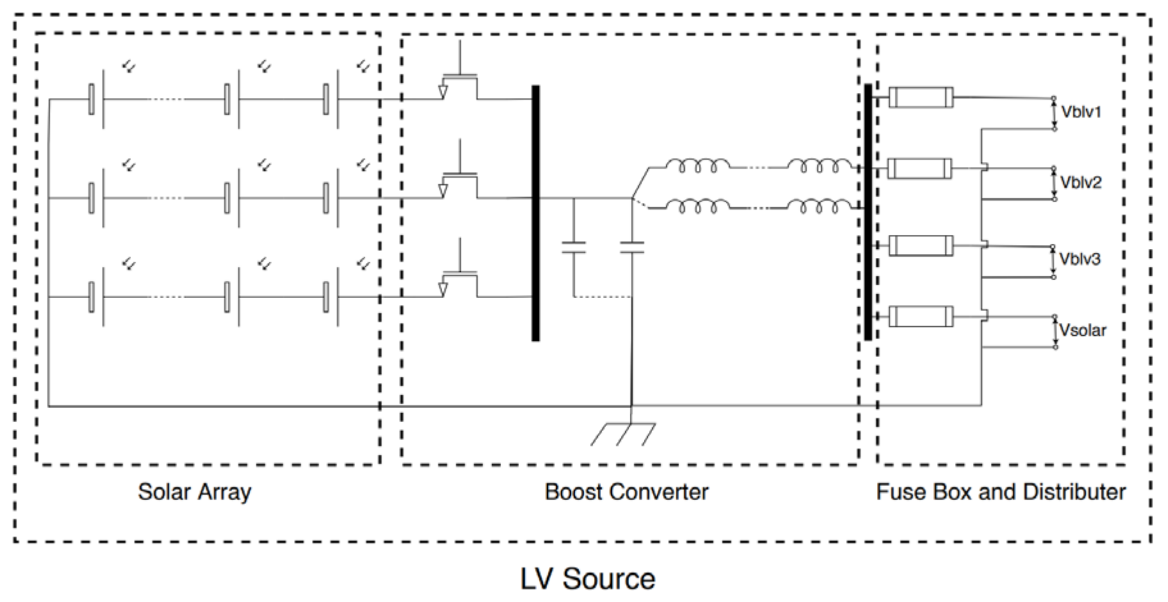


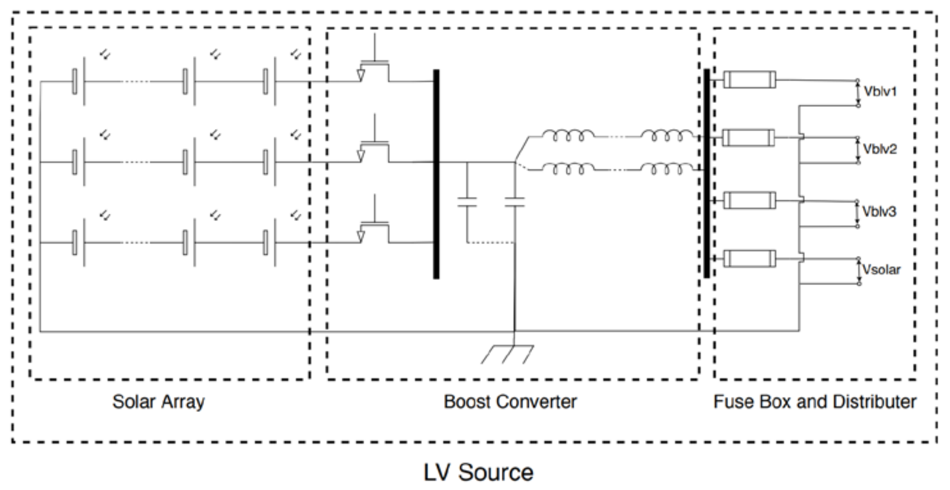
EPS: LV SOURCE



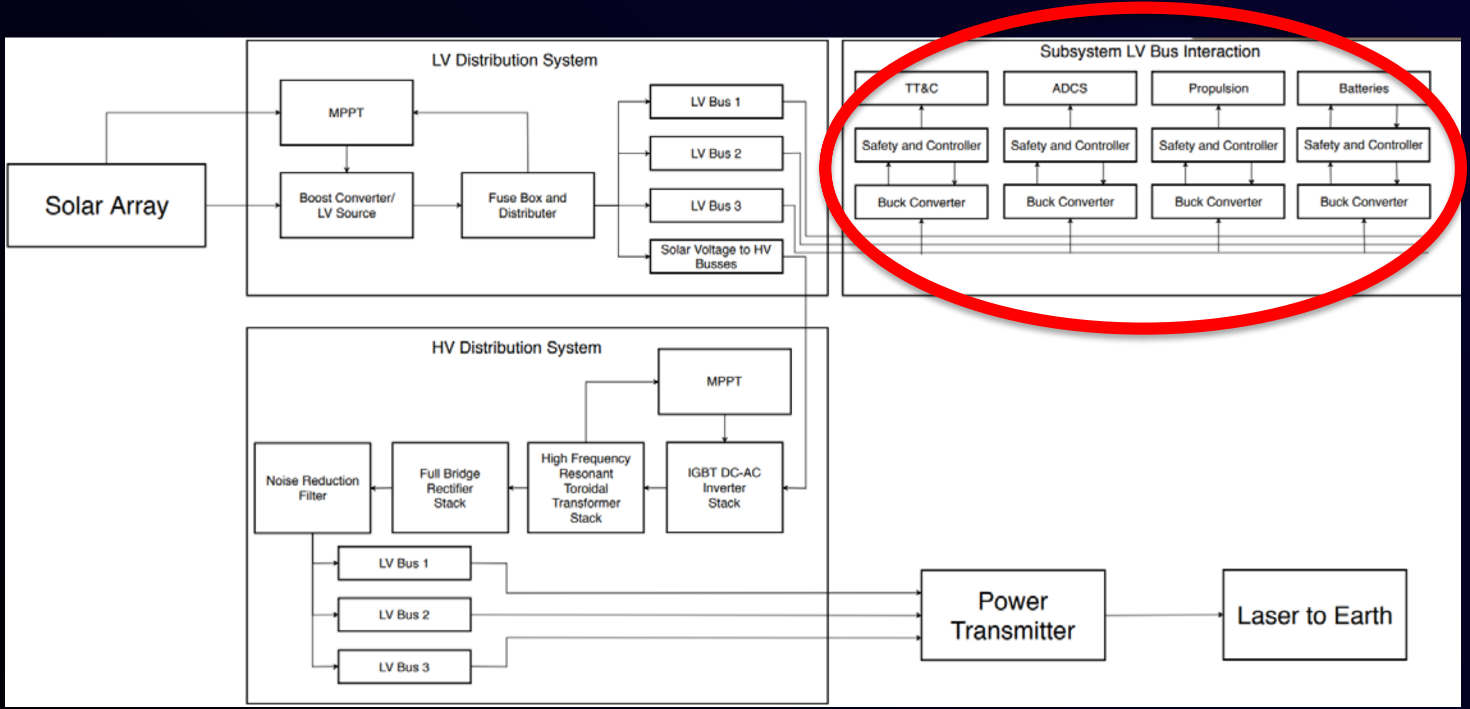
EPS: LV SOURCE

LV Source Design Challenges:

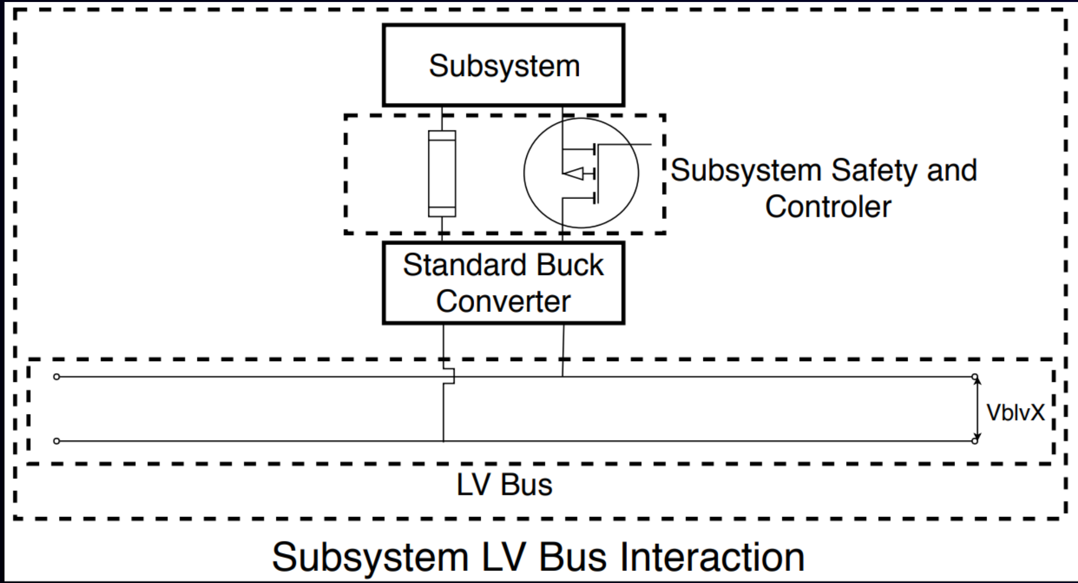
- Solar Cells Output Low Voltage (mV range)
- Solar Cells Tend not to Operate at Max Power Point
- Conductor Skin Losses
- Eddy Current Losses



EPS: BLOCK DIAGRAM



EPS: SUBSYSTEM INTEGRATION



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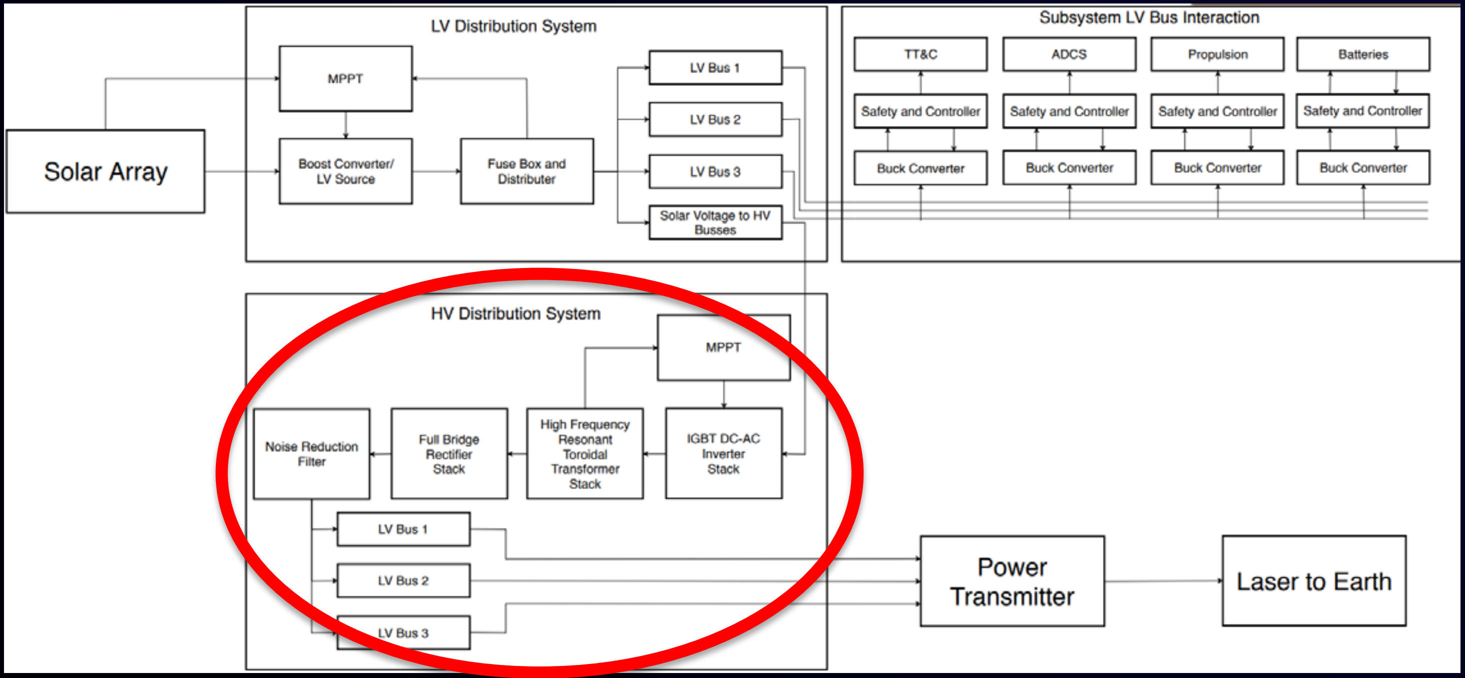
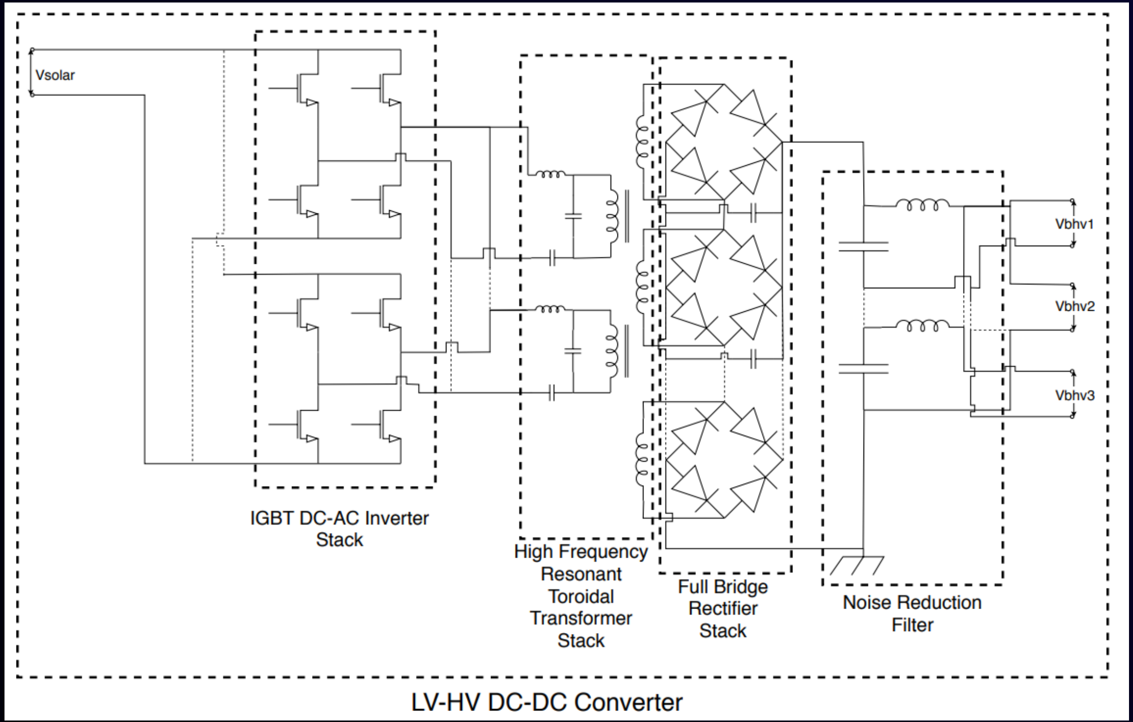


EPS: LV-HV DC-DC Converter



EPS: EXTRA SLIDES

Transformer Design Challenges:

- Flux Leakage
- Hysteresis Losses
- Conductor Skin Losses
- Eddy Current Losses

EPS: EXTRA SLIDES

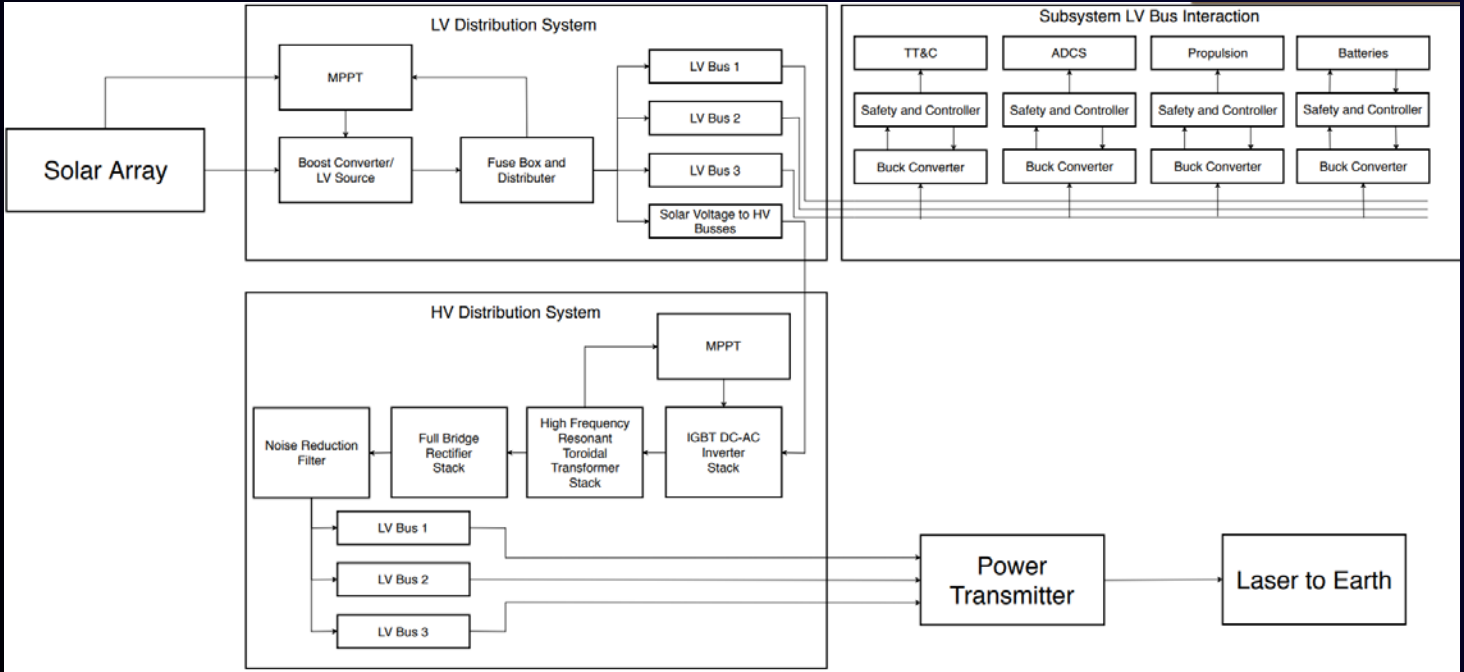
Transformer Design Challenges:

- Flux Leakage
- Hysteresis Losses
- Conductor Skin Losses
- Eddy Current Losses

Transformer Design Solutions:

- Toroidal
- Silicon Steel Alloy
- Transformer Stack
- Micro Laminations

EPS: BLOCK DIAGRAM



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SPECTRE

EPS: STATS

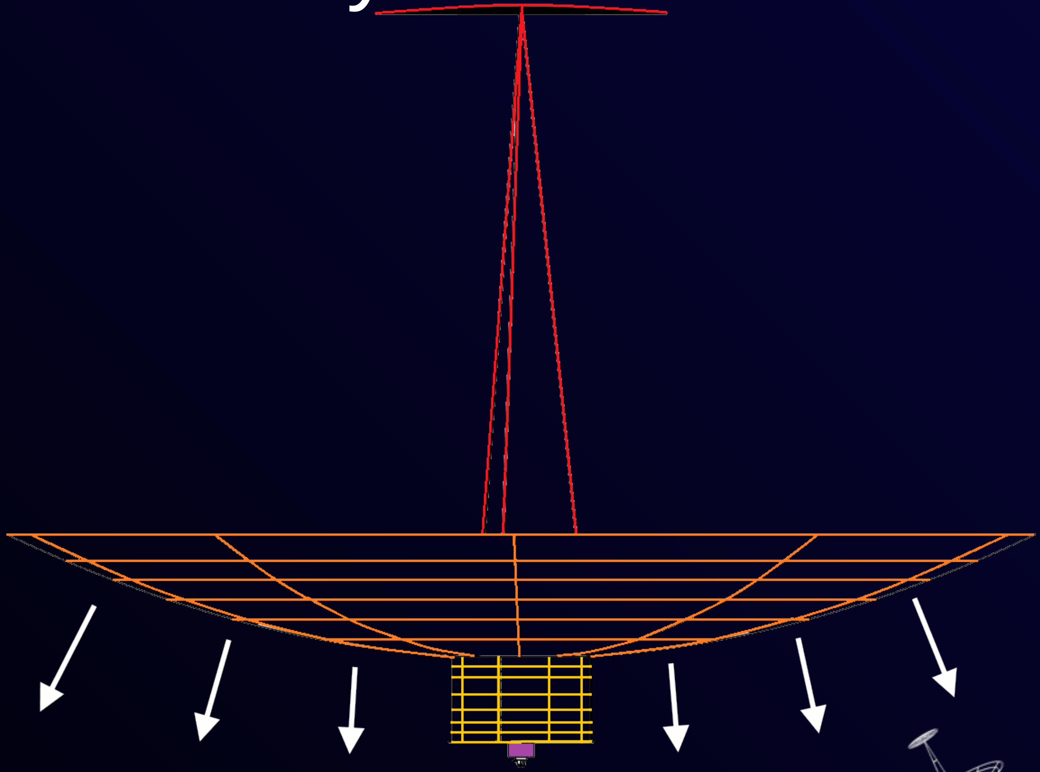
- High Power Density (172 kW/kg)
- High Efficiency (95%+)
- Compatible
- Modular

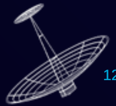
Subsystem	Electric power distribution [%]	Per Spacecraft [MW]	Total [MW]
Propulsion	0.00	0.0019	0.037
ADCS	0.00	0.0018	0.036
Thermal Control	0.00	0	0
TT&C	0.00	0.001	0.002
Power Collection	0.00	0	0
Power Storage	0.00	0.003	0.060
EPSY	0.04	2.24	44.78
Maintenance	0.00	0	0
Structures	0.00	0	0
Power Transmission	0.96	58.93	1178.67
Total	**1.00**	**61.18**	**1223.58**

Thermal Control Backup Slides

Thermal Control System

- Secondary mirror heat pipes
- Primary mirror heat pipes
- ‘Knikkerbaan’ heat pipes
- Thermal Energy Storage Container

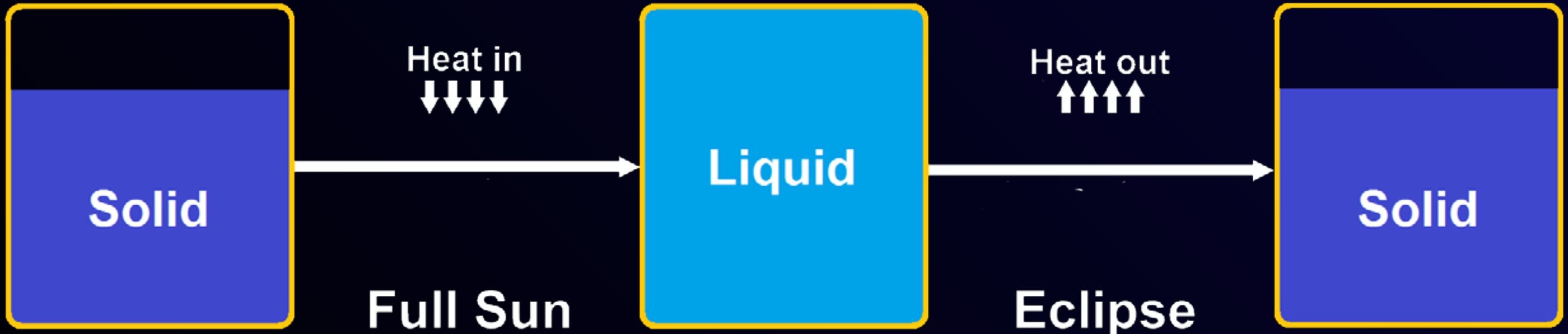




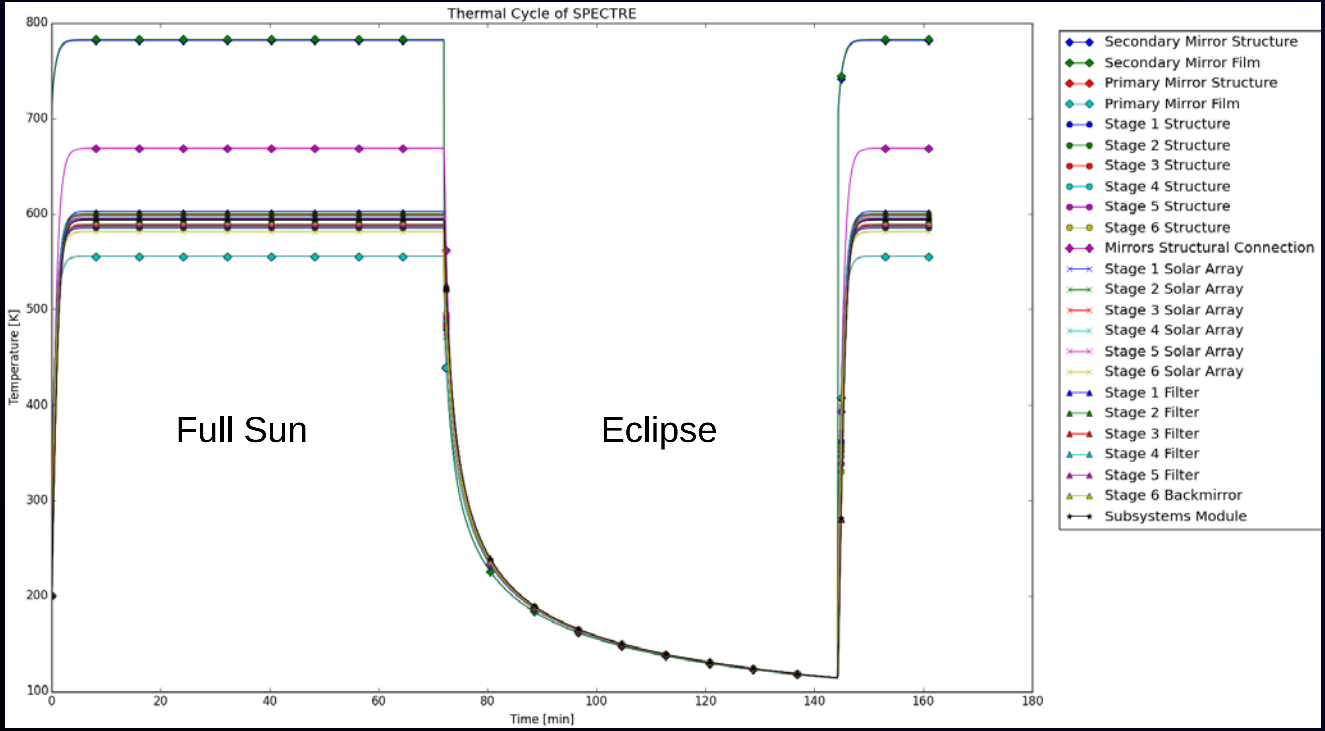
SPECTRE

Thermal Control System

Thermal Energy Storage

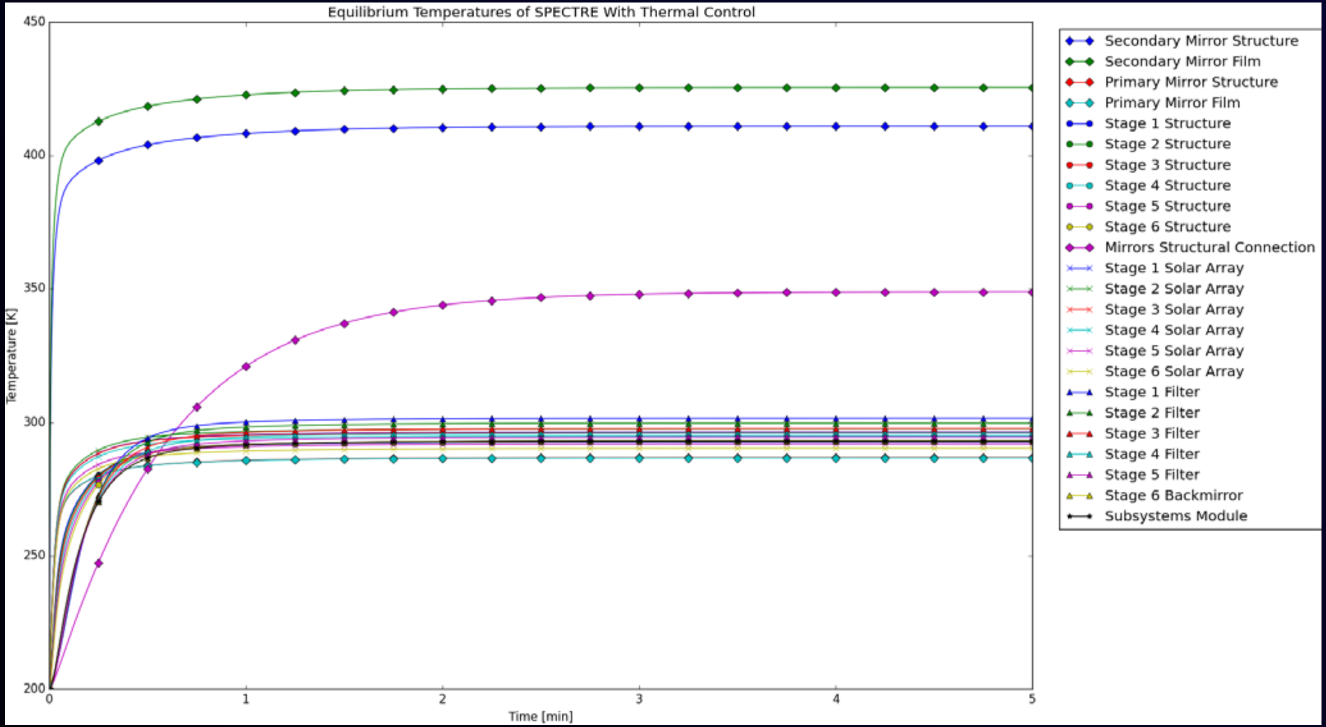


Thermal Control System



SPECTRE temperatures without thermal control measures

Thermal Control System



SPECTRE temperatures in full Sun with thermal control

TU Delft

SPECTRE

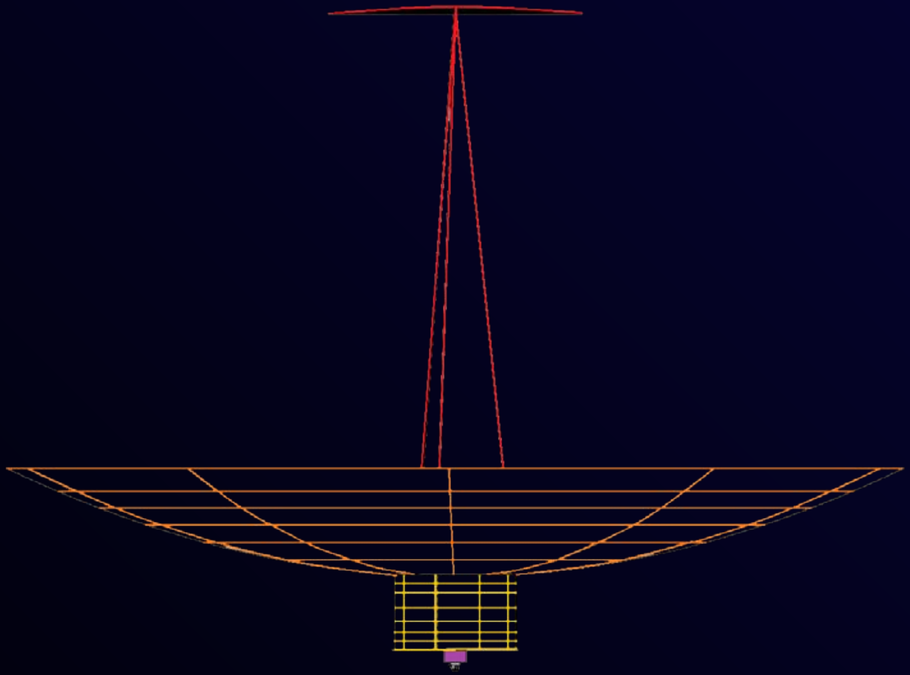
Thermal Control System

	Allowable Temperatures		No Thermal Control		With Thermal Control	
Critical Components	*Min T [K]*	*Max T [K]*	*Min T [K]*	*Max T [K]*	*Min T [K]*	*Max T [K]*
Solar cells	-	300	114	600	200	297.5
Filters	-	500	114	603	290	301.5
Subsystem module	250	300	114	594	273	293

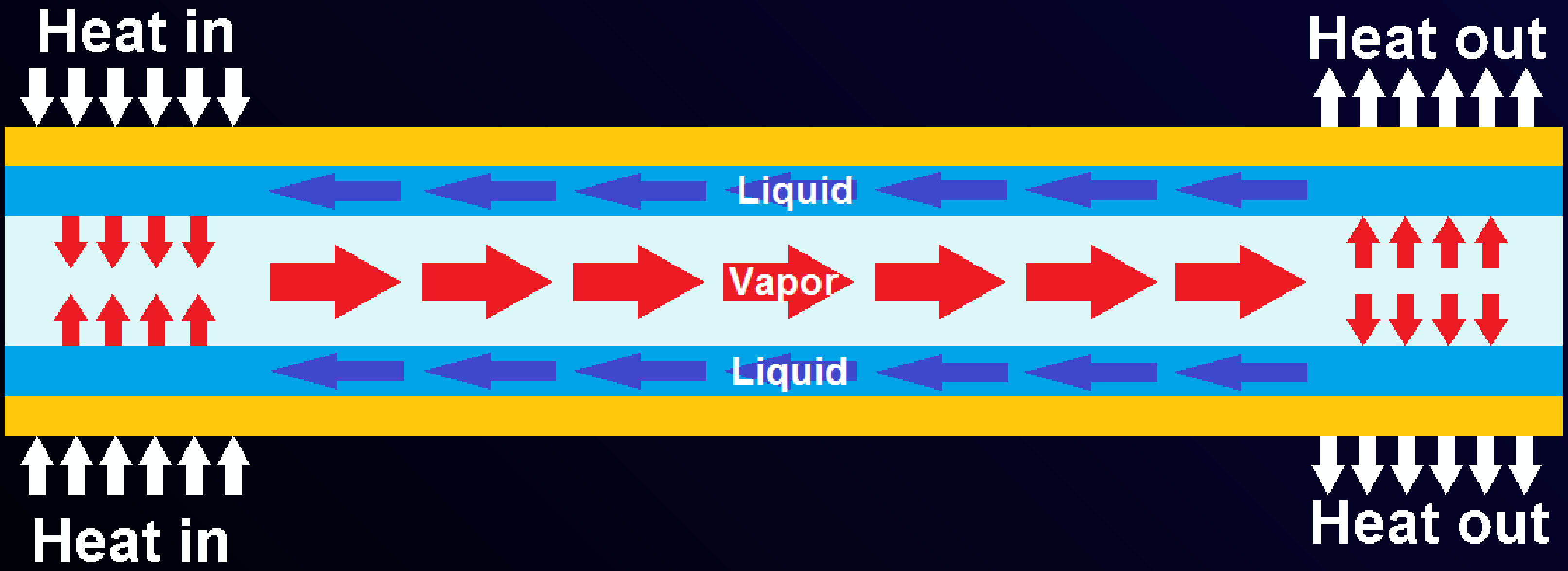
SPECTRE temperatures before and after thermal control is applied

Thermal Control System

- Secondary mirror heat pipes
- Primary mirror heat pipes
- ‘Knikkerbaan’ heat pipes
- Thermal Energy Storage Container

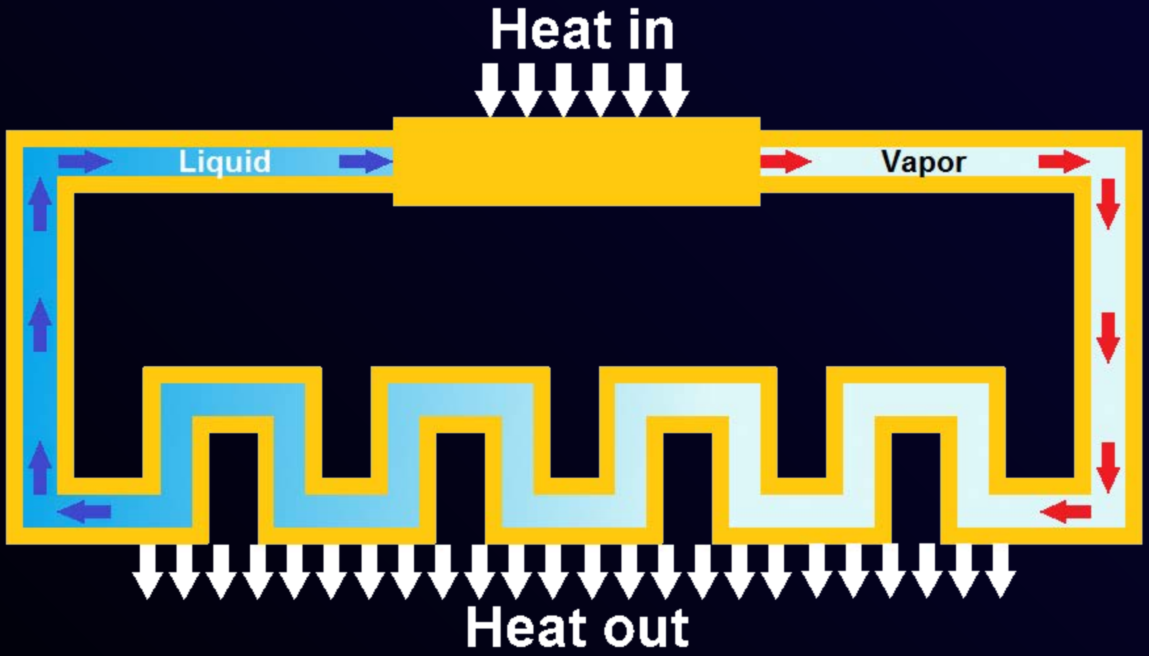


Thermal Control System

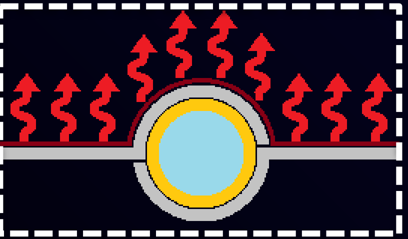


Standard Heat Pipe operation

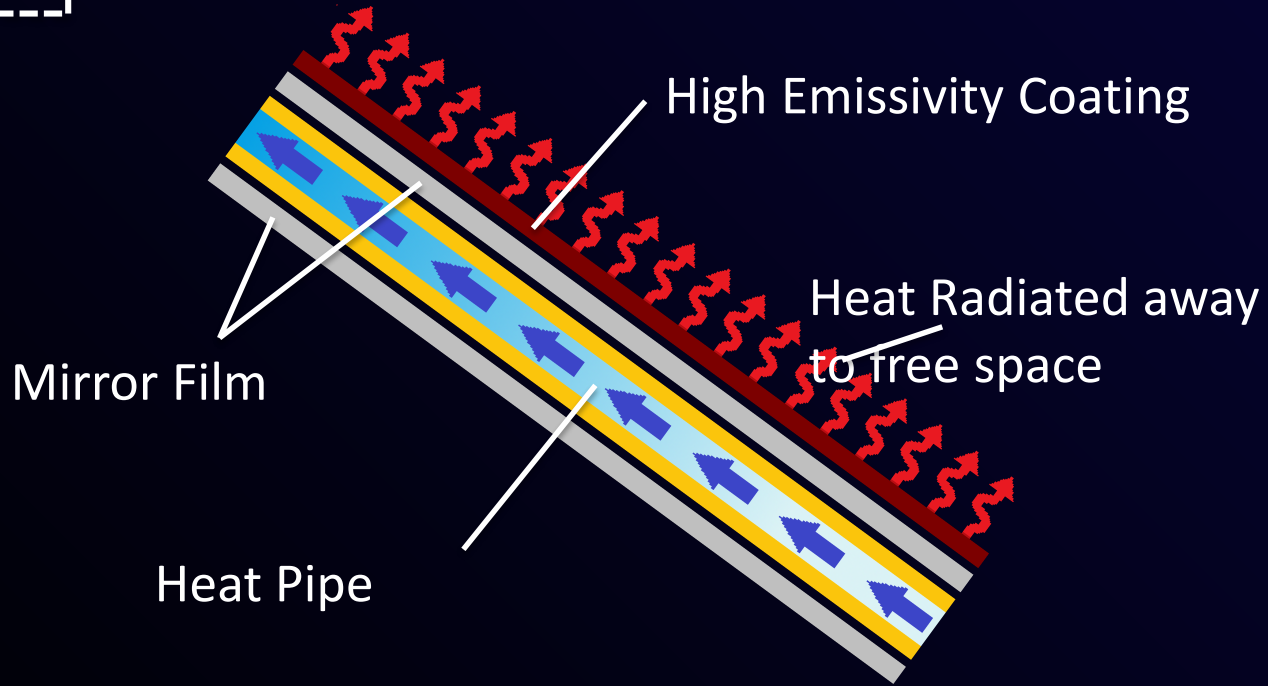
Thermal Control System



Loop Heat Pipe operation

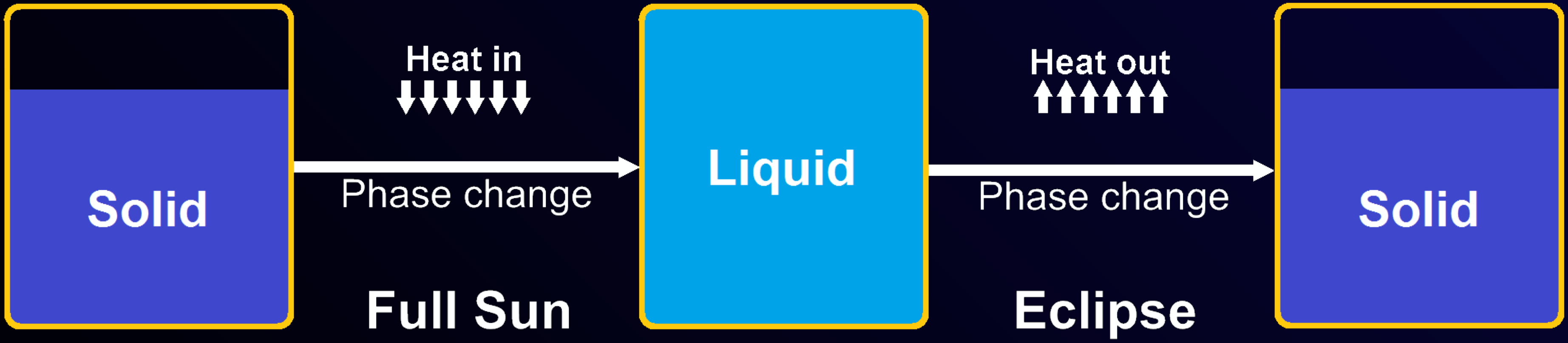


Thermal Control System



Radiator operation

Thermal Control System



Thermal Energy Storage operation

Thermal Control Theory

Radiative Thermal Coupling

$$Q_r = \sigma \cdot \varepsilon \cdot A_1 \cdot F_{1\rightarrow 2} \cdot (T_1^4 - T_2^4)$$

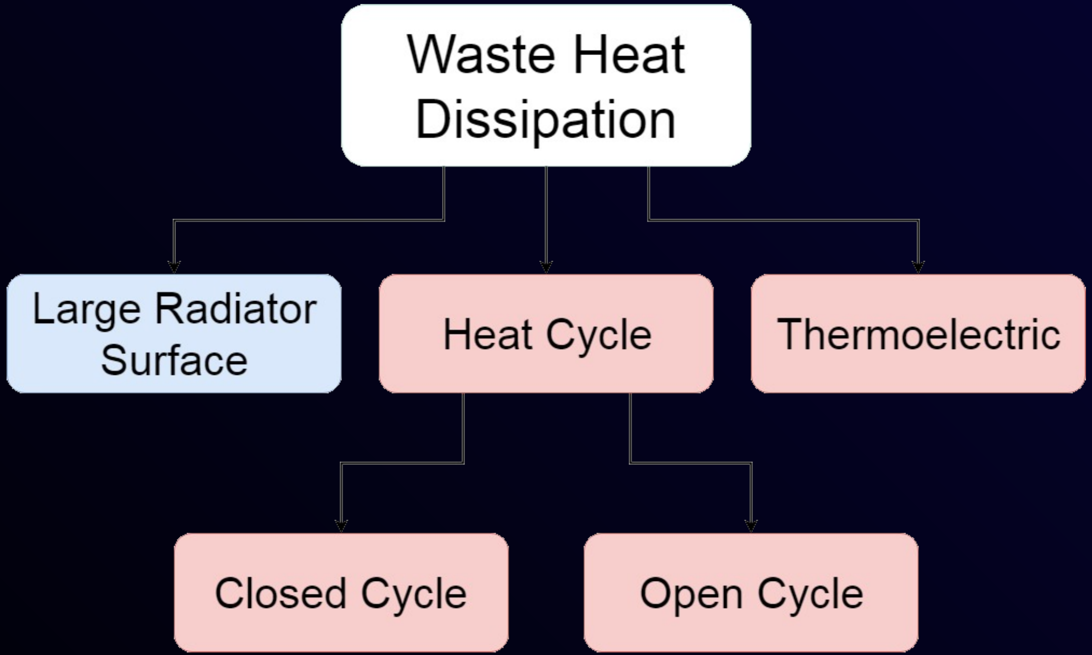
Conductive Thermal Coupling

$$Q_c = h_t \cdot A_c \cdot (T_1 - T_2)$$

Component temperature due to heat

$$T = \frac{Q_r + Q_c + Q_{in}}{H_c} \cdot t$$

Thermal Control System



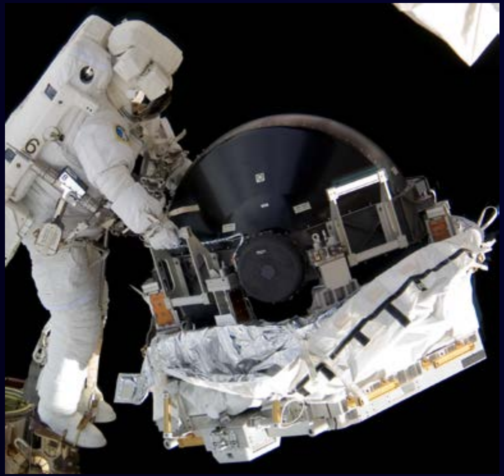
Thermal Control Design Option Tree

ADCS
Backup Slides

ADCS: Actuators

Attitude Control:

- *Control Moment Gyroscopes*
- *Stability & Control*
- *9 CMGs per satellite*



ADCS: Disturbances

Solar radiation pressure:

$$T_s = \frac{\Phi}{c} \cdot A_s \cdot \left(c_{p,s} - c_m\right) \cdot (1 + q) \cdot \cos(\varphi)$$

$$T_s = 0.0364\ Nm$$

Magnetic disturbance torque:

$$T_m = D_m \cdot \frac{M_m}{R^3} \cdot \lambda_m$$

$$T_m = 2.08 \cdot 10^{-6}\ Nm$$

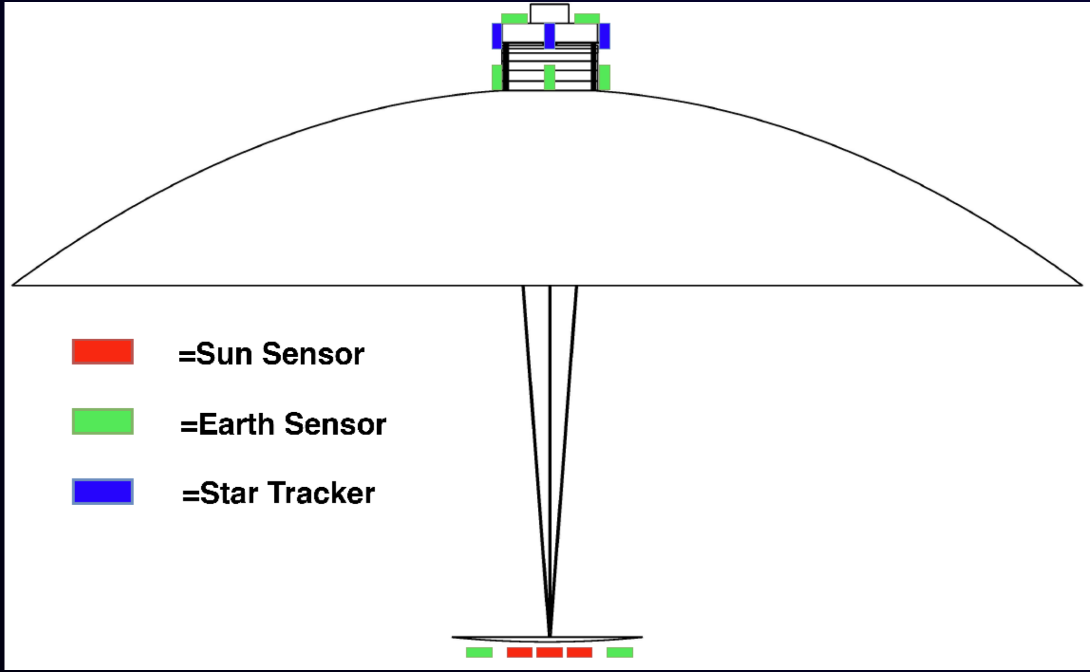
Safety factor of 1.25 to account for other smaller disturbances leads to:

$$T_{max} = 0.04555\ Nm$$

ADCS: Sensors

Attitude Determination:

- 3 Sun sensors
- 8 Earth sensors
- 4 Star trackers

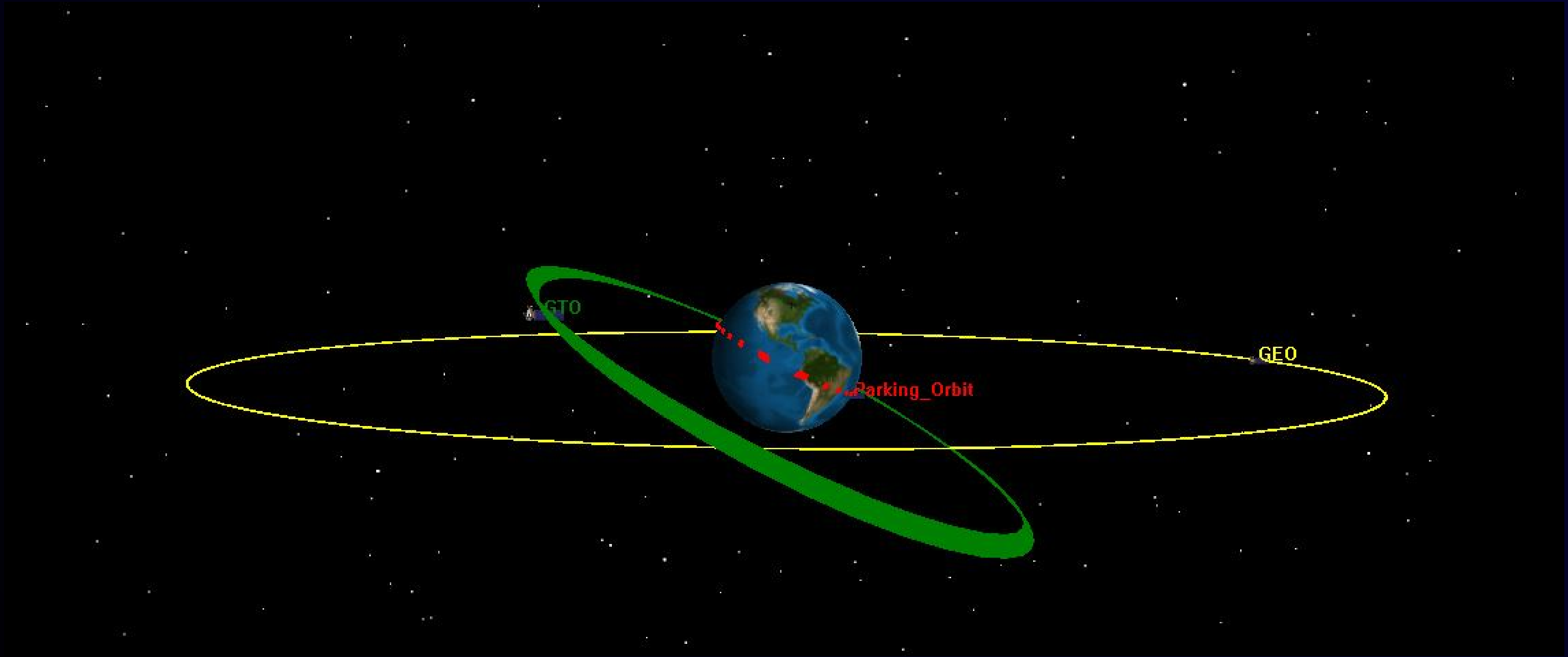


Astrodynamics Backup Slides

Astrodynamics: ΔV Budget

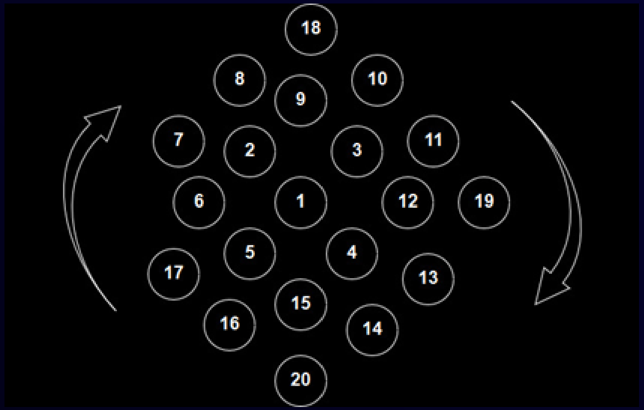
Trajectory	ΔV [m/s]
Launch	7759
GTO	2442
GEO	1779
Station Keeping	47 x 32 years
Disposal	186
Contingency Factor	1.25
Total	**17089**

Astrodynamics: Trajectory



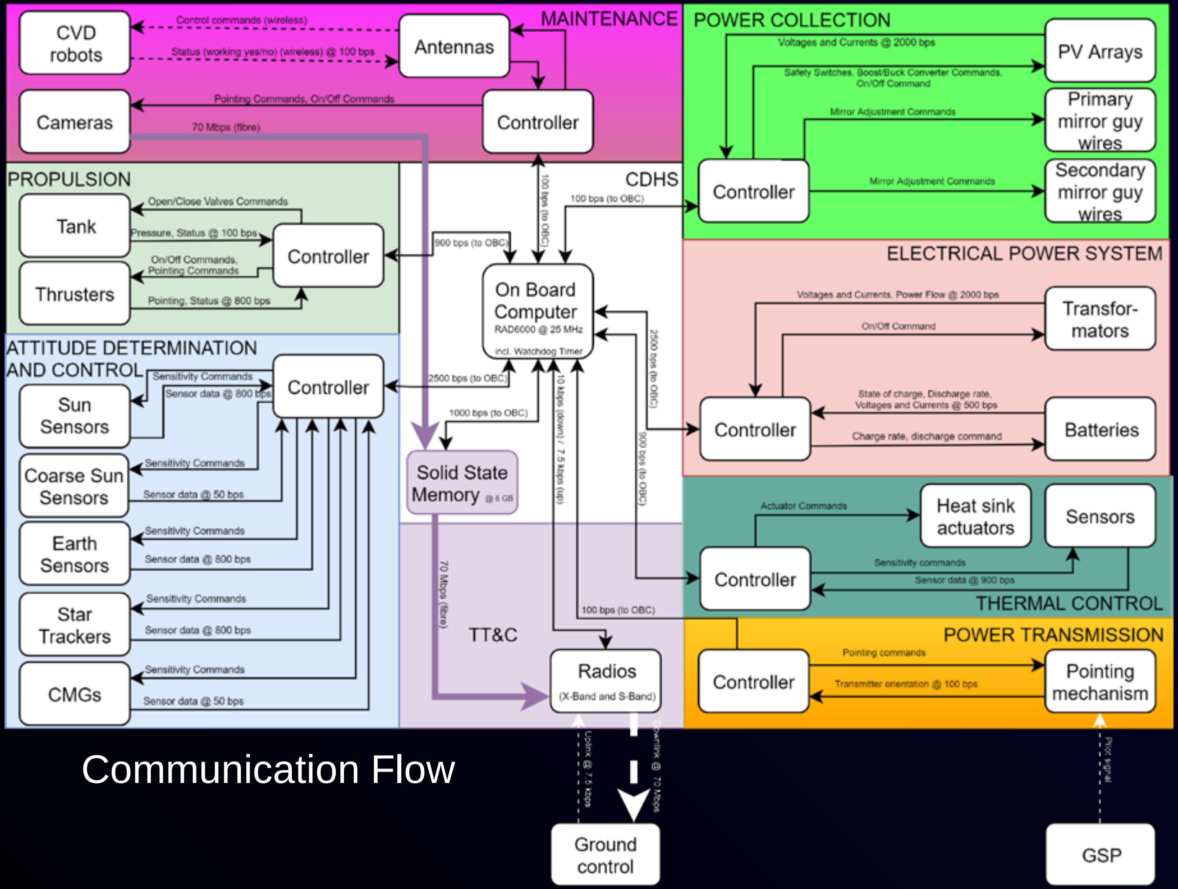
Astrodynamics: Cluster Flying

- 20 Spacecraft
- Orbit around GEO belt ‘axis’
- 1 km separation



C&DH
Backup Slides

Command and Data Handling System



Communication Flow

Market, Operations and Contingencies Backup Slides

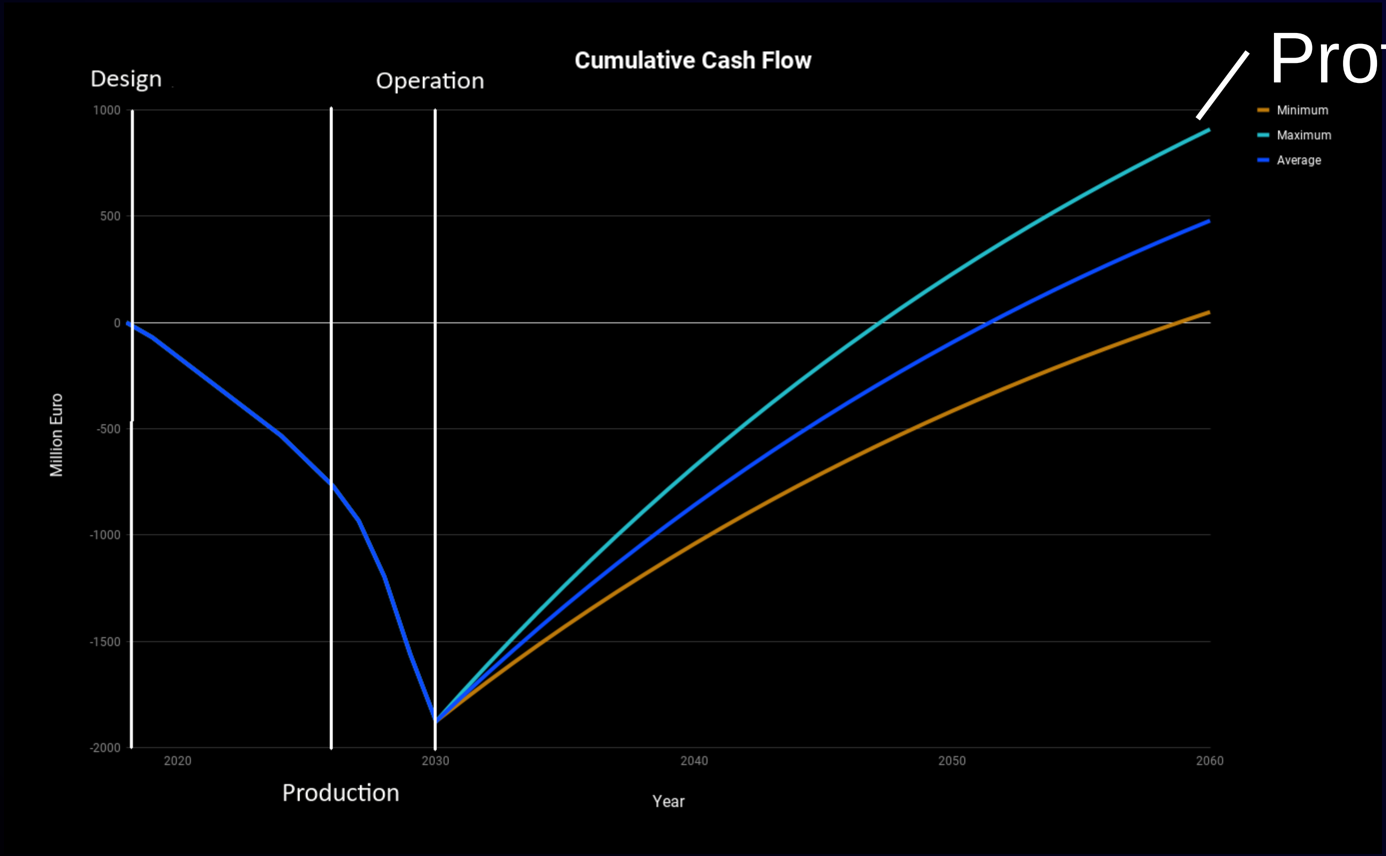
Economics: Profitability

Market:
Fast developing Asian countries

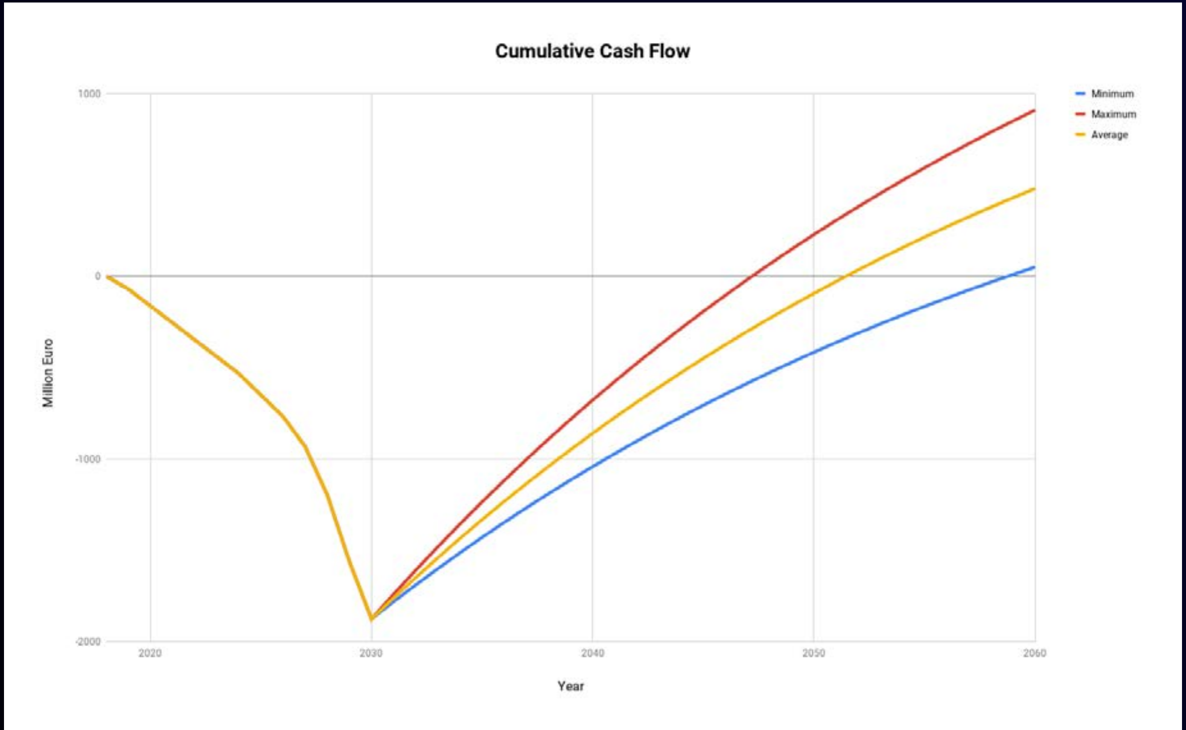
Source: trumpf

Economics: Profitability

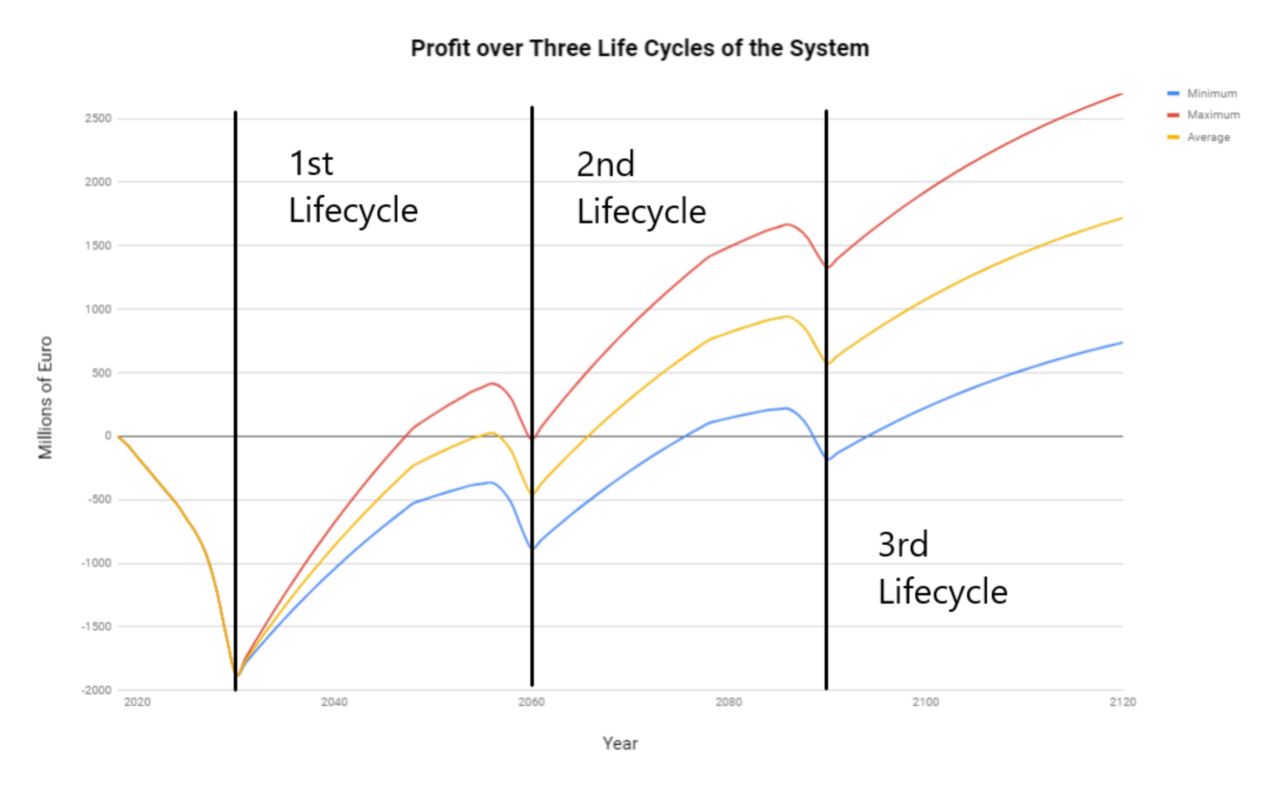
Profit: €1B!



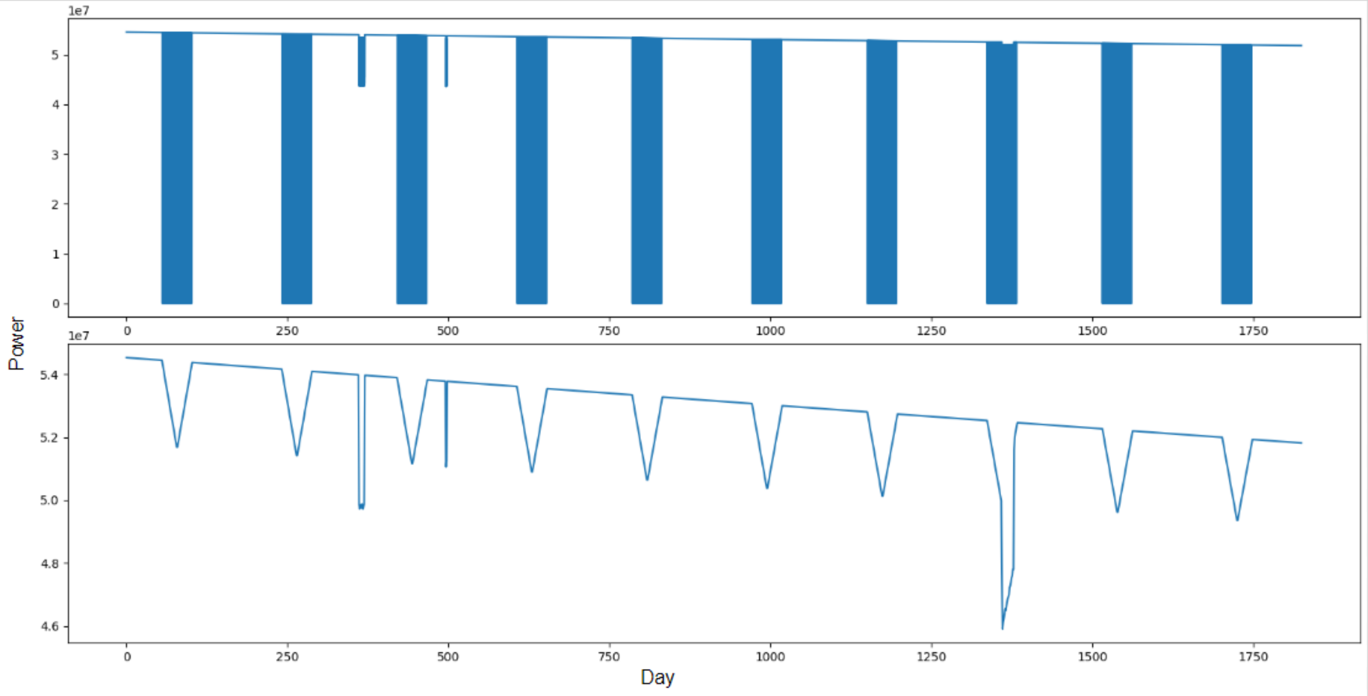
Cash Flow into SPECTRE



Continued Investment into



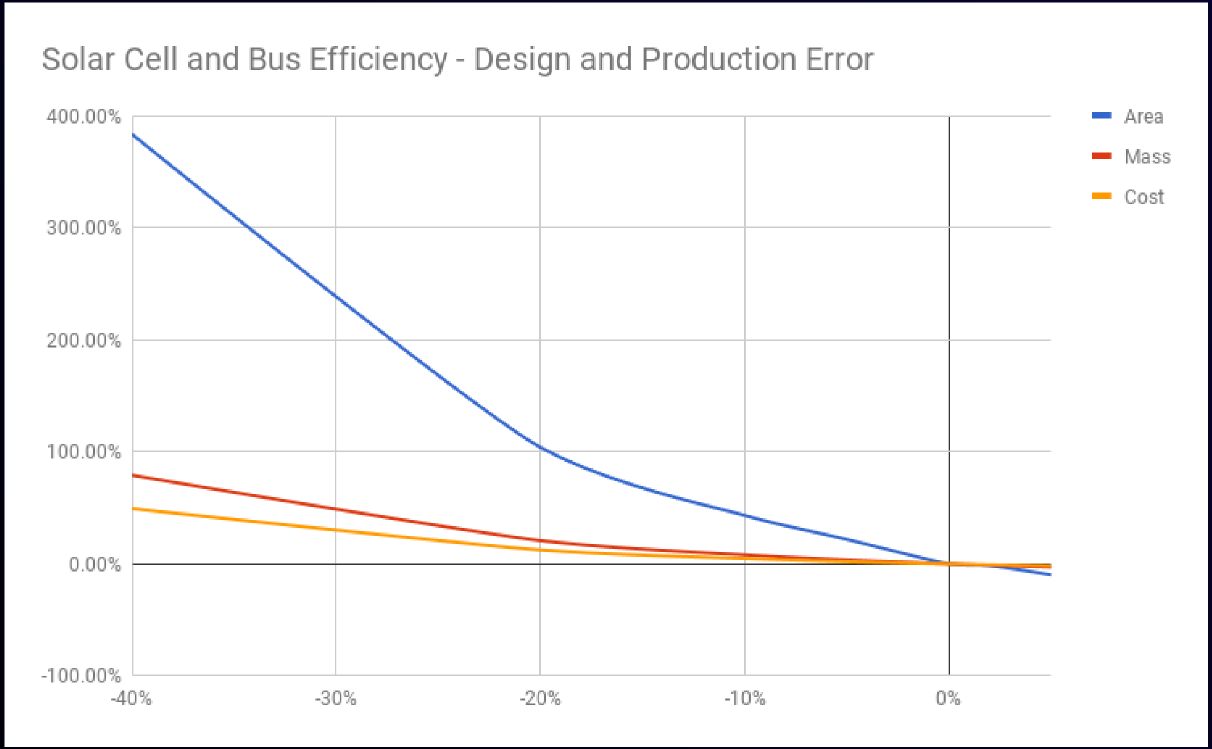
Monte Carlo Simulation



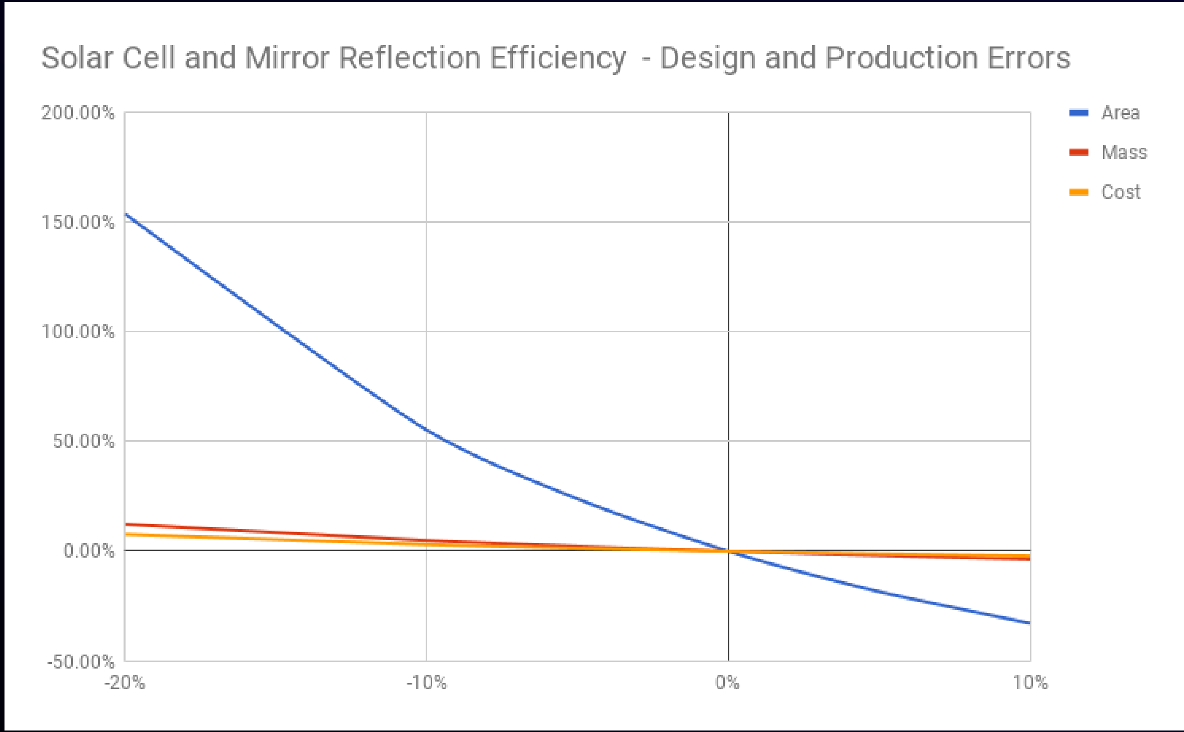
Monte Carlo Specifications

- Three Normal Distributions and one Logarithmic Distribution for Randomisation
- Mirror and Solar Cell Degradation
- Partial Mirror Failure, Partial Failure, Ultimate Failure and ADCS Failure
- Debris Impacts on Solar Cells and Mirrors
- Partial Mirror Repair, Partial Repair, ADCS Repair
- Integration of Eclipse Periods
- One Minute Resolution for 30 Years

Sensitivity Analysis



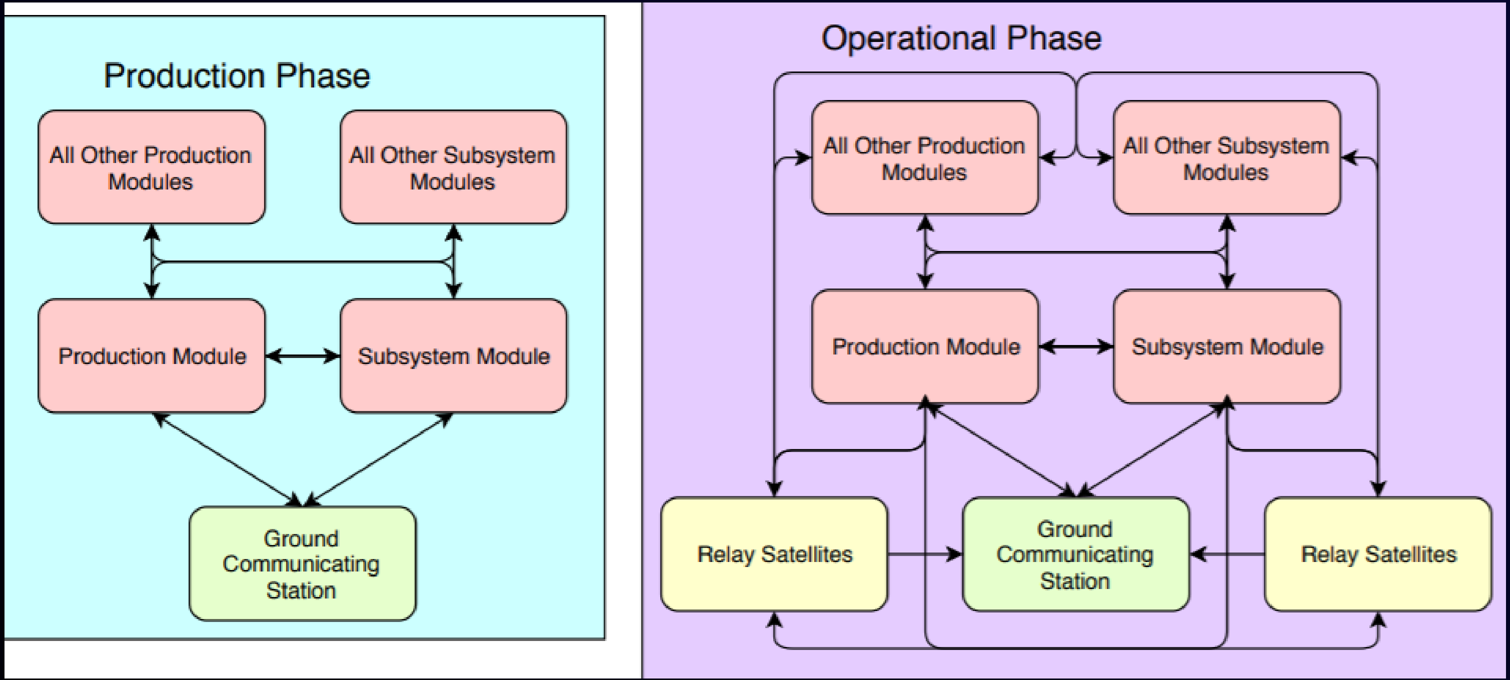
Sensitivity Analysis



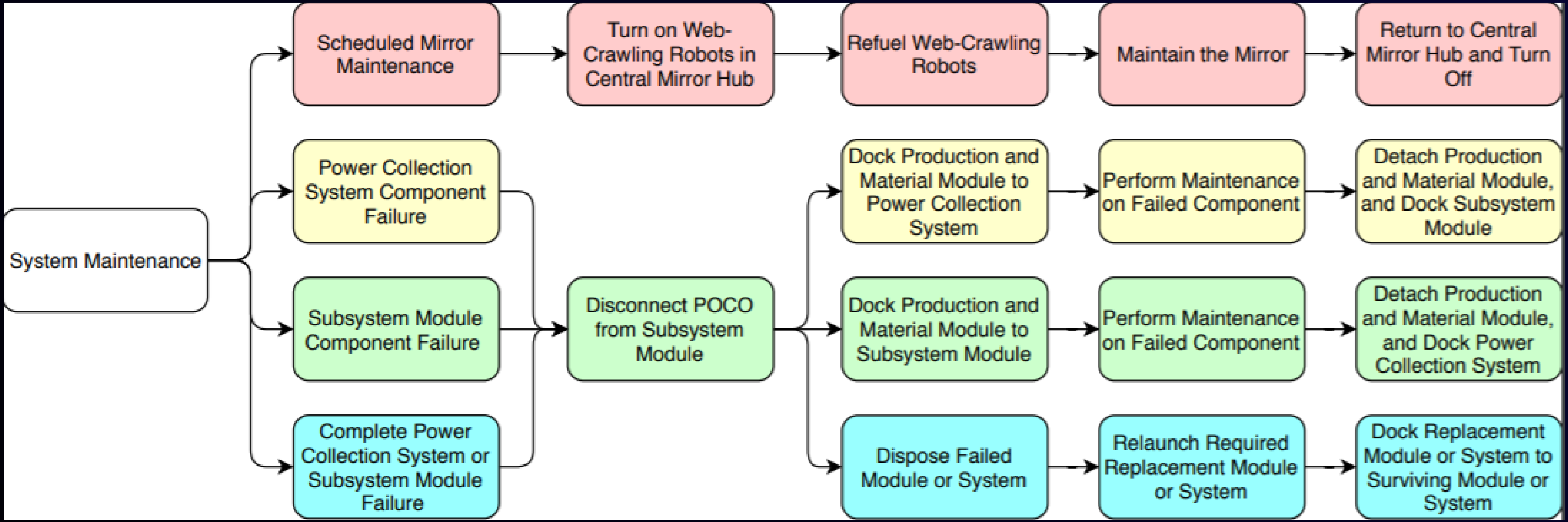
TUDelft

SPECTRE

Communication Operations

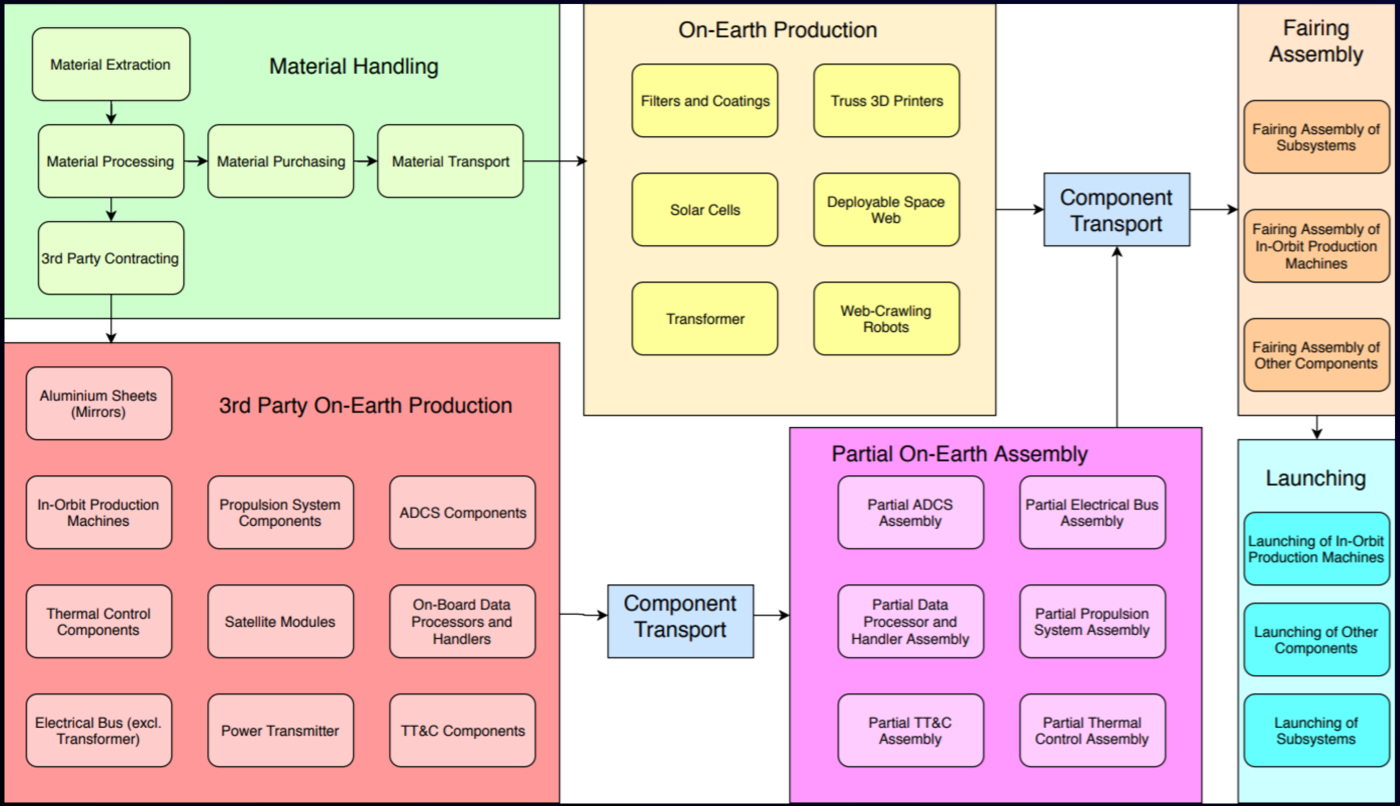


Maintenance Operations

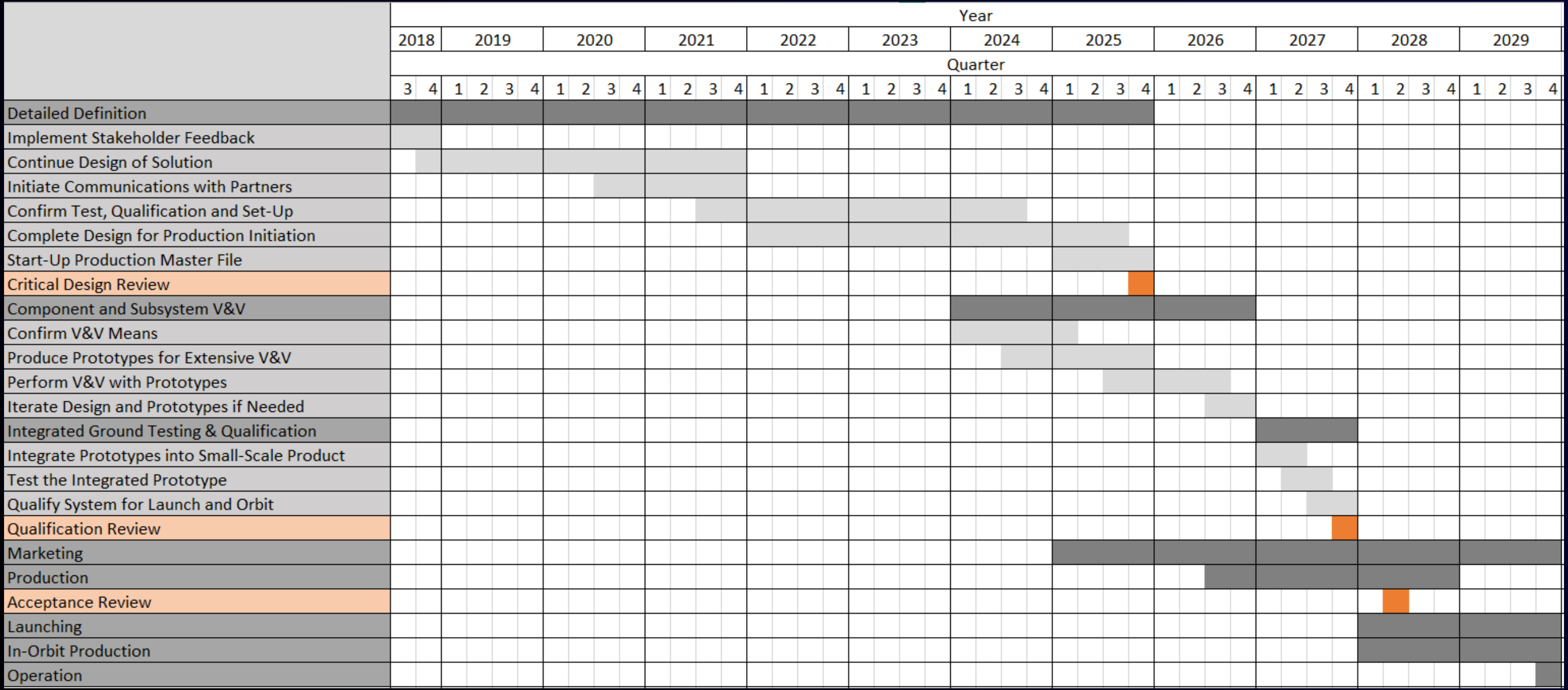


TUDelft SPECTRE

Production Operations and Logistics



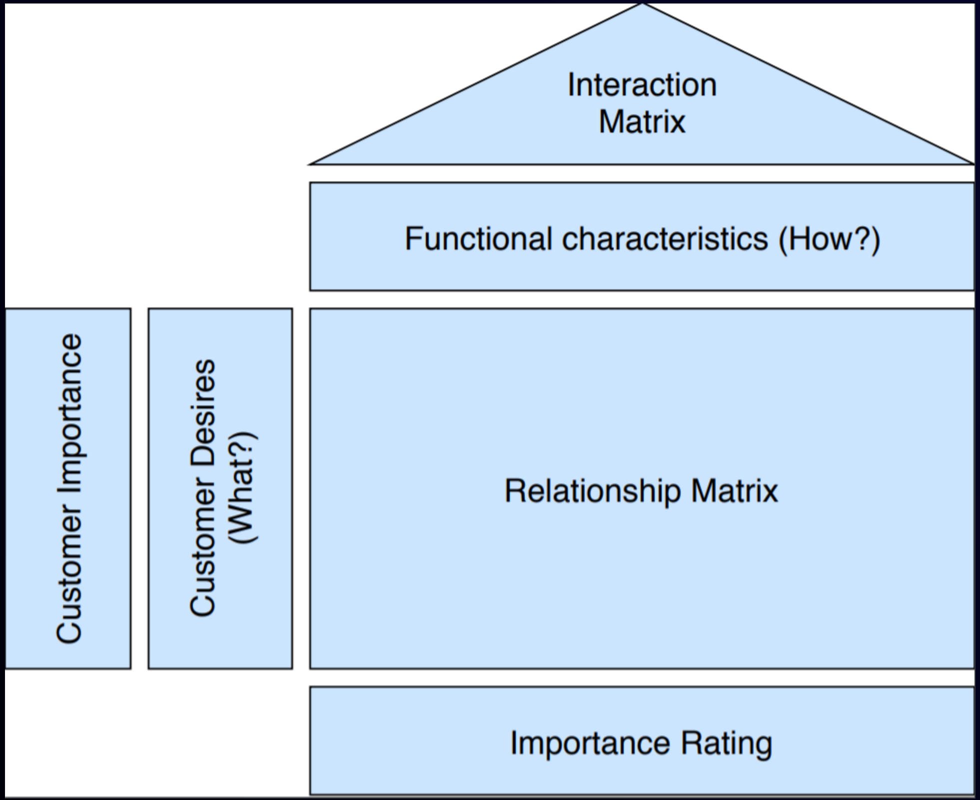
Post DSE Gantt Chart Simplified



TUDelft

SPECTRE

QFD Structure and Method



Risk Contingencies

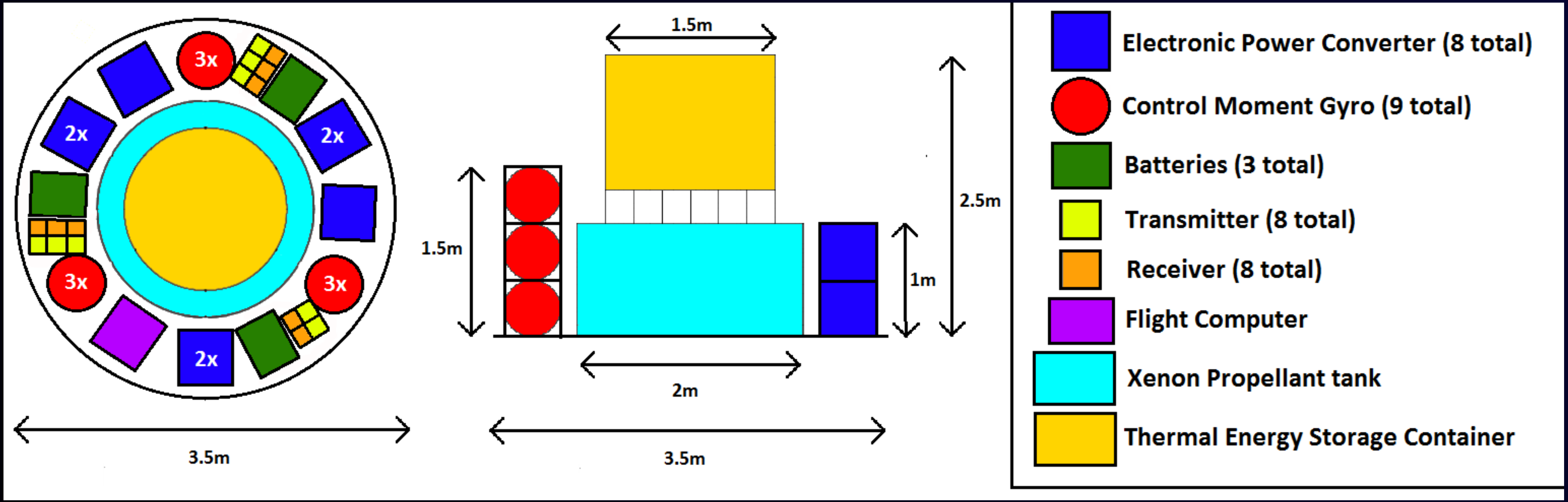
- 14 Developed Contingency Plans that Encapsulate all Risks
    - Launcher Failure
    - Transport Failure
    - Schedule Delay
    - Maintenance Failures
    - In-Orbit Production Failure
    - Harsh Environment
    - +8 More

Risk Contingencies

- Launcher Failure
- Transport Failure
- Schedule Delay
- Maintenance Failures
- In-Orbit Production Failure
- Harsh Environment
- Unsatisfied Investors/Workforce
- Maintenance Resupply Failure
- Improper System Design
- Production/Integration Delays
- Payload Failure
- Improper Design/Production On-Earth
- Improper Design/Production In-Orbit
- Stakeholder Requirement Failure

Volume
Backup Slides

Subsystems Module



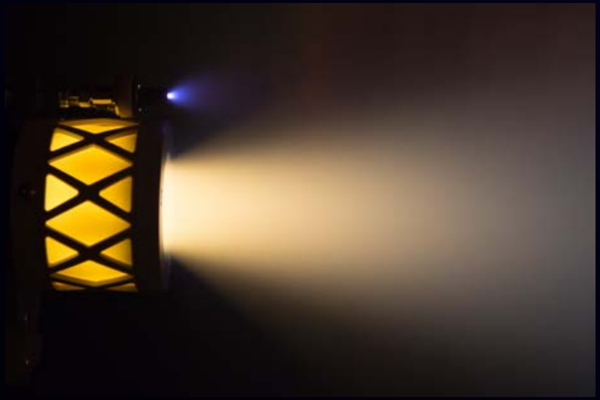
Subsystems Module

Subsystem Components	**Total Mass [kg]**	**Volume [m^3]**
Xenon propellant tank	1500	1.012
Thermal Energy Storage Container	2000	2
9 Control Moment Gyros	2448	1.125
8 Power Converters	13	1
3 Batteries	193	0.035
Electrical Wiring	13	0.18
8 Transmitters	10.4	0.000876
8 Receivers	10.4	0.000876
Flight Computer	4	0.016
Data Cables	2.5	0.001
Total Subsystem Module	6194.3	5.37

Propulsion Backup Slides

Propulsion:Thruster Specifications

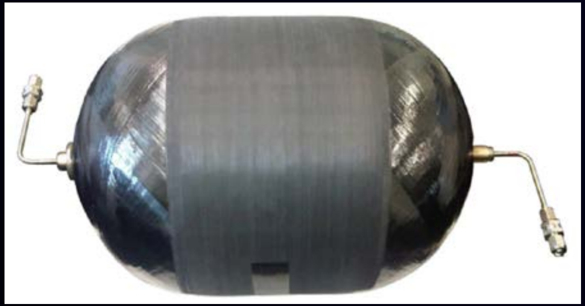
5x Busek BIT-7 Ion Thruster



Parameter	Value
Thrust	11 mN
Isp	3300 s
Power	460 W

Propulsion:Thruster Specifications

Xenon Propellant Tank



Parameter	Value
Prop. mass	1450 kg
Volume	1.01 m^3
Pressure	250 bar

Requirements Backup Slides

REQUIREMENTS: DRIVING

- M-ST-S-ECON-000- The total cost of constructing such a system shall be less than 1.5 billion Euros (FY2018),including manufacturing, launching and assembling adjusted for inflation.
- M-ST-S-ECON-001- The system shall be operational before 2030.
- D-ST-S-ECON-002- The break-even point will occur before the end of 30 years in service, adjusted for inflation.
- M-SY-S-ECON-000- The system shall be operational for at least 30 years in space.
- D-SY-S-ECON-000- The mass of the space segment should be no more than 1000 tonnes.
- M-SY-P-POCO-000- The space-based solar collection system shall produce at least 1 Gigawatt of electrical power at end of life

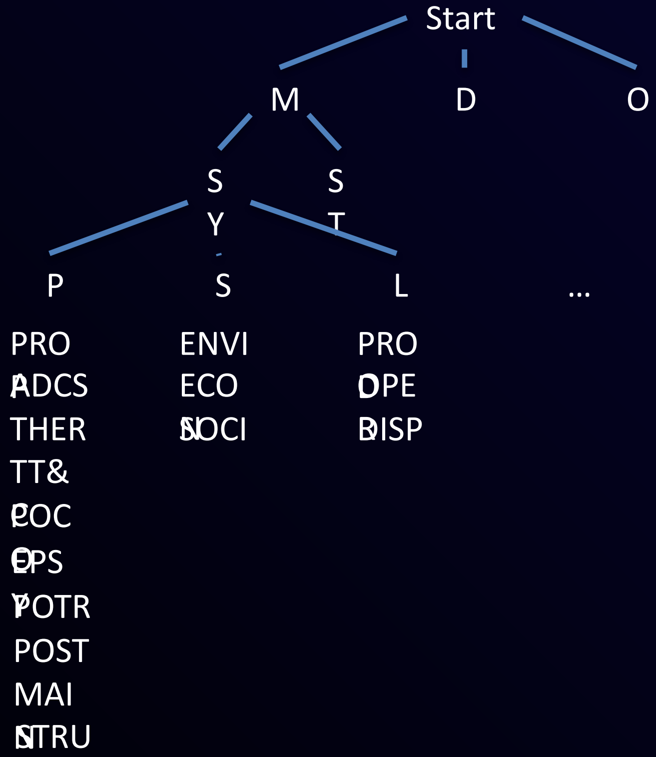
REQUIREMENTS: DRIVING

- Priority: Mandatory, Desirable and Optional
- Subdivisions include: Performance, Sustainability and Life
- Performance: Subsystems
- Sustainability: Environmental, Economic and Social
- Life: Production, Operations and Disposal

REQUIREMENTS: DRIVING

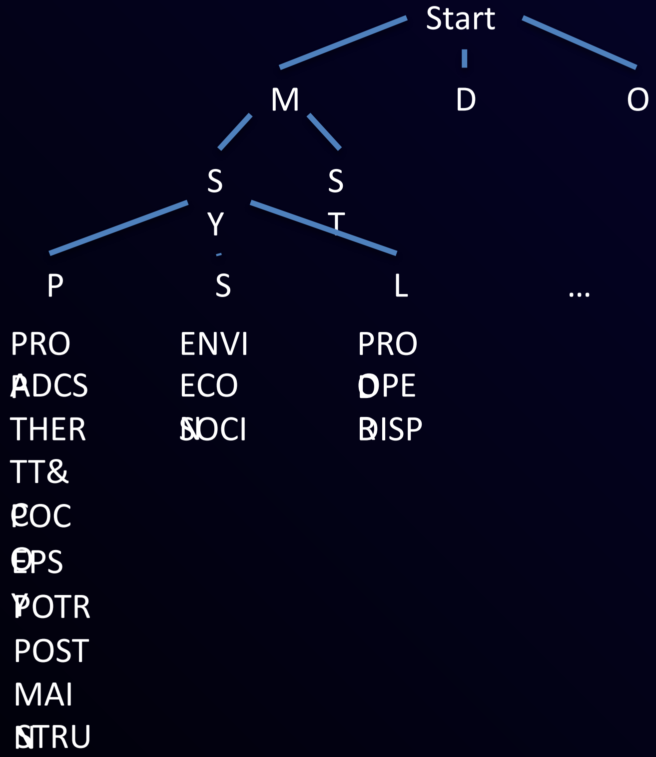
- Priority: Mandatory, Desirable and Optional
- Subdivisions include: Performance, Sustainability and Life
- Performance: Subsystems
- Sustainability: Environmental, Economic and Social
- Life: Production, Operations and Disposal

REQUIREMENTS: TREE



Example: M-SY-S-ECON-001

REQUIREMENTS: TREE

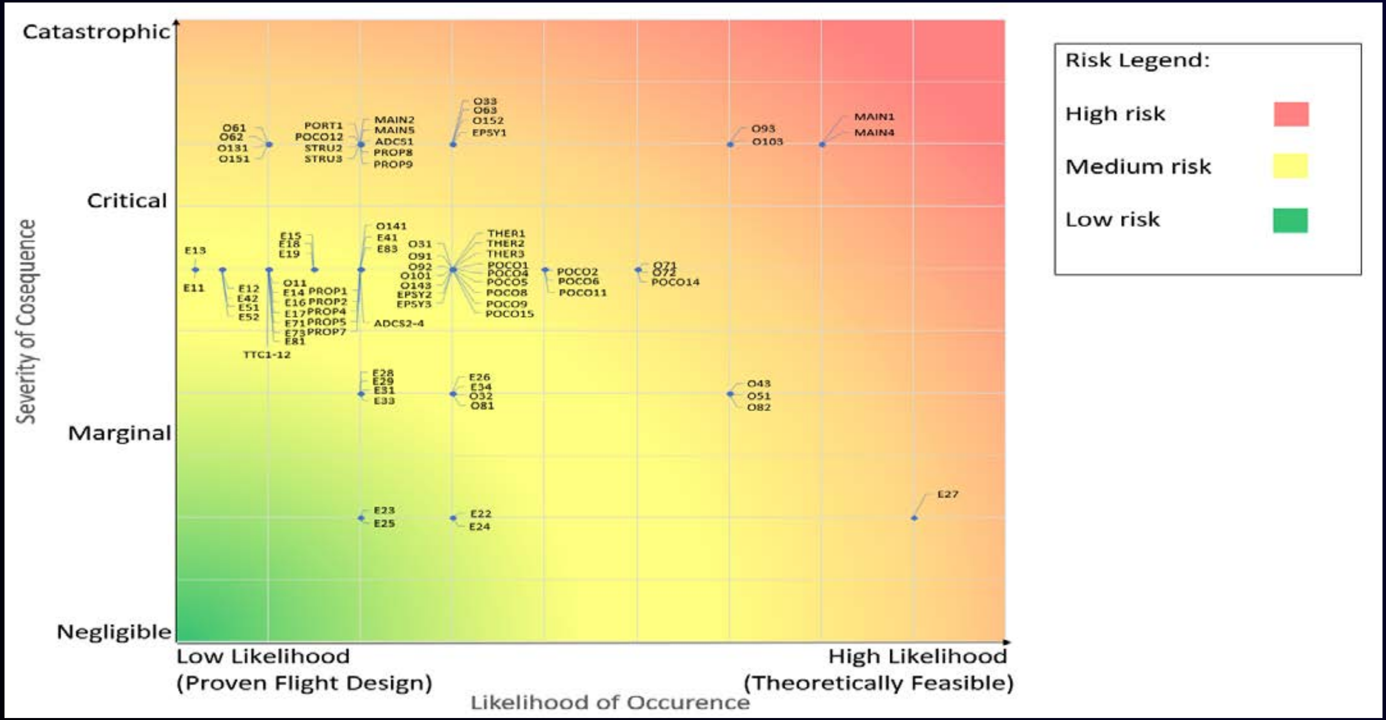


Example: M-SY-S-ECON-001

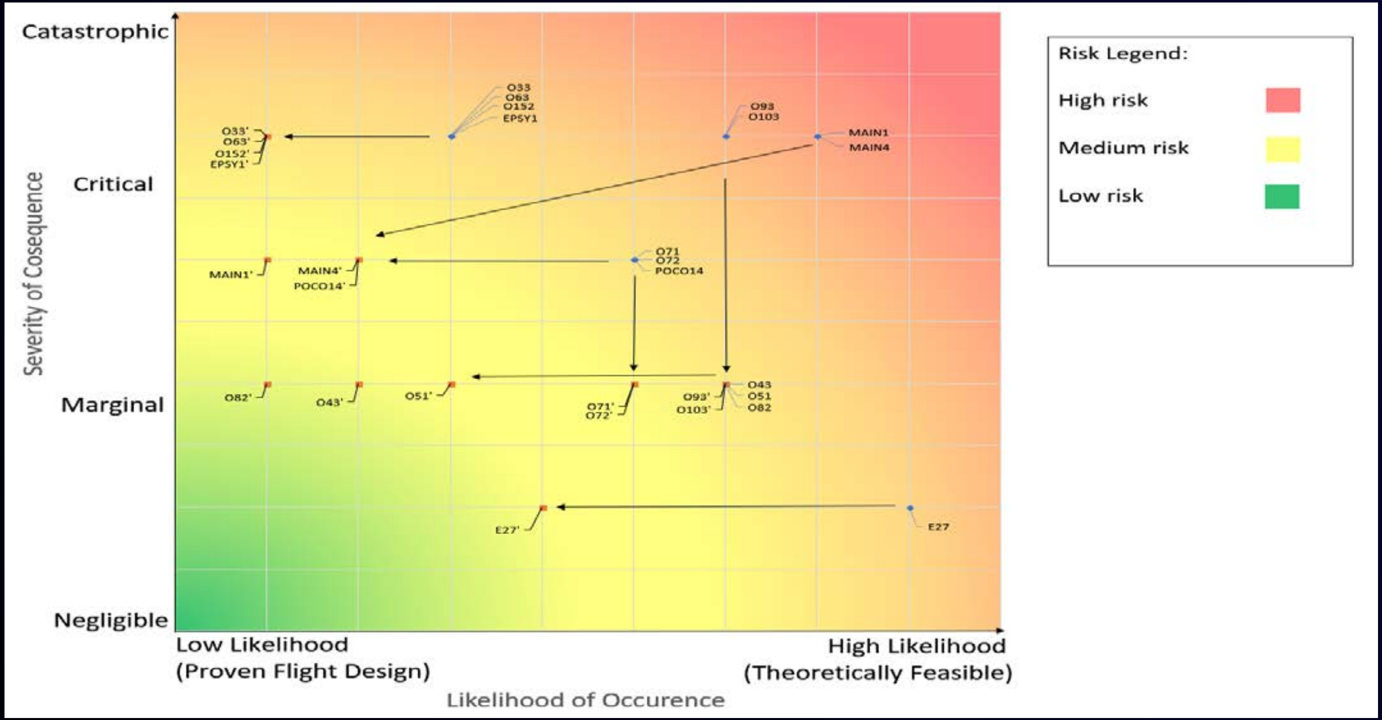
There are over 100!

Risk Backup Slides

Technical Risk Assessment

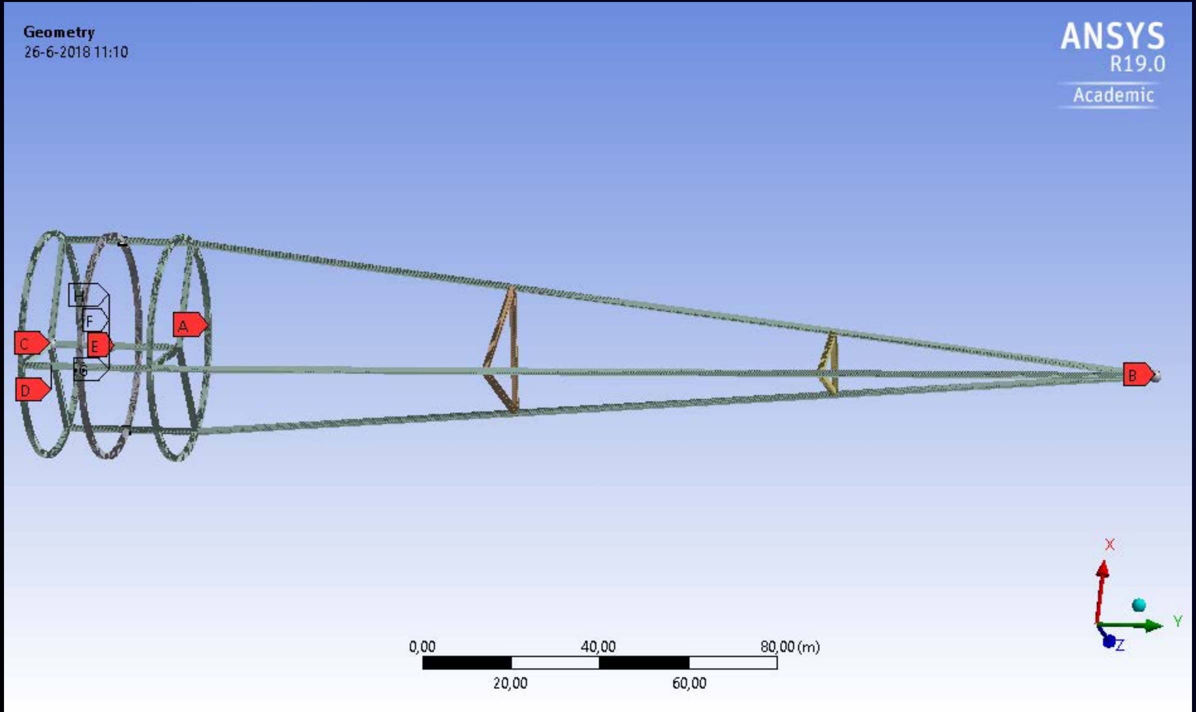


Technical Risk Mitigation



Structure Backup Slides

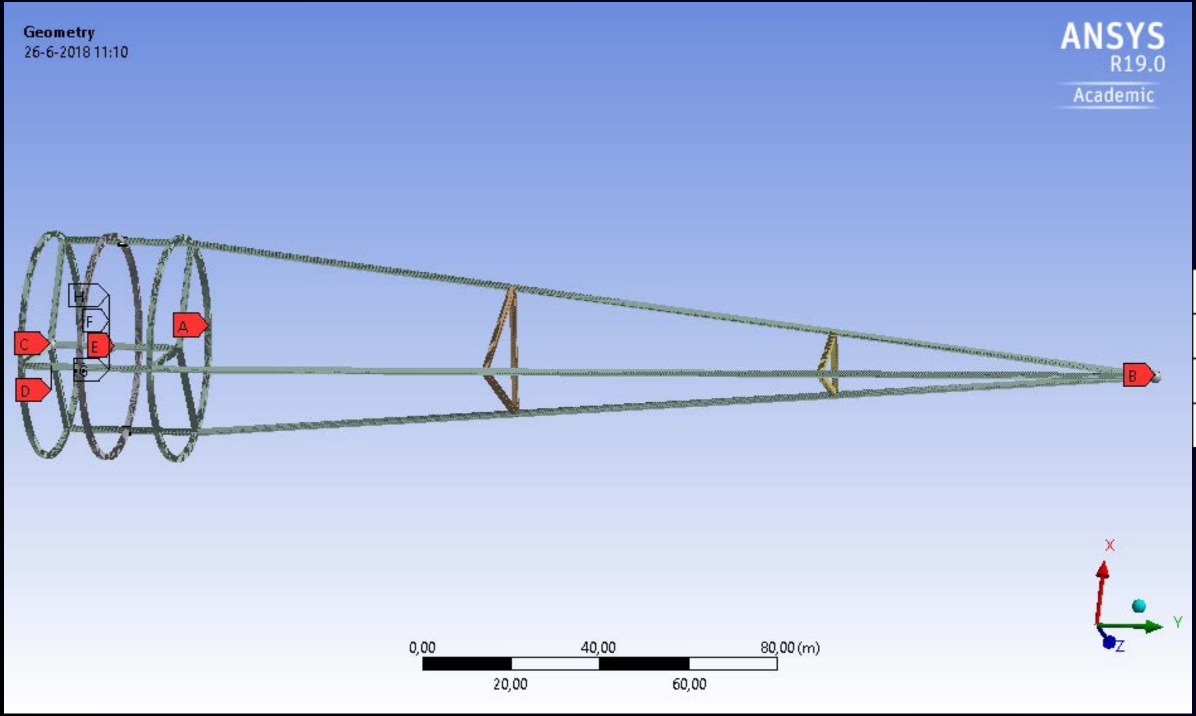
Spacecraft Structure – Primary Structure



Label	Type of mass in model	Corresponding part	Mass
A	Distributed mass	Primary Mirror (incl. web)	350 kg
B	Point mass	Secondary mirror (incl. web)	58 kg
C	Point mass	Subsystems module	6500 kg
D	Distributed mass	Solar cells	911 kg
E	Distributed mass	Filters	2000 kg
F, G, H	Point masses	Electric converters	352 kg each

Primary structure with modelled masses

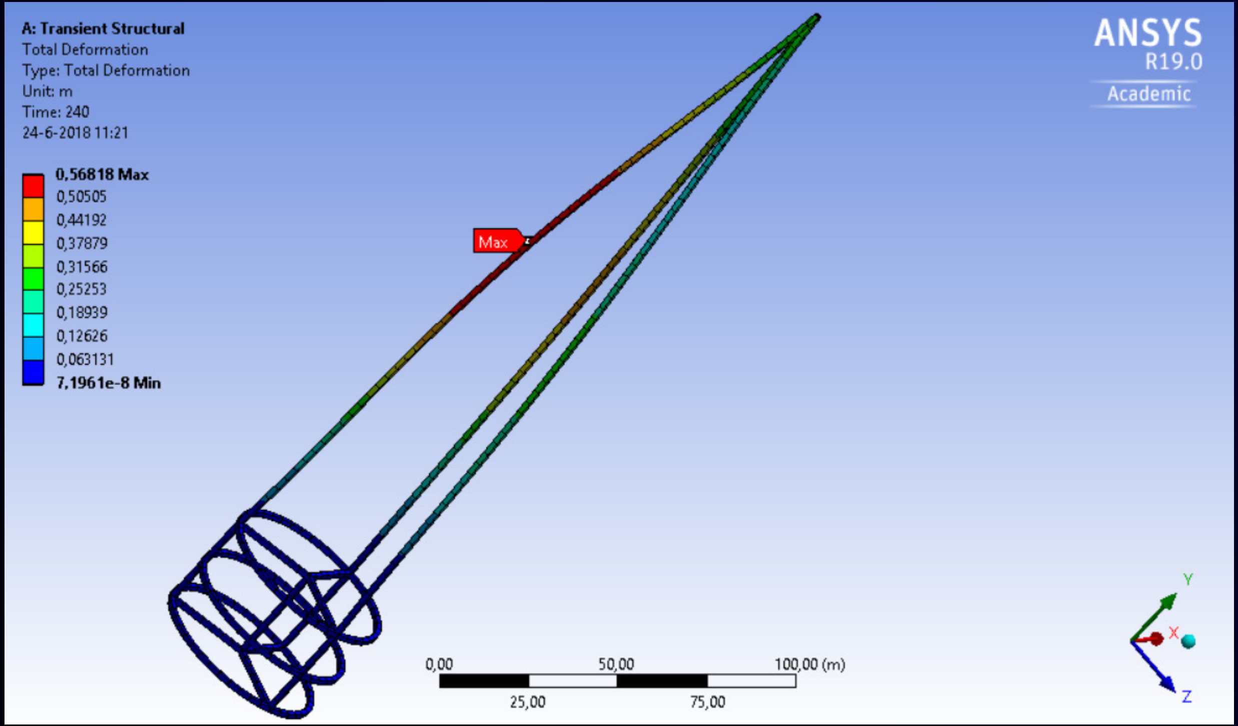
Spacecraft Structure – Primary Structure



Primary structure critical load case

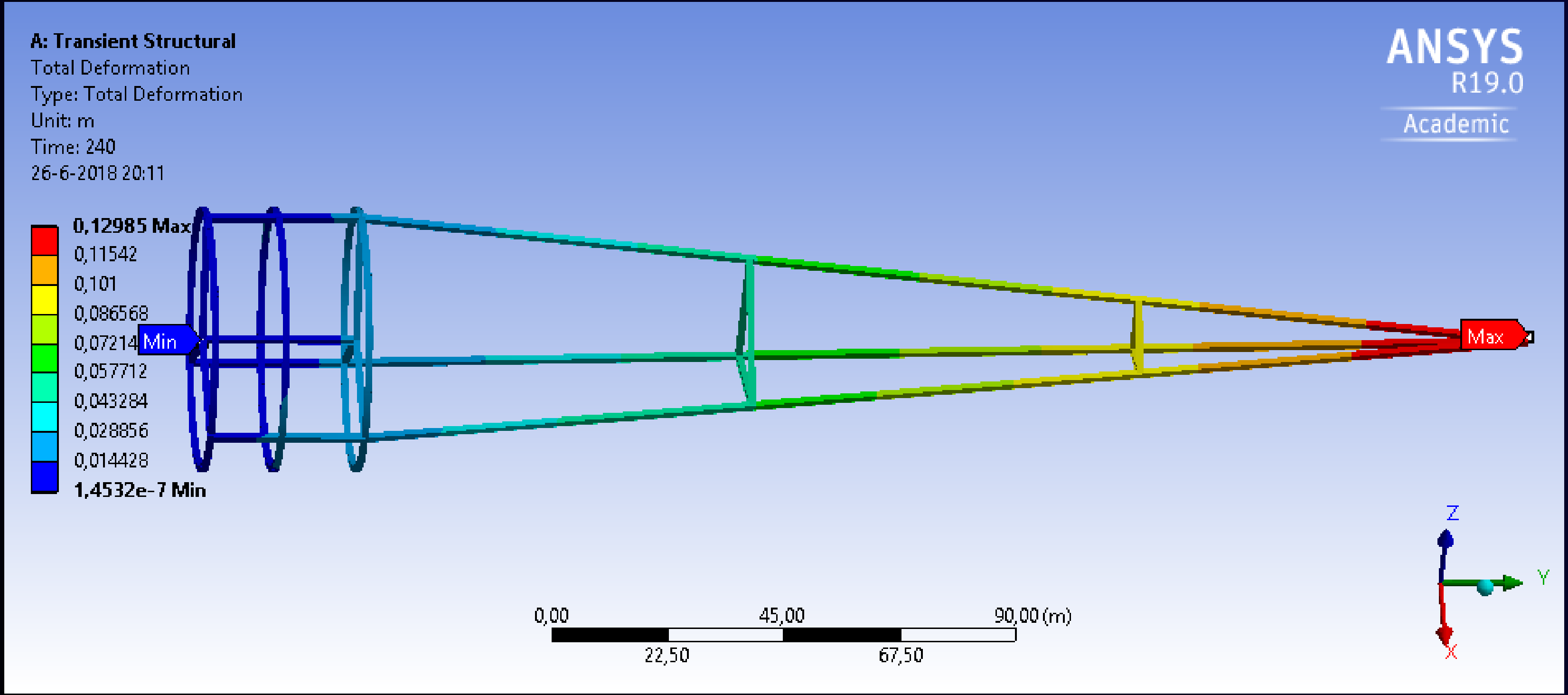
Spinning spacecraft	0.052 rad/s
Maximum pitch rate	0.0002 rad/s
Ion thruster	0.011 N
Req. **D-SY-P-STRU-001**	<0.04 degs deflection

Spacecraft Structure – Primary Structure



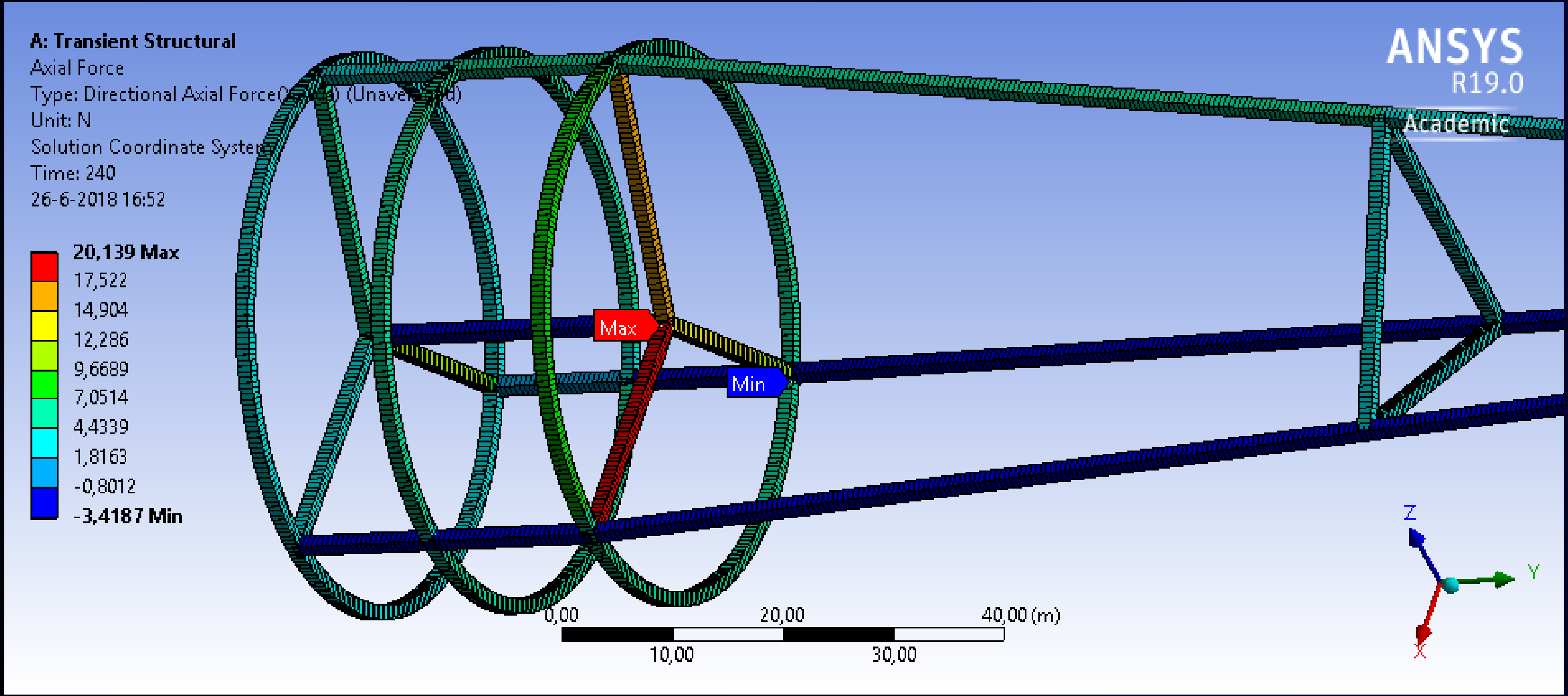
Primary Structure deformation before iteration

Spacecraft Structure – Primary Structure



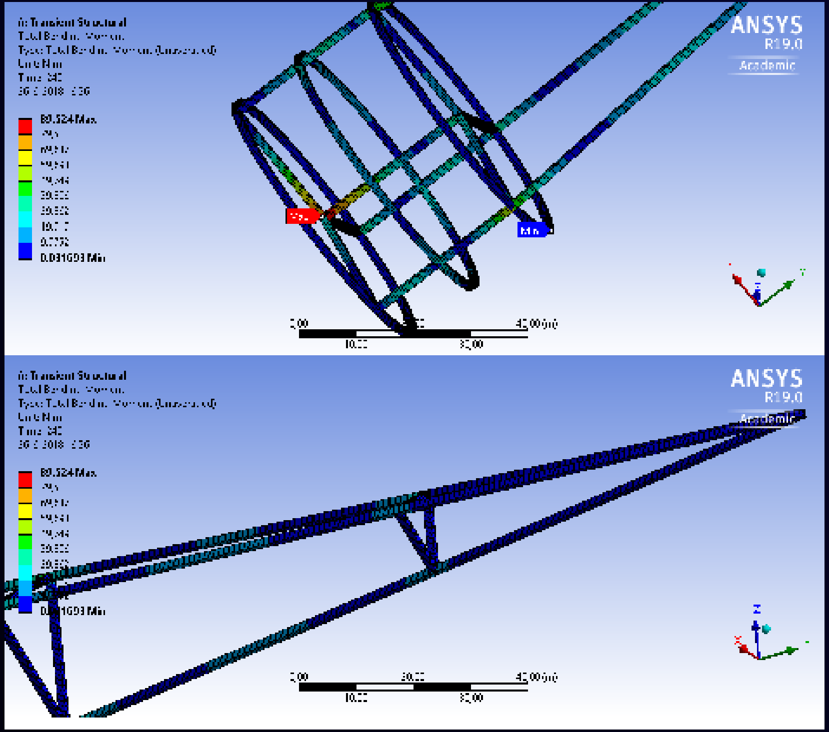
Primary Structure deformation after iteration

Spacecraft Structure – Primary Structure



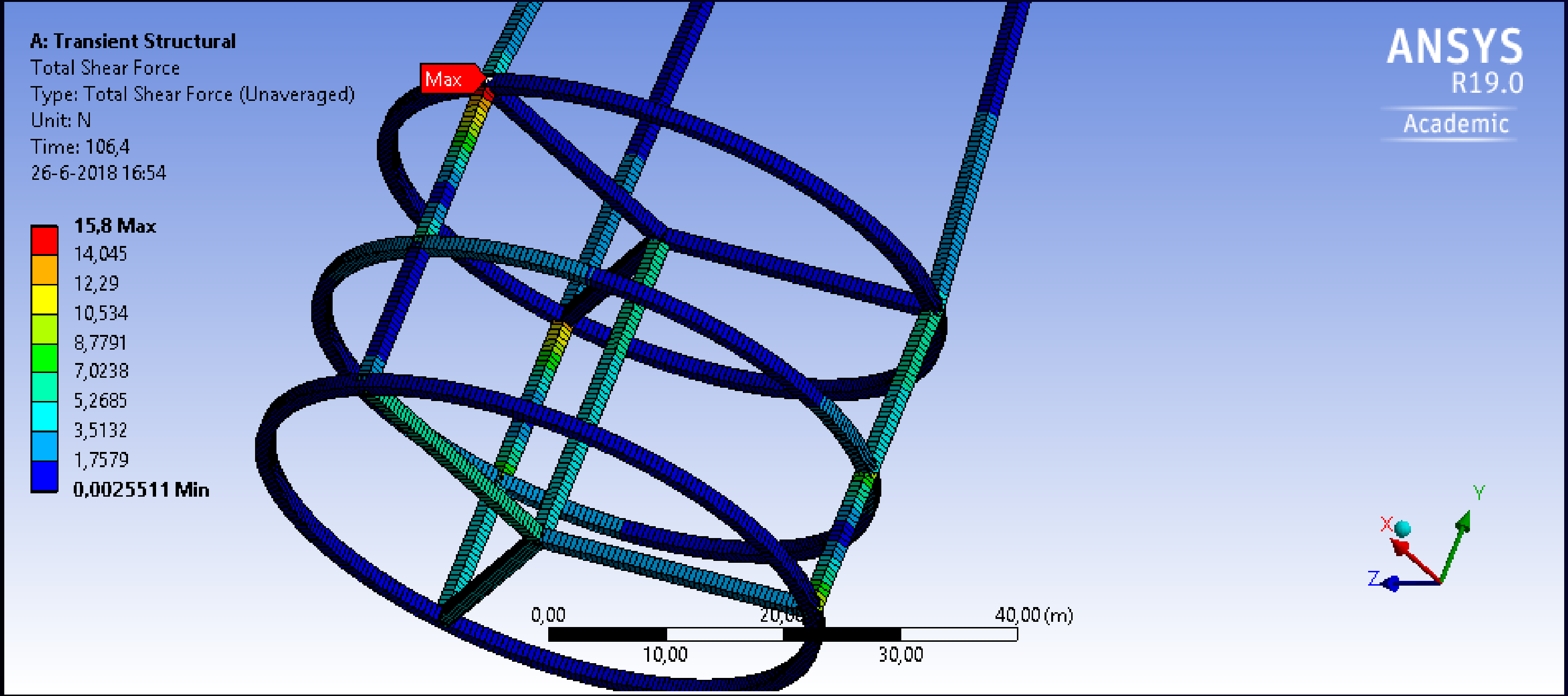
Axial forces in Primary Structure

Spacecraft Structure – Primary Structure



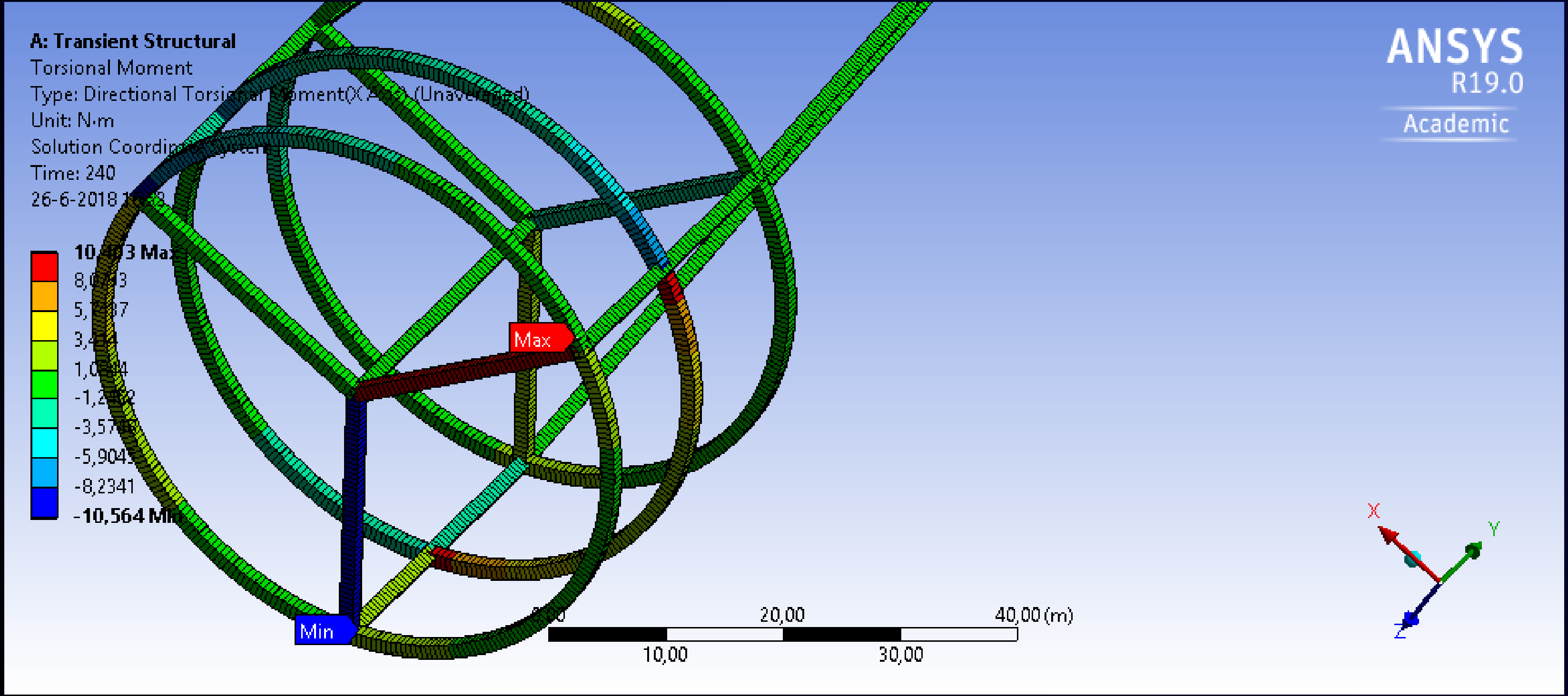
Bending forces in Primary Structure

Spacecraft Structure – Primary Structure



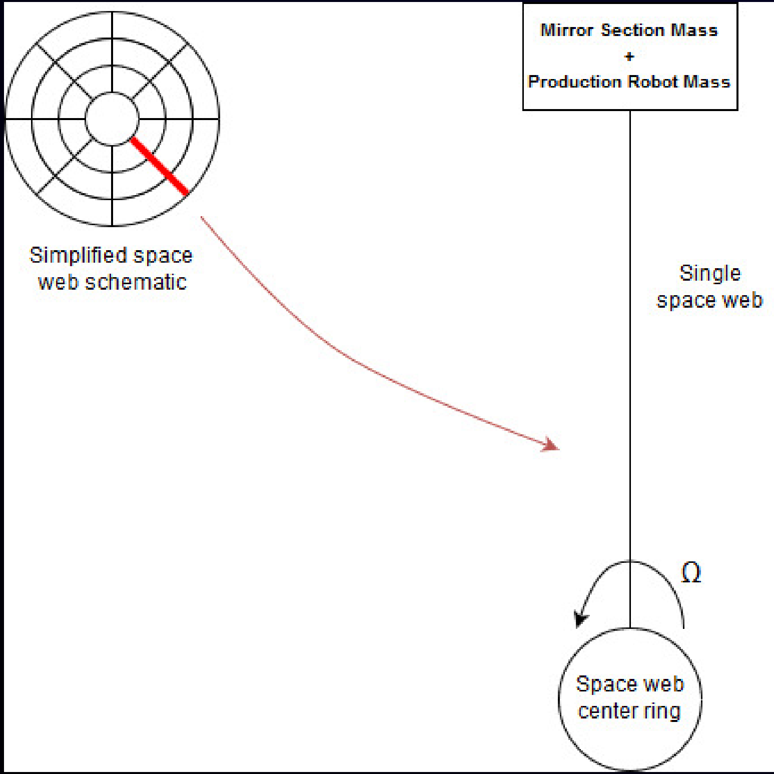
Shear forces in Primary Structure

Spacecraft Structure – Primary Structure



Torsional forces in Primary Structure

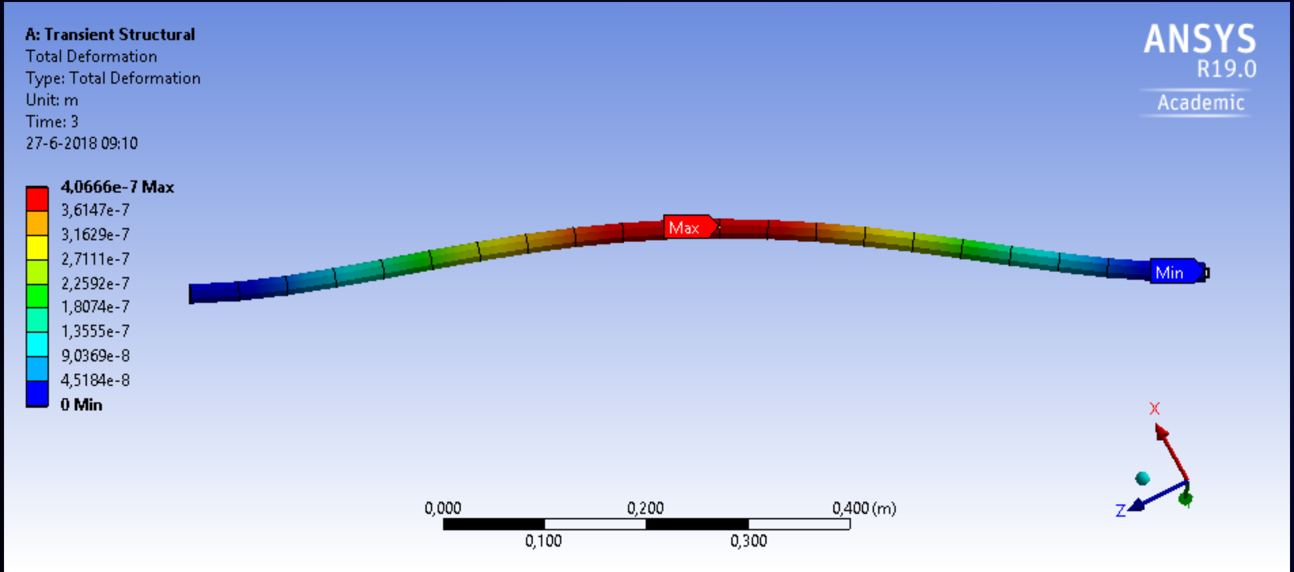
Spacecraft Structure – Space Web



Load case for one 'clock hand'	
Spinning spacecraft	0.052 rad/s
Mirror mass	73.3 g
Web crawler robot mass	180 kg
Safety factor	4
Req. **D-SY-P-STRU-001**	<0.04 degs deflection

Space web critical load case

Spacecraft Structure – Space Web



Req. **D-SY-P-STRU-001**	<0.04 degs deflection

Space web deformation

TUDelft

SPECTRE

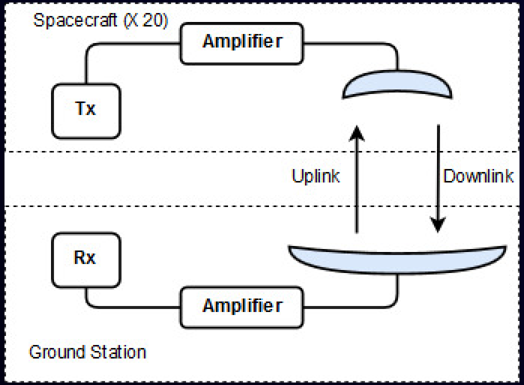
Spacecraft Structure

Spacecraft structure	Mass [kg]
Primary structure	852.44
Primary mirror space web	87.5
Secondary mirror space web	2.5
Total structure	942.44

Spacecraft structure results

TT&C Backup Slides

TT&C: Architecture



TT&C: Link Budget

Uplink Budget		
Parameter	**Value**	**Unit**
Tx Power	26.98970004	dBW
Tx Antenna Loss	-0.9691001301	dB
Tx Gain	44.33783033	dB
Path Losses	0.02999280216	dB
Rx Antenna Loss	-0.7058107429	dB
Rx Antenna Gain	24.33783033	
Space Loss	-190.0496664	dB
Pointing Loss Tx	-3.057414966	dB
Pointing Loss Rx	- 0.00764353741 5	dB
Coding Gain	4	dB
Data Rate	-36.98970004	dB
System Temperature	-24.98310554	dB
Boltzmann	228.6012091	dB
SNR	71.53412127	dB
Link Margin	40.53412127	dB

Downlink Budget		
Parameter	**Value**	**Unit**
Tx Power (RF Output)	10	dBW
Tx Antenna Loss	- 0.9691001301	dB
Tx Gain	36.29695501	dB
Path Losses	-0.3	dB
Rx Antenna Loss	- 0.9691001301	dB
Rx Antenna Gain	56.29669884	
Space Loss	-202.0087911	dB
Pointing Loss Tx	-1.92	dB
Pointing Loss Rx	-0.12	dB
Reception Feeder Loss	- 0.9691001301	dB
Data Rate	-78.4509804	dB
System Temperature	-24.98310554	dB
Coding Gain	4	dB
Boltzmann	228.6012091	dB
SNR	24.50468556	dB
Link Margin	14.19097706	dB

V&V Backup Slides

Verification & Validation

Requirement Validation

- Verifiable
- Achievable
- Logical
- Integral
- Definitive

Model Verification

- Analytical Calculations
- Unit Tests
- Inspection

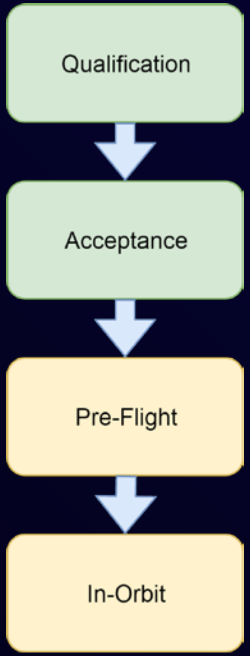
Product V&V: Stages

Qualification

- Assembly, Integration and Test
  - Electrical integration
  - Mechanical integration
  - Hardware-software integration
- Production testing

Acceptance

- Workmanship errors
- Vacuum testing (including thermal)



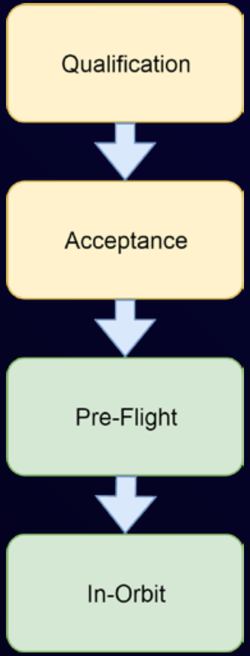
Product V&V: Stages

Pre-Flight

- Vibration testing

In-Orbit

- Production and Assembly in Space
- Electrical Power System
- Transmission System
- Prototype Test in LEO



TUDelft

SPECTRE