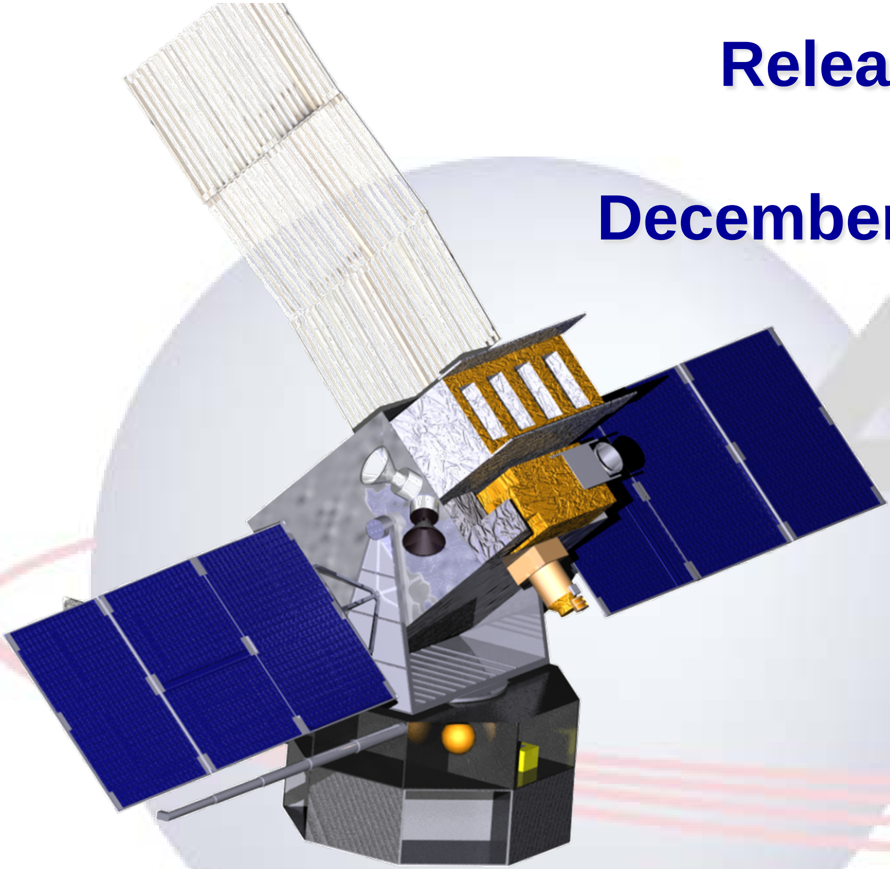
Solar-C Conceptual Spacecraft Design Study: Final Review

Release 2

December 7, 2010



Purpose

- **This briefing package contains the conceptual spacecraft design completed by the Advanced Concepts Office (ED04) in support of the Solar-C Study.**

- **This package is the final deliverable to Jonathan Cirtain (VP62) and the Solar-C science team, and is submitted in fulfillment of the Conceptual Spacecraft Design Study requirements.**

Point of Contact: Randall Hopkins
ED04
Office of Advanced Concepts
Marshall Space Flight Center, AL 35812

Notes

- **Due to time constraints, the spacecraft team was able to complete only one iteration of the design process. Mass estimates are reasonable, but subsequent iterations could change these values slightly.**

- ***All costs and spacecraft subsystems are for a configuration with a 100x100 meter solar sail (115 meter actual side length). Near the end of the study, the team determined that a larger sail (160x160 meter) was needed to achieve the desired characteristic acceleration. However, there was insufficient time to redesign the spacecraft, so to ensure a consistent data package, the configuration was baselined to have the 100x100 meter solar sail.***

Table of Contents

Solar-C: Introduction

- **Customers**
  - Jonathan Cirtain (VP62) and Tony Kim (VP22)

- **Mission Description**
  - successor to Hinode (Solar-B)
  - Heliocentric orbit, 40 degree (TBR) inclination, approximately 1AU from sun
    - can a solar sail be used to meet this requirement?
  - Science mission: to study the polar regions of the sun
    - Differential rotation and meridional flow in the polar regions and the deep convection zone
    - Photospheric magnetic flux distribution and evolution in the polar regions
    - Dynamical coupling between magnetic fields and flows
    - Structure and evolution of solar convection

Goals and Responsibilities

- **Study Goal**
  - Complete a conceptual spacecraft deign that will meet the requirements for the Solar-C mission

- **Responsibilities**

Advanced Concepts Office

Spacecraft
- Communications
- Electrical Power
- Trajectory / GN&C
- Propulsion
- Thermal
- Launch Stack Shroud Integration
- Mass
- Cost

Science Instruments
- Cost (with support from VP62)

VP62

Instruments
- Design
- Power
- Mass
- Data requirements
- support cost estimate

Solar-C Study Team

Name	Role	Organization
Jonathan Cirtain	PI	MSFC-VP62
Tony Kim	Co-I	MSFC-VP22
Les Johnson	Study Manager	MSFC-ED04
Randy Hopkins	Study Lead	MSFC-ED04
Mike Baysinger	Integrated Systems Design	MSFC-ED04 / Qualis
Dan Thomas	Propulsion	MSFC-ED04
Jerry Owens	Science Instruments	MSFC-ES11
Spencer Hill	Cost	MSFC-CS50
Roy Young	Solar Sail Systems	MSFC-ES11
Leo Fabisinski	Avionics / Power / GN&C	MSFC-ED04 / ISSI
Scott Thomas	Thermal / Structures	MSFC-ED04 / Dynetics
Andy Heaton	Trajectory Design	MSFC-EV42
Rob Stough	Trajectory Design	MSFC-EV42

Solar-C Study Schedule

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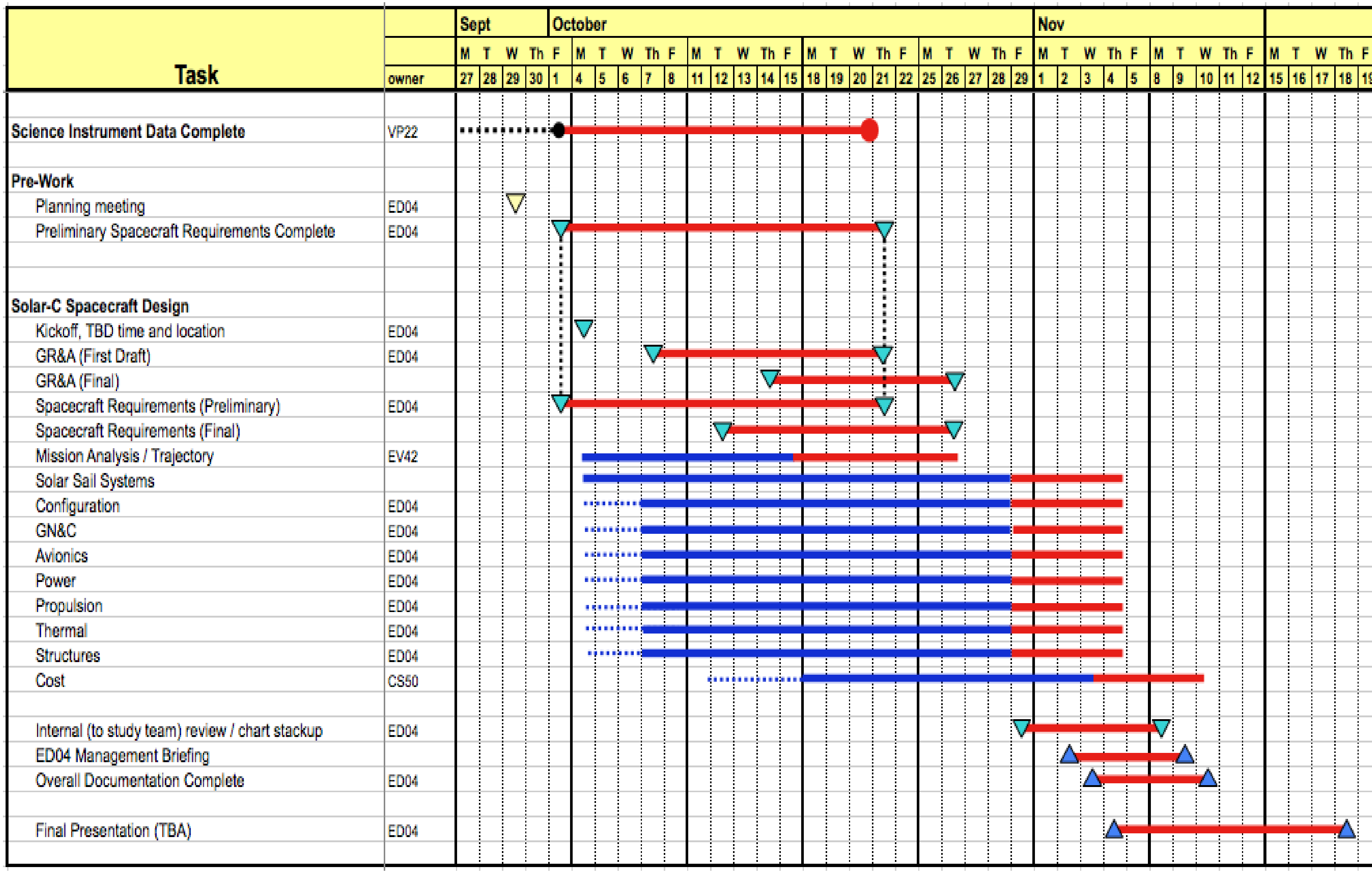


Ground Rules and Assumptions (GR&A) / Payload Data

This section includes high level Ground Rules and Assumptions, as well as the payload and instrument data.

Additional Ground Rules and Assumptions may appear in each subsystem discipline section.

Overall GR&A

- **Margin**
  - 30% mass and power for spacecraft systems
  - 30% mass margin on instrument data provided by science team
  - no margin on science instrument power (assuming 1kW already has plenty of margin)
- **Target Orbit**
  - Heliocentric, 40 degree inclination or higher, approximately 1AU circular (study output)
  - Required inclination achieved in 5 years (or less) from launch
- **Spacecraft Lifetime (in addition to the time needed reach the target orbit)**
  - 3 year required
  - 5 year goal
- **Estimated Launch Date**
  - 2017/2018
- **Assumed Launch Vehicle**
  - JAXA H-II A202
- **Spacecraft Requirements:**
  - Pointing Accuracy: 1 arc second
  - Pointing Knowledge: 0.01 arc second
  - Pointing Stability: X/Y =0.06" (>20Hz), 0.6"/2s, 4.5"/1 hour; Z = 200" per hour
  - Main Instruments (see instrument #1 and #2 below) must articulate in a 45 degree cone relative to solar sail

Payload Data

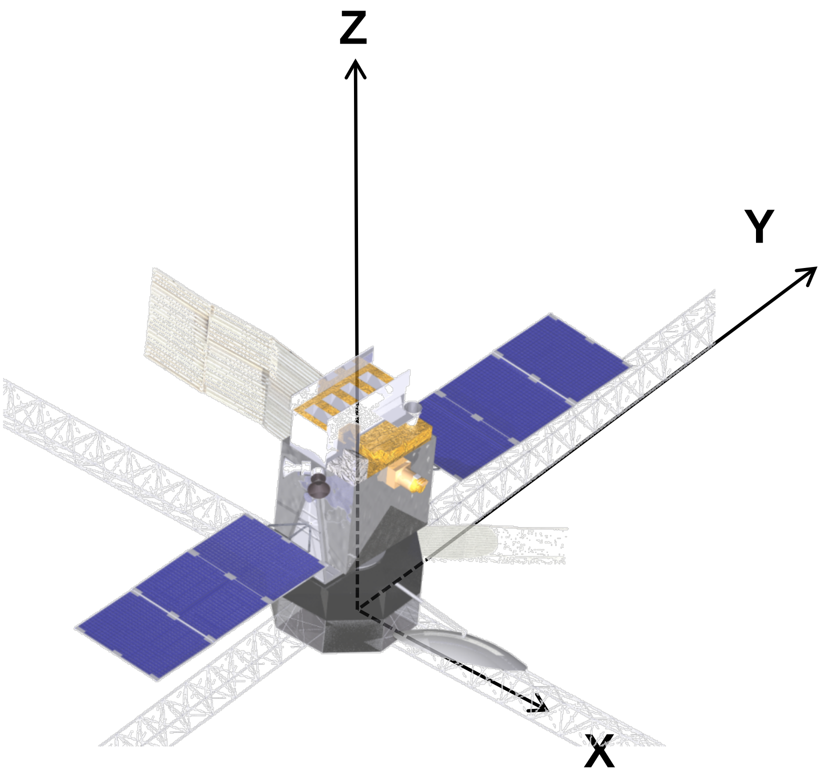
- **1. Magnetograph/ Helioseismology instrument at about 30kg and 1.5 x 1 x 0.5 meters**
  - HAI (Helioseismic Activity Imager)
  - Visible-Light Doppler/Magnetic Imager
- **2. EUV Imaging/ Spectrograph (25kg, 2.0 x 1.5 x 1.0 meters)**
  - EAI (EUV Activity Imager);
  - ESS (EUV Scanning Spectrograph)
  - EAI and ESS could be combined
- **3. In-Situ Instruments:**
- **3.a. Particle Detector (modeled after PLASTIC from STEREO mission) (25 kg, 0.5 x 0.3 x 0.3 meters)**
- **3.b. Other minor pieces of hardware (IMPACT) (5 kg, boom and small instruments) Details below and at http://sprg.ssl.berkeley.edu/impact/instruments.html.**
- **These IMPACT instruments are divided into two groups, the SEP suite and the BOOM suite**
  - BOOM SUITE (mounted on a boom extending from the spacecraft)
    - SWEA (Solar Wind Electron Analyzer)
    - Suprathermal Electron Telescope (STE) [one on each end of the boom)
    - Magnetometer (MAG)
  - SEP SUITE (mounted on the spacecraft body)
    - SEPT (Solar Electron Proton Telescope)
    - SIT (Suprathermal Ion Telescope)
    - LET (Low Energy Telescope)
    - HET (High Energy Telescope)

Total science instrument power, including margin, is 1000 Watts.

- **4. (OPTIONAL) Heliographic Imager like the one on STEREO if there is sufficient mass and volume available (21.8 kg, 1.2 x 0.7 x 0.3 meters)**

Coordinate System

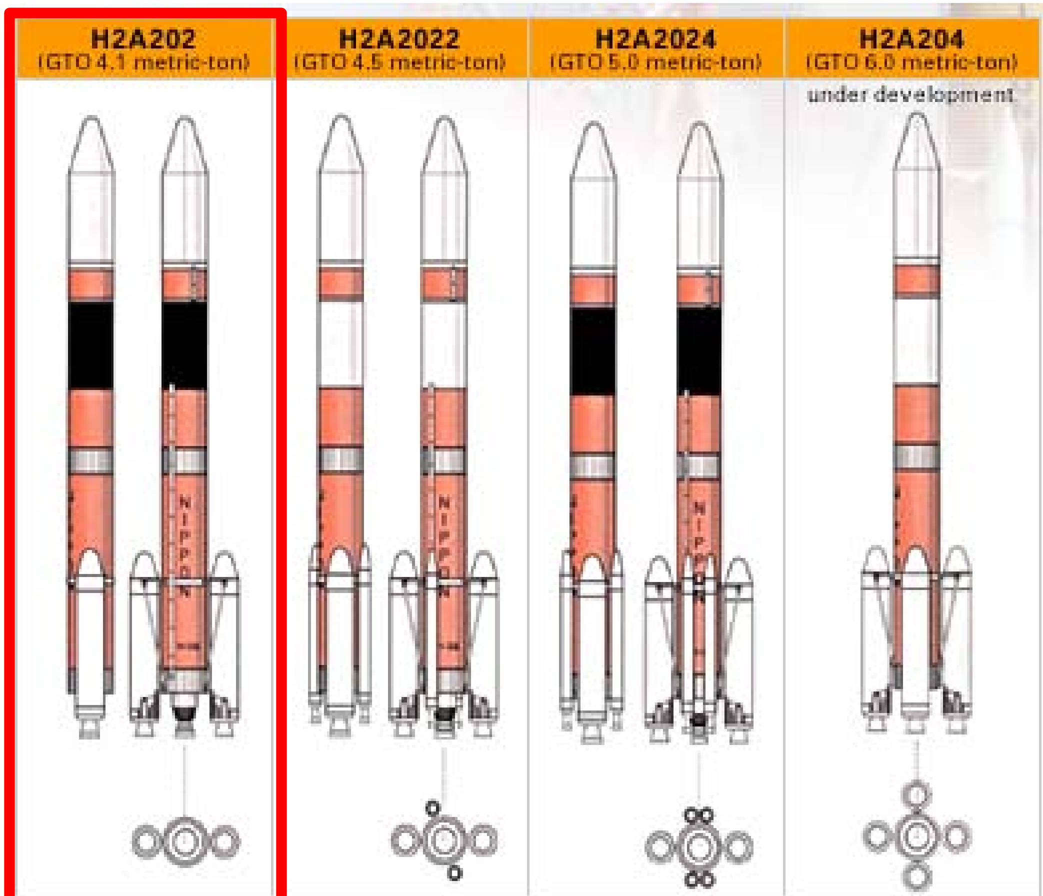
- **The coordinate system for the spacecraft configuration is defined as follows:**
  - Positive z-axis is perpendicular to the solar sail, and along the boresight of the main science instruments when in the stowed position
  - Origin is in the plane of the launch interface ring.

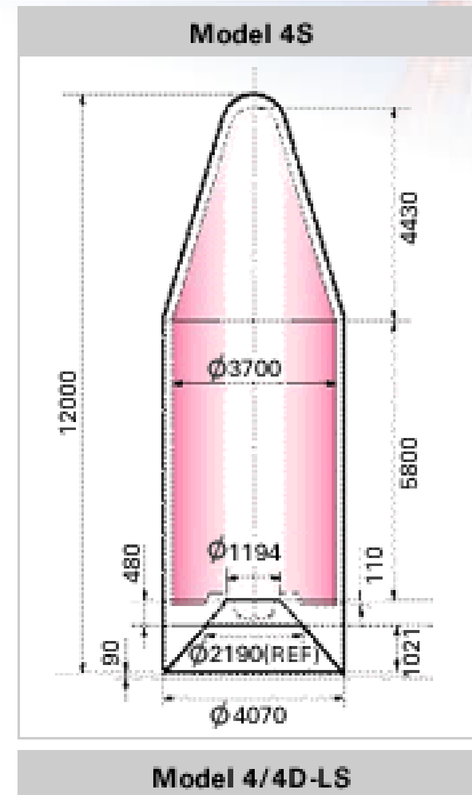


Mission Analysis / Trajectory Design

Launch Vehicle Data

- **Baseline launch vehicle for study:**
  - JAXA H2A202
  - Payload to C3 = 0 km^2/s^2: 2500 kg
  - Larger variants are available





Quasi-Static Launch Loads (g's)	
Axial	+4 / -1
Lateral	1.8

Trajectory Design Background

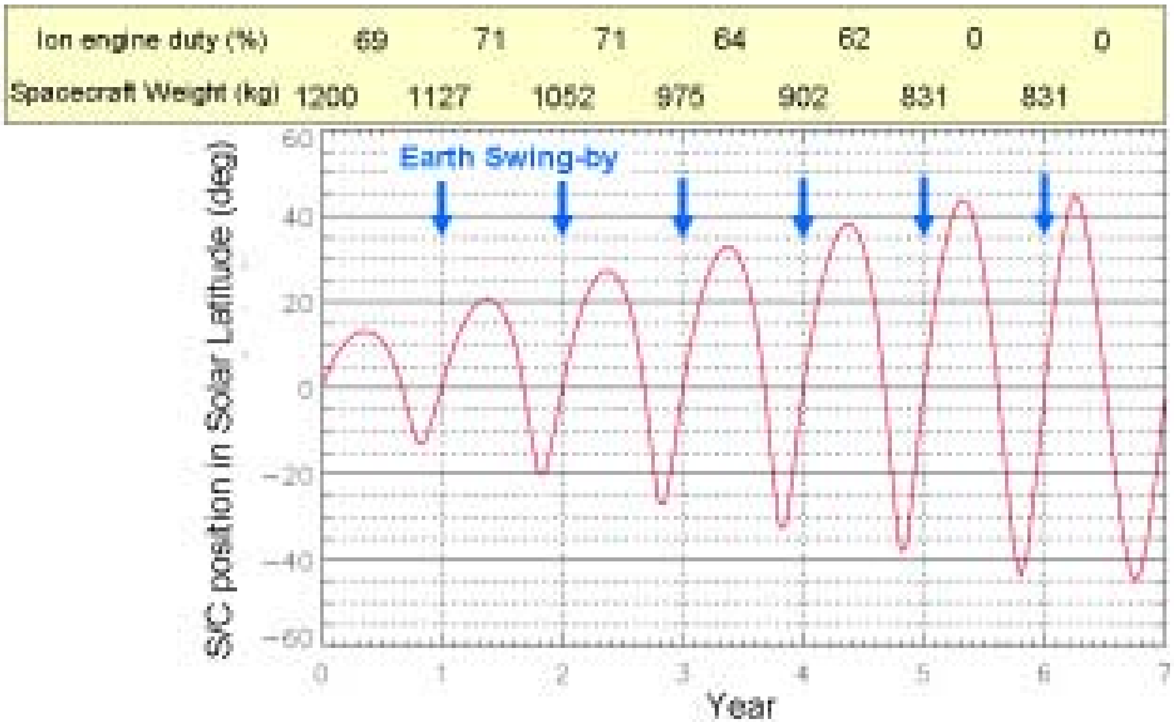
- **We looked at the following options:**
  - Sail only
  - Sail + Earth Gravity Assists (JAXA baseline)

Sail Only Option(s)

- **With sail only, we achieve the following:**
  - a0 of 0.2 mm/sec^2 gives flight time of ~ 10 years
  - a0 of 0.3 mm/sec^2 gives flight time of ~ 6.5 years
- **A ~0.21 mm^2 a0 is possible with the existing ATK data**
  - Sail length of 160 meters per side
  - 0.3 mm/s^2 implies a sail size of 32,000 m^2 (194 meters length with fill factor and 9 gm/m^2 areal density)
  - Note this is beyond any actual ATK design point (extrapolated)
- **Another option would be to relax perihelion constraint**
  - This would allow a shorter TOF
  - We did not explore this option
- **0.3 mm/s^2 could also be achieved via payload mass reduction**
  - Total system mass including sail would have to be 595 kg

JAXA Trajectory Design

- **The JAXA approach is to use 5 Earth flybys to alter inclination, with SEP used to modify the orbit in between flybys**



- **Details of their design are very sketchy!**

EGA Ground Rules and Assumptions

- **Perihelion constrained to 0.7 AU**
- **The trajectory will consist of Earth Gravity Assist (EGA) with Low Thrust (LT) arcs between flybys**
- **Solar pole is inclined 7.25 deg to Ecliptic, and we take advantage of that**

Trajectory Design Options

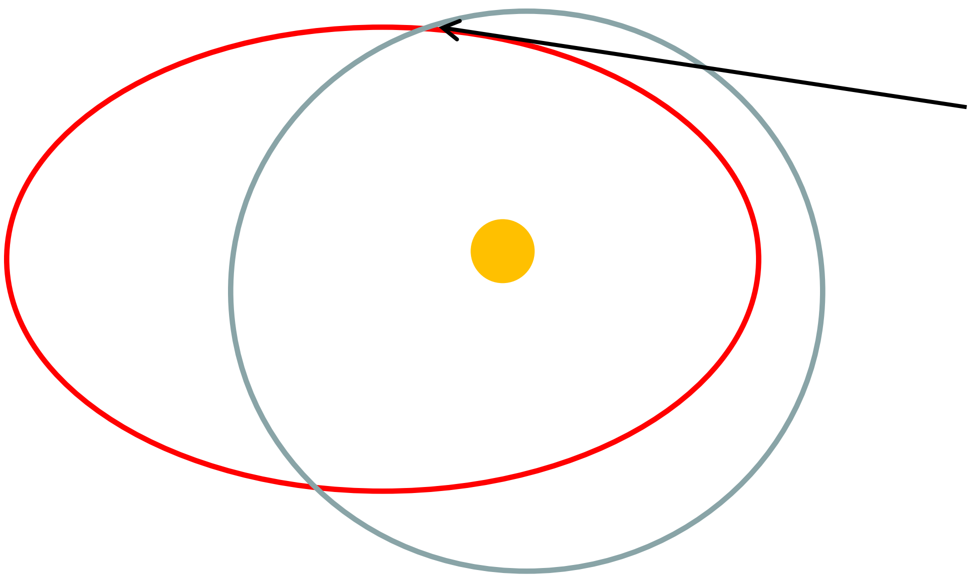
- **Each orbit between EGAs could be used to:**
  - (a) Shape orbit for subsequent flyby
  - (b) Change inclination

- **Due to time constraints we only looked at (a)**

EGA + Sail

- **Earth EGAs change orbit parameters other than Inclination substantially**

- **In order to hit Earth ~ 1 year later, the sail (and/or SEP) has to be used to target Earth**



Location of EGA ***- for phasing reasons, time between EGAs must be ~ 1 year***

EGA-Sail Trajectory

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Below is a rough outline of how a trajectory design that combines sails and EGAs might work (0.2 mm/s^2 sail)

Event	MET (yr)	Delta Inc (deg)	Inclination (deg)
Initial Condition	0.0	0	7*
1st EGA	0.6	14	21
LT arc 1	0.6 - 2.6	0	21
2nd EGA	2.6	6	27
LT spiral to 0.72 AU**	2.6 - 4.9	10	37
LT to raise Inc	4.9 – 6.5	8	45

* Assumes solar pole aligned with orbit plane
** Combination of spiraling in to 0.72 AU while changing Inc

Ability to achieve a 45 degree heliocentric orbit is a game-changing capability!

Comments:

- **Trying to line up with the solar pole restricts the EGAs**
- **Two EGAs seems to be all that is beneficial**
- **LT arc 1 was never fully closed…we just assume it can be done**
- **the LT spiral to 0.72 AU could be refined more**
- **there are many trades we did not look at**

Conclusions

- **The sail alone trajectory is challenging, but could work by:**
  - Increasing sail area
  - Decreasing payload mass
  - Relaxing perihelion constraint
  - Some combination of above

- **Earth Gravity Assist + sail could work**
  - What exists is a nominal sketch of what might be possible
  - Our preliminary investigation raises questions on JAXA mission design

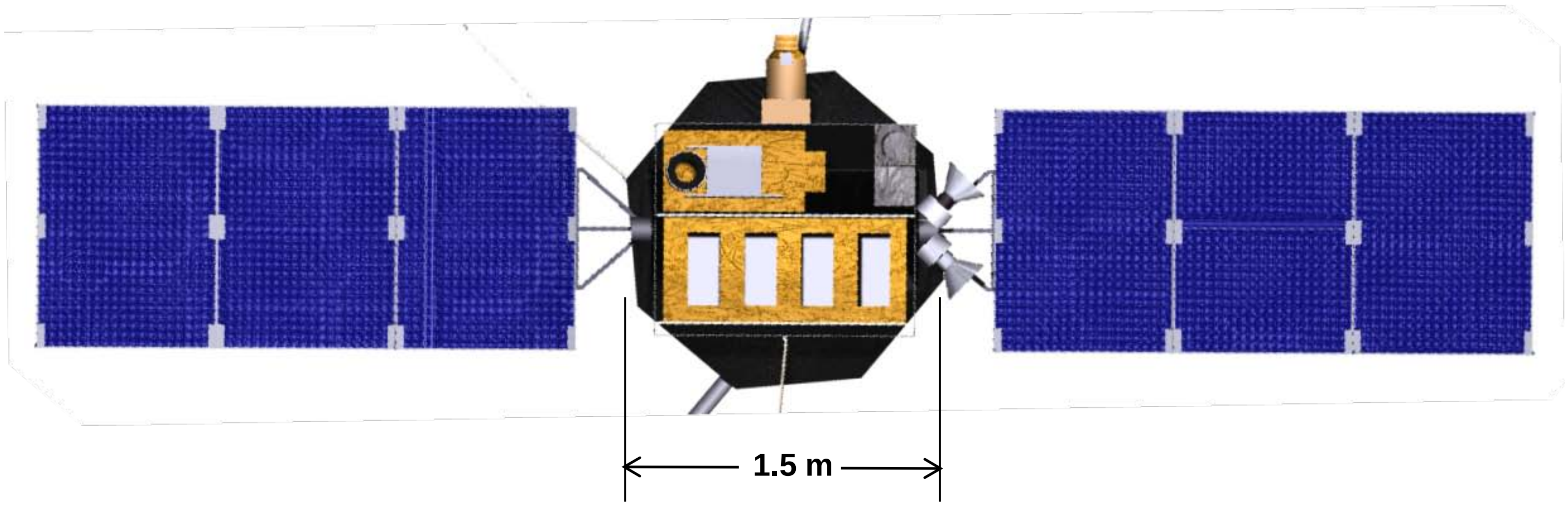
- **If EGA + sail work continues, we suggest**
  - Exploring the use of C3 from mass savings to improve initial condition
  - Use resonant (1 year) orbits for EGA flybys
  - Fully optimizing LT arcs
  - Trading LT for inc change vs. LT for EGA improvement

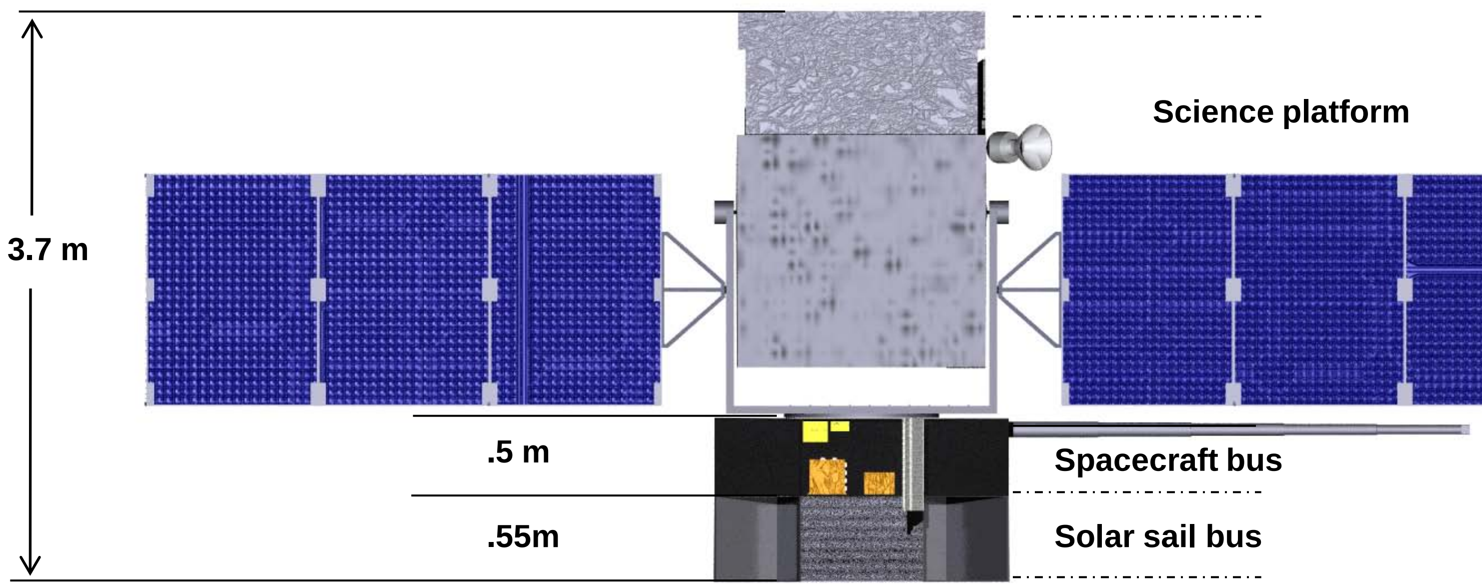
Integrated Systems Design

Launch Configuration

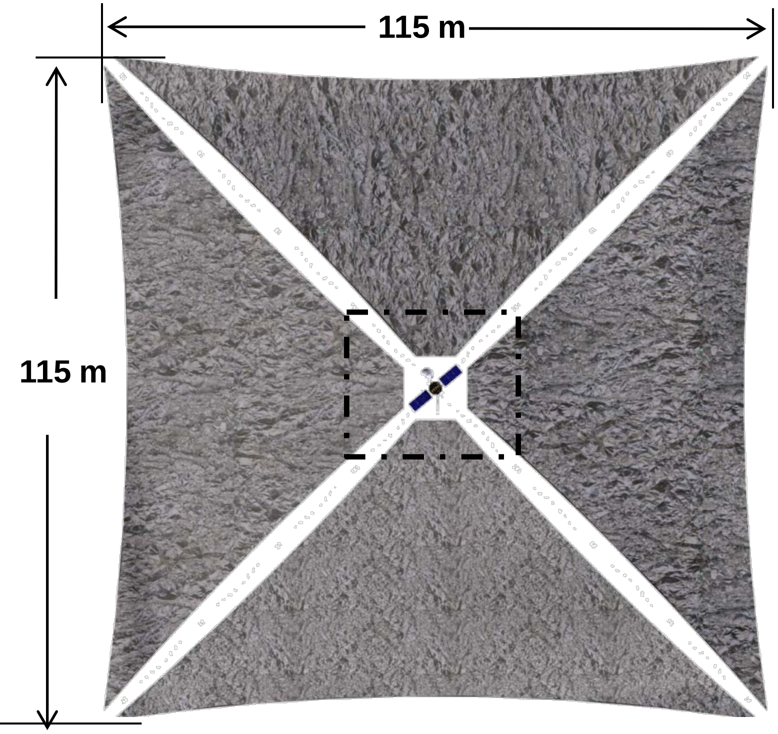
JAXA 4/4D shroud

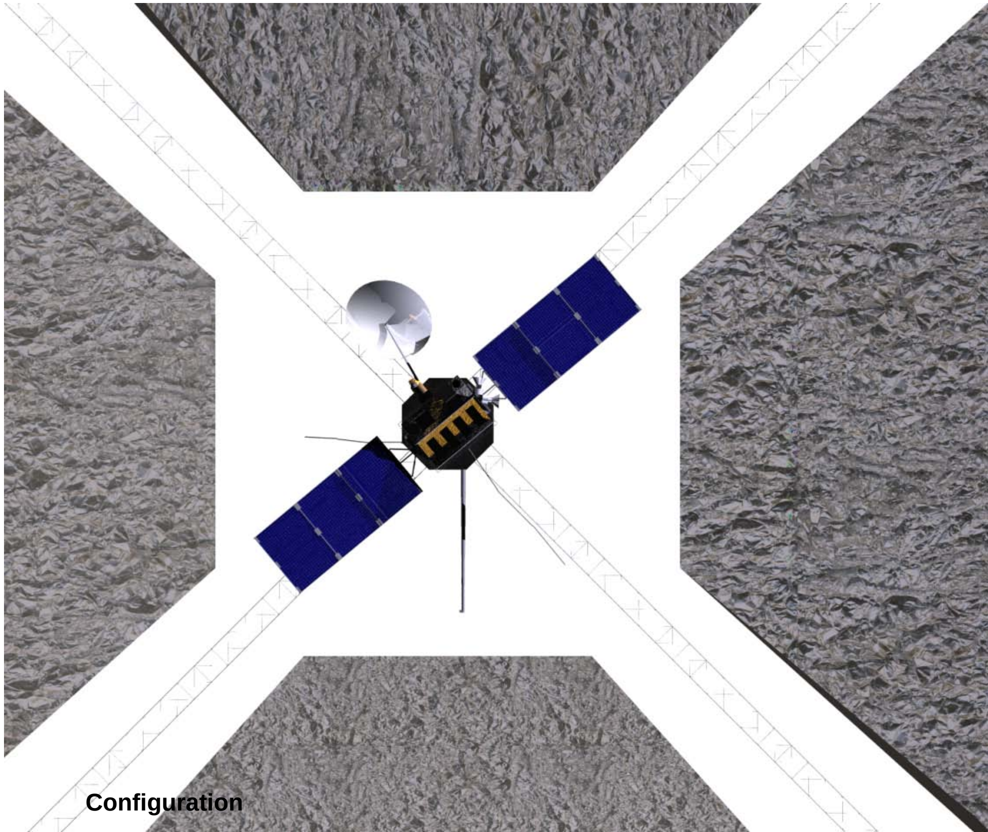
Spacecraft Design



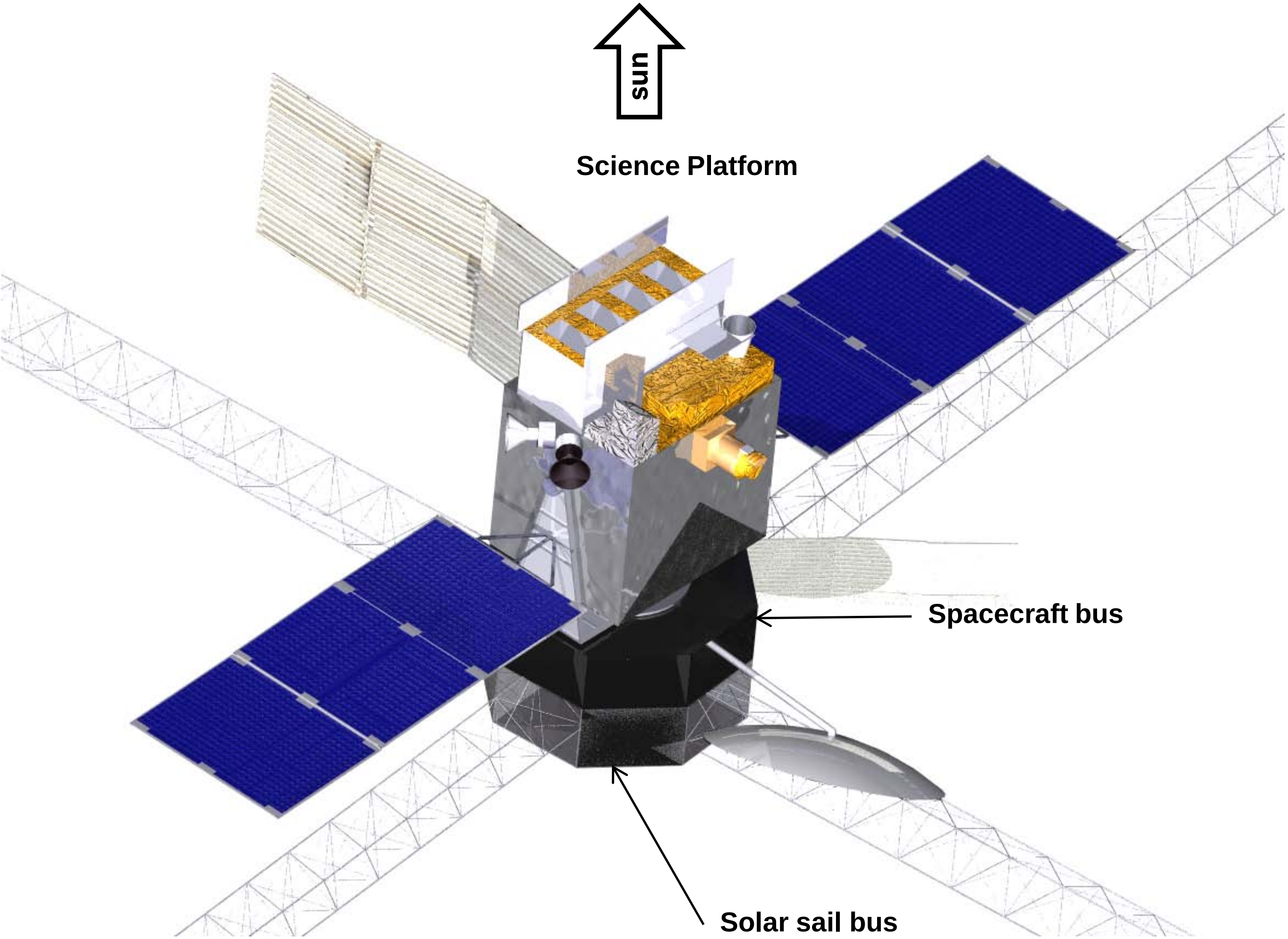


Solar Sail

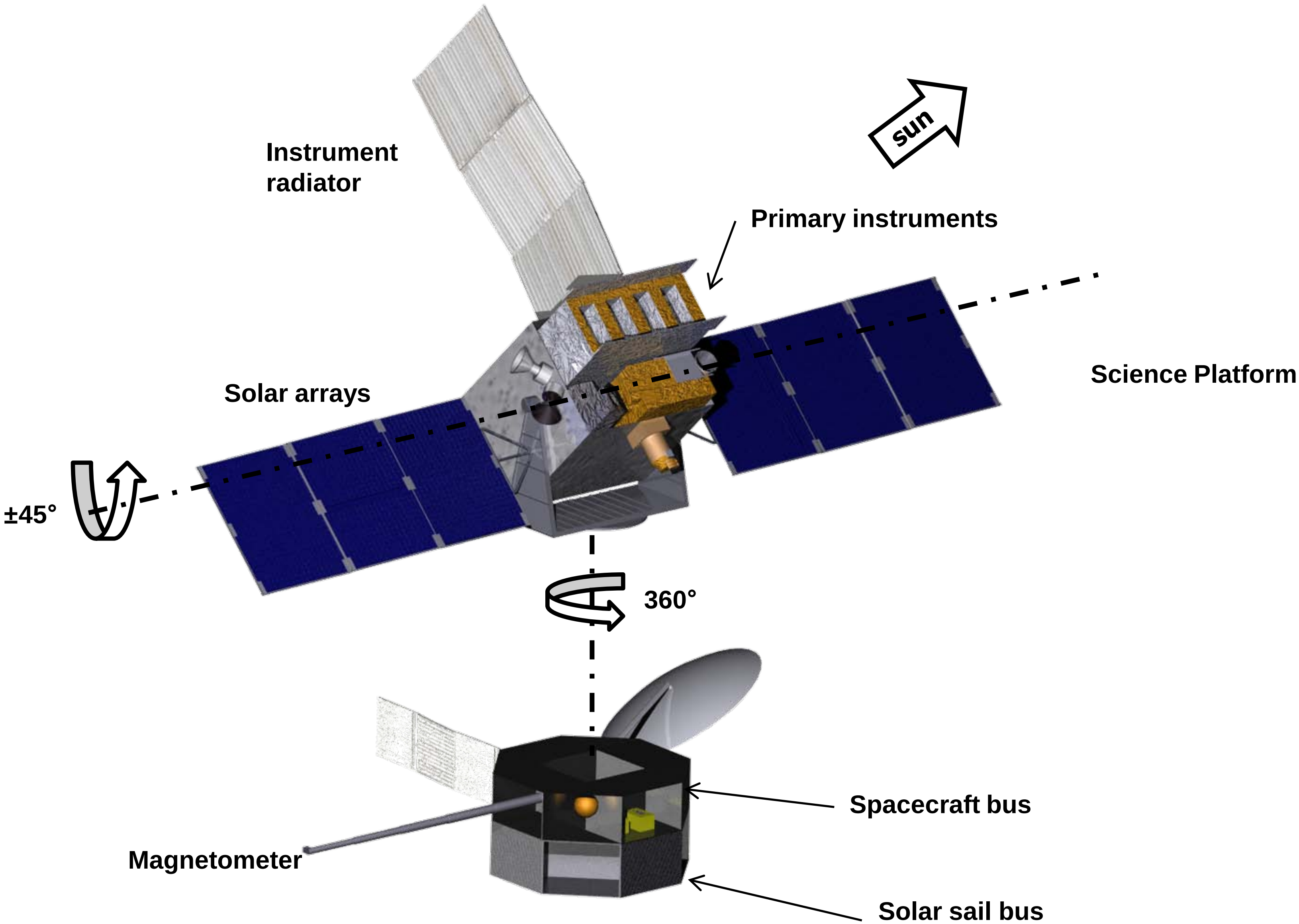




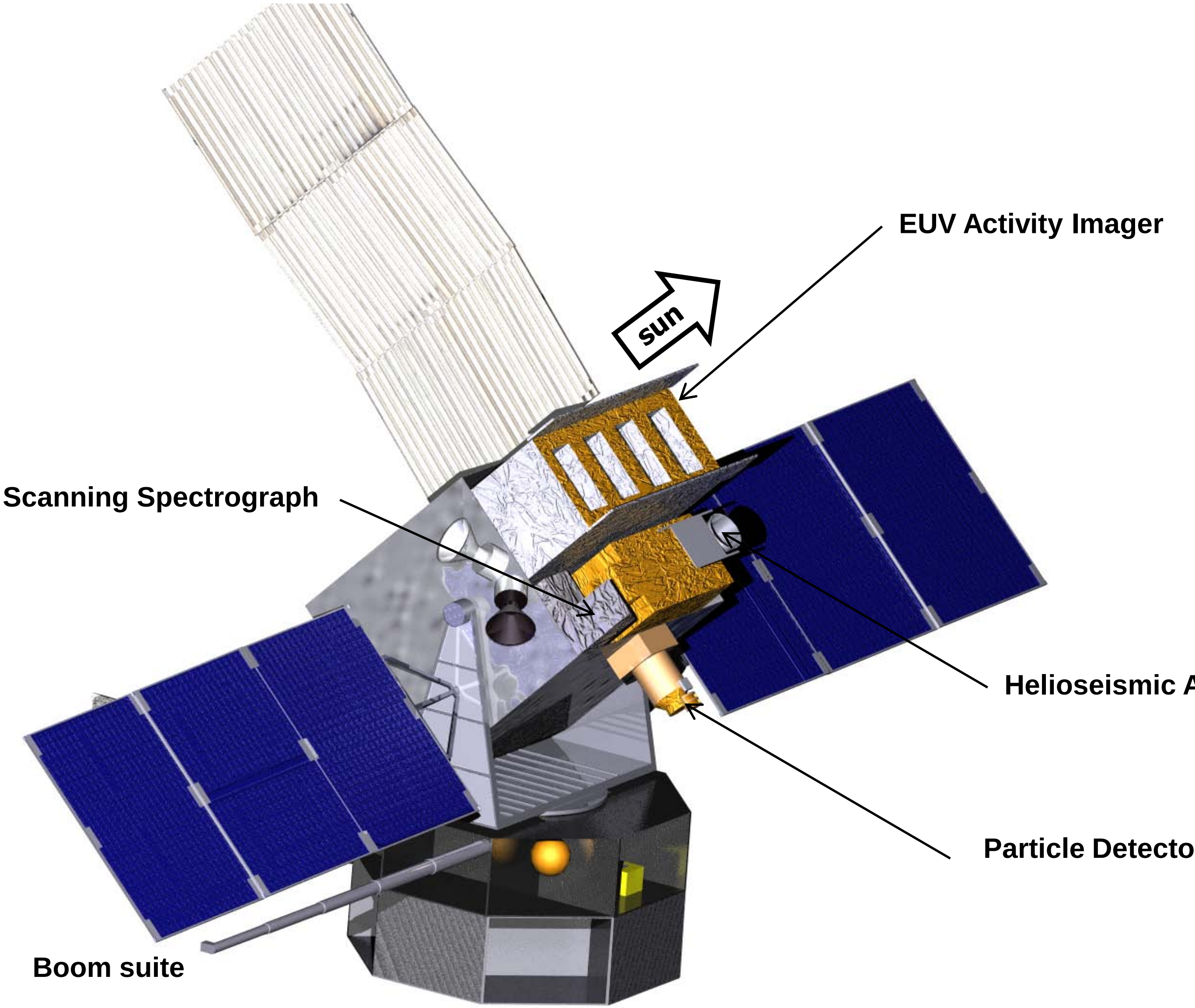
Spacecraft Design



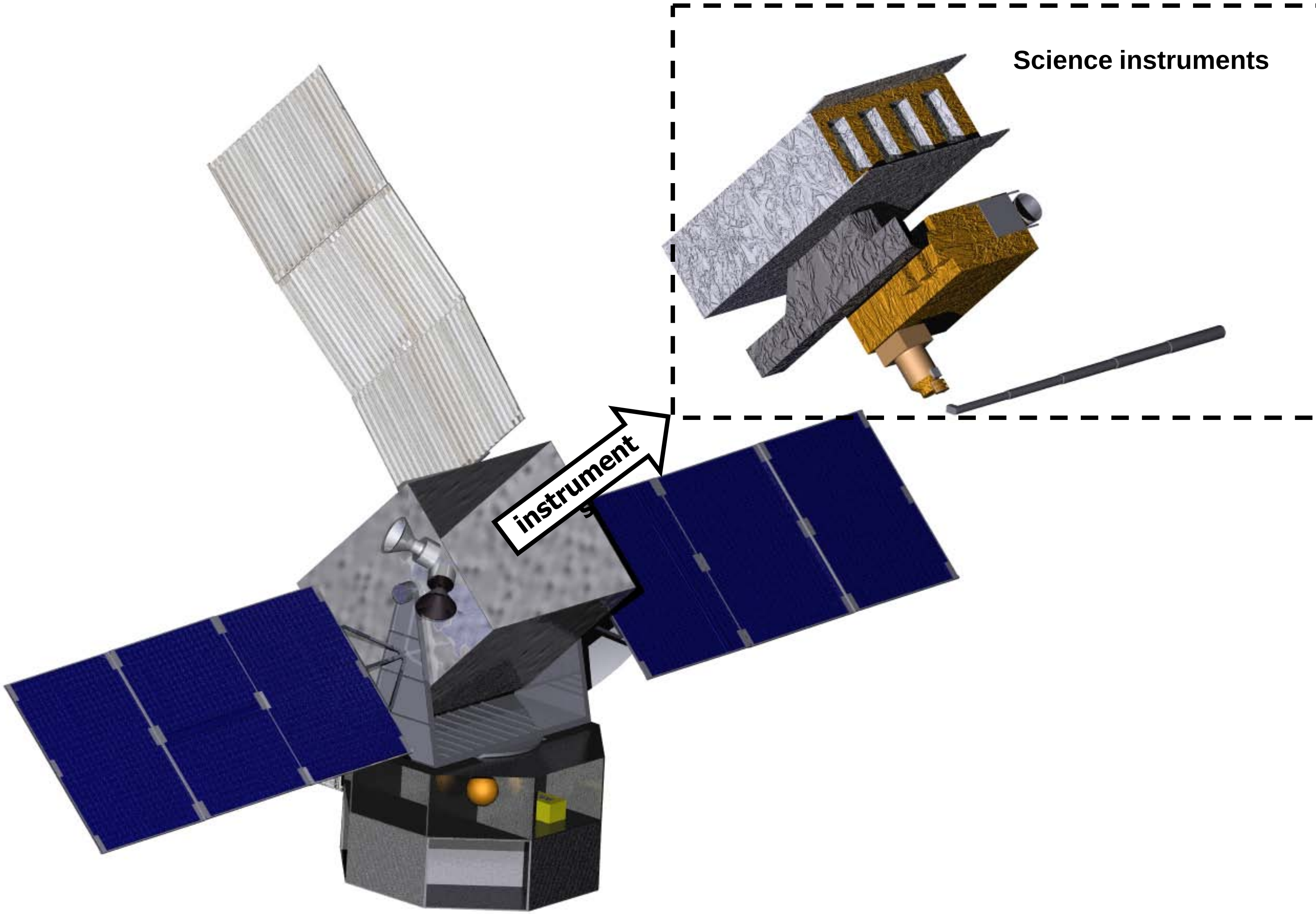
Spacecraft Design



Science Instruments

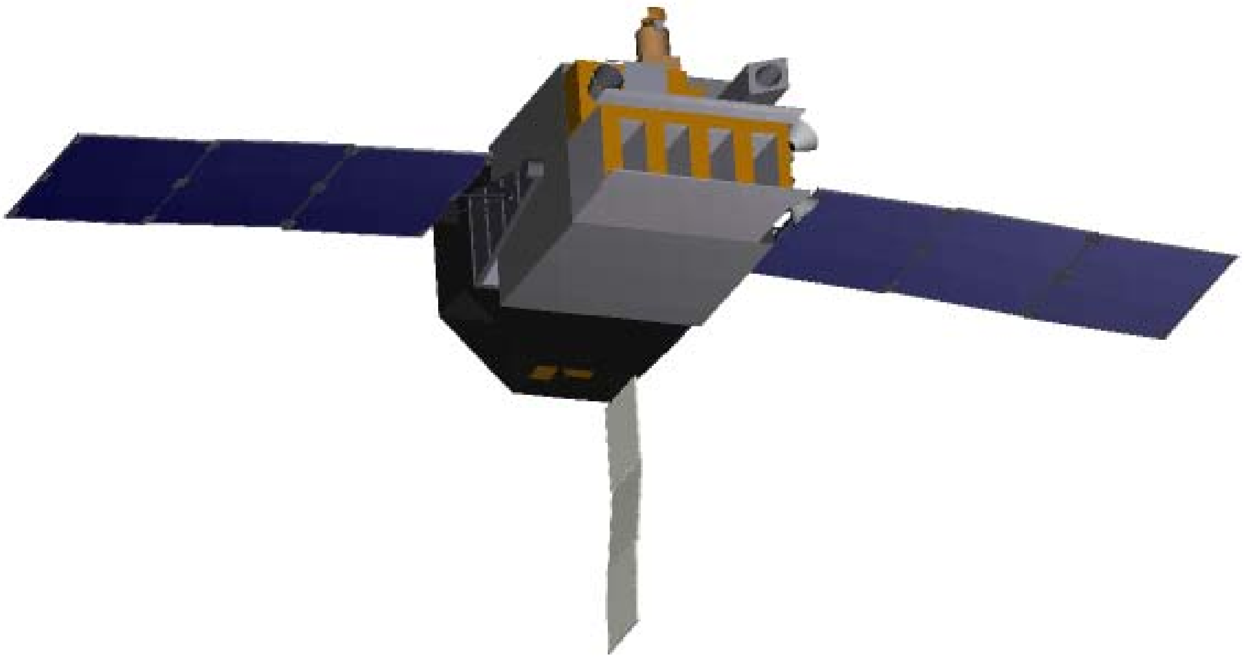


Science Instruments



Spacecraft

3D model



View in 3D with Deep View
Free at
www.righthemisphere.com/dv

Follow-on work

Release 2

- Further Evaluation of Solar Sail pointing in relation to science instrument platform pointing
- Location of radiators and mechanisms to avoid sun exposure
- Conduct more mechanism trades and interference issues
- Develop interface between spacecraft bus and solar sail bus

Mass Properties

Mass Summary

Release 2

- **Mass Properties Ground Rules and Assumptions**
  - 30% Contingency is added to the spacecraft Dry Mass
- **Iteration 1 Mass Estimates below (details in backup section):**

	mass total	Mass with growth (kg)
TOTAL OBSERVATORY MASS	**582**	**742**
Science Instruments	**85**	**108**
Spacecraft	**495**	**632**
Propulsion	10	12
Power and Distribution	57	74
Thermal Management	118	153
Attitude Control	24	31
Communications	50	65
Internal Communication and Data Handler	12	16
Structure	112	134
Solar Sail Systems	113	147
Observatory Dry Mass	**580**	**740**
Propellant	**2**	**2**
TOTAL OBSERVATORY MASS	**582**	**742**
Launch Vehicle Adapter	**23**	**27**
LAUNCH MASS	**605**	**769**

Cost Estimate

Ground Rules and Assumptions

1. The NAFCOM (NASA/Air Force Cost Model) was used to estimate the Solar-C spacecraft and Instrument costs herein.

2. Technical data and mass properties were supplied by the Solar –C proposal team.

3. All Costs are estimated in Fiscal Year (FY) 2011 dollars in millions based on NASA Inflation tables.

4. System Test Hardware Costs represent proto-flight approach. All applicable system integration (wrap) costs represent the wrap cost for one test unit.

5. Costs associated with the DDT&E effort encompass the period from the beginning of full scale development through factory checkout of test vehicle.

6. Individual subsystem totals contain all hardware costs and engineering and manufacturing labor costs charged to that subsystem.

7. Fee is calculated at 10% of the Spacecraft and Scientific Instrument costs.

8. Program Support (Level One PM, SE&I, and S&MA) cost are calculated at 20% of the Spacecraft and Scientific Instrument costs.

9. Vehicle Integration costs are calculated at four percent of the Spacecraft and Scientific Instrument costs.

10. Reserves are set at 30%.

Spacecraft Costs (2011$ in Millions)

WBS ITEM	DDT&E	Flight Unit	Total
Subsystem Level	**58.0**	**46.9**	**104.9**
Structures/Mechanisms	11.8	2.6	14.4
Thermal Control	4.6	1.4	6.0
Electrical Power	5.0	3.5	8.4
Communications	12.3	8.6	20.9
Command & Data Handling	5.5	2.7	8.2
Guidance & Navigation	2.4	1.8	4.2
Reaction Control	6.6	1.3	7.9
Sail Propulsion	10.0	25.0	35.0
System Level	**23.6**	**12.6**	**36.2**
Integration, Assembly & Checkout	1.5	4.1	5.6
Systems Test Operations	2.1	0.0	2.1
Ground Support Equipment	7.7	0.0	7.7
Systems Engineering & Integration	5.2	4.5	9.7
Program Management	4.8	4.1	8.9
Launch & On-Orbit Support	2.3	0.0	2.3
Subtotal	**81.6**	**59.5**	**141.2**
Vehicle Integration	**3.3**	**2.4**	**5.6**
Fee	**8.5**	**6.2**	**14.7**
Program Support	**18.7**	**13.6**	**32.3**
TOTAL	**112.1**	**81.7**	**193.8**

Scientific Instrument Costs (2011$ in Millions)

Release 2

WBS ITEM	DDT&E	Flight Unit	Total
Magnetograph/Helioseosmology Instrument	15.3	6.7	22.0
EVU Imaging/Spectrograph	12.4	4.7	17.1
Particle Detector	12.8	5.2	18.0
SEP Instruments	3.3	1.6	4.9
Boom Instruments	3.1	1.5	4.6
Subtotal	**46.9**	**19.7**	**66.6**
Vehicle Integration	**1.9**	**0.8**	**2.7**
Fee	**4.9**	**2.0**	**6.9**
Program Support	**10.7**	**4.5**	**15.2**
TOTAL	**64.4**	**27.0**	**91.4**

Total Costs (2011$ in Millions)

WBS ITEM	DDT&E	Flight Unit	Total
Spacecraft	112.1	81.7	193.8
Scientific instruments	64.4	27.0	91.4
Reserves (@30%)	52.9	32.6	85.6
TOTAL	229.4	141.4	370.8

Solar Sail Systems

Plan

OBJECTIVE

- Scale the ATK 20m (300 m^2) Ground System Demonstration (GSD) to larger sizes required for Solar-C mission

PROCESS

- Use ATK 10,000 m^2 Point Design presented as part of the GSD Formal Review to demonstrate scalability
- Use scaling data from ATK as well as concepts for lowering the mass of the sail system to achieve higher accelerations
- Provide TRL assessments of all the major sail subsystems from the 20m GSD

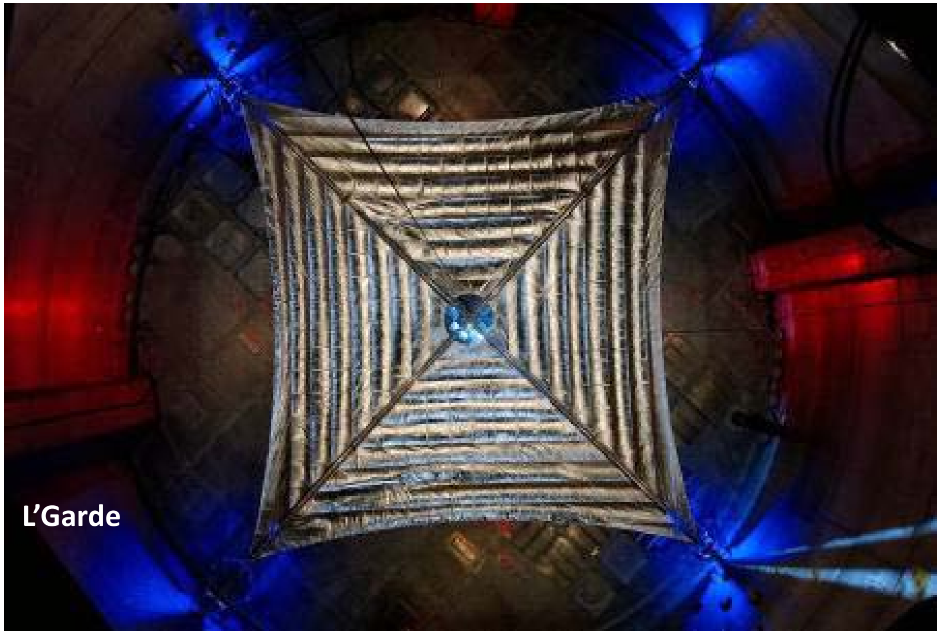
Solar Sail: GR&A

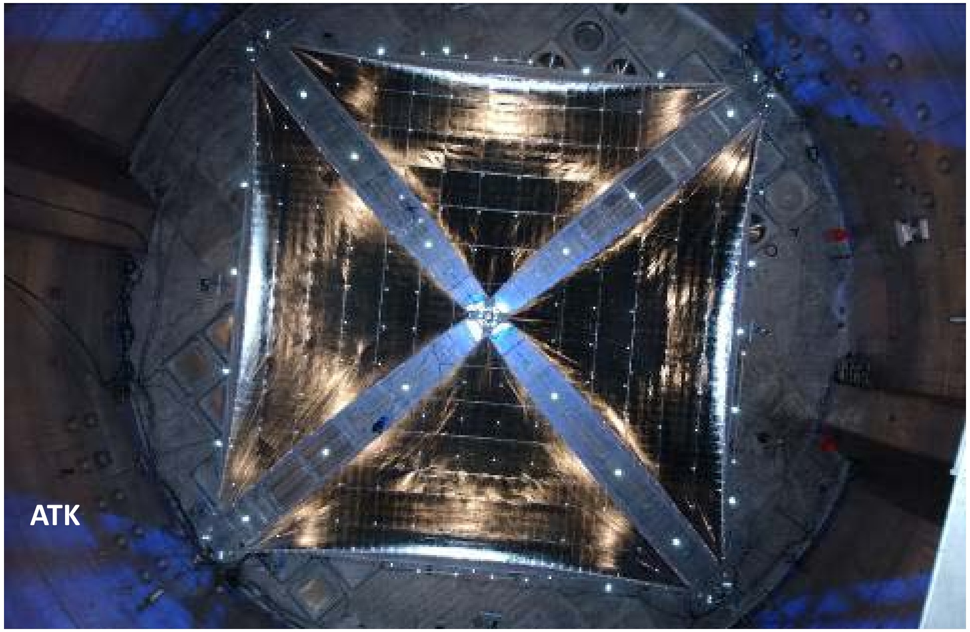
Release 2

- **Ground Rules and Assumptions**

Solar Sail Systems GR&A	The solar sail concept will be based on the ATK 20 meter Ground System Demonstrator (GSD) completed in 2006.	Scale up to 10,000 m^2 will use the scaling factors published in the ATK GSD Final Report
		A 10,000 m^2 sail has an edge length of 115 meters due to a fill factor of ~75%
		The characteristic accelaration of 10,000 meter^2 sail with a 80 kg bus and a 50 kg payload is .35 mm/sec^2
		The areal density for a 10,000 m^2 sail is 11.8 g/m^2

Solar Sail Technology Background

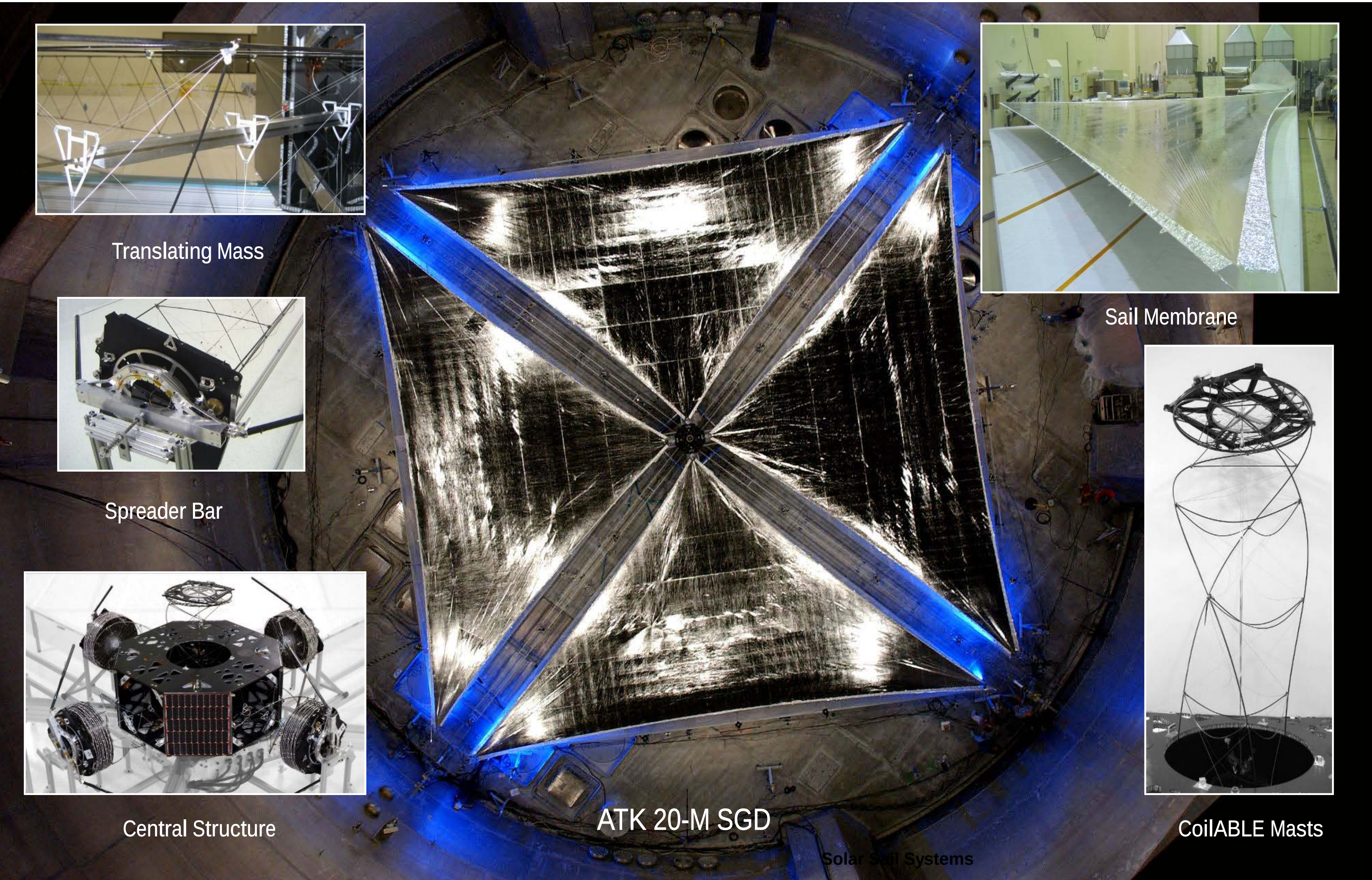




- **Two parallel awards to design, fabricate, and test competing sail concepts for system level ground demonstration from 2003 - 2005**
  - **Phase A Concept Study in 2003**
  - **10-m system ground demonstrators were developed and tested in 2004.**
  - ***20-m system ground demonstrators designed, fabricated, and tested under thermal vacuum and flight conditions in 2005.***
- **Multiple awards to develop and test high-fidelity computational models, tools, and diagnostics.**
- **Multiple awards for materials evaluation, optical properties, long-term environmental effects, charging issues, smart adaptive structures.**

ATK 20-m System Ground Demonstrator

Release 2



ATK 10,000 m² Point Design

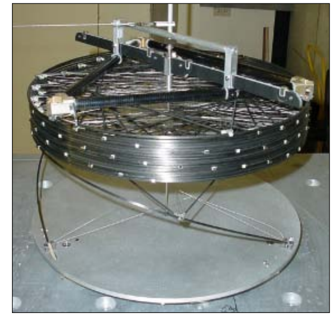
Scale up from the 20m Ground System Demonstration Program by ATK:

- Operating Temperature
  - 25°C at 1.0 au
- First Natural Frequency
  - 0.03 Hz
- Stowed Package
  - 1.9 m dia. by 0.54 m
- Control Systems
  - Runners & Spreader Bars
- System Mass:
  - 113 kg
- Characteristic acceleration
  - 0.73 mm/s²
  - 0.35 mm/s² with 130 kg SC

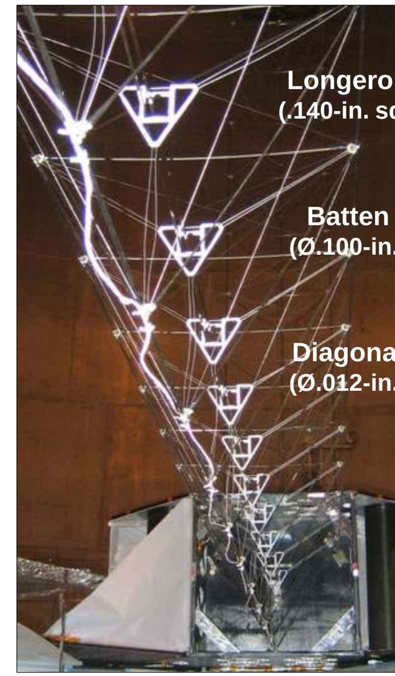
Stowed CoilABLE

Ø20-in. (50.5 cm)

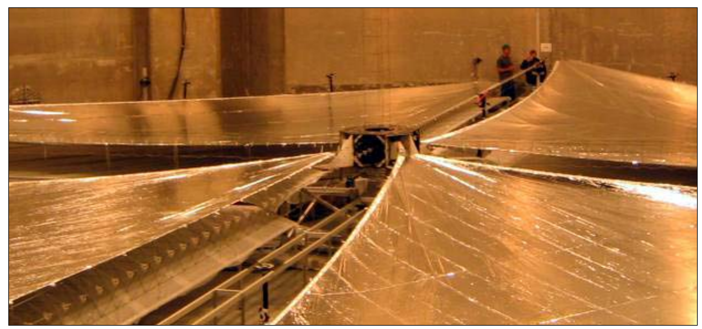
25.7-in.-tall (<0.80% of length)

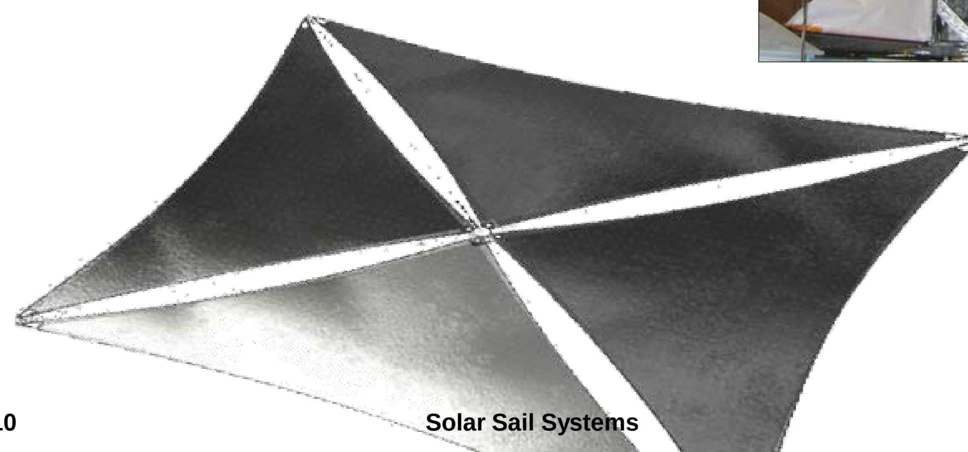


Mast Linear Mass: 115 g/m (with 11 g/m harness)

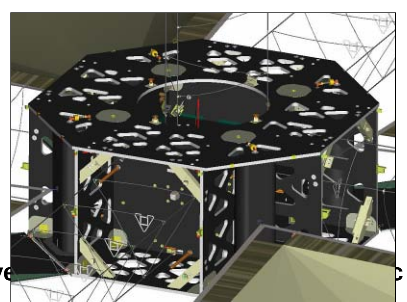


Sail Thickness: 2.25 μm





Detail of Central Assembly



Solar Sail: Conclusions

- **Conclusions**
  - Based on preliminary, pre-Phase A level analyses solar sails can provide the required accelerations needed for the Solar-C mission.
    - Sail may have to be larger than 10,000 m^2
  - Mass projections are based on the ATK Ground System Demonstration projected 10,000 m^2 Point Design as reported at the ATK Formal Review in 2006.

- **Future Work:**
  - Investigate the thermal environment of the sail at the orbit of Venus as well as at a closer orbit to the Sun
  - Assess the Scalability and Spiral tasks identified by ATK to lower the areal density (g/m^2)

Scaled 160 Meter Design

- Based on "The Solar Polar Orbiter: A Solar Sail Technology Reference Study" for the Science Payload and Advanced Concepts Office of ESA by Malcolm Macdonald, Gareth W. Hughes, Colin R. McInnes
- Design based on ATK 10m GSD, masses updated to reflect 20m GSD

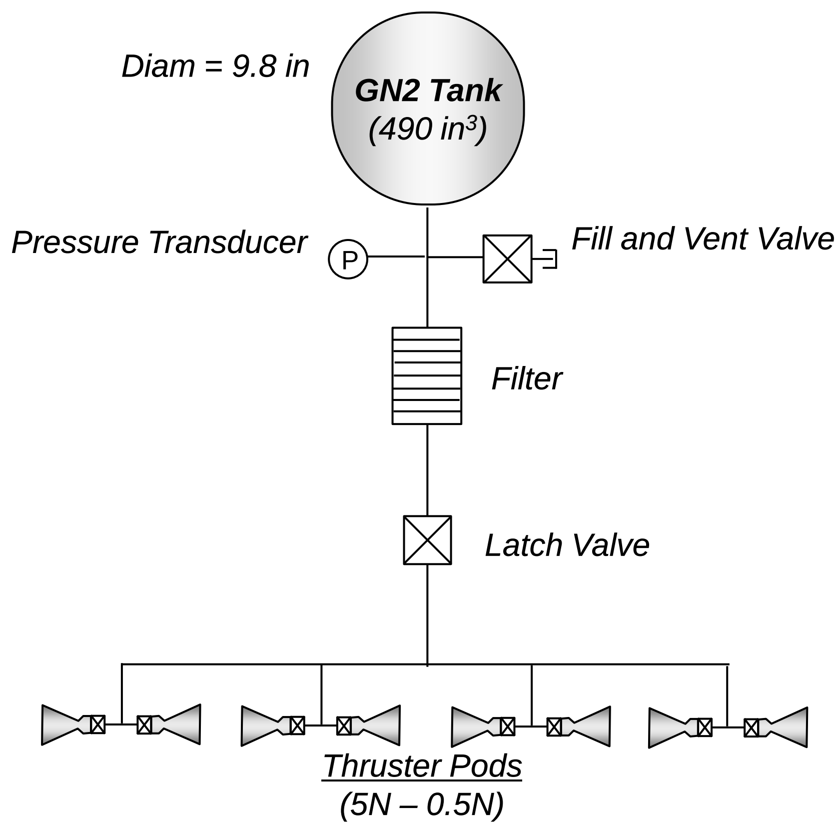
Propulsion

Solar-C Chemical Propulsion System

Release 2

- **Gaseous nitrogen blowdown system**
  - Tank pressure = 3000 – 300 psia
  - Thrust = 5 – 0.5 N
  - Usable propellant = 1.61 kg
    - Available maneuver propellant for given tank and blowdown assumptions

Used components from VACCO Cold Gas Propulsion System (CGPS)



Component	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	Predicted Mass (kg)
Thrusters	8	0.07	0.56	30%	0.73
Pressure Vessel	1	4.00	4.00	30%	5.20
HP transducer	1	0.45	0.45	30%	0.59
Fill & drain valve	1	0.11	0.11	30%	0.15
Filter	1	0.11	0.11	30%	0.15
Isolation Valve	1	0.34	0.34	30%	0.44
Lines & Fittings	1	4.00	4.00	30%	5.20
Total Dry Mass:			***9.58 kg***	***30.0%***	***12.45 kg***

Available Maneuver GN2:	1.61 kg
Unusable GN2:	0.19 kg
Total GN2:	***1.80 kg***
Propulsion System Wet Mass:	***14.25 kg***

Structures

Structural Analysis: GR&A

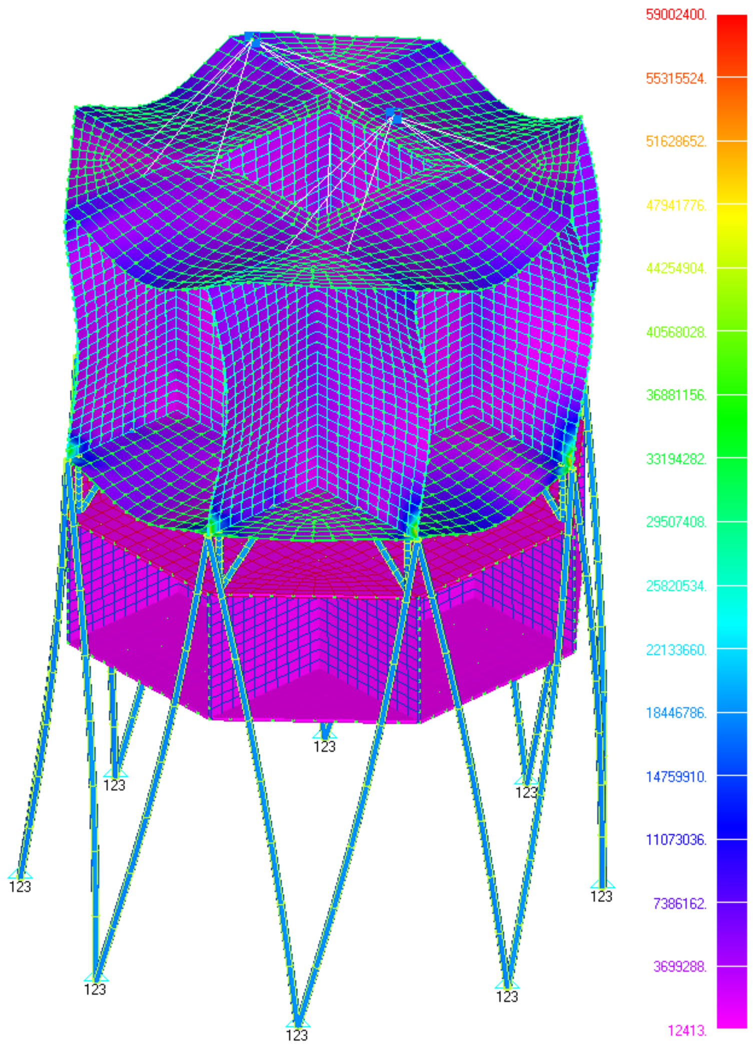
Release 2

- **Ground Rules and Assumptions**

Factor of Safety for Composite Materials	**~**
Yield Factor of Safety	n/a
Ultimate Factor of Safety (Uniform Areas)	1.5
Ult. Factor of Safety (Discontinuity Areas)	2.0
Factor of Safety for Metallic Materials	**~**
Yield Factor of Safety	1.25
Ultimate Factor of Safety	1.40
Factor of Safety for Propellant Tanks	**~**
Proof Pressure Factor	1.5
Burst Pressure Factor	2.0
Minimum Allowable Frequency	**25 Hz**
Launch Loads	**4.0g axial, 1.8g lateral**

Structural Analysis: Approach

- **Tools and Approach**
  - FEMAP model of spacecraft bus and solar sail box was developed to assess bus structural mass
  - Structure modeled as Al 7075
  - Subsystems equipment added as mass elements
  - Launch loads applied at 0°, 45°, and 90° due to symmetry
  - All positive MOS



Structural Dry Mass

QTY	THERMAL SYSTEM COMPONENTS	UNIT MASS (kg)	TOTAL MASS (kg)	COMMENTS
1	Primary Structure	72.9	72.9	18% MGA
1	Secondary Structure	14.6	14.6	18% MGA
1	Struts, Joints, and Fittings	4.3	4.3	18% MGA
1	Mechanisms for Articulating Instruments	20.0	20.0	30% MGA
TOTAL DRY MASS			**111.8**	

Total mass after contingency: 134.3 kg

Structural Analysis: Conclusions

- **Conclusions**
  - Spacecraft bus structures are straightforward with no new technology required
  - Based on preliminary, pre-Phase A level analyses, all launch stresses are within acceptable range for spacecraft bus
  - Future work should include normal modes and buckling analyses

Thermal

Thermal Analysis: GR&A

Release 2

- **Ground Rules and Assumptions**

Passive thermal control of spacecraft shall utilize:	MLI, heaters, thermostats, radiators, heat pipes, etc. to maintain spacecraft subsystem components within acceptable temperature ranges.
Environmental heat loads will be calculated for:	Heliocentric orbit at 0.7 - 1.3 AU, sun-pointing.
Instrument temperature prediction is:	Thermal analysis output
Instruments reject heat to thermal transfer aparatus.	Loads are denoted on instrument GR&A.

Thermal Analysis: Approach

- **Tools and Approach**
  - Closed-form equations used to calculate worst-case environmental loads
    - Distance to sun = 0.7 AU
    - Worst-case sail reflection to spacecraft bus and instrument box
  - 50% heat load margin added to all environmental loads
  - Thermal radiators sized using end-of-life characteristics
  - Thermal radiators reject all excess heat
    - Conservatively assumed no spacecraft bus or instrument box radiation
  - Closed-form equations used to calculate thermal masses
  - Closed-form equations used to calculate radiator area

Thermal Dry Mass

QTY	THERMAL SYSTEM COMPONENTS	UNIT MASS (kg)	TOTAL MASS (kg)	COMMENTS
24	Multilayer Insulation/Thermal Tape	0.5	12.0	10-12 Layer Blanket
5.5	Spacecraft Bus Radiators w/ Heat Pipes	5.0	27.4	White Paint
9.2	Instrument Box Radiators w/ Heat Pipes	8.0	73.3	White Paint
1	Misc. Hardware	5.0	5.0	
TOTAL DRY MASS			**117.7**	

Total mass after 30% contingency: 153.0 kg

Thermal Analysis: Conclusions

- **Conclusions**
  - Based on preliminary analyses, temperatures are within acceptable range for worst-case thermal loads
  - Thermal management is accomplished with typical, flight proven components and no technology development is required
  - Future work should include system level thermal model (Thermal Desktop, etc.) to determine all interface temperatures are within acceptable range

Power

Power: GR&A

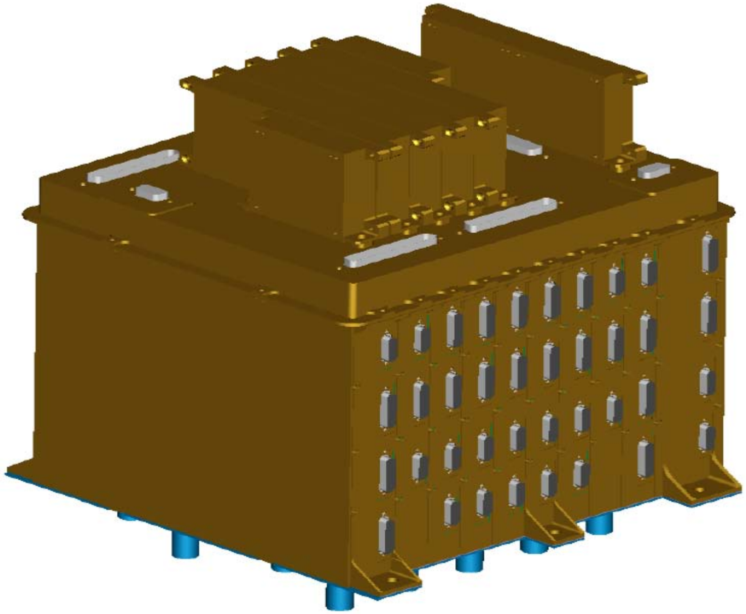
- 1 Fault Tolerance wherever possible.
- Solar Irradiance is 810 W/m^2 (at 1.3 AU)
- Rigid Panel Solar Arrays, 24% efficiency @Max Op Temp 80C, 90% Cell Coverage.
- Sun's angle of incidence to the sail will always be <= 90°
- Solar Arrays will always be in sunlight.
- All Power Electronics are TRL 9

Power: Design Approach

- Power Generation: 2 Solar Panels, mounted on sun-pointing instrument unit with panels directly facing the sun. Solar panels use flight-proven cells and standard construction techniques.
- Primary Battery for power during Solar Array deployment (>3 hours).
- Array Regulation and Power Electronics: Use existing TRL 9 components taken directly from MESSENGER spacecraft.
- Max Power Requirement: 1335 W

Solar C Power Systems Design Features

Power System Electronics Box



Power Distribution Unit

- All Power System Electronics and Distribution components Taken Directly from MESSENGER Spacecraft
- Components designed for very long (10+ year) mission duration under harsh conditions.

Power: Mass Breakdown

Item	Unit Mass(kg)	Qty	Total Item Mass(kg)
Solar Array Panel (5m^2)	10.9	2	21.8
Solar Array Struct	6	2	12
Solar Array Junction Box	1.3	1	1.3
Power Systems Electronics Box	6.6	1	6.6
Power Distribution Unit	12.5	1	12.5
Primary Battery	2.5	1	2.5
Total			**56.7**

Total mass after 30% Growth Allowance: 73.7 kg

Avionics / GN&C

Avionics: GR&A

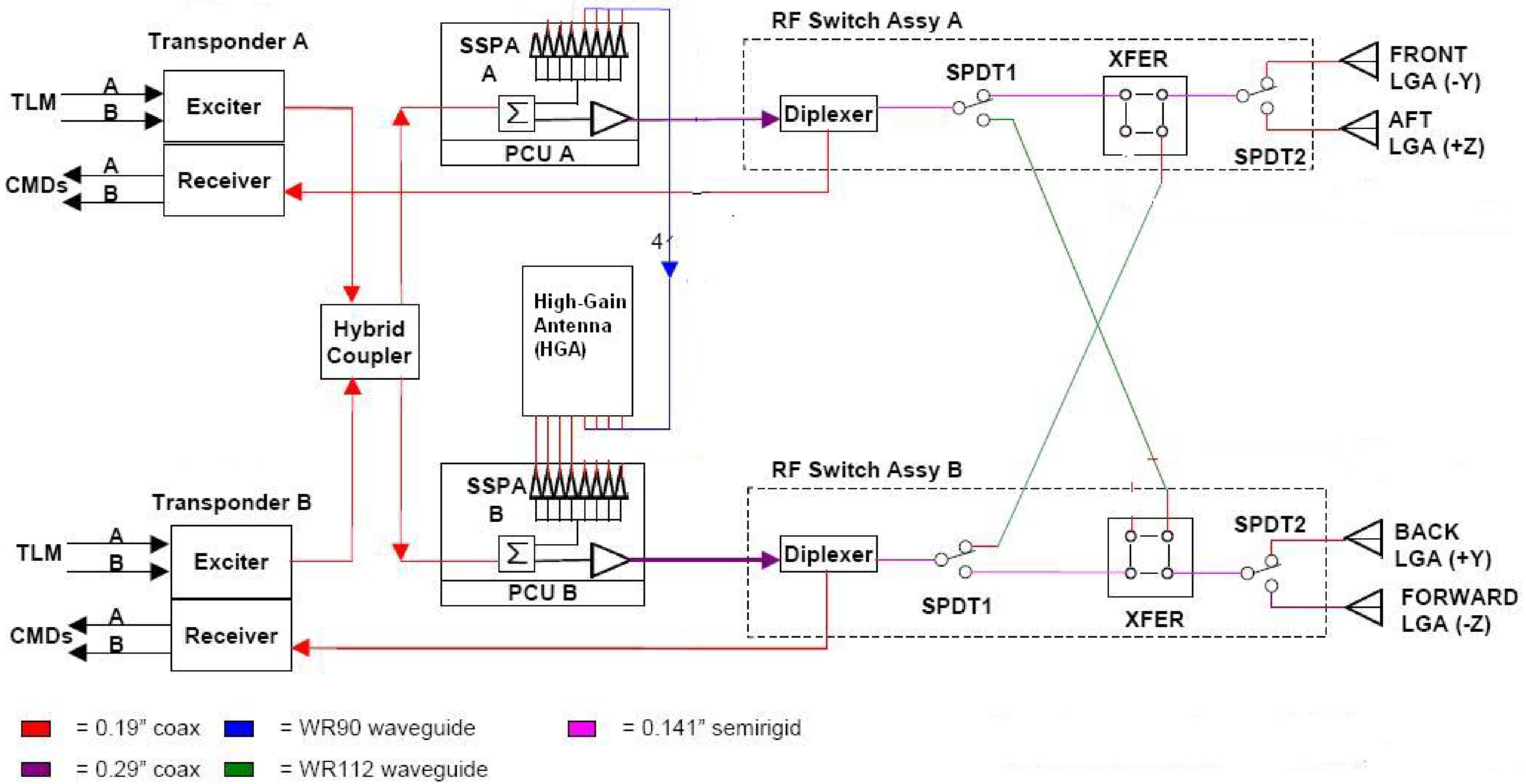
- 1 Fault Tolerance wherever possible.
- Heliocentric Orbit with 1 yr period 1.3 x 0.7 AU
- Mission duration: 10 years.
- Use of Deep Space Network (DSN) for Communications and Navigation
- Ka-Band communications (26.5 gHz).
- 300 kbps Downlink, 9 kbps telemetry
- Precise ephemerides available for spacecraft and celestial body locations
- Solar Sail used for all propulsion and attitude control

Avionics: Design Approach

- Navigation: Tracking – Ka Band 2-way Doppler.
- Communications: Ka Band for voice, data using Deep Space Network (DSN) with High Gain (50 db) Antenna for high bandwidth science data and Low-Gain antenna for command and telemetry.
- Guidance, Data handling: All components from MESSENGER Spacecraft.
- Attitude Determination: All Components from MESSENGER Spacecraft.

Avionics: Communications

Release 2

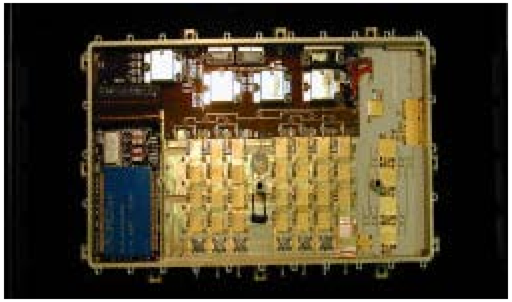


Avionics: Communications

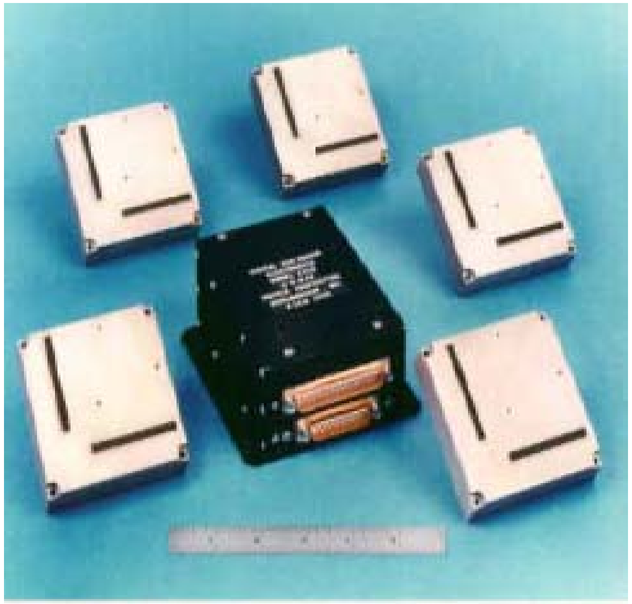
High Gain Antenna

Low Gain Antenna (4)

Solid State Power Amp (2)



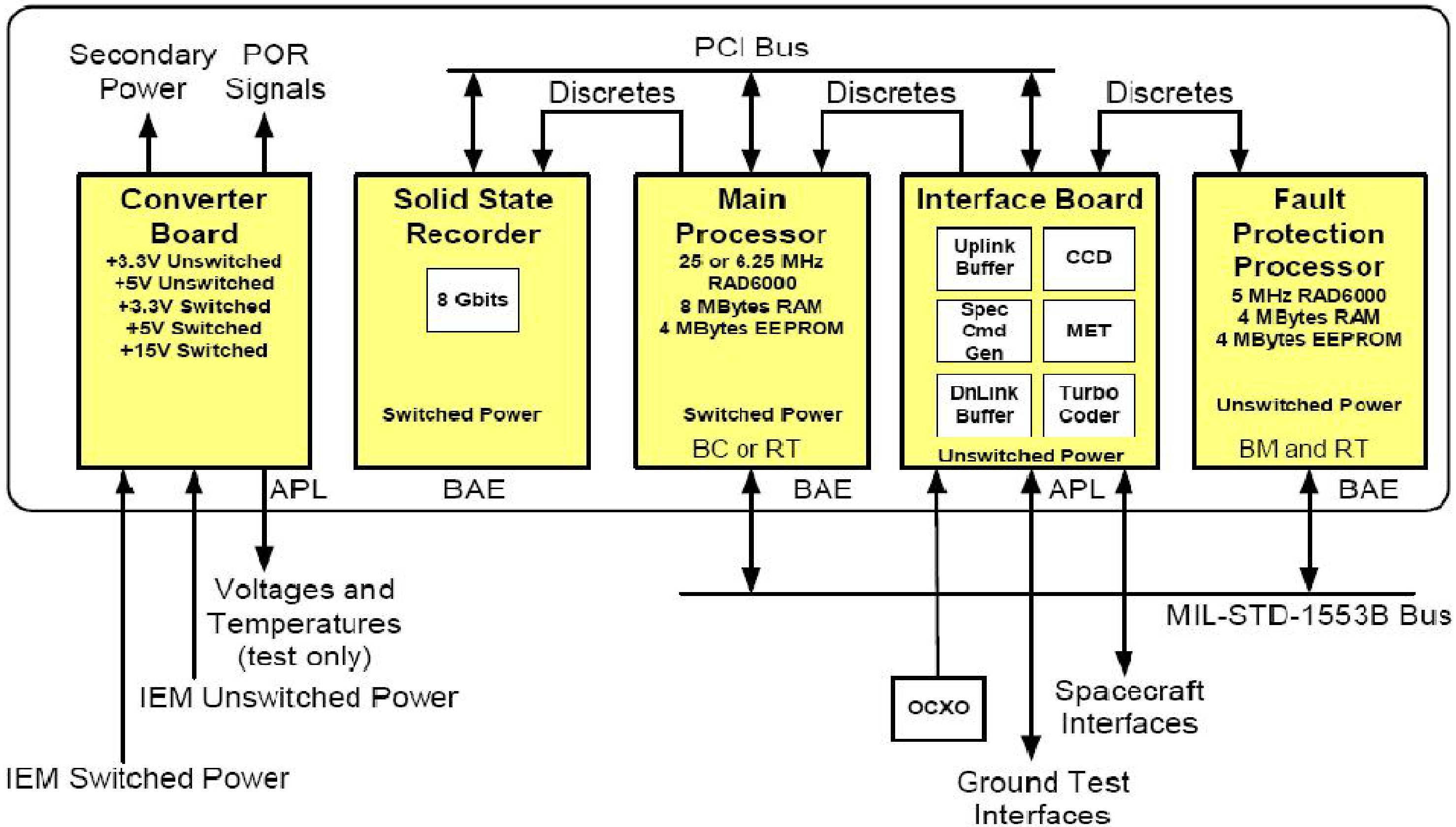
Avionics: Attitude Determination



- Sun Sensors determine attitude with respect to Sun within 1°
- Star Tracker determines attitude with respect to given Star Field

Avionics: Command & Data Handling

Release 2



MESSENGER Heritage Integrated Electronics Module (IEM) Provides Command, Control and Data handling / storage.

Avionics: Mass Breakdown

Release 2

Item	Unit Mass (kg)	Qty	Total Item Mass
Transponder	3.2	2	6.4
Solid State Power Amplifier	6.75	2	13.5
Power Conversion Unit	0.75	2	1.5
Low-Gain Antenna	0.28	4	1.1
Passive Components	2.57	2	5.1
RF Bracket	0.7	2	1.4
High-Gain Antenna (w/Pointing)	21.2	1	21.2
Integrated Electronics Module	6	2	12.0
Star Tracker	6.25	2	12.5
Inertial Measurement Unit	6.9	1	6.9
Sun Sensor Set (6 sensor heads, Electronics box)	4.4	1	4.4
Total			**86.1**

Total mass after 30% Growth Allowance: 111.9 kg

Conclusions and Forward Work

Conclusions

- **Results of the spacecraft conceptual design study:**

	Value	Units
Total Observatory Mass	742	kg
Total Launch Mass	769	kg
Final Orbit Inclination (with 160x160m sail)*	45	deg
Spacecraft Technologies Needing Development	None	
Time to Reach Desired Orbit (with 160x160m sail)	6.5**	yrs
Estimated Spacecraft Cost (2011$ millions)	194	
Estimated Total Cost (2011$ millions)	371	

*** See NOTES on slide 3.**
**** Not optimized. Perhaps time can be reduced through trajectory optimization or mass reduction.**

- **SEP option dropped from study due to time constraints**
  - difficult to analyze the trajectory of a hybrid sail / SEP system
  - initial calculations indicated that a sail by itself could accomplish mission
- **Due to more massive spacecraft than anticipated, had to revise sail size from the original 100x100 meter design to 160x160 meters**
  - raised characteristic acceleration back up to the original estimate of 0.2 mm/s^2

Conclusions: Requirements Not Met

Topic	Requirement	Estimated Performance	Cause	Resolution
Transit Time to Target Orbit	5 years	6.5 years	The estimated total mass is higher than was anticipated at the beginning of the study. In addition, there was not sufficient time to fully optimize the trajectory.	Options include (but are not limited to): reducing the spacecraft mass; optimizing the trajectory; investigating the possibility of using a larger solar sail; adding a SEP system.

All other performance requirements met.

Conclusions: Technical Issues

Release 2

Topic	Issue	Resolution
Solar Sail Survivability	The solar sail material longevity at 0.7 AU is something that should be investigated, as it may need to survive these conditions for many years (depending on the trajectory).	First, trajectory should be optimized to determine the environment that the solar sail must endure during its lifetime.

- No technical issues with the spacecraft systems.
- No spacecraft systems or components require any technology development.

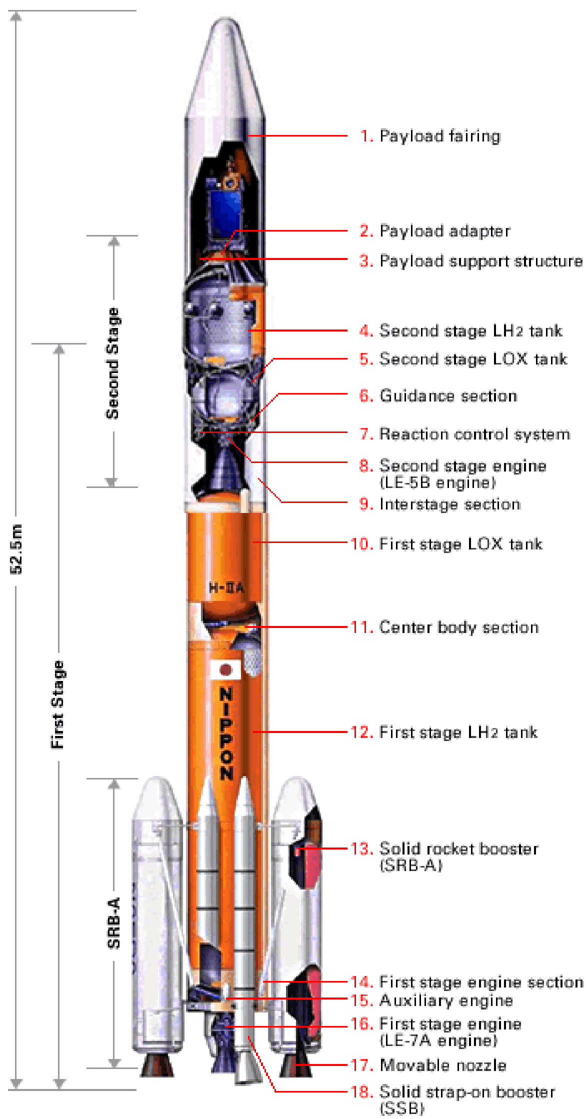
Forward Work

- **Below are recommendations for follow-on activities**
  - investigate solar sail lifetime
  - optimize the trajectory
  - we use the solar pole inclination to our advantage; however, need to investigate the implications that this has on launch opportunities and the trajectory
  - can the solar sail be used to loft, allowing the science instruments to remain at the same solar latitude for several days?
  - look at mass savings: can increase the performance of the solar sail by reducing the spacecraft mass
  - reduce the power allocated for the science instruments
    - reducing the current allocation of 1kW can save some mass
  - better definition of science instruments
    - more accurate power, mass, and dimensional data will decrease the uncertainty in the spacecraft design
  - *additional recommendations appear at the end of each discipline section*

Backup

JAXA H-IIA Launch Vehicle

Release 2



Vehicle	
Overall Length	52.5 m (with 4S or 5S Fairing)
Mass	285 metric-ton (H2A202, not including the payload)
Launch Capability	4.15 metric-ton (GTO, H2A202)

Fairing	
Diameter	4.0 m
Length	12.0 m

Second Stage	
Propellant	LH2/LOX
Propellant Mass	16.7 metric-ton
Thrust	137 kN (in vacuum)
Burning Time	540 sec. Multiple restart capability
Specific Impulse	447 sec. (in vacuum)
Total Mass	20.0 metric-ton

First Stage	
Propellant	LH2/LOX
Propellant Mass	100.0 metric-ton
Thrust	1,098 kN (in vacuum)
Burning Time	390 sec.
Specific Impulse	440 sec. (in vacuum)
Total Mass	114.0 metric-ton

SRB-A	
Propellant	Solid Propellant
Propellant Mass	130.0 metric-ton (2 units)
Thrust	4,511 kN (max 2 units, in vacuum)
Burning Time	100 sec.
Specific Impulse	280 sec. (in vacuum)
Total Mass	150.0 metric-ton (2 units)

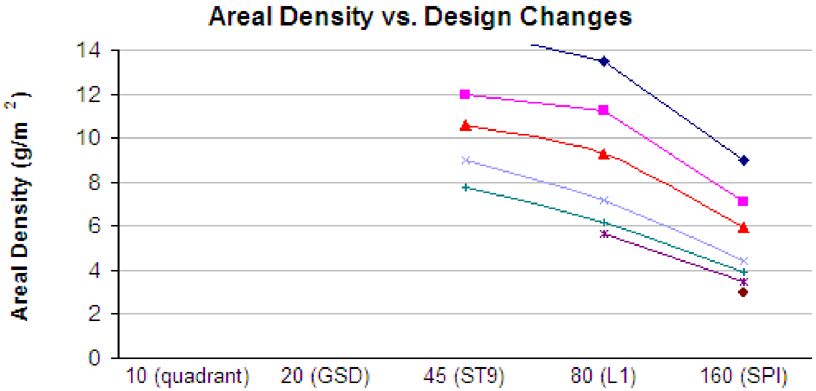
SSB	
Propellant	Solid Propellant
Propellant Mass	26.0 metric-ton (2 units)
Thrust	1,470 kN (max 2 units, in vacuum)
Burning Time	60 sec.
Specific Impulse	282 sec. (in vacuum)
Total Mass	31.0 metric-ton (2 units)

The standard type H-IIA (H2A202) is length of 52.5 m, diameter of 4 m, and mass of 285 ton without spacecraft mass. It consists of the first and second stages, fairing, and Solid Rocket Booster-A (SRB-A), and is the high-powered large-scale launch vehicle equipped with propellant systems using liquid hydrogen / oxygen.

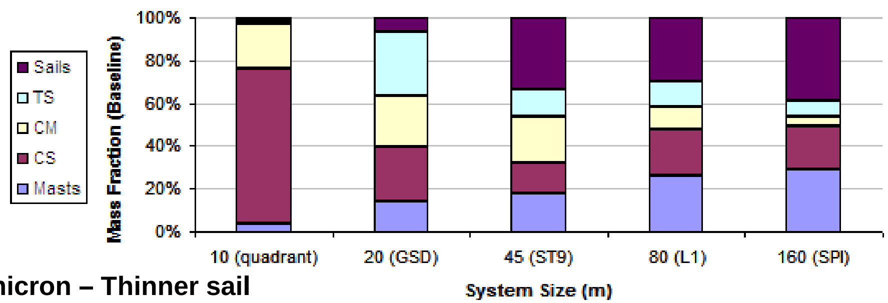
Two or four Solid Strap-on Boosters (SSBs) can be added for increased performance. Alternatively, two additional SRB-As can be added.

Backup

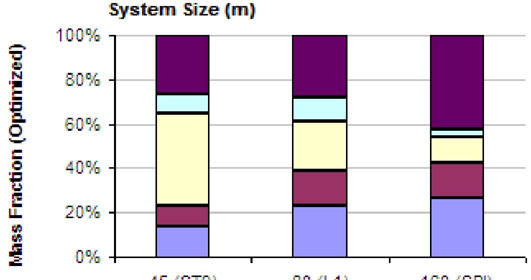
Scalability and Spiral Development



	10 (quadrant)	20 (GSD)	45 (ST9)	80 (L1)	160 (SPI)
Baseline	1873.5	89.1	15.0	13.5	9.0
w/ 1 micron			12.0	11.2	7.1
& e-CS			10.6	9.3	5.9
& 0.1 psi			9.0	7.2	4.4
& Diag Mph			7.8	6.2	3.9
& SALT				5.6	3.5
& Stayed					3.0



1 micron – Thinner sail
e-CS – Jettisonable CS
0.1 psi – Reduced sail stress
Diag Mph – Active Diagonals
SALT – Augmented Truss
Stayed – Stayed masts
TS – Tip Structure
CM – Central Mechanisms
CS – Central Structure



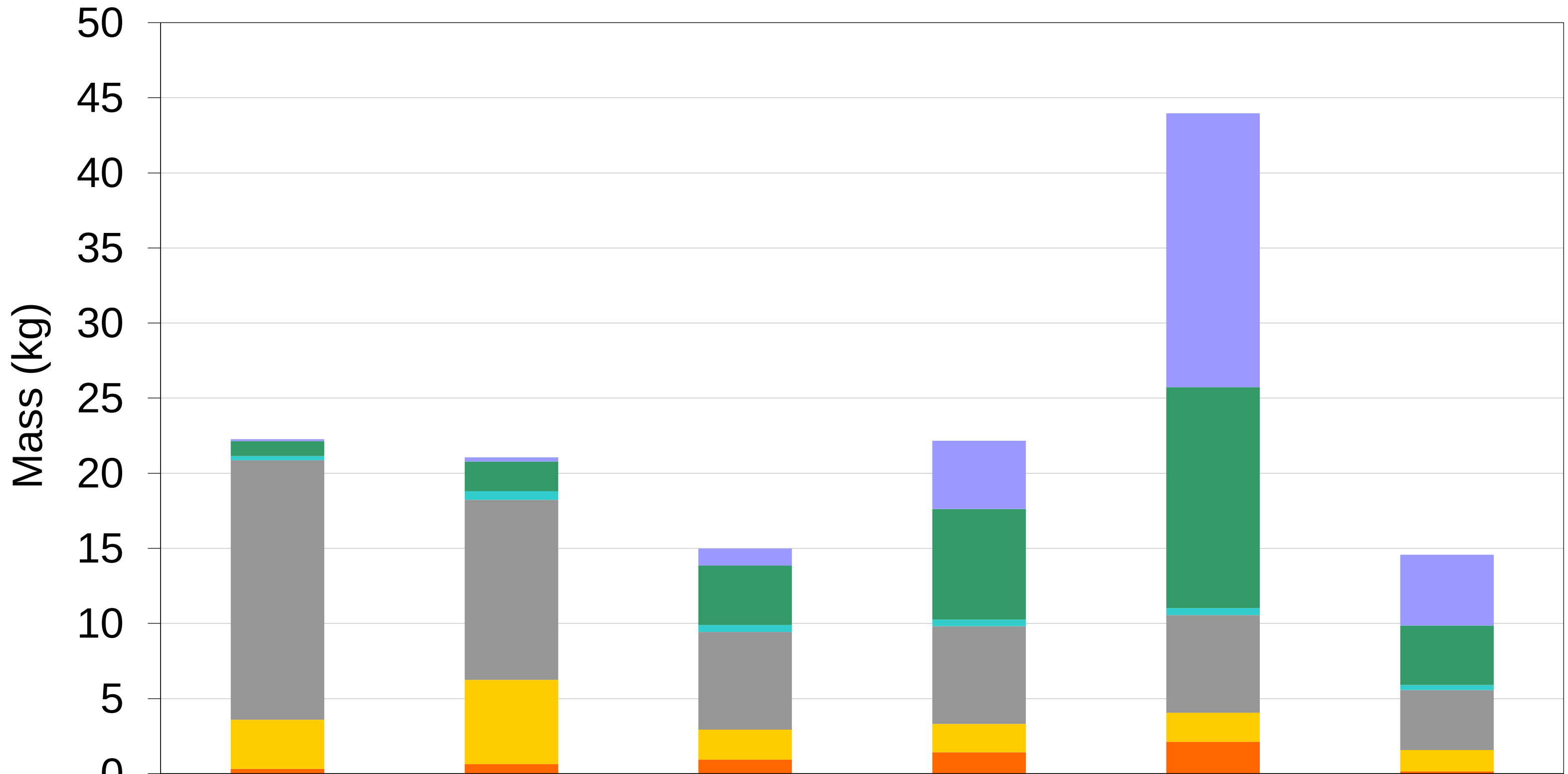
Additional mass savings are projected based on a spiral development process:

- **Areal Density Performance**
  - Top trend line is for the GSD scaled to 160 meters
  - Other lines show trends for the incorporation of various technology advancements, both expected and conceptual
- **100-m system performance**
  - Interpolating the performance of the demonstrated system provides an areal density of
    - 11.8 g/m^2 at 115-m (10,000 m^2)
    - Ph. 1 prediction: 10.8 g/m^2
  - Volume Comparison
    - Phase 1: 1.0 m^3
    - Current: 1.5 m^3
      - Due to higher strain mast design
      - Still reasonable fairing: 2 m

Backup

ATK Mass Projections 80m Max

Release 2



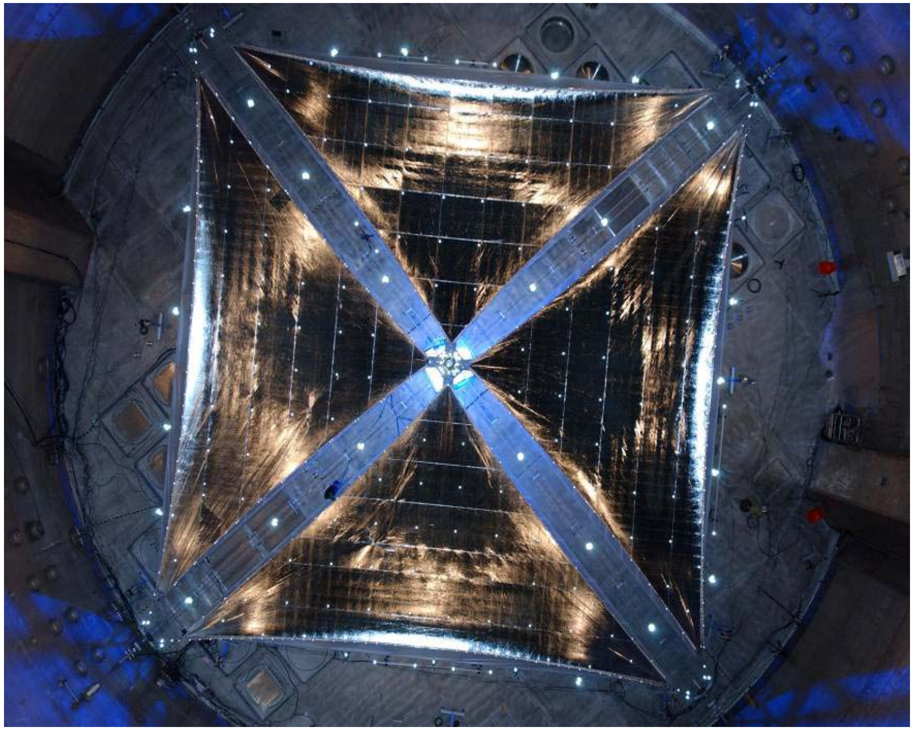
	10-m Quadrant	10-m Ground	20-m Ground	40-m Flight	80-m Flight	40-m Min. Vol.
Sail Mass	0.14	0.28	1.13	4.56	18.2	4.71
Mast mass	0.99	1.98	3.96	7.35	14.71	3.96
Tip Structures	0.28	0.56	0.45	0.45	0.45	0.34
Central Structure	17.27	12.00	6.50	6.50	6.50	4.00
Mechanisms	3.28	5.61	1.99	1.89	1.95	1.43
Misc.	0.31	0.63	0.94	1.41	2.12	0.14

Backup

TRL Assessment Results Comparison

Release 2

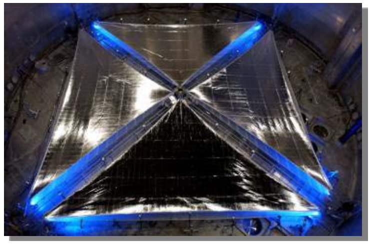
Vendor	Post 10M TRL 5 Completion Average	Post 20M TRL 5 Completion Average	Post 10M TRL 6 Completion Average	Post 20M TRL 6 Completion Average
ATK	76%	89%	60%	86%
L'Garde	75%	84%	68%	78%

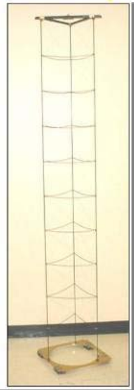


ATK

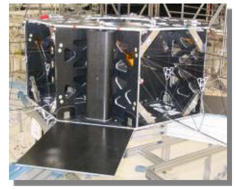
L'Garde

TRL Assessment Methodology

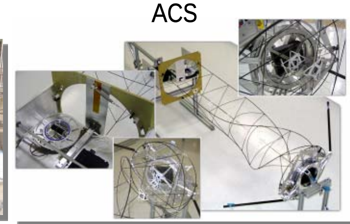

ATK 20M System

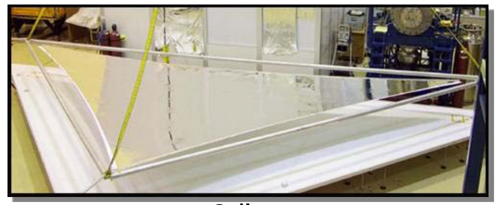

Masts

Central Structure



ACS




Sails

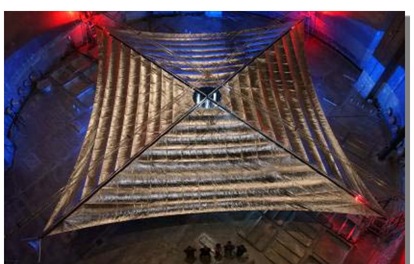
System	Subsystems	Components
ATK 20M Quadrant	Sails	Materials & Coating
		Deployment Sequencers
		Grounding Straps
		Compliant Border
	Masts	Battens
		Longerons
		Diagonals
		Corner Group
		Halyards
		Lanyards
		Deployment Motors
	ACS	Translating Masses
		Motors/ Control Mechansms
		Spreader Bars
		Mast Tip Mechanism
		Control Wiring
		Software
	Central Structure	Carrier Assembly
		Doors & Actuators
		S/C Interface
		Sail Drum

ACS
Central Structure
Sails
Masts/Beams

Identify Solar Sail Major Subsystems

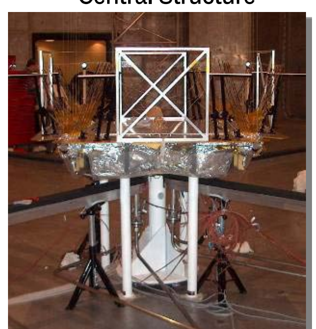
ATK
L'Garde

→ Identify Subsystem Components → Assess Component/ Subsystem TRL (3-5) → Assess System TRL (6)


L'Garde 20M System

Beams

Central Structure




ACS


Sails

System	Subsystems	Components
L'Garde 20M System	Sails	Materials & Coatings
		Integrated Ripstop
		Grounding Straps
		Stripped Net
	Beams	Boom & Rigidization System
		Inflation Subsystem
		Heater Wires
		Insulation
		End Caps
		Spreader System & Rings
		Cat's Cradle
	ACS	Tip Vanes
		Vane Cant Mechanism
		Vane Rotation Mechanism
		Control Wiring
		Software
	Central Structure	Carrier Assembly
		Doors & Actuators
		S/C Interface

Backup

Mass Properties (1/4)

	qty	mass each	mass total	growth margin (%)	growth	Mass with growth (kg)
TOTAL OBSERVATORY MASS			**582**		**162**	**742**
Science Instruments			**85**		**25**	**108**
Magnetograph /Helioseosmology Instrument	1	30	30	30.00%	9	39
Helioseismic Activity Imager (HAI)	1					
Visible Light Doppler / Magnetic Imager	1					
EUV Imaging / Spectrograph	1	25	25	30.00%	7.5	33
EAI (EUV Activity Imager)	1					
ESS (EUV Scanning Spectrograph)	1					
Particle Detector	1	25	25	30.00%	7.5	33
SEP Instruments	1	3	3	30.00%	0.9	4
SEPT (Solar Electron Proton Telescope)	2					
SIT (Suprathermal Ion Telescope)	1					
LET (Low Energy Telescope)	1					
HET (High Energy Telescope)	1					
Boom Instruments	1	2	2	30.00%	0.6	3
SWEA (Solar Wind Analyzer)	1					
STE (Suprathermal Electron Telescope)	2					
MAG (Magnetometer)	1					

Mass Properties (2/4)

	qty	mass each	mass total	growth margin (%)	growth	Mass with growth (kg)
Spacecraft			**495**		**137**	**632**
Propulsion			**10**		**3**	**12**
Thrusters	8	0.07	0.56	30.00%	0.17	0.73
Pressure Vessel	1	4.00	4.00	30.00%	1.20	5.20
HP transducer	1	0.45	0.45	30.00%	0.14	0.59
Fill & drain valve	1	0.11	0.11	30.00%	0.03	0.15
Filter	1	0.11	0.11	30.00%	0.03	0.15
Isolation Valve	1	0.34	0.34	30.00%	0.10	0.44
Lines & Fittings	1	4.00	4.00	30.00%	1.20	5.20
Power and Distribution			**57**		**17**	**74**
Solar Array Panel (5m^2)	2	10.9	21.8	30.00%	6.54	28
Solar Array Struct	2	6	12	30.00%	3.6	16
Solar Array Junction Box	1	1.3	1.3	30.00%	0.39	2
Power Systems Electronics Box	1	6.6	6.6	30.00%	1.98	9
Power Distribution Unit	1	12.5	12.5	30.00%	3.75	16
Primary Battery	1	2.5	2.5	30.00%	0.75	3
Thermal Management			**118**		**35**	**153**
MLI	24	0.5	12	30.00%	3.6	16
S/C Radiators w/ heat pipes	5.49	5	27.45	30.00%	8.235	36
Instrument Box Radiators w/ heat pipes	9.16	8	73.28	30.00%	21.984	95
Misc. Hardware	1	5	5	30.00%	1.5	7
Attitude Control			**23.8**		**7.14**	**30.94**
Star Tracker	2	6.25	12.5	30.00%	3.75	16
Inertial Measurement Unit	1	6.9	6.9	30.00%	2.07	9
Sun Sensor Set (6 heads, Junction)	1	4.4	4.4	30.00%	1.32	6

Backup

Mass Properties (3/4)

	qty	mass each	mass total	growth margin (%)	growth	mass with growth (kg)
Communications			**50.26**		**15.078**	**65.338**
Transponder	2	3.2	6.4	30.00%	1.92	8
Solid State Power Amplifier	2	6.75	13.5	30.00%	4.05	18
Power Conversion Unit	2	0.75	1.5	30.00%	0.45	2
Low-Gain Antenna	4	0.28	1.12	30.00%	0.336	1
Passive Components	2	2.57	5.14	30.00%	1.542	7
RF Bracket	2	0.7	1.4	30.00%	0.42	2
High-Gain Antenna (w/Pointing)	1	21.2	21.2	30.00%	6.36	28
Internal Communication and Data Handler			**12**		**3.6**	**15.6**
Flight Computer, Data Recorder, etc.	2	6	12	30.00%	3.6	16
Structure			**112**		**23**	**134**
Primary Structure	1	72.91	72.91	18.00%	13.12	86.03
Secondary Structure	1	14.58	14.58	18.00%	2.62	17.20
Struts, Joints, and Fittings	1	4.31	4.31	18.00%	0.78	5.09
Mechanisms for articulating science instruments	1	20	20	30.00%	6.00	26.00
Solar Sail Systems			**113**		**33.9**	**146.9**
Sail and cannister	1	113	113	30.00%	33.9	147

Backup

Mass Properties (4/4)

Release 2

		qty	mass each	mass total	growth margin (%)	growth	Mass with growth (kg)
Observatory Dry Mass				**577**		**162**	**737**
Propellant				**2**		**0**	**2**
	Usable GN2	1	1.61	1.61	0.00%	0.00	1.61
	Unusable GN2	1	0.19	0.19	0.00%	0.00	0.19
TOTAL OBSERVATORY MASS				**579**		**162**	**739**
Launch Vehicle Adapter				**22.98**		**4.1364**	**27.1164**
	Struts, Joints, and Fittings	1	22.98	22.98	18.00%	4.14	27.12
LAUNCH MASS				**602**		**166**	**766**