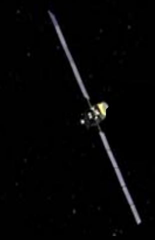
Solar Power for Outer Planets Study



Presentation to Outer Planets Assessment Group

November 8, 2007

Scott W. Benson/NASA Glenn Research Center

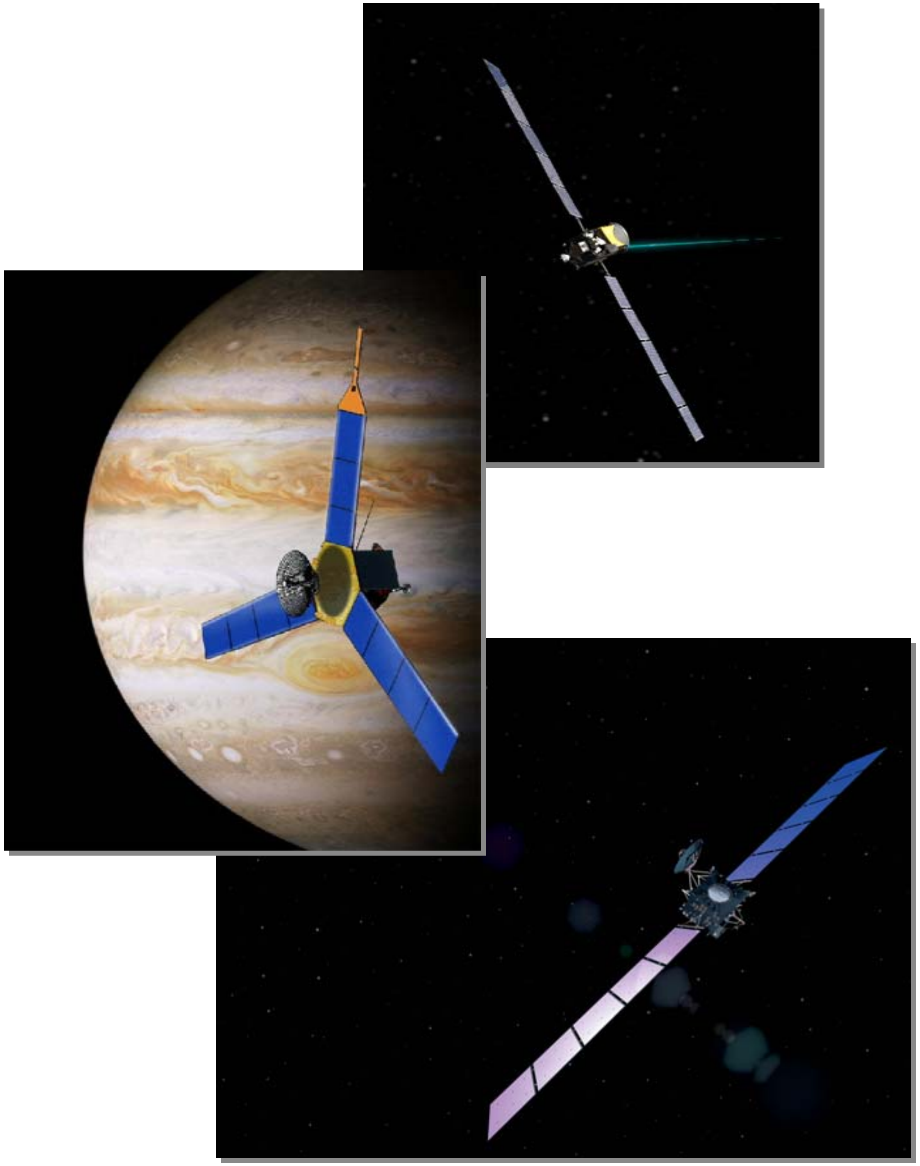
Background & Outline

- Alan Stern request: "…a quick look study for how we could extend the Juno and Rosetta 5 AU-class missions on solar arrays to enable solar array missions at Saturn (10 AU) and Uranus (20 AU)"

- Study Process
- Cell and Array Technology Findings
- Power System Sizing
- Mission and System Integration Studies
- Technology Planning
- Conclusions

Most Distant Use of Solar Arrays

- **Dawn**
  - *36.4 m^2 planar array area*
  - *10.3 kW at 1 AU*
  - *1.3 kW at 3 AU (-88 ℃)*
  - *Triple Junction cells*
- **Juno**
  - *Phase B design*
  - *45 m^2 planar array area*
  - *9.6 kW BOL at 1 AU*
  - *414 W at 5.5 AU (-130 ℃)*
  - *Triple Junction cells*
- **Rosetta**
  - *61.5 m^2 planar array area*
  - *7.1 kW BOL at 1 AU*
  - *400 W at 5.25 AU (-130 ℃)*
  - *Silicon Hi-ETA cells*



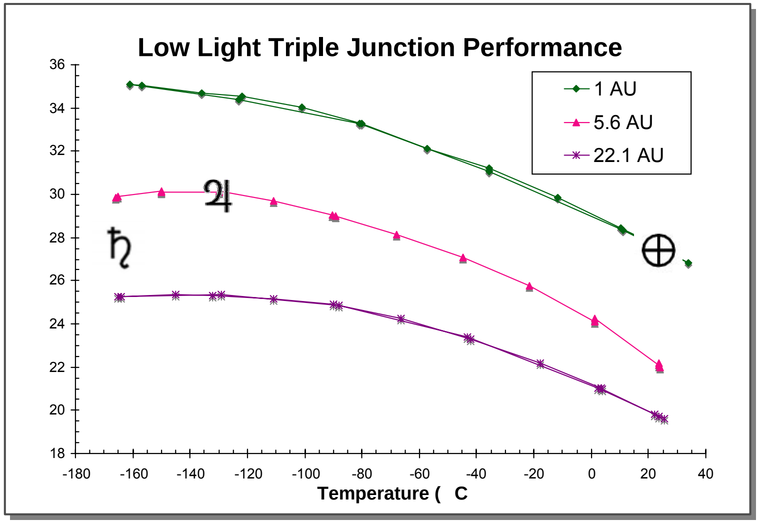
Study Process

- Review prior studies and flight system publications
- Assess PV cell and array technologies
- Understand cell performance in outer planet applications
- Analyze power system performance
- Coordinate with technology, vendor and user community through workshop at Space Photovoltaic Research & Technology (SPRAT)
- Coordinate with Juno project
- Characterize system integration considerations
- Define technology paths

Solar Cell Technology Findings

Solar Cell Capability

- Nominal low intensity, low temperature (LILT) state-of-the-art (SOA) cell performance is viable at 5 AU and beyond
  - *Cell efficiency increases with lower temperature but decreases with lower intensity*



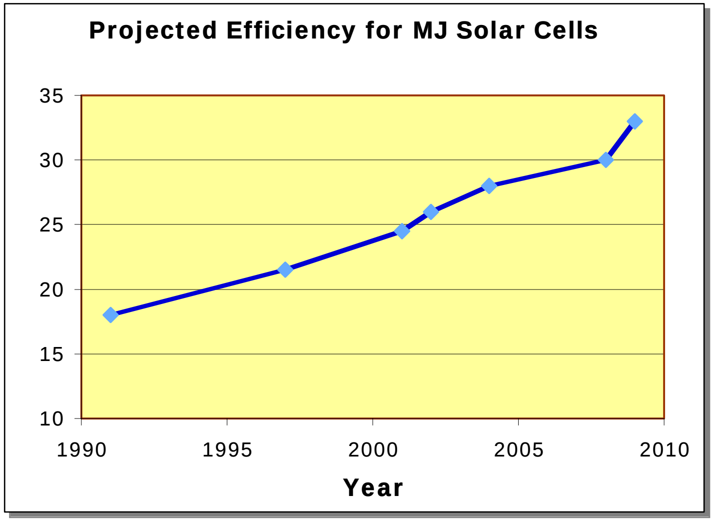
GRC FY07 LILT IRAD testing results

- LILT Effect: off-nominal drop in cell performance, must be mitigated to effectively use solar power in outer solar system
  - *Understood and mitigated on earlier silicon cells*
  - *Effect observed on SOA multi-junction (MJ) cells, cause not yet identified*
    - *Cell-to-cell variation*
  - *LILT Effect can be mitigated:*
    - *Cell screening, optimization or advanced concentrator technology*

- On-going advances in cell technology can provide improvements
  - *NASA will need to adapt those to LILT conditions*

Applicable Technologies – Solar Cells

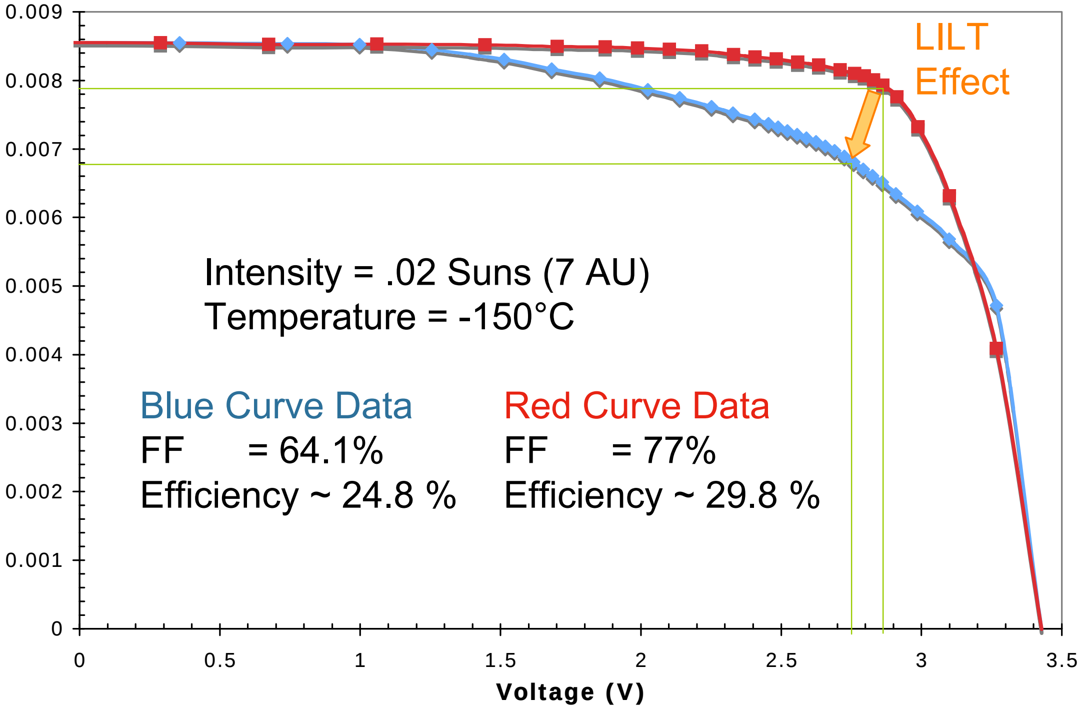
- **State-of-art performance at 1AU (AM0, 25C)**
  - *Multi-junction III-V cells, triple-junction: 28 - 30%*
  - *Silicon: 16 - 19%*
  - *Thin-film: not space-qualified (6 - 10% currently)*
- **Expected advances in cell performance**
  - *Multi-junction: 30 - 33% in next 3 years*
    - *Development pursued by both cell vendors*
    - *Driven by military/commercial applications*
    - *35 - 40% cell design under development*
  - *Multi-junction: mass and cost reduction*
    - *Thinned substrate or no-substrate technology to drastically reduce cell/array mass*
    - *Reusable substrates and improved manufacturing to increase yield and reduce cost*



- **Advanced cell approaches**
  - *Cells designed or optimized for outer solar system missions*
    - *Eliminate LILT Effect in future MJ cell generations*
    - *Optimize cells for bandgap narrowing at low temperatures*
  - *Quantum dots, nanotechnology to increase efficiency*
    - *Far-term: efficiency increase through better utilization of solar spectrum*

Solar Cell LILT Effects

Data collected at GRC on SOA MJ production-line cells



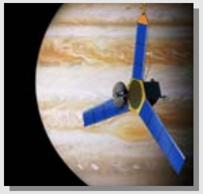
- Cause of LILT Effect has not been identified for multi-junction III-V cell technology
  - *Occurs on a cell-to-cell basis*
  - *Magnitude of effect is not currently predictable*
  - *Little research has been done in this area, none to understand root cause of problem*

LILT Effect Mitigation

Cell Screening

- Successful on Dawn

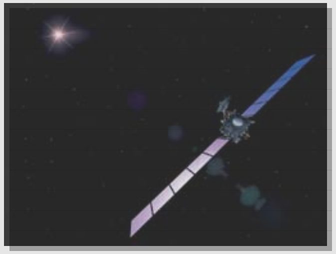
- In progress for Juno



- GRC and Juno data indicate that effect worsens in frequency and magnitude with lowering intensity
- *Cell screening may not be applicable beyond Jupiter*

Cell Optimization

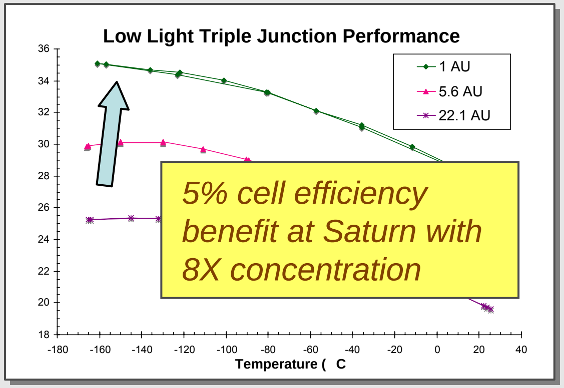
- Silicon cells designed for LILT on Rosetta
  - 5.2 AU, -130 °C



- Future cells could be optimized
  - To eliminate LILT Effect
  - To optimize cell performance and mass for LILT conditions

Concentration

- Maintains intensity
- Minimizes LILT Effect
- Reduces cell count



5% cell efficiency benefit at Saturn with 8X concentration

- Increased spacecraft system effects (pointing requirements)

Array Technology Findings

Advanced Solar Array Technology

- Multiple technical paths exist to extend photovoltaic power use towards the outer solar system

- UltraFlex
  - *Near-term, high maturity*
  - *Baseline for Orion power*
    - *TRL6 by 2009 with subsequent qualification*

UltraFlex Wing

- SquareRigger
  - *Mass competitive at large power levels*
  - *Rectangular bays offer better scaling characteristics*
  - *Compatible with planar and concentrator designs*

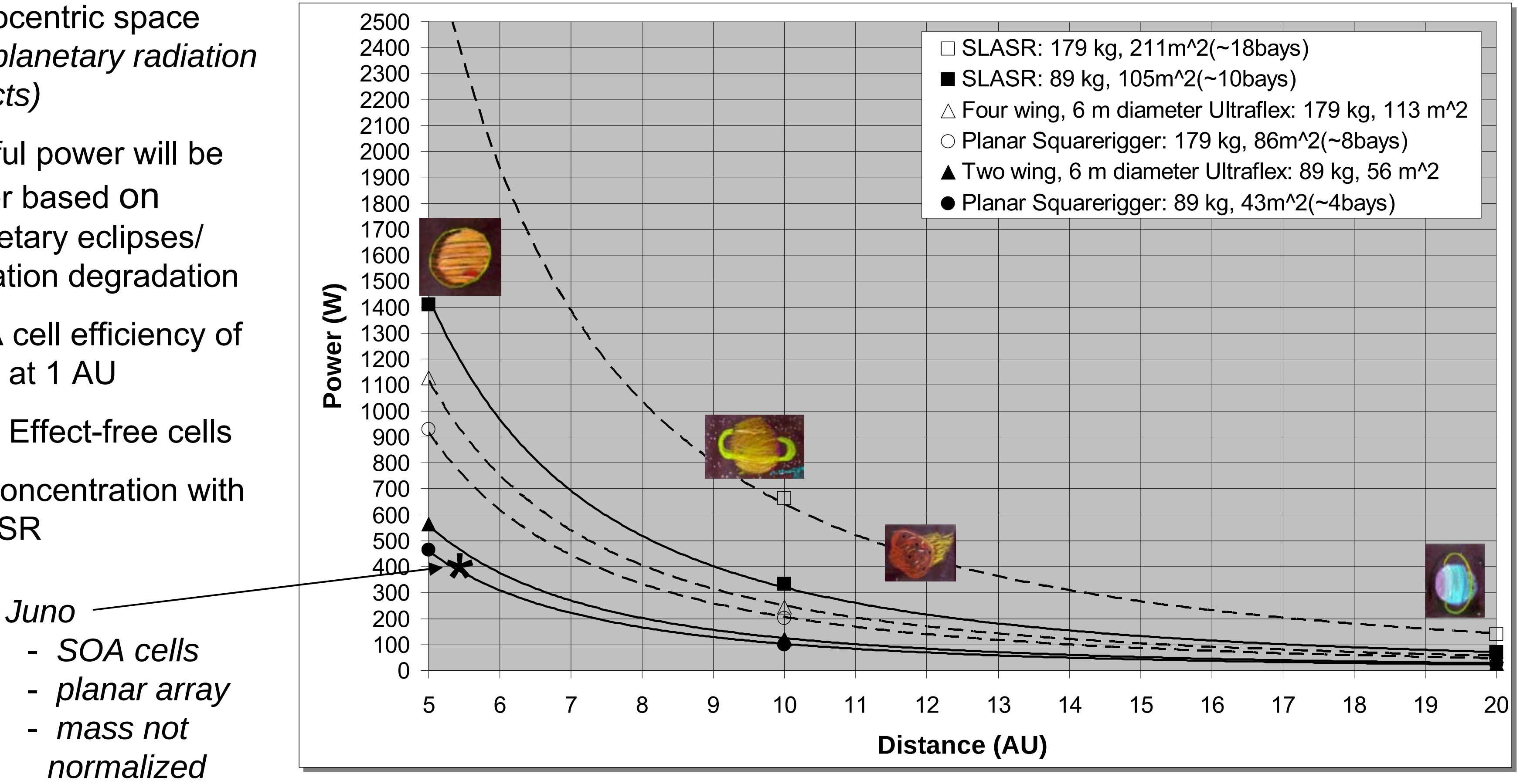
- Stretched Lens Array SquareRigger (SLASR)
  - *Incorporates lightweight linear refractive concentrator derived from Deep Space 1 SCARLET*
  - *SLA component flight demonstration on TACSAT-4*
  - *Can scale to very high power levels*

- Technology development is required:
  - *To extend UltraFlex diameter beyond state-of-art size*
  - *To complete SquareRigger development at the array level*

SLASR Bay
2.5 x 5m

Near Term Capability:
Power from a Fixed Power System Mass

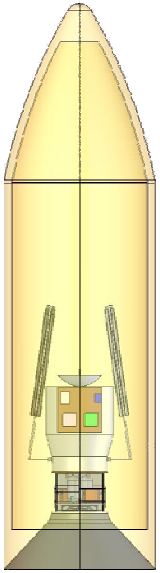
- Heliocentric space *(no planetary radiation effects)*
- Useful power will be lower based on planetary eclipses/ radiation degradation
- SOA cell efficiency of 30% at 1 AU
- LILT Effect-free cells
- 8X concentration with SLASR



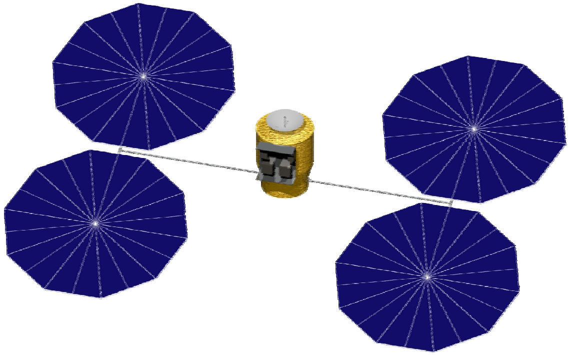
- Solar array options are sized to be the same mass as the two and four wing Ultraflex arrays.
- Solar array mass includes hardware outboard of gimbal
- SquareRigger standard bay size of 2.5 m by 5 m
- 2.5 yr gravity assist period + 2 years at AU location + 2 AU/year transit time

System Integration Considerations

- **Mass impacts of carrying the solar array into deep space**
  - *Additional/larger systems: solar array, batteries, power conditioning systems, pointing systems (larger reaction wheels)*
  - *Heavier thermal systems (lack of RPS waste heat)*
  - *Structures/mechanisms to attach the solar arrays (impact from capture propulsion system)*
  - *Net impact is reduced payload compared to RPS systems*



- **Launch vehicle integration**
  - *Volume constraints in packaging stowed arrays*
- **Spacecraft integration and operations in mission orbit**
  - *Multiple subsystem requirements for pointing and slew*
  - *Possible incompatibilities with science objectives*
- **Power system design**
  - *Maintaining power through eclipse periods*
  - *Radiation tolerant design*
  - *Managing power in inner solar system, when generated power from array can be 10’s - 100’s of kW*



Mission Applications

- A range of missions were considered to encompass power system sizing and spacecraft integration drivers, including:
  - *Heliocentric distance: 5 - 20 AU*
  - *Operations concept & power management: moon orbiters*
  - *Radiation: Jovian moon orbiter*
  - *Simplest missions: flybys*

- Flagship-class
  - *Saturn Orbiter, Titan Orbiter*
  - *Uranus Orbiter*
  - *Ganymede or Europa Orbiter*

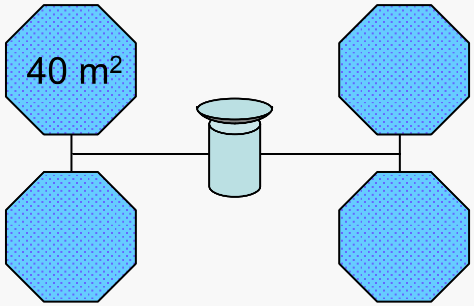
- PI-led
  - *Saturn Flyby*
  - *Centaur Flyby or Rendezvous*

- Saturn Orbiter analyzed in COMPASS team study
  - *Used GSFC Enceladus architecture option Saturn-OL as reference*

- Europa, Centaur and Uranus missions assessed analytically
  - *Representative point analyses performed with selected mission power*

Example: Saturn Orbiter Mission

- **Mission assumptions:**
  - *Titan/Enceladus cycling orbit*
  - *335 W continuous nominal power (per Enceladus study)*
  - *11.5 yr VVEEGA voyage to Saturn*
  - *Saturn and rings eclipse periods*
  - *Total radiation degradation of 15%*
- **Power system design options**
  - *SOA cells/array:*
    - *Nine SLASR bays at 237 kg*
    - *Twelve Planar Squarerigger bays at 470 kg*
    - ***Four, 7.2 m diameter Ultraflex arrays at 415 kg***
  - *Projected cells/array:*
    - *Eight SLASR bays at 205 kg*
    - *Ten Planar Squarerigger bays at 321 kg*
    - *Four, 6.7m diameter Ultraflex arrays at 268 kg*
- **System-level drivers**
  - *COMPASS study performed to assess system drivers, details follow*
- **Technology feasibility**
  - ***Target power level can be achieved with near-term PV technology***



Near-SOA Ultraflex Arrays
SOA MJ Cell Performance

48 kW BOL at 1 AU

Interplanetary voyage

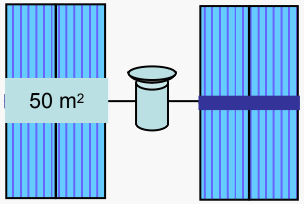
377 W at Saturn arrival

- Planetary radiation
- Energy storage for eclipse periods

335 W EOL power

Other Missions

Europa Orbiter



Advanced SLASR Arrays
SOA MJ Cell Performance

45 kW BOL at 1 AU, 362 kg

Interplanetary voyage

1400 W at Jupiter arrival

- Planetary radiation, 30% total degradation
- Energy storage for eclipse periods

720 W EOL at Europa

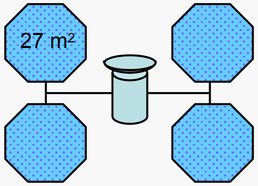
System-level drivers

- Radiation and eclipse power level
- Orbital operations and pointing requirements

Technology feasibility

- ***SLASR and UltraFlex provide feasible paths***
  - Four, 7.0 m diameter Ultraflex arrays at 513 kg
- Requires detailed radiation degradation trade study

Centaur: Echeclus



SOA Ultraflex Arrays
SOA MJ Cell Performance

33 kW BOL at 1 AU, 287 kg

Interplanetary voyage

300 W EOL at Echeclus

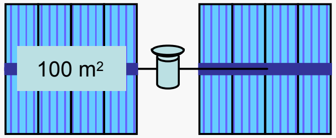
System-level drivers

- Similar to Saturn Orbiter study

Technology feasibility

- ***Target power level can be achieved with near-term PV technology***

Centaur: Chiron



Advanced SLASR Arrays
Projected MJ Cell Performance

95 kW BOL at 1 AU, 327 kg

Interplanetary voyage

200 W EOL at Chiron

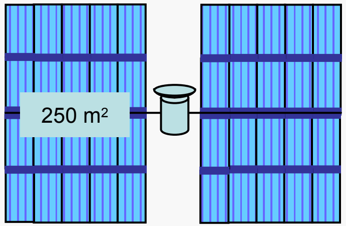
System-level drivers

- Array size amplifies all spacecraft integration considerations

Technology feasibility

- ***Technology is achievable***
- ***Significant changes in spacecraft concept required***

Uranus Orbiter



Advanced SLASR Arrays
Projected MJ Cell Performance

232 kW BOL at 1 AU, 781 kg

Interplanetary voyage

400 W EOL at Uranus

System-level drivers

- Array size amplifies all spacecraft integration considerations

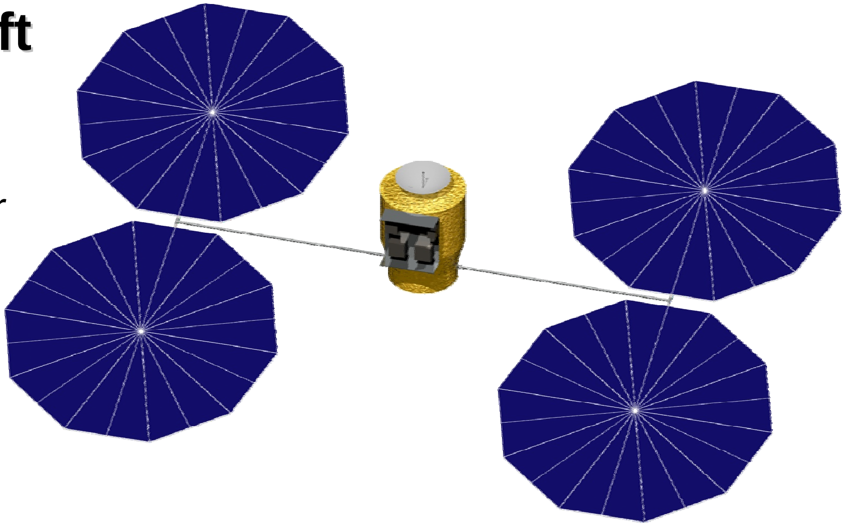
Technology feasibility

- ***Significant changes in spacecraft concept required***

Solar Saturn Probe Design Study

- **Reference ASRG-powered spacecraft**
  - *Power: 335 W*
  - *3 ASRGs*
  - *Science payload: ~1000 kg, includes lander*

- **Solar-powered spacecraft**
  - *48 kW solar arrays at 1AU*
  - *Science payload: ~550 kg*

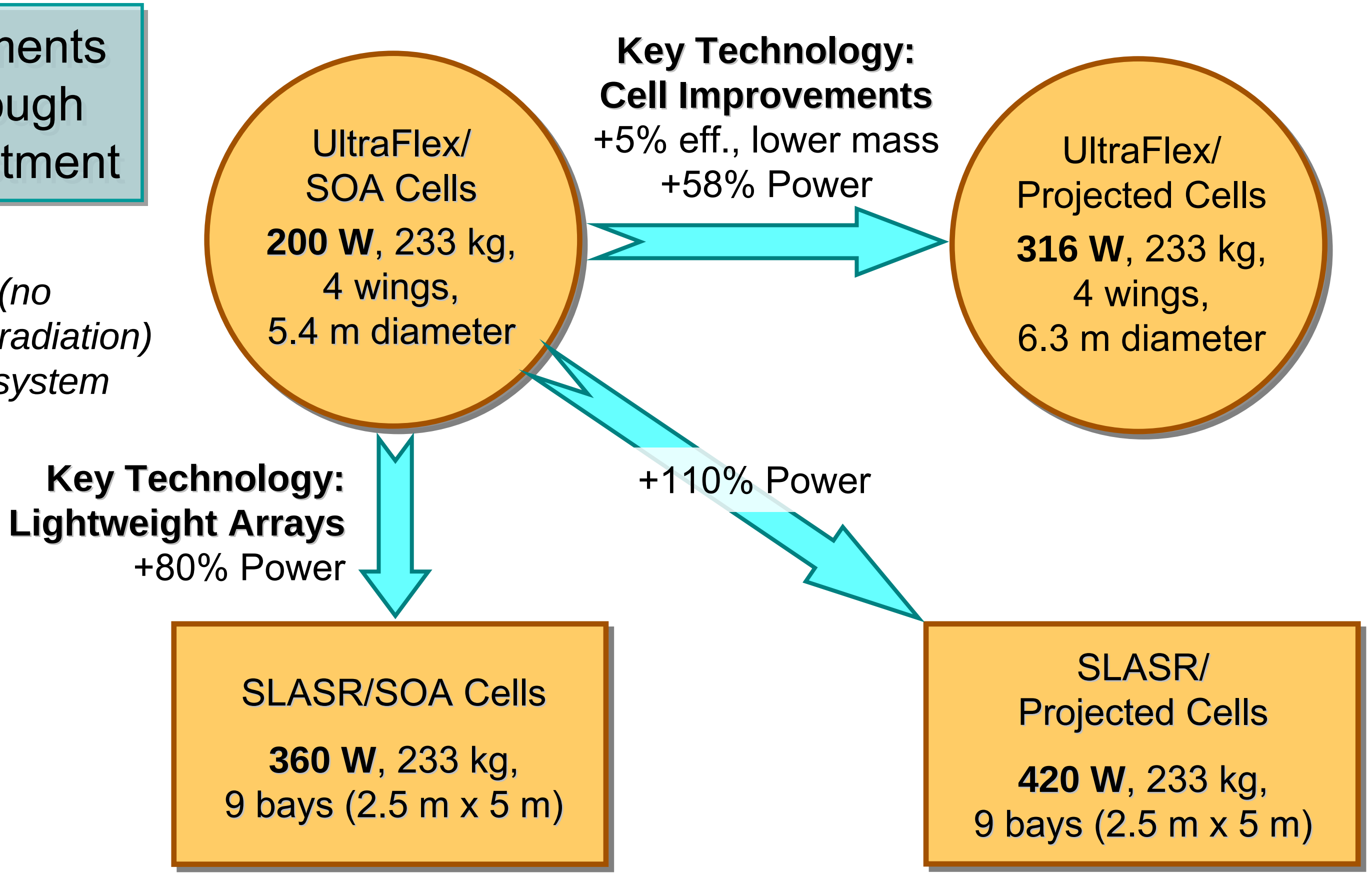


Solar Powered Subsystem	Mass Change Compared to RPS probe	Cause
Payload	- 450 kg	Increase in bus subsystems mass
Power	+ 340 kg	Solar arrays, mechanisms, PMAD
ACS	+ 30 kg	Heavier wheels (ACS propellant increased)
C&DH/Comm	+ 15 kg	Increase in pointing, more complex spacecraft operations
Thermal	+ 30 kg	Additional blankets, heaters, RHUs due to lack of waste heat for RPS
Structures	+ 30 kg	Solar array booms

Technology Leverage Summary

Power improvements achievable through technology investment

*Power at **Saturn**:*
- *Interplanetary-only (no eclipses, planetary radiation)*
- *Fixed mass power system*



UltraFlex/
SOA Cells
200 W, 233 kg,
4 wings,
5.4 m diameter

Key Technology:
Cell Improvements
+5% eff., lower mass
+58% Power

UltraFlex/
Projected Cells
316 W, 233 kg,
4 wings,
6.3 m diameter

Key Technology:
Lightweight Arrays
+80% Power

+110% Power

SLASR/SOA Cells
360 W, 233 kg,
9 bays (2.5 m x 5 m)

SLASR/
Projected Cells
420 W, 233 kg,
9 bays (2.5 m x 5 m)

Underlying Development and Technologies
- *Qualify UltraFlex for low temperature application*
- *LILT Effect Evaluation for MJ Cells*
- *Blanket Technologies for Low Temperature Conditions*

Conclusions

- Near-term Ultraflex arrays and SOA multi-junction cells can provide capability to perform low power (200-300 W) missions out to 10 AU
  - *300 W mission to an inner Centaur appears achievable*
- Further investigation of LILT Effect is warranted if PV power is to be considered for more demanding outer planet missions
  - *LILT Effect can be avoided through multiple approaches*
- Advanced cell and array technologies would extend the practical application of PV power through mass and efficiency benefits
  - *Clear technology paths exist to enhance PV application to outer planet missions*
- Implementation of PV power will decrease payload mass
- Feasibility of PV use critically depends on mission and spacecraft concept