

Solar Power for Outer Planets Study





Presentation to Outer Planets Assessment Group
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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

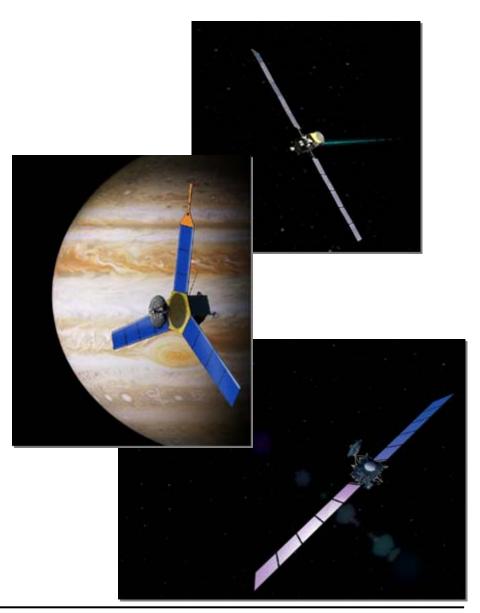
- 36.4 m² planar array area
- 10.3 kW at 1 AU
- 1.3 kW at 3 AU (-88 ℃)
- Triple Junction cells

Juno

- Phase B design
- 45 m² planar array area
- 9.6 kW BOL at 1 AU
- 414 W at 5.5 AU (-130 °C)
- Triple Junction cells

Rosetta

- 61.5 m² planar array area
- 7.1 kW BOL at 1 AU
- 400 W at 5.25 AU (-130 °C)
- Silicon Hi-ETA cells



Study Process



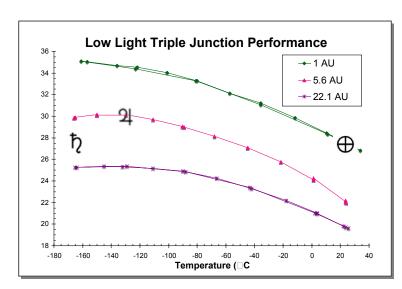
- Review prior studies and flight system publications
- Assess PV cell and array technologies
- Understand cell performance in outer planet applications
- Analyze power system performance
- Coordinate with technology, vendor and user community through workshop at Space Photovoltaic Research & Technology (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
- LILT Effect: off-nominal drop in cell performance, must be mitigated to effectively use solar power in outer solar system



GRC FY07 LILT IRAD testing results

- 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

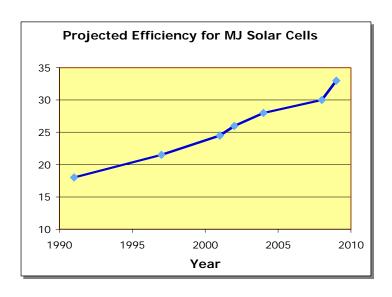


State-of-art performance at 1AU (AM0, 25C)

- 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



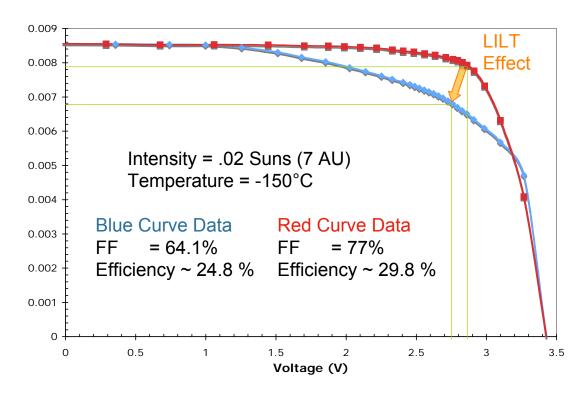
Advanced cell approaches

- 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-



- 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

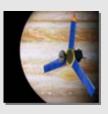


Cell Screening

 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

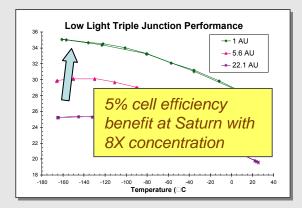
- Silicon cells designed for LILT on Rosetta
 - 5.2 AU, -130 °C



- 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



Increased spacecraft system effects (pointing requirements)

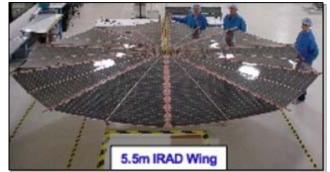
Array Technology Findings



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
- 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



UltraFlex Wing



SLASR Bay 2.5 x 5m

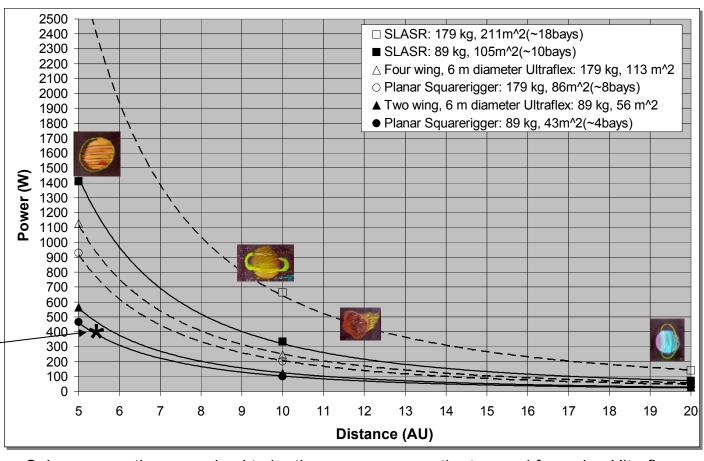
Near Term Capability: Power from a Fixed Power System Mass



- 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**

Juno

- SOA cells
- planar array
- mass not normalized



- 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

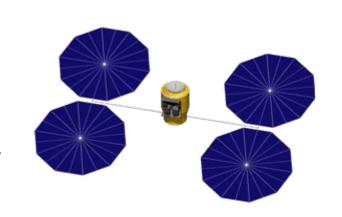
Volume constraints in packaging stowed arrays

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

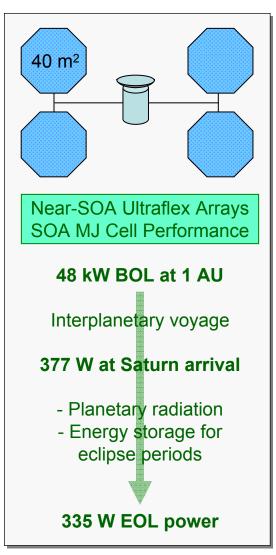
- SOA cells/array:
 - Nine SLASR bays at 237 kg
 - Twelve Planar Squarerigger bays at 470 kg
 - Four, 7.2 m diameter Ultraflex arrays at 415 kg
- Projected cells/array:
 - Eight SLASR bays at 205 kg
 - Ten Planar Squarerigger bays at 321 kg
 - Four, 6.7m diameter Ultraflex arrays at 268 kg

System-level drivers

 COMPASS study performed to assess system drivers, details follow

Technology feasibility

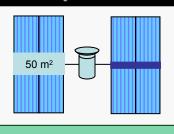
Target power level can be achieved with near-term PV technology



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

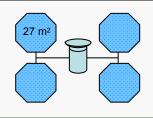
System-level drivers

- 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

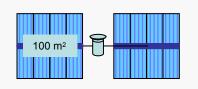
System-level drivers

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

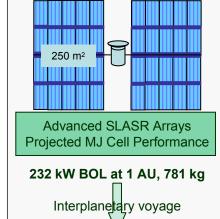
System-level drivers

 Array size amplifies all spacecraft integration considerations

Technology feasibility

- Technology is achievable
- Significant changes in spacecraft concept required

Uranus Orbiter



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

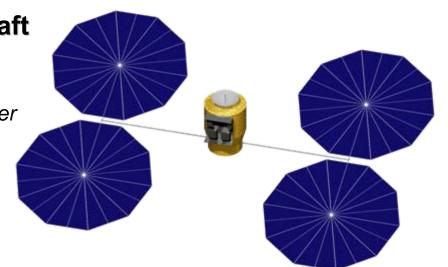
Power: 335 W

- 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

Key Technology: Cell Improvements +5% eff., lower mass UltraFlex/ UltraFlex/ +58% Power **SOA Cells Projected Cells** 200 W, 233 kg, 316 W, 233 kg, 4 wings, 4 wings, 5.4 m diameter 6.3 m diameter **Key Technology:** +110% Power **Lightweight Arrays** +80% Power SLASR/ SLASR/SOA Cells **Projected Cells**

360 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

420 W, 233 kg,

9 bays (2.5 m x 5 m)

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