Solar Array Structures for 300 kW-Class Spacecraft

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Need: Solar Electric Propulsion (SEP) for cost-effective transfer of cargo (and possibly crew) beyond LEO. SEP is ~10x more fuel-efficient than chemical.

Goal: Develop mass- and volume-efficient solar array structures >> in size than SOA for proposed exploration and science SEP missions.

Objectives: Mature key technologies to TRL 5+. In the near term, develop 30-50 kW designs for in-space demonstration by 2018. Far term objective is 300+ kW arrays.
ISS Solar Array Blanket – 150 m²
A 300 kW solar array needs ~10x this area
## Assumptions/Goals for 300 kW-Class Solar Arrays

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<tbody>
<tr>
<td><strong>Power</strong></td>
<td>• 450 kW BOL &lt;br&gt;• 300 kW EOL, assuming 33% worst-case degradation</td>
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<tr>
<td>Deployed area (2 wings)</td>
<td>1500 m², assuming 300 W/m² BOL or 200 W/m² EOL</td>
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<tr>
<td>Deployed stiffness</td>
<td>&gt; 0.05 Hz</td>
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<tr>
<td>Deployed strength</td>
<td>&gt; 0.1 g (chemical stage thrusting in some SEP missions)</td>
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<td>Specific power</td>
<td>&gt; 120 W/kg BOL (&gt; 100 W/kg EOL), including SADA</td>
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<tr>
<td>Stowed volume</td>
<td>&gt; 40 kW/m³ BOL</td>
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<td>Voltage</td>
<td>160-300+ V</td>
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<tr>
<td>Blanket</td>
<td>Flexible substrate, assuming &lt; 1 kg/m² areal density, 0.030” thick</td>
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<td>Planar vs concentrators</td>
<td>Assuming planar arrays will be used</td>
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<tr>
<td>Deployment reliability</td>
<td>Goal: “100%” – Deployment is highest perceived project risk</td>
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NASA “Game Changing” Activities for 30-300 kW Solar Array Structures

**State-of-the-Art**

- **ATK UltraFlex**
  - 14 kW array

- **DSS ROSA**
  - 20 kW (for 2 wings)

**18-month NRA Contracts**

- **ATK MegaFlex**
  - 30-50 kW Prototype

- **DSS Mega-ROSA**
  - 30-50 kW Prototype

**300 kW Solar Arrays (1500 m²) Technology Development**

- **ATK MegaFlex**
- **DSS Mega-ROSA**
- **300 kW Government Reference Array**

**Government Team Focus Areas:**

- Insight & Oversight of ATK & DSS Tech Work
- IV&V of Contractor 30-50 kW Phase I Designs
- Extensibility of 30-50 kW Designs to 300 kW
- Ground Test Support (Plum Brook & Boeing)
- Structural Concepts
- Scaling and Performance Metrics
- Modeling, Simulation, and Advanced Analysis
- Development of 300 kW Govt Reference Array
Structures for Large Solar Arrays

• **Challenge** - Scaling up solar array power by an order-of-magnitude to ~300 kW requires game changing advances in
  - structural mass fraction
  - packaging, and
  - deployment reliability

• **Goal/Objective** – Develop and validate array structural concepts with a
  - structural mass fraction of 0.2 or lower and a
  - power/packaging volume ~ 25 to 40 kW/m³

• Need rational method to compare arrays on a level playing field

• Major question is how reliably results scale
Develop:

- **Performance metrics** that enable a rational comparison of array concepts over a wide range of sizes and requirements
  - Mass, volume, deployment reliability
- **Government Reference Array** (GRA)
  - Intended as a bellwether for very low mass and stowage volume solar arrays
  - Provide comparison with contractors concepts
  - Establish understood array performance limits
- **Analytical simulations** to substantiate structural and deployment system-level array behavior
- **Scaled validation tests** of critical array structural characteristics identified in analytical simulations
Major Challenge to Achieving High Structural Efficiency is the Compact Packaging Requirement

250 kW
4 Launches + EVA
8 Winglets

300 kW
1 Launch, No EVA
16 Winglets
Technologies for Improving Array Structural Mass Fraction and Packaging Volume

- **Structural Form**
  - Tensioned arrays
  - Concentrated compression loads
  - Modular construction
  - Guy stiffening as needed

- **Very high modulus composites**

- **Trade structures and controls requirements**
  - Reduce required natural frequency
  - Allow arrays to feather during periods of high acceleration

- **Lightweight deployment mechanisms**

- **Discard no longer needed hardware (staging)**
Good Structural Form is Key to Structural Efficiency

Channel (concentrate) all Loads Into one Major Support Structure
300 kW GRA Stowed Configuration

Stowed GRA inside Falcon 9 allowable payload volume

Spacecraft
(2.6 m x 2.6 m)

4.6 m diameter

2.1 m

2.6 m

0.65 m

11.4 m

6.6 m
300 kW GRA Deployment Sequence

Stowed Configuration

Wings Unfolded
300 kW GRA Deployment Sequence

Trunk Beam Partially Extended
300 kW GRA Deployment Sequence

Trunk Beam Fully Extended

Blanket Tube Stacks Initially Vertical
Begin Winglet Deployment

Blanket Tube Stacks Rotate to Horizontal Position
300 kW GRA Deployment Sequence

Blanket Tube Partially Extended
300 kW GRA Deployment Sequence

Blanket Tube Fully Extended
300 kW GRA Deployment Sequence

Blanket Deployment
300 kW GRA Deployment Sequence

Blanket Fully Deployed
Single Winglet Physical Properties

Blankets
- Tension = 88.96 N (20 lbs)
- $t = 0.762$ mm (0.03 in)
- $E = 3.45$ GPa (0.5 Msi)
- $\rho = 1281.6$ kg/m$^3$ (0.0463 lb/in$^3$)

Trunk Beam (rectangular tube)
- $w = 152.4$ mm (6.0 in)
- $h = 304.8$ mm (12.0 in)
- $t = 1.524$ mm (0.06 in)
- $E = 140$ GPa (20.3 Msi)
- $\rho = 1993.0$ kg/m$^3$ (0.072 lb/in$^3$)

Blanket Tube (square tube)
- $w = 101.6$ mm (4.0 in)
- $h = 101.6$ mm (4.0 in)
- $t = 1.27$ mm (0.05 in)
- $E = 140$ GPa (20.3 Msi)
- $\rho = 1993.0$ kg/m$^3$ (0.072 lb/in$^3$)

End Support Beam (circular solid)
- $R = 76.2$ mm (3.0 in)
- $E = 140$ GPa (20.3 Msi)
- $\rho = 64.0$ kg/m$^3$ (0.0023 lb/in$^3$)
Tension Stiffening Could be Added to Winglets or Trunk Beam as Necessary
Portable Tension Supported Video Camera Support Cranes
Summary of 300 kW Government Reference Array Design Features

- Folded box beam members
- High-modulus composites
- No restrictions on beam wall thickness (not rolled)
- Trunk beam doubles as winglet base
- Dual blanket/single-boom winglet configuration (like ISS)
- Cable stiffening of winglets and/or trunk beam as needed
- 300 kW EOL / 450 kW BOL “easily” fits on Falcon 9
- Configurable to meet requirements
- Intended as a bellwether for very low mass and stowage volume solar arrays
Idealized Solar Array Structure Selected as a Baseline for Performance Comparison

- Assume array blanket mass is distributed along the beam
- Provide baseline against which other arrays can be compared
Baseline Solar Array **Four Governing Equations** and **Four Unknowns**

\[
\begin{align*}
\text{Ms} &= n \pi R t L \rho, \\
\frac{\text{Ms}+\text{Ma}}{L} &= a g osf L^2, \\
\gamma \frac{\text{Ec} t}{R} &= \frac{m R}{n \pi R^3 t}, \\
\frac{cf}{2 \pi} &= \sqrt{\frac{\text{Ec} n \pi R^3 t}{(\text{Ms} + \text{Ma}) L^3}}.
\end{align*}
\]

\[
\text{Solve} \left\{ \right. \}
\]

1 - Structural mass eq.

2 - Structural moment due to inertial loading

3 - Wall buckling due to moment

4 - Array natural frequency

**Solve in Mathematica**
Array Structural Mass Equation Showing Functional Dependence on Major Parameters

\[ M_{Structure} = \frac{2 a^{2/5} f^{2/5} g^{2/5} n^{2/5} 4/5}{cf^{2/5} E^{3/5} 2/5} L^2 M^{3/5}_{Blanket} \]

Re-arrange equation to obtain the structural performance metric, \( M_S/M_{Bl} \)

\[ \frac{M_{Structure}}{M_{Blanket}} = \frac{2 g^{2/5} n^{2/5} 4/5}{cf^{2/5} 2/5} \cdot \frac{E^{3/5}}{M_{Blanket}^{1/5} L^{2/5}} \]

- Shape parameter
- Material parameter
- Loading parameter
Select Solar Array Parameters for a Baseline Mass Curve

Composite Tube

\[ E_c = 68.9 \times 10^9 \text{ Pa} \quad (10 \times 10^6 \text{ psi}) \]
\[ r_c = 1660 \text{ kg/m}^3 \]

Frequency = 0.1 Hz

Acceleration = 0.2

FS = 1.5

Dynamic overshoot factor = 2
Solar Array Structure Mass Fraction Trend is to Increase With Acceleration and Frequency

\[
\frac{M_{\text{Structure}}}{M_{\text{Blanket}}} = \frac{a f^{1/5}}{M_{\text{Blanket}}} \div L
\]

Mass Parameter

Baseline Mass Curve

Loading Parameter
Current Program Goal Provides Game Changing Increases in Solar Array Power per Unit Volume

![Graph showing solar array power per volume vs. a parameter](image-url)

- **Program Goal**
- **Sandwich Array Designs**
- **Government Reference Array**
- **Dawn PUMA**
- **Space Station Array**
Concluding Remarks

- Mass performance metrics established
- Array data needed for level playing field comparison:
  - Natural frequency
  - Acceleration capability
  - Overshoot factor used if any
  - Structural factor-of-safety
  - Blanket mass and dimensions
  - Array packaging volume

*It would be desirable if this data were not proprietary

- 300 kW government reference array developed
  - Bellwether for structural mass fraction & packaging volume
  - Major effort remaining to develop and validate a viable reliable deployment system