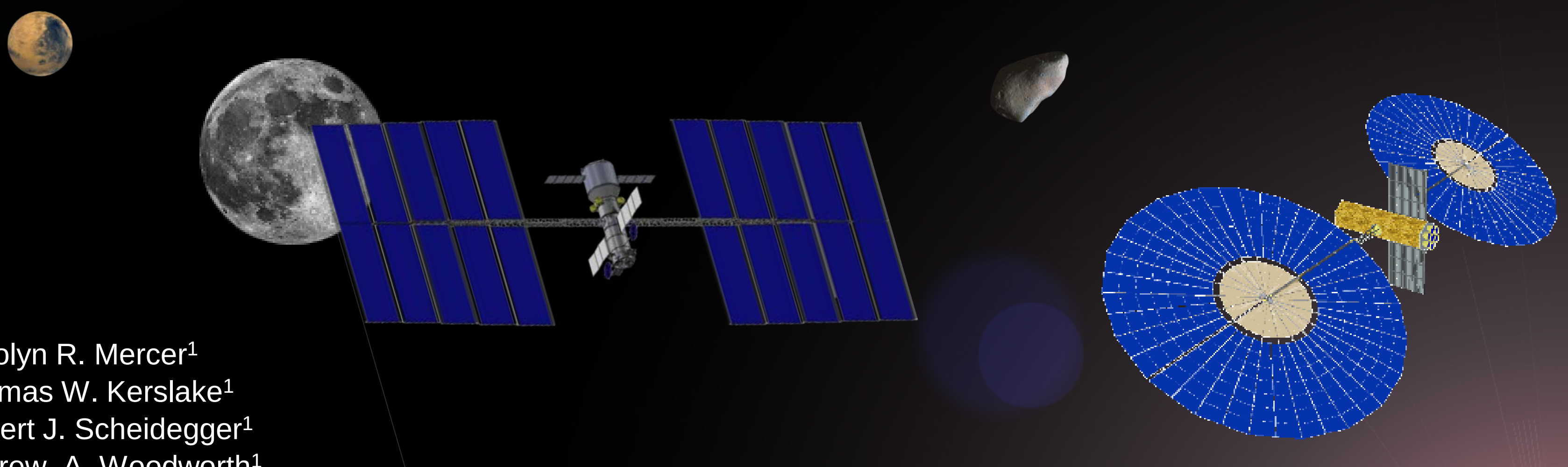
National Aeronautics and Space Administration

Solar Electric Propulsion Technology Development for Electric Propulsion

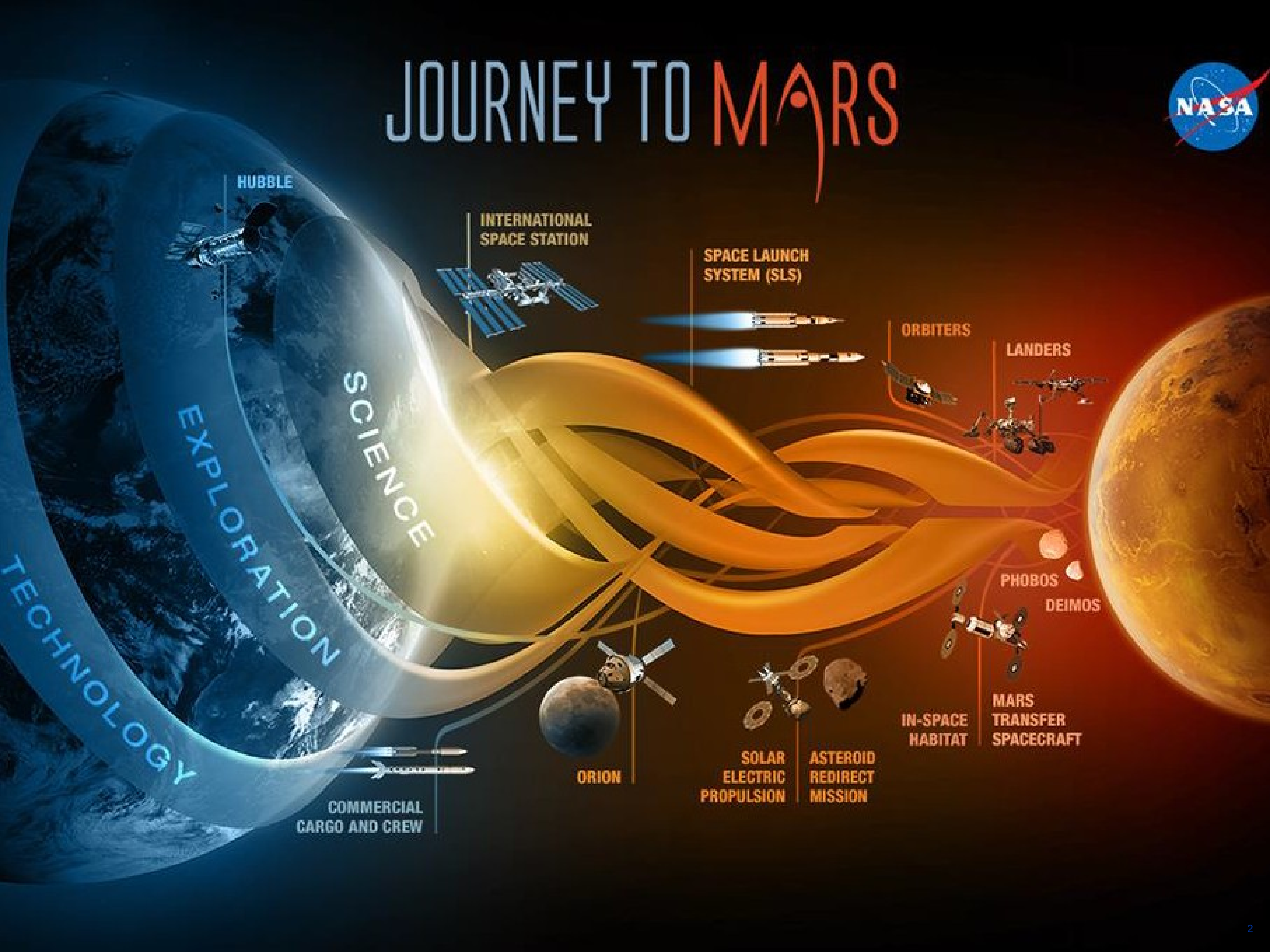
Space Power Workshop | Huntington Beach, CA | May 11-14, 2015



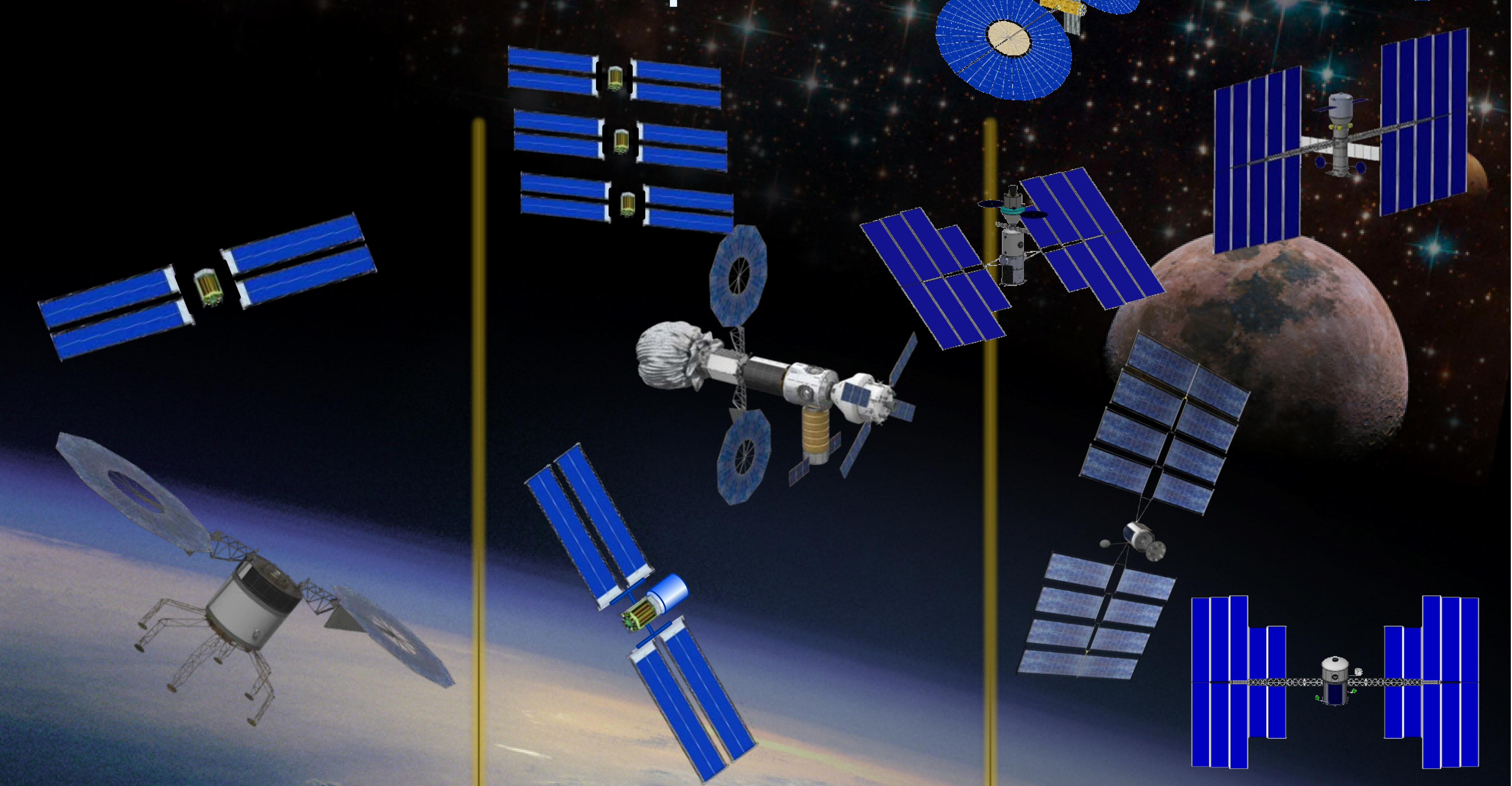
Carolyn R. Mercer[1]
Thomas W. Kerslake[1]
Robert J. Scheidegger[1]
Andrew A. Woodworth[1]
Jean-Marie Lauenstein[2]

[1]**NASA Glenn Research Center**
Cleveland, Ohio
[2]**NASA Goddard Space Flight Center**
Greenbelt, Maryland
cmercer@nasa.gov

www.nasa.gov


JOURNEY TO MARS
NASA
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
MARS TRANSFER SPACECRAFT
IN-SPACE HABITAT
ASTEROID REDIRECT MISSION
SOLAR ELECTRIC PROPULSION
ORION
COMMERCIAL CARGO AND CREW

Solar Electric Propulsion: Extensible for Human Exploration



PUSHING THE BOUNDARIES

(~50 kW solar)

- Asteroid Redirect Mission

DEMONSTRATE EARTH INDEPENDENCE

(~200 kW solar)

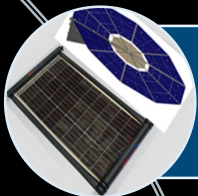
- Mars Orbit, Mars Moons

ONWARD TO MARS

(>400 kW solar)

- Mars Surface

Solar Electric Propulsion Technologies: Challenges to extend to very high power levels



Solar Array Structures

- Large deployed area, small stowed volume, high strength and stiffness

Photovoltaic Coupons

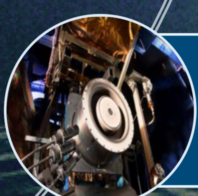
- Robust operation at high voltage near thruster plasma

High Power Electronic Parts

- High voltage, high power, low losses, radiation tolerant

Power Processing Units

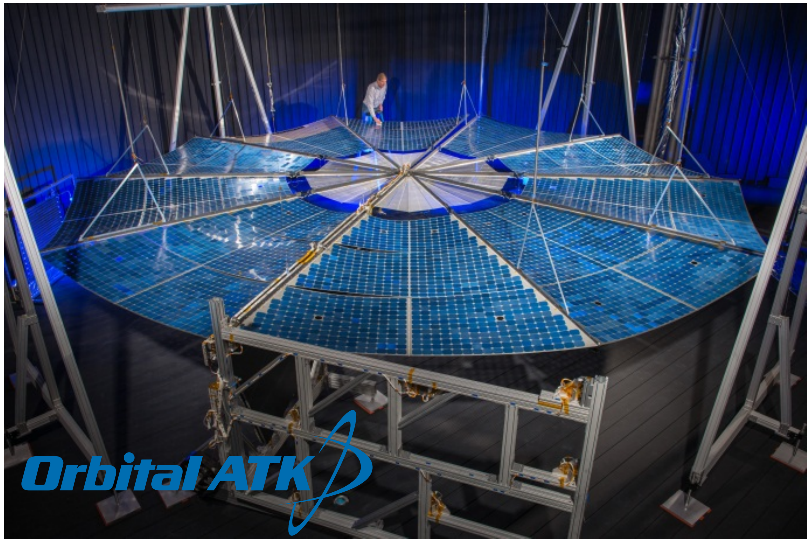
- High voltage, high power

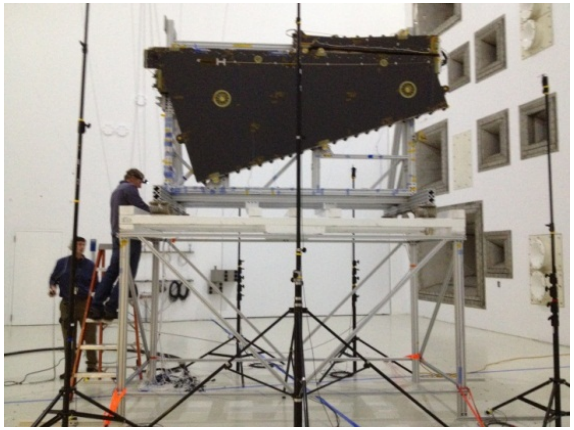


Hall Effect Thrusters

- Long life, high throughput, high power

Solar Array Structures Technology Development





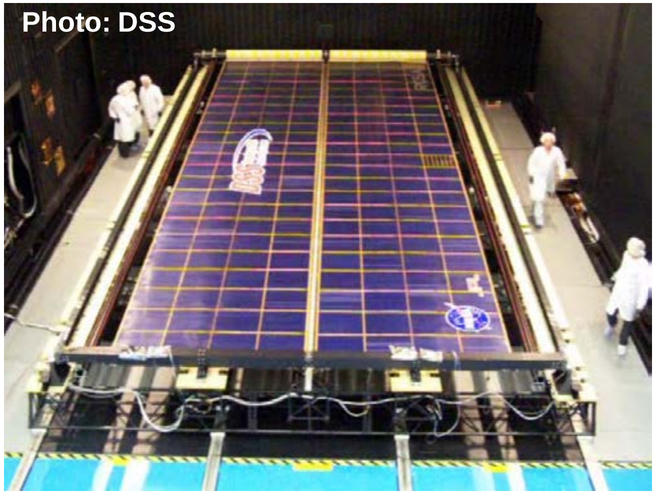
MegaFlex Engineering Development Unit (EDU) employs an innovative spar hinge to reduce stowed volume. Alliant Technical Systems (ATK)

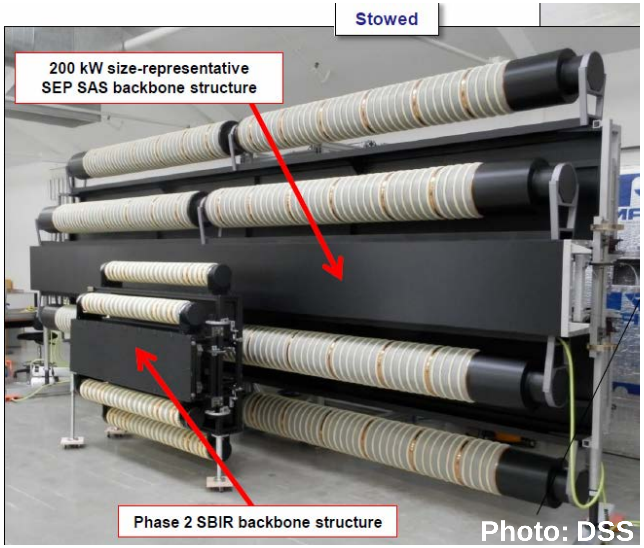
ROSA Engineering Development Unit (EDU) employs an innovative stored strain energy deployment to reduce the number of mechanisms and parts. Deployable Space Systems (DSS)

Novel Solar Arrays sized for nominally 20kW/wing BOL

Ready for development for flight missions

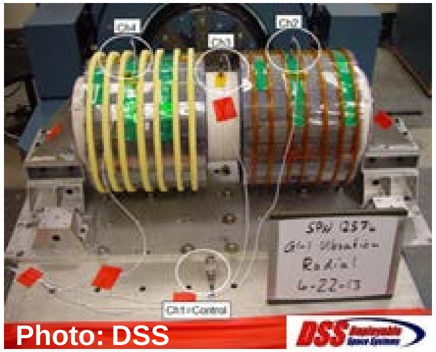
Solar Array Structures – Mega-ROSA Technology Development



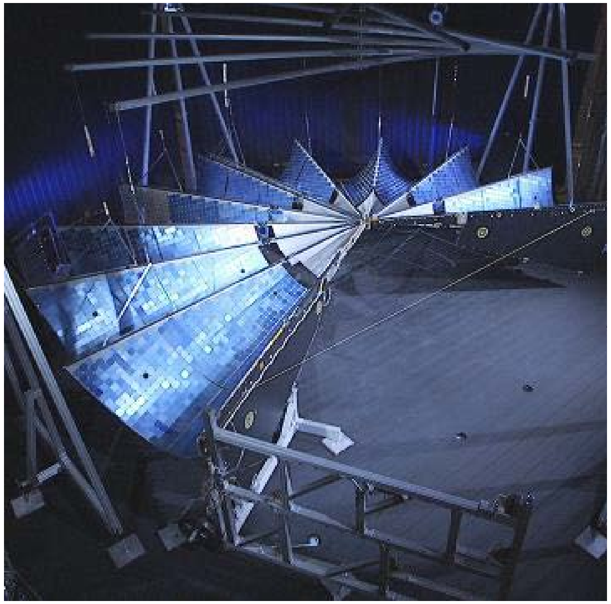


Tests:
- Wing thermal vacuum deployment
- Wing vacuum deployed dynamics
- Subsystem random vibe testing
- Deployed modes/frequencies validated with test data
- Backbone: hot/cold deployments

Models:
- Deployed dynamics and thermal models –
  - winglet, backbone, and integrated
- Stowed structural
- Boom detailed structural
- Backbone deployment kinematics



Solar Array Structures – MegaFlex Technology Development



Tests:
- Wing thermal vacuum deployment
- Wing vacuum deployed dynamics
- Zero-G deployment dynamics
- Deployed modes/frequencies validated with test data
- Deployed and Deploying strength testing

Models:
- Deployed dynamics
- Deploying dynamics
- Deployed thermal
- Stowed structural

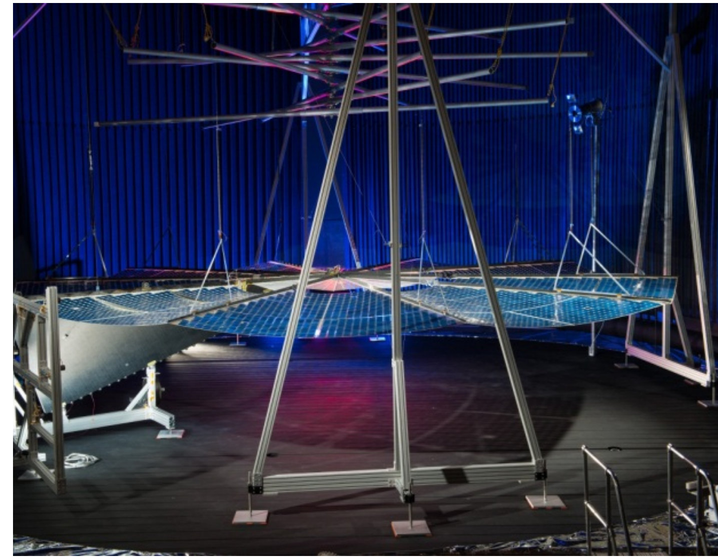


Photo: Orbital ATK

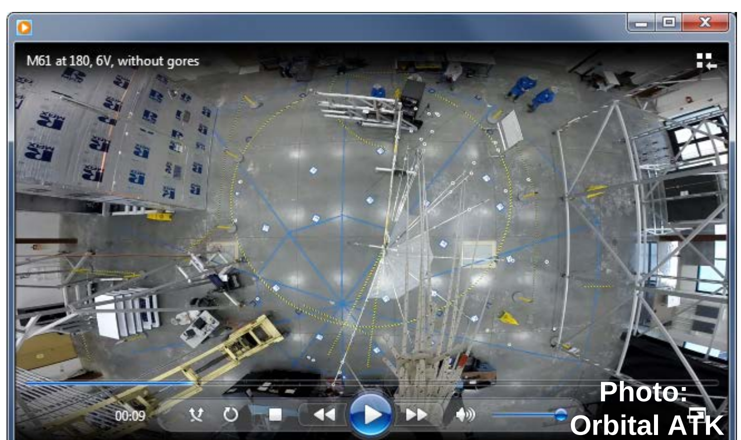
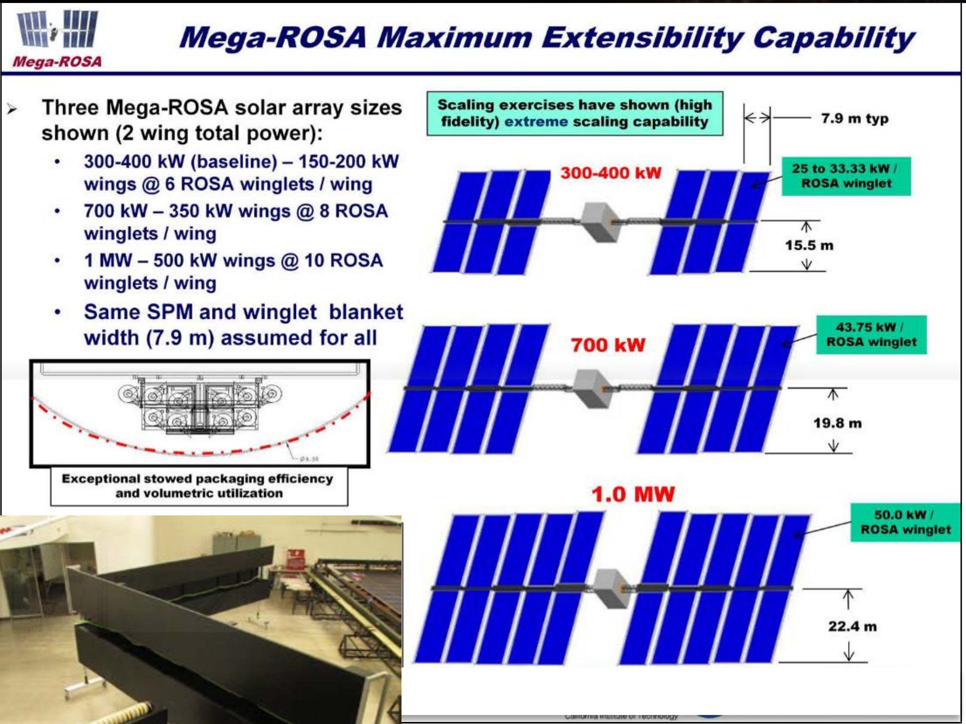


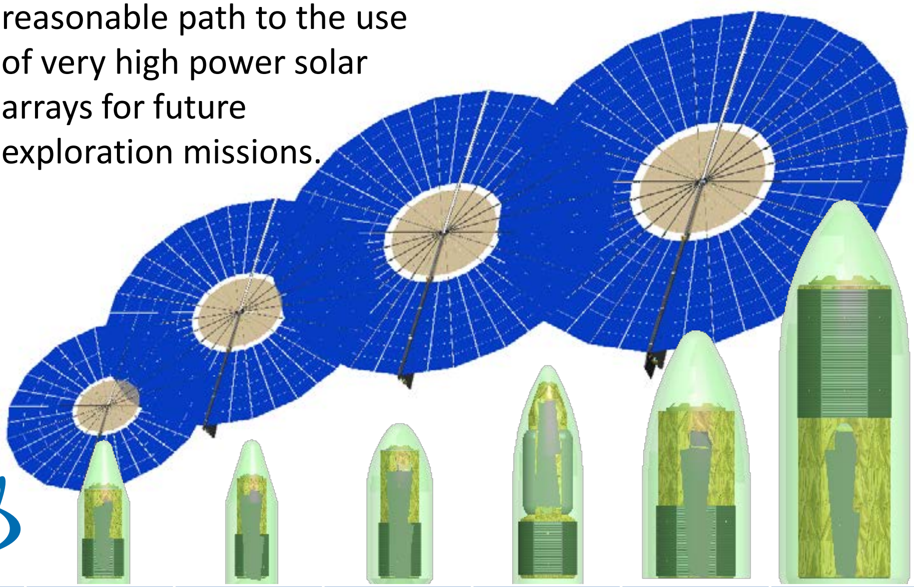
Photo: Orbital ATK

Solar Array Structures Scalability



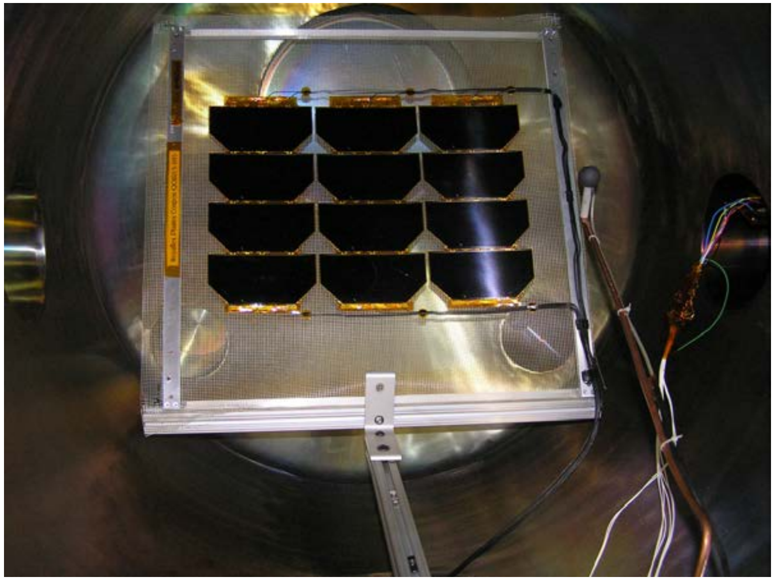
Component sub-assembly and system configuration concepts were developed and structural analyses were done to asses the scalability of a nominally 50 kW power system to much higher power levels.

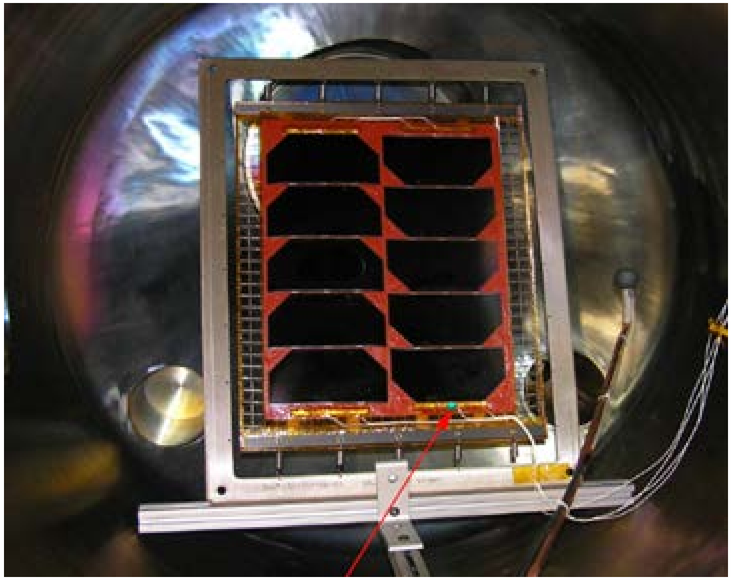
These studies and demonstrations show a reasonable path to the use of very high power solar arrays for future exploration missions.



Fairing Class Fairing Diameter	Delta IV 4-m	Delta IV 4-m	Falcon 9 5.2-m	Ariane5 5.4-m	SLS PF1B 8.4-m	SLS PF2 10-m
Wing Diameter (m)	15	20	**25**	25	30	30
Array Power Class (kW, IMM)	105	190	**300**	300	440	440

Photovoltaic Coupon Technology Development





- Photovoltaic coupon samples were tested under conditions representative of those expected at the 45 degree keep out zone of Hall effect thrusters.

- The testing showed that mounting designs exist such that there is negligible current collection under a +600V bias, and no sustained arcing at a -600V bias, and no damage to the cells.

- Dark and/or Light I-V testing and Electroluminescence testing confirmed no damage to the PV cells after acoustic/vibration testing and thermal vacuum wing deployment.

D.M Goebel, et al. Spacecraft Charging Technology Conference 2014

Electronic Parts
Benefits of high voltage, wide bandgap devices

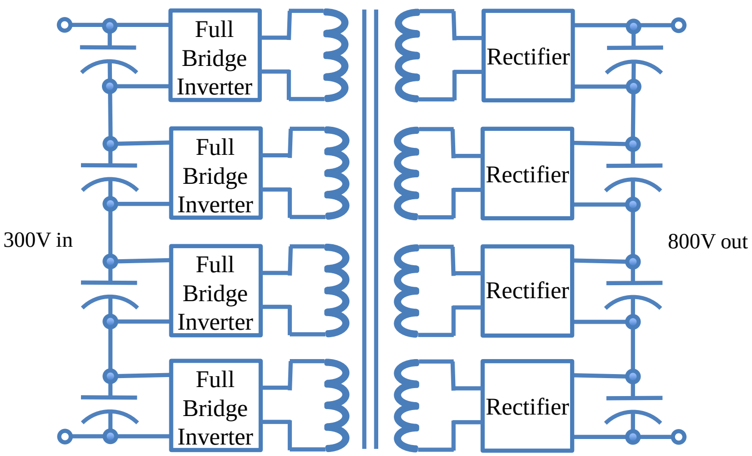
300V vs 120V for 400 kW SEP

~1250 kg dry mass savings from reduced wiring harness (~2500 kg at the system level)
~2200 kg dry mass savings with direct drive

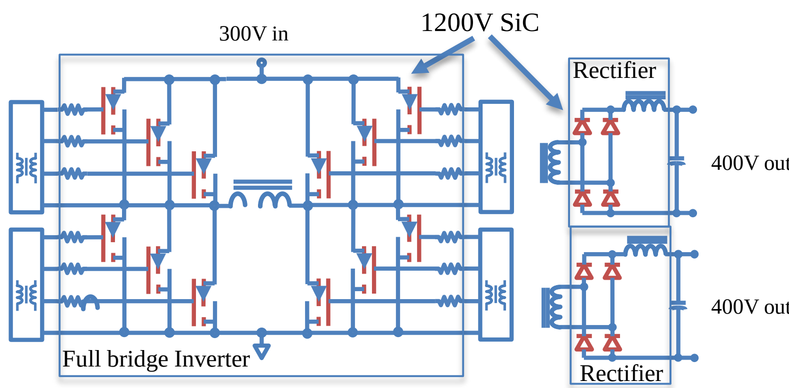
Technology "A"as compared to...	...Technology "B"	Vehicle Mass Impact (kg)	Mass Impact
300 VDC Power Bus Feeding DDU	120 VDC Power Bus Feeding PPU	4394 savings	HH
300 VDC Power Bus Feeding PPU	120 VDC Power Bus Feeding PPU	2457 savings	HH
DDU (requires >=300VDC Power Bus)	PPU @ 300 VDC	1937 savings	H
One 3m COPV Xe tank	Four 1.6x2.8m COPV Xe tanks	2797 savings	HH
Active Cooling for Xe Tanks	Passive Cooling for Xe Tanks	1693 savings	H
37% PV Cell Efficiency	29% PV Cell Efficiency	~879 savings	M
2X concentrator solar array	Planar solar array	383 savings	L
50 kW Hall Thrusters (1 spare)	30 kW Hall Thrusters (no spare)	211 increase	L

C.Mercer et al., AIAA Space 2011 conference

300V circuits using Si vs SiC parts



Auto-Balancing Series-Stacked Topology
4 full bridge inverters + 4 rectifiers



Full Bridge Inverter
1 full bridge inverter + 2 rectifiers

15 kW-class 300 Volt input PPU (250 V Si parts):
- 93% PPU efficiency
- 2880 active parts count (4 Inverters, 4 rectifiers)
- High complexity
- PPU + Radiator + S/A mass: ~4600 kg

15 kW-class 300 Volt input PPU (1200 V SiC parts):
- 97% PPU efficiency
- 800 active parts count (1 inverter, 2 rectifiers)
- Low complexity
- PPU + Radiator + S/A mass: ~3700 kg

Electronic Parts
Heavy Ion Radiation Testing

Commercial parts tested for single event effects

SiC Schottky Diodes:

Cree	1200 V, 27 A
GeneSiC	1200 V, 20 A
Infineon	650 V, 40 A

SiC MOSFETs:

Cissoid	1200 V, 10 A, n-type
Cree	1200 V, 80 A, packaged by MSK
Cree	1200 V, 50 A, packaged by MSK

Drivers for SiC MOSFETs:

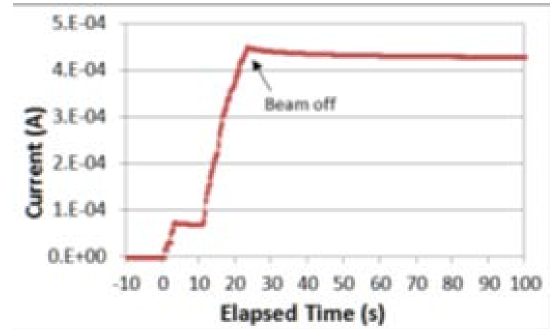
Analog Devices	800 V, 4 A, half-bridge gate driver
IXYS gate	35 V, 30 A, MOSFET driver

All tested commercial parts failed well below rated voltage under heavy ion testing

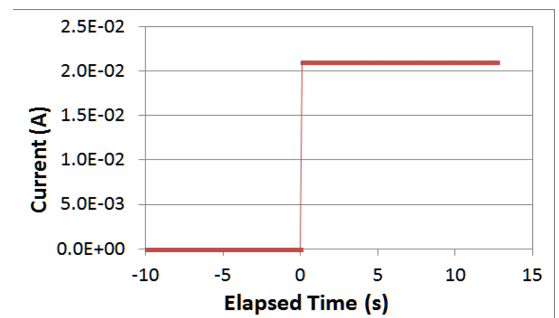
- Gate ruptures
- Burnouts
- Thermal damage

Ion Species	Surface Incident Energy (MeV)	Range (μ)	Surface Incident LET (MeV cm^2/mg)	Applied Reverse Bias (V)	1200 V, 20 A Genesic Schottky Diode GB20SLT12 Result
Ag	1289	119	42	350 500	Damage: elevated I_R; degraded V_{RRM} Immediate catastrophic failure
Cu	785	136	20	375 500	Damage: elevated I_R; degraded V_{RRM} Immediate catastrophic failure
Ne	278	279	2.7	550 600 750	No change in I_R or V_{RRM} Non-immediate catastrophic failure Immediate catastrophic failure

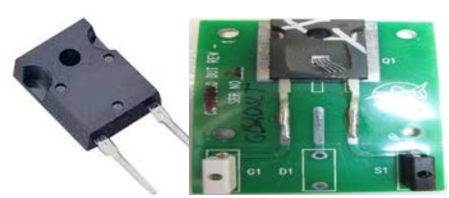
Test results from: J.-M. Lauenstein et al., 2013



Heavy ion (Ag) induced damage at 350 V applied reverse bias: Elevated reverse-bias current and degraded threshold reverse voltage.



Heavy ion (Ag) induced damage at 500 V applied reverse bias: Failure occurred immediately upon ion beam exposure.



Schottky Diode, decapsulated for test

Electronic Parts Failure Analysis

Non-destructive assessment

Failed Parts

Visible light microscopy to identify the point of failure

Visible failure?

No → Alternate failure point identification method

Yes

Characterization of failure point
- X-ray topography
- Scanning electron microscopy
- Microprobe

Compile Results

Preliminary Report

Destructive assessment

Select samples for planer analysis and those for cross sectional analysis using non-destructive assessment

Focused ion beam milling/ scanning electron microscopy cross sectional analysis

Remove top most layer

Characterization of failure point
- Visible light microscopy
- X-ray topography
- Scanning electron microscopy
- Microprobe

Has bare SiC been reached?

Yes

No

Full Report

Summary and Conclusions

- Solar Electric Propulsion is a key technology that can be scaled to support piloted missions to Mars
- Key SEP technologies have been developed and are ready for infusion into flight systems
  - Solar array structures are ready for infusion into SEP flight missions requiring high strength and stiffness and small stowed volume
  - Photovoltaics are ready for infusion into high voltage (300V) SEP flight missions
  - SiC electronic parts are not ready for use in 300V deep space missions.
    - Failures occurred from single event effects across a variety of devices and vendors
    - Failure analyses are underway to determine root cause(s)
    - High voltage SEP systems can be flown using Si parts, but with higher losses and more complex power processing units

2015 Recipient of the Rotary National Award for Space Achievement: NASA GRC, LaRC, GSFC, JPL, DSS, Orbital ATK, VMI, NIA, SLI, VPL