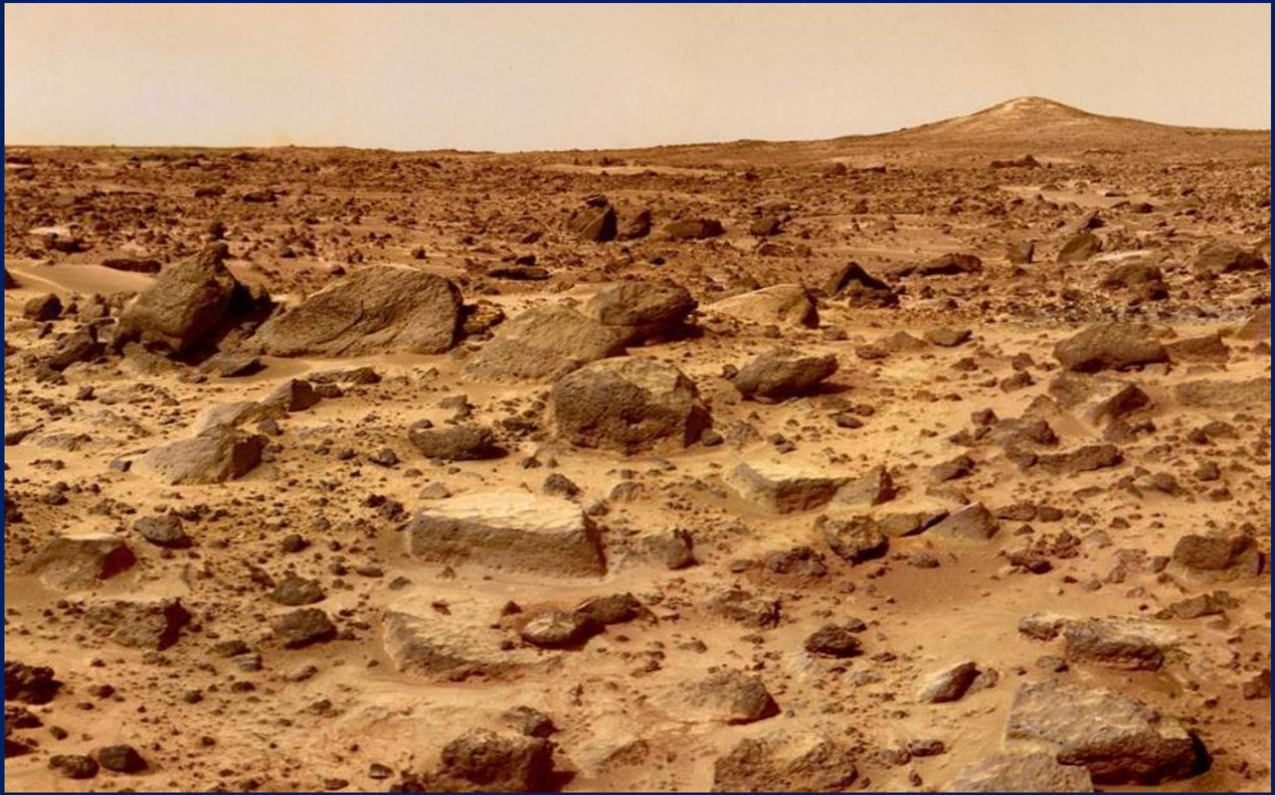
Mars Surface Solar Arrays: Part 2 (Power Performance)



Future In-Space Operations (FISO) Working Group

June 7, 2017

NASA

Part 1. Langley Research Center/Richard Pappa

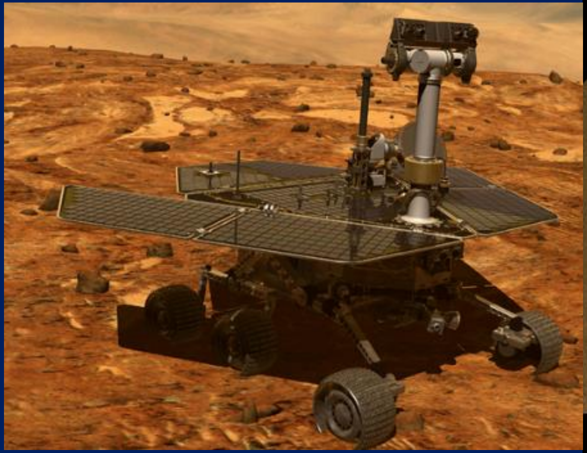
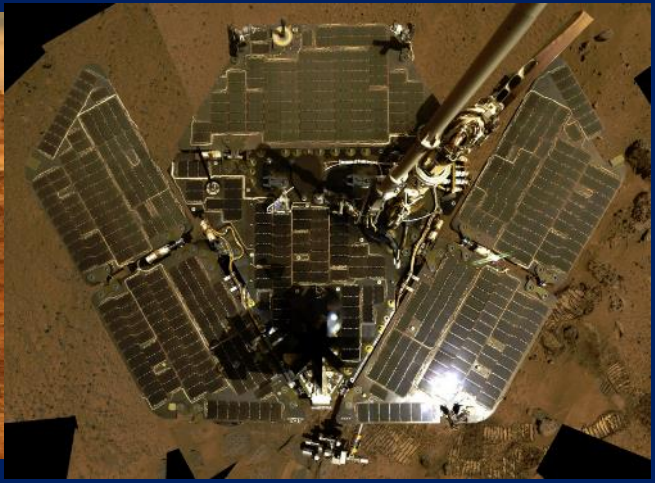
Part 2. Glenn Research Center/Tom Kerslake

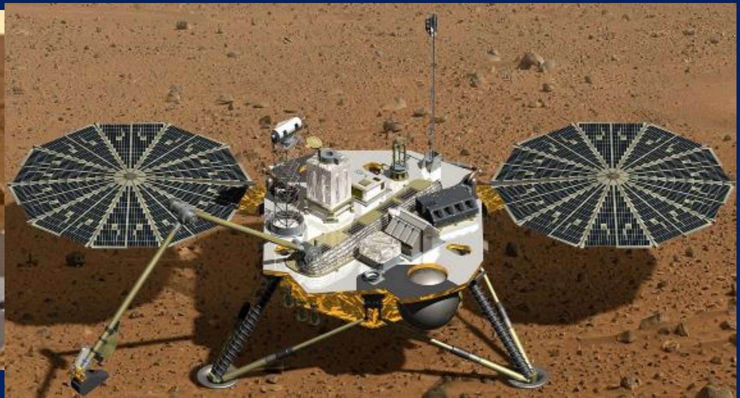
Outline

- Heritage solar Mars missions
- Solar Power for a future Human Mars Base
- Mars surface solar fluxes, dust storms
- Solar array configurations, degradation, dust
- “SAWS” conceptual power module
- Daily solar power flow management
- Yearly mission power performance
- Closing comments

Solar Arrays on Mars Right Now

- Robotic missions with flexible power conops
  - Pathfinder (19°N, 1.5m^2, 0.25 m^2/<20 W)
  - MER Spirit & Opportunity (15°S/2°S, 2m^2, <200 W)
  - Phoenix (68°N, 3m^2 wings, <150 W)

Human Mars Surface Base Power

- Need continuous day time, night time high power levels
  - Crew/base survival contingency (~5-10 kW?)
  - Effective surface operations (match power availability/usage), 40 kW class
- Limited ability for "safe mode" power downs
  - Sols (for trouble shooting)
  - Months (major dust storm, winter season)
  - So, more onus is on redundancy, system worst case sizing
- Strong desire to demonstrate power capability/margins on Earth during acceptance testing prior to launch
  - Minimize over-sizing (mass penalty) for risk management
  - Known precision landing site, known surface properties
  - Known solar array configuration
  - Engineered/qualified dust abatement/removal
- Emplace & confirm power systems ops before crew launch

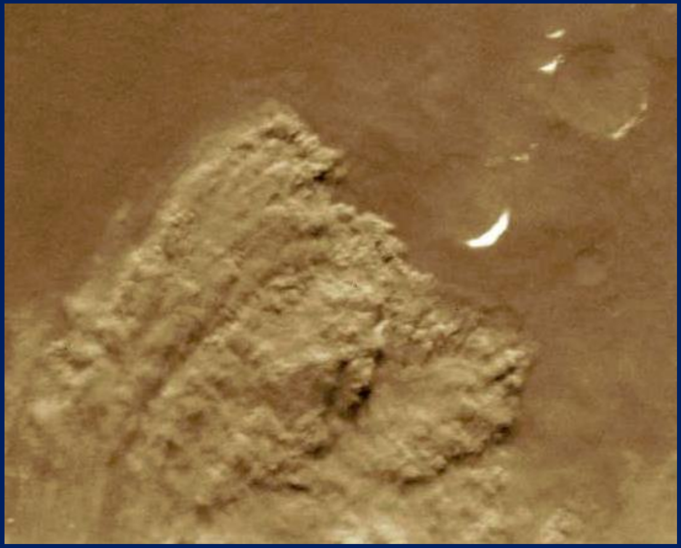
Mars Surface Solar Fluxes

- Flux on top of atmosphere (AM0) depends on:
  - Season (Mars Sun distance changes by 18.5%, flux by 38%)
- Total surface flux depends on:
  - Mars season
  - Landing site latitude (sun angles, clear sky & dust storm OD)
    - OD = optical depth (opacity)
  - Landing site longitude (local surface albedo)

19°N

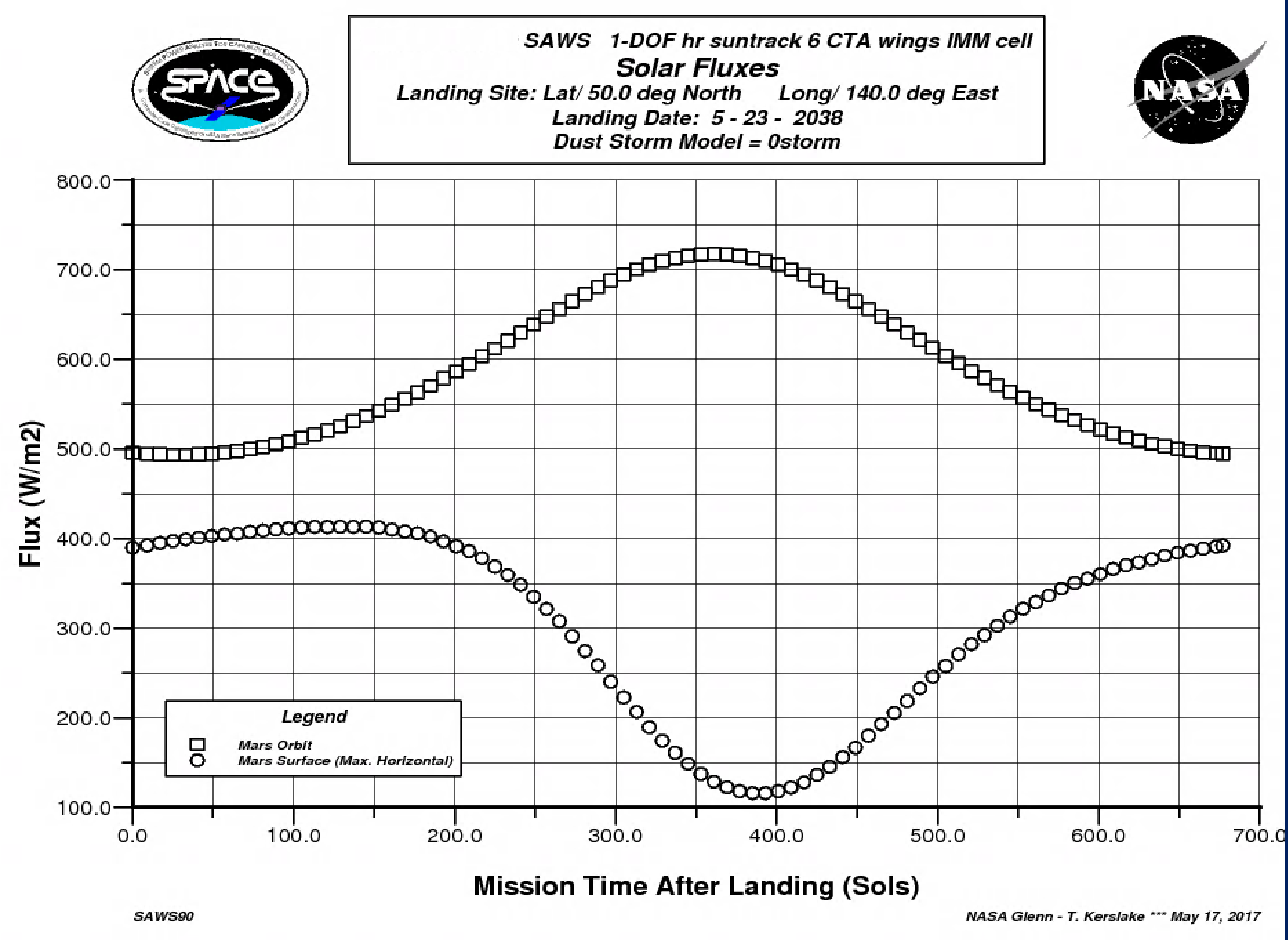
15°S

Dust Storm



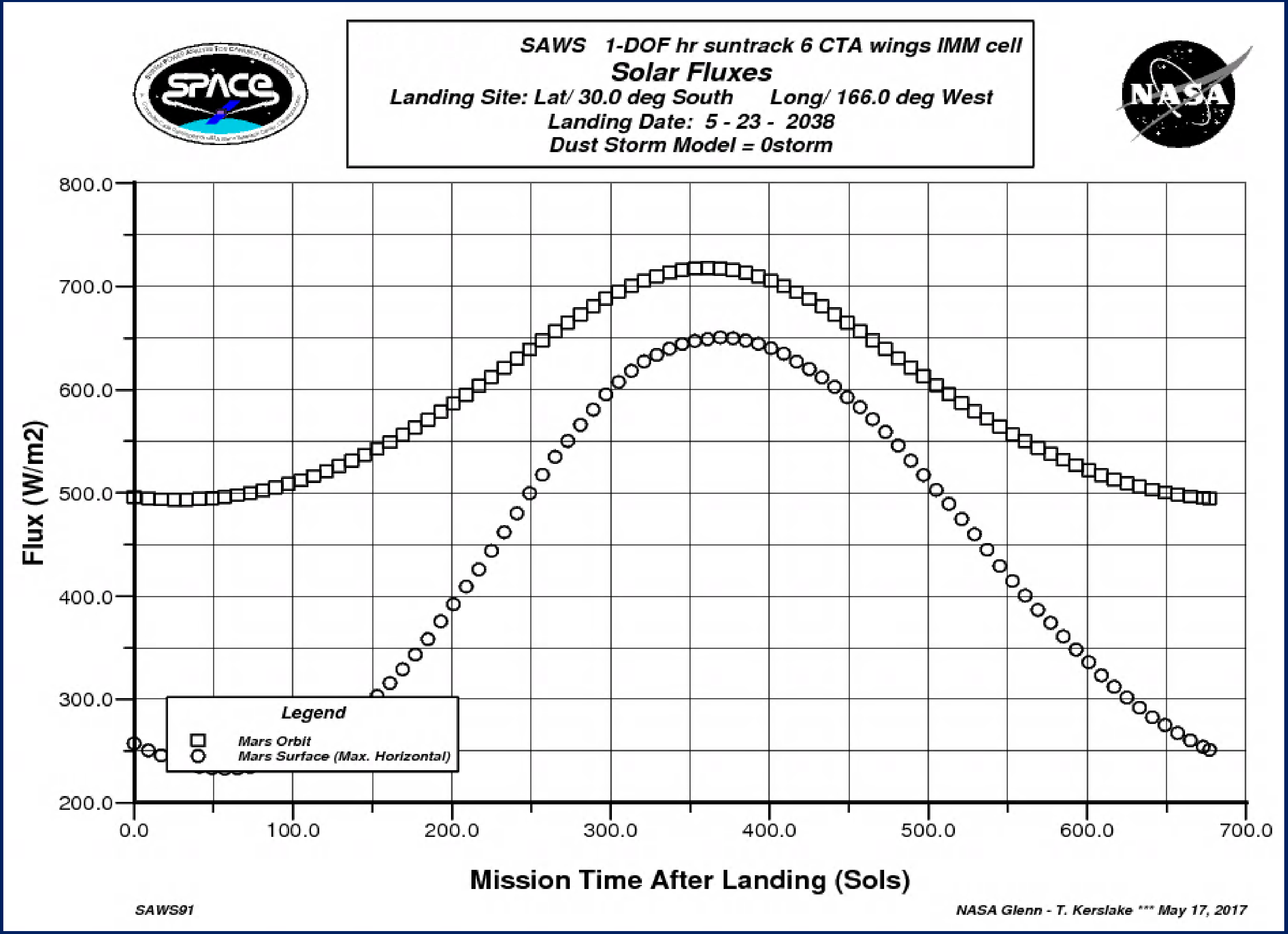
Yearly Mars Surface Solar Flux

- 50° North latitude landing site, clear skies



Yearly Mars Surface Solar Flux

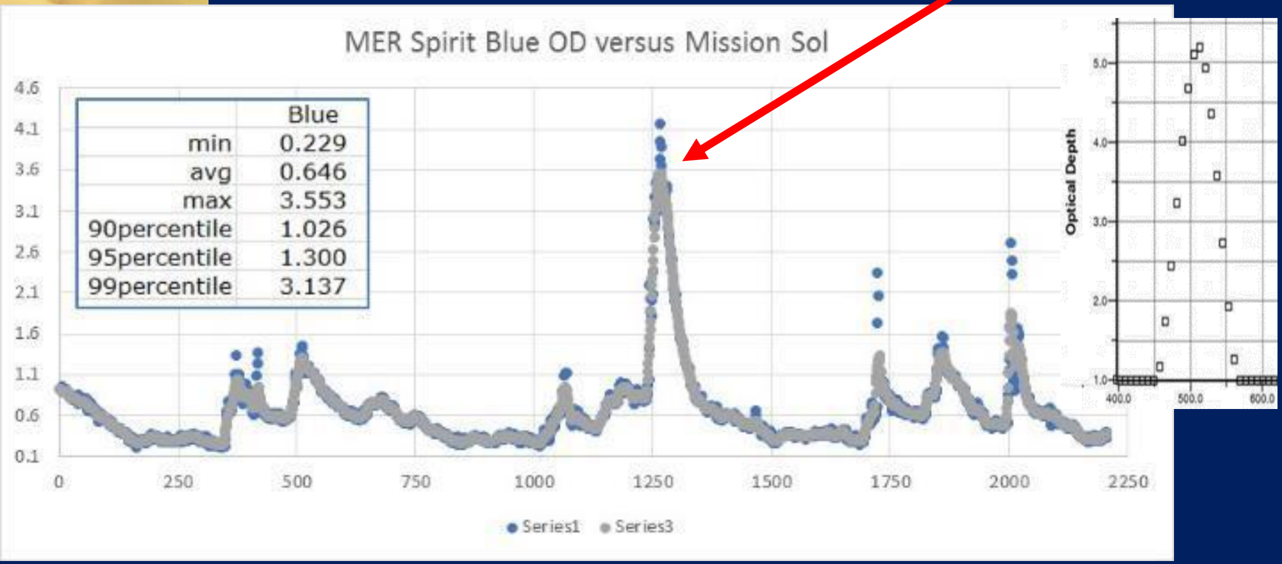
- 30° South latitude landing site, clear skies



Major (Global) Dust Storms

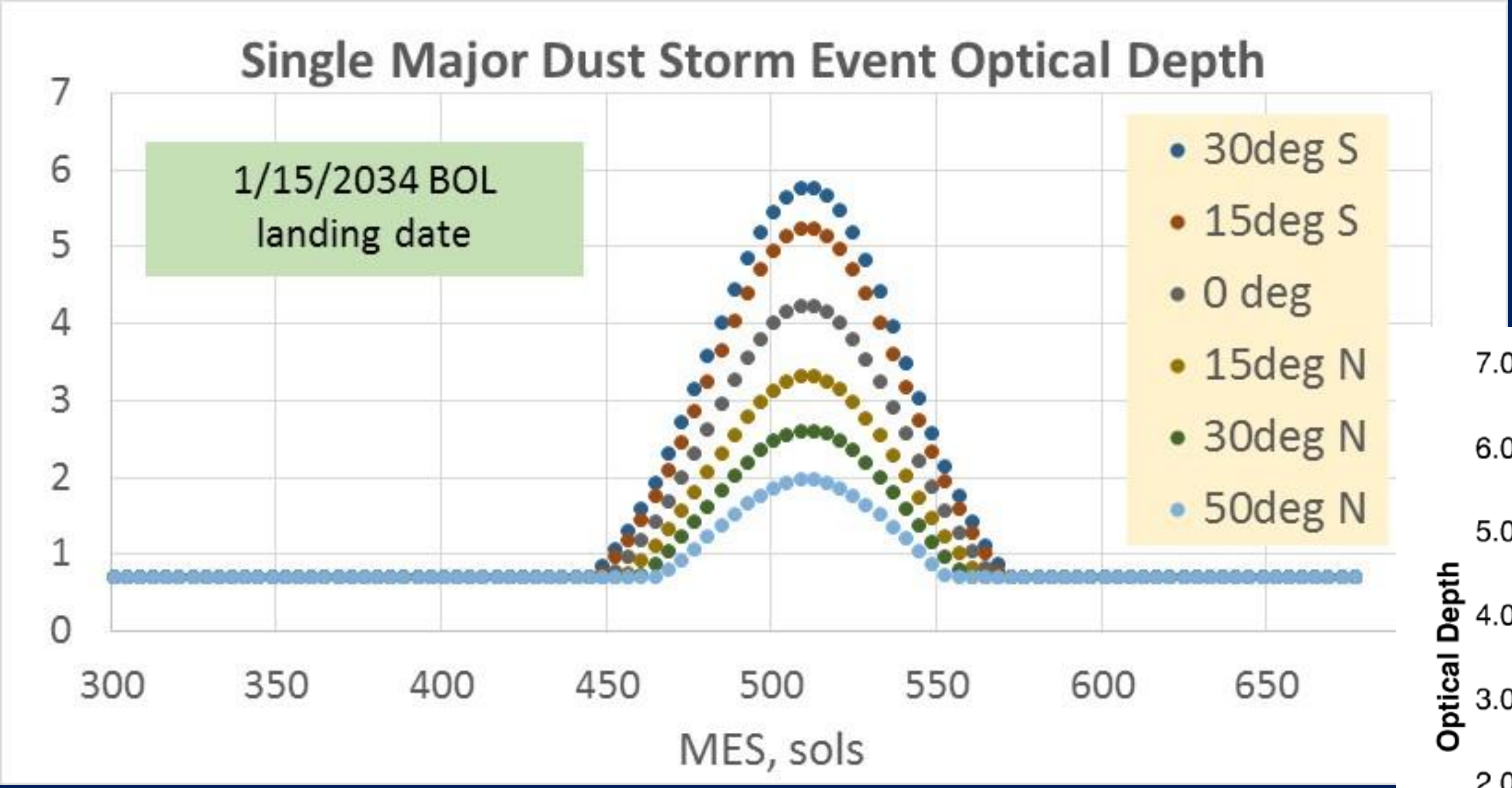
Major Dust Storms - Frequency

- 0,1,2 major dust storms may occur per Mars year
  - Dust storm covers the globe, 3 month duration, high OD values
  - Occur during summer in the southern hemisphere
  - OD modeled as f(season, latitude, time)
    - Highest OD in the South, lower in the North
  - Historically, ~1/3rd chance each for 0,1,2 major dust storms/yr
  - For these 3 years, MER encountered 1 major dust storm (Jul 2007)

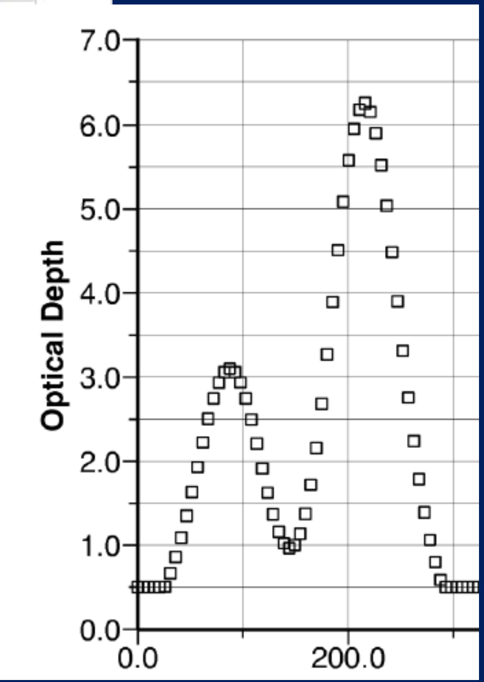


Major Dust Storm OD (Optical Depth)

- Single storm year OD values



OD at a 19°N site

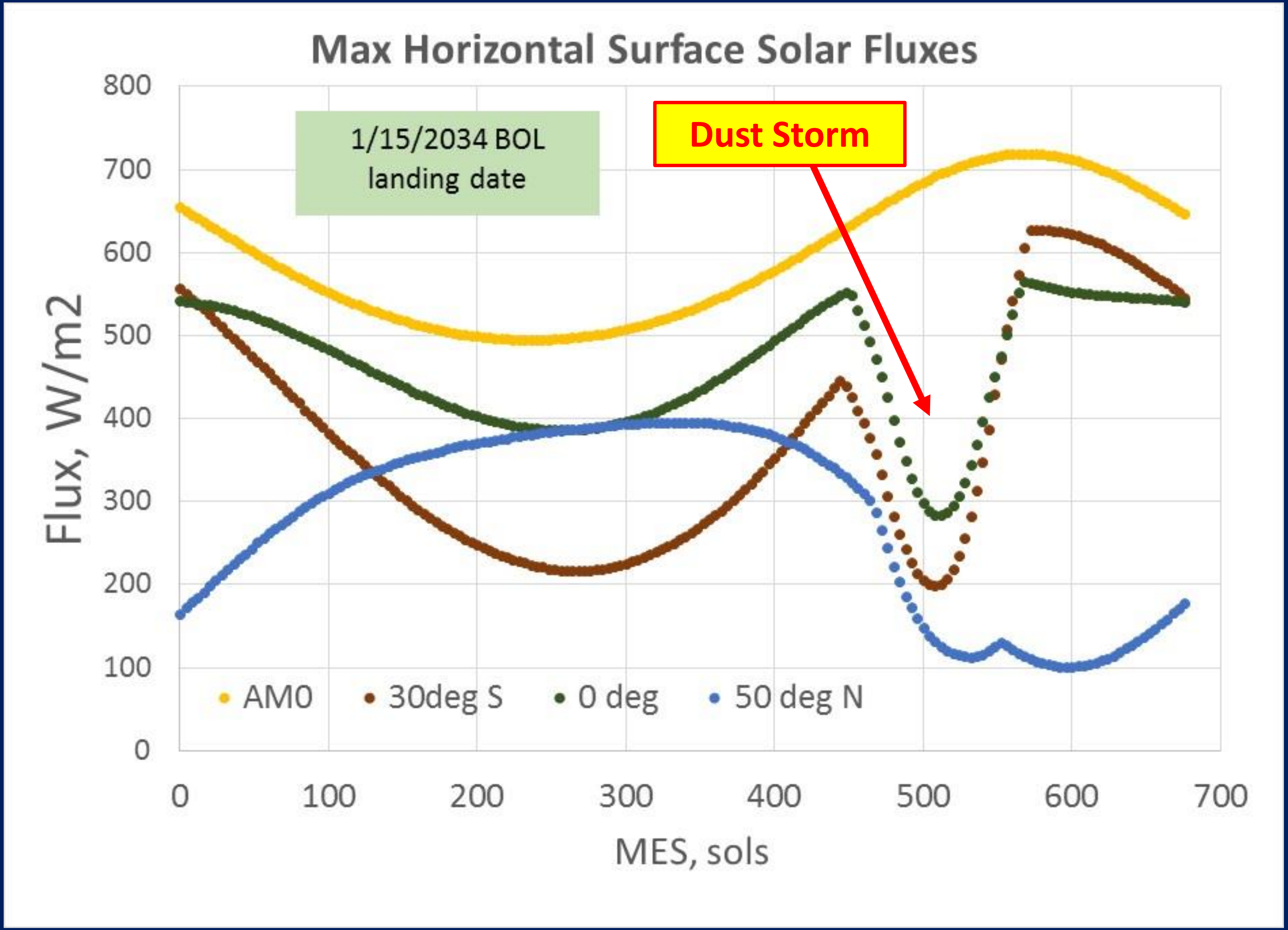


MES, sols

- Higher OD values, if a 2nd major storm occurs

Major Dust Storm Loss in Solar Flux

- From ~30% to 3X reduction in maximum flux – single storm



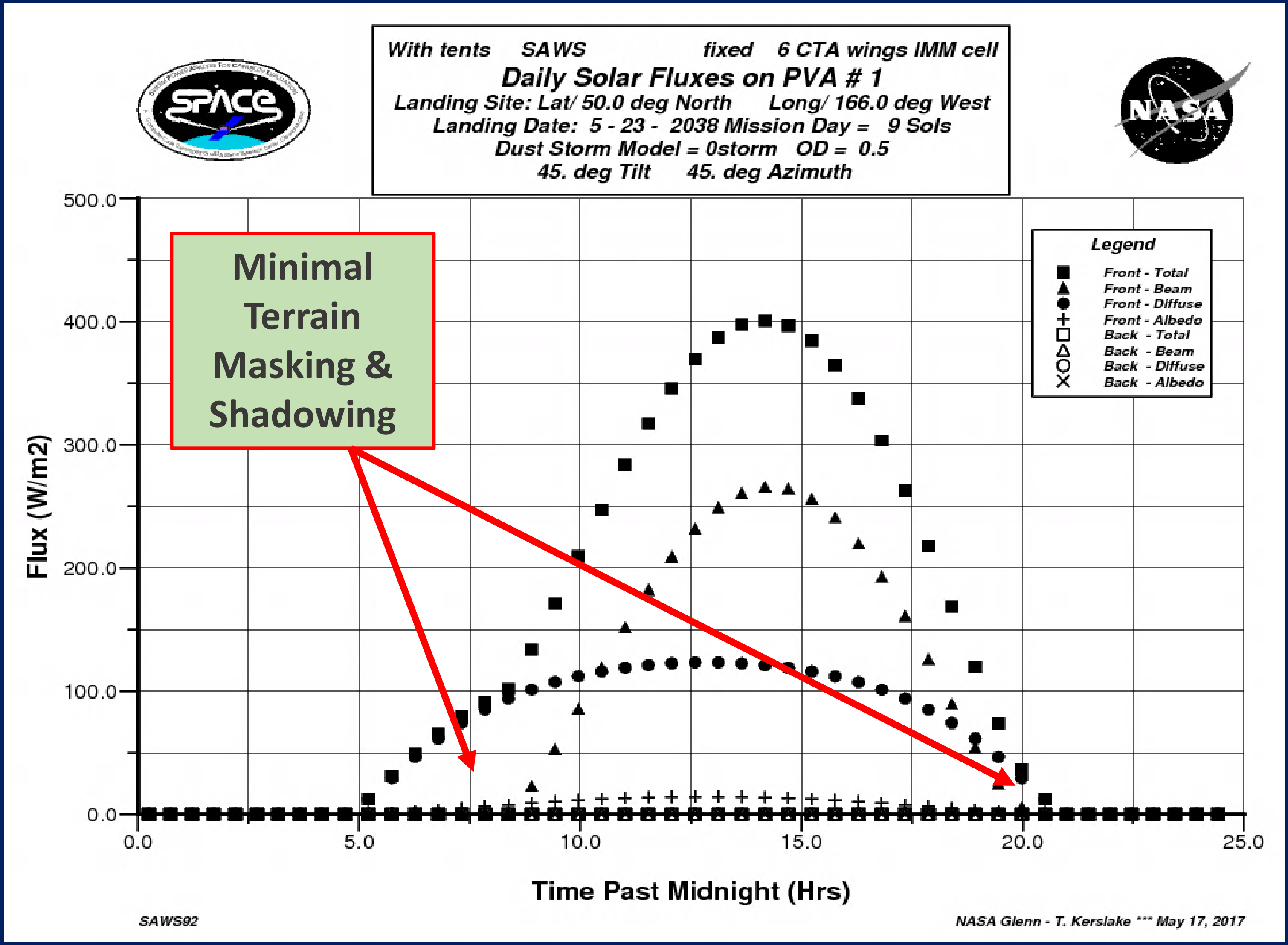
Mars Surface Solar Flux Components
(Important for solar array performance)

- Total Surface Flux = Beam + Diffuse + Albedo terms
  - Total flux based on net flux function; f(OD,z,al)
    - Directional, spectral forward-back scattering radiation calculation
  - Beam flux based on Beer's Law; f(OD,z,beta)
  - Diffuse flux = Total – Beam; f(OD,z,al,theta,beta)
  - Albedo flux based on total irradiance; f(OD,z,al,beta)

OD = optical depth　　z = solar zenith angle
al = surface albedo　　beta = solar array tilt angle
theta = solar array sun incidence angle

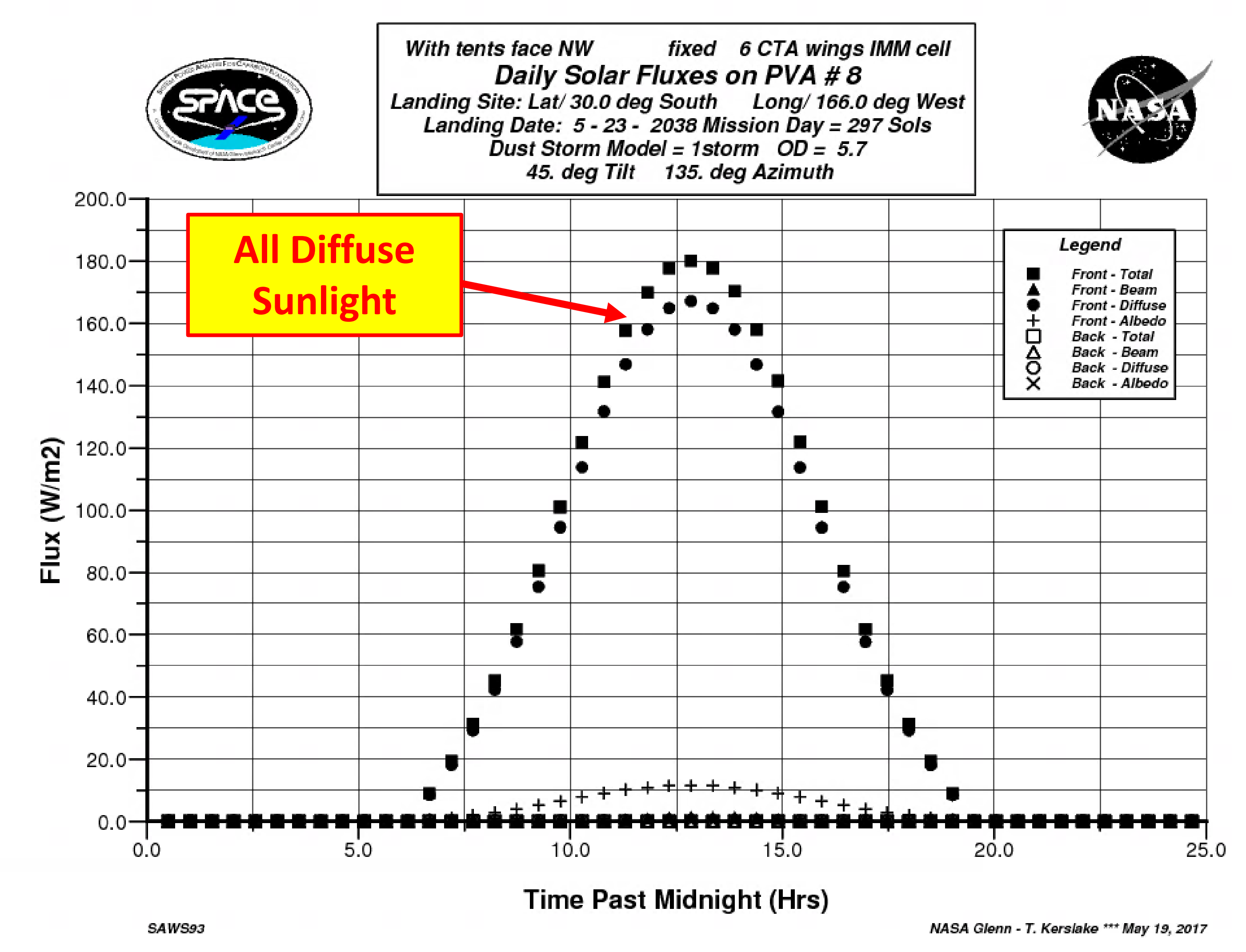
Daily Mars Surface Solar Flux – Clear Skies

- 45° tilted, fixed South-West facing solar array, 50° North latitude landing site



Daily Mars Surface Solar Flux: At Peak Major Dust Storm OD of ~6

- 45° tilted, fixed North-West facing solar array, 30°S latitude landing site



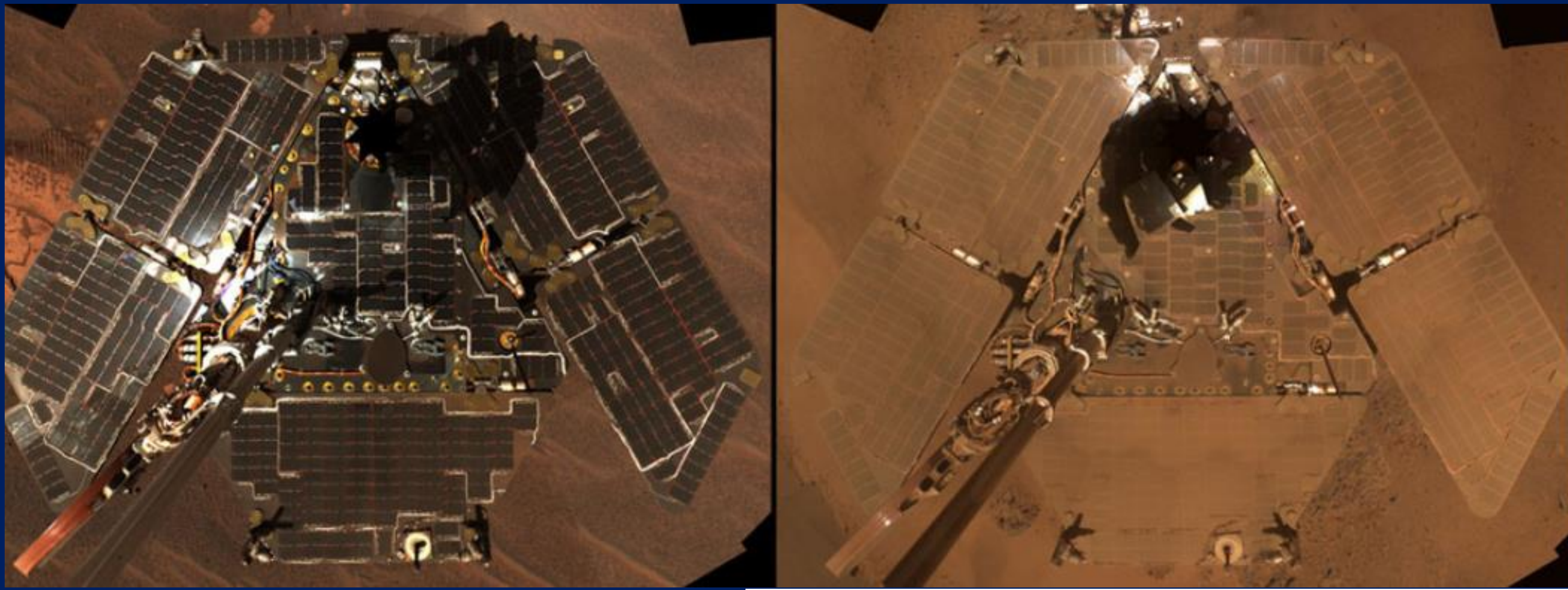
Mars Surface Solar Array Configuration

- Must be deployable for high power applications
- Desire planar solar panels
  - Concentrator (8X GCR class) solar arrays less effective (lost diffuse/albedo flux, cleaning optics from dust, substantial tracking losses via uncorrelated errors)
- Fixed horizontal/tilted panels, tracking panels
  - Fixed horizontal panels are simple, little azimuth dependence, maximize power generation for low latitude sites; but lower power at high latitude, highest dust collection rate, passive dust control insufficient
  - Fixed tilted panels (or tents) are simple, can enhance power for high latitude sites, East-West facing panel pairs broaden daily power generation hump, can achieve more strength/stiffness, effective passive dust abatement possible; but have azimuth dependence, reduced power generation (by 20-25%)
  - Tracking panels (typically 1-DOF, N-S or E-W) offer modest power enhancement (5-15%), offer tilting for dust removal / wind load management; but have strong azimuth dependence and mechanisms introduce risk, cost, mass penalties
  - Panels should be kept above the Mars surface ~0.5m to avoid regolith saltation, local string current limiting (possible major/complete loss in power)

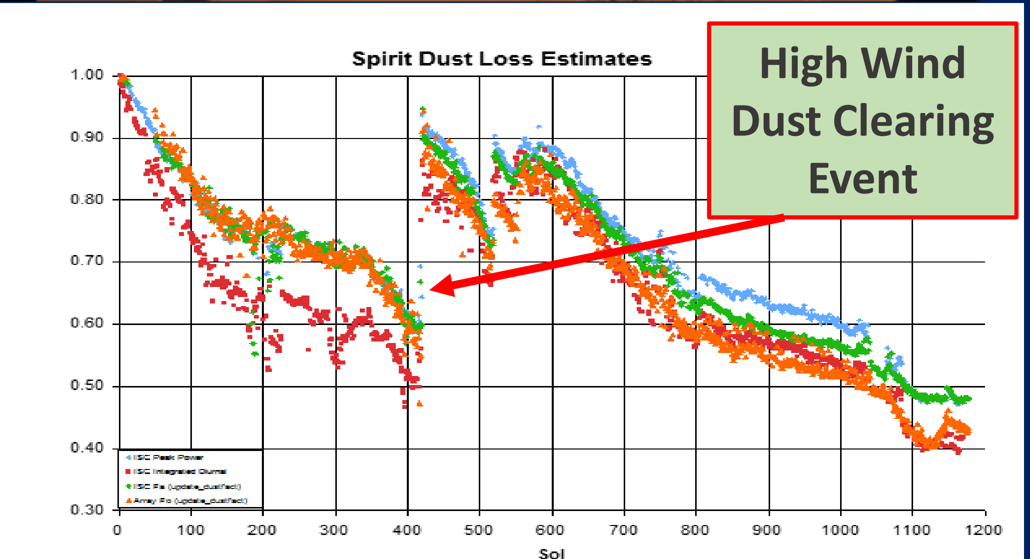
Mars Surface Solar Array Power Degradation Factors

- Even for long missions (6 Mars years), Mars surface environment is mostly benign for solar arrays
  - No concern for proton/electron radiation or GCRs
  - No micro-meteor strike damage
  - Paschen discharge damage eliminated by design
  - Modest thermal cycling, aero-flutter fatigue damage
  - Modest NUV/VUV equivalent sun hours for darkening
  - Modest loss from random failures with proper QTP/ATP
- Dust collection on solar cell coverglass is a major power degradation challenge that must be managed
  - Resident dust blocks sunlight, degrades current output
  - High speed wind blown dust could scratch covers/optical coatings, increase reflectance (degrades current output)
  - Dust could contain corrosive peroxide or perchlorate (need H_2O?)
  - Solar arrays for a high value mission (human life, $100B’s) cannot rely on probabilistic aeolian dust cleaning, i.e. dust devils

MER solar panel dust collection

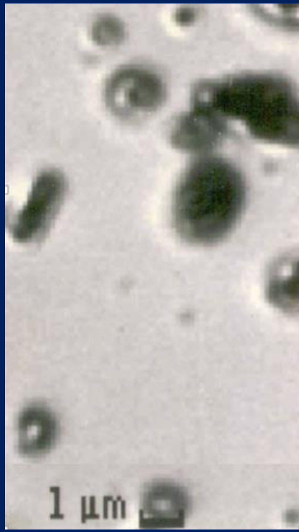


- 0.14% loss per sol
- No power after ~1 year



Dust Management (Abatement, Removal)

- Fine dust (micron scale) is an aerosol in the Mars atmosphere constantly precipitating
  - Dust clings via Van der Waals, electrostatic forces
- Human Mars surface base will have many sensitive surfaces (need dust management)
  - Solar arrays, radiators, windows, antennas, lights, nav aides
- “Abatement” avoids dust collection
  - Electrostatic, tilted surfaces
- “Removal” allows dust to collect for periodic removal
  - Piezoelectric shakers, mechanical wipers, electrodynamic, peel-n-discard films, high speed jets (leaf blower, dust devil)
  - Piezoelectric dust removal demonstrated very high effectiveness in ground tests with rigid panels; low mass/power/conops penalties
- Long duration in situ Mars surface demonstration of dust management will be required



Solar Cell Must Operate With Reddened Spectrum

- Mars surface solar fluxes are blue-deplete
  - Function of OD, z (=>landing site, season); MER data below

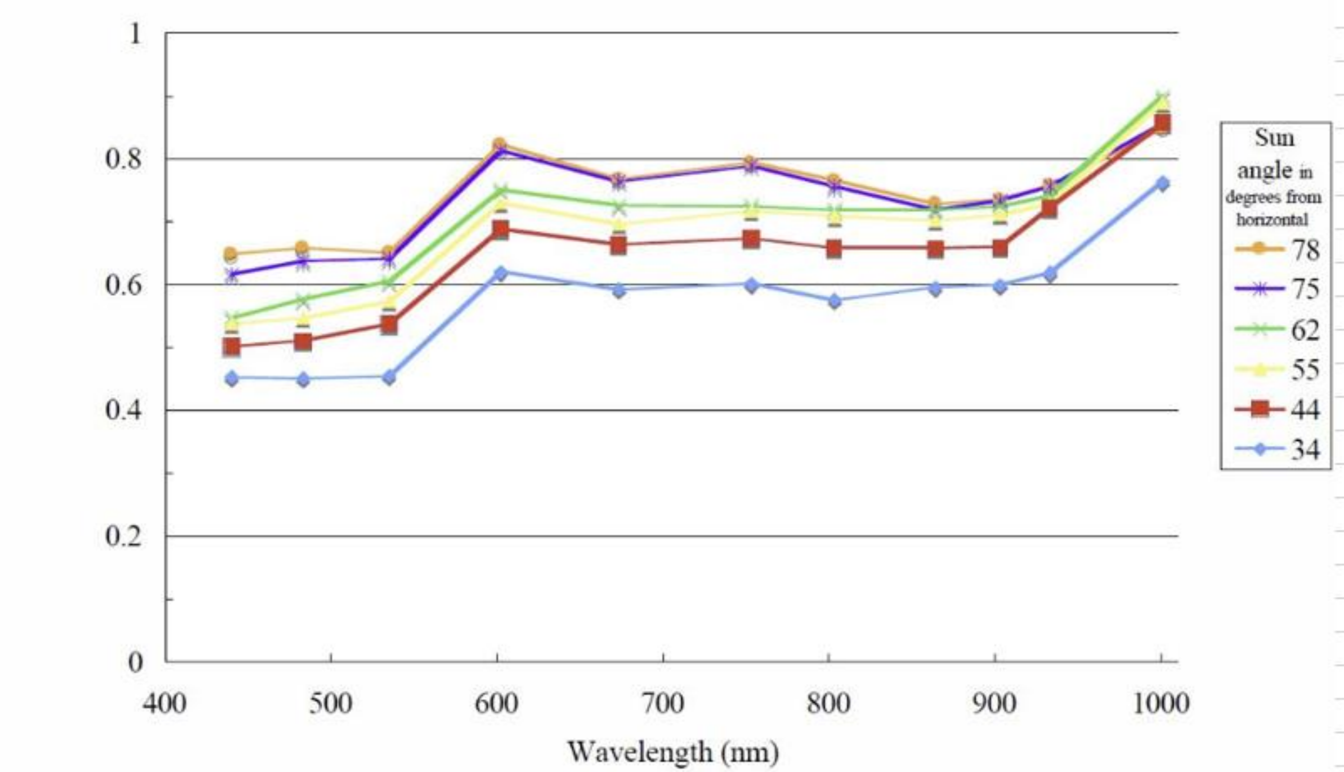


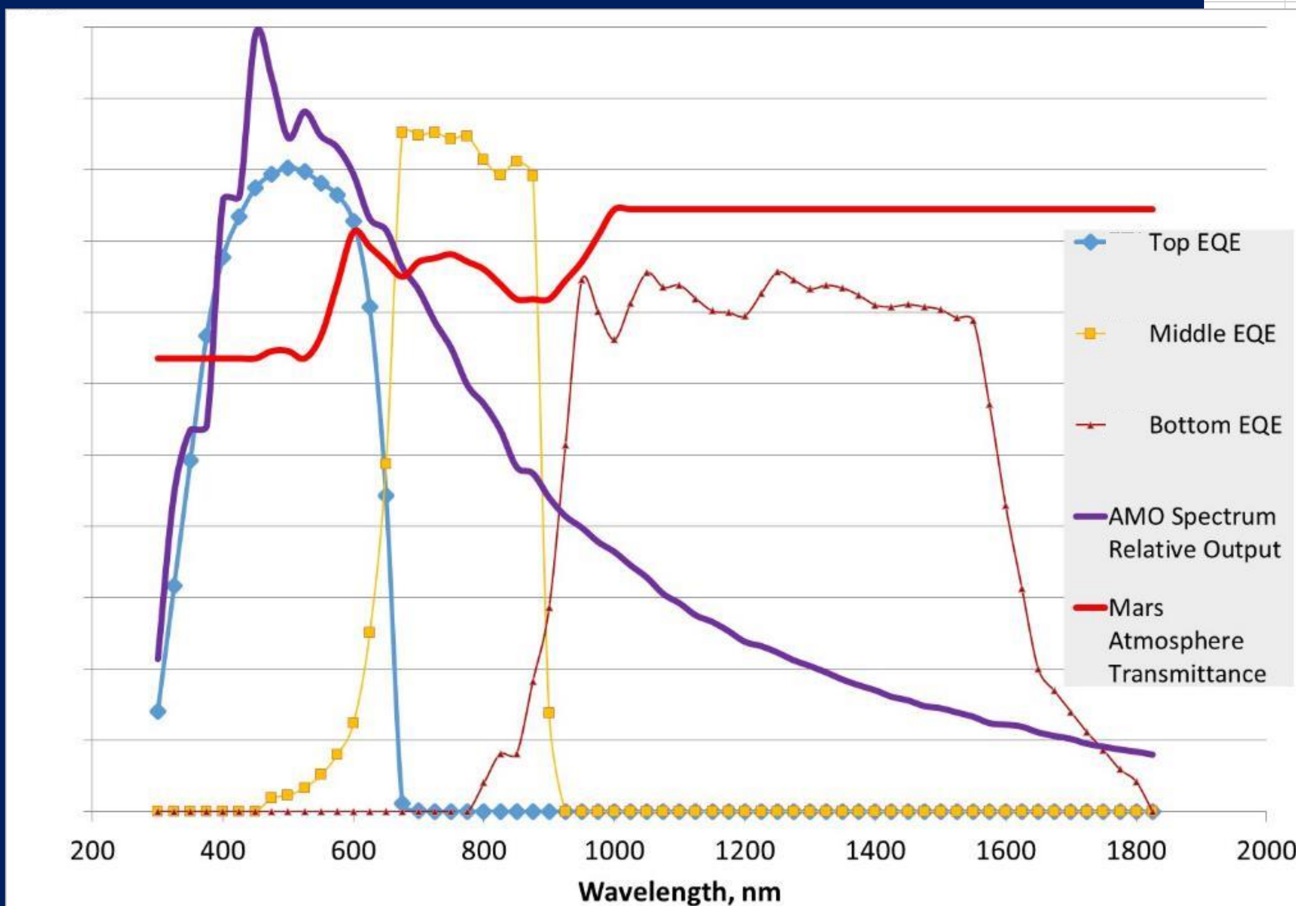
Figure 5: Atmospheric transmission for the global sunlight, 400 nm to 1000 nm, for varied sun angles (averaged for Spirit and Opportunity data, tau approximately 0.94).

G. Landis

Solar Cell Spectral Loss on Mars

- Top sub-junction in a high efficiency SOA space multi-junction solar cell (using UV/blue wavelengths) will produce less current output than tandem sub-junction
  - Limits full solar cell current generation

TJ / IMM4 Cells				
OD =	0	0.25	0.5	
	1	2	3	
	4	5	6	Zen, deg
	1.000	0.969	0.944	0
	0.899	0.818	0.750	
	0.694	0.647	0.608	



Solar Cell Spectral Loss on Mars

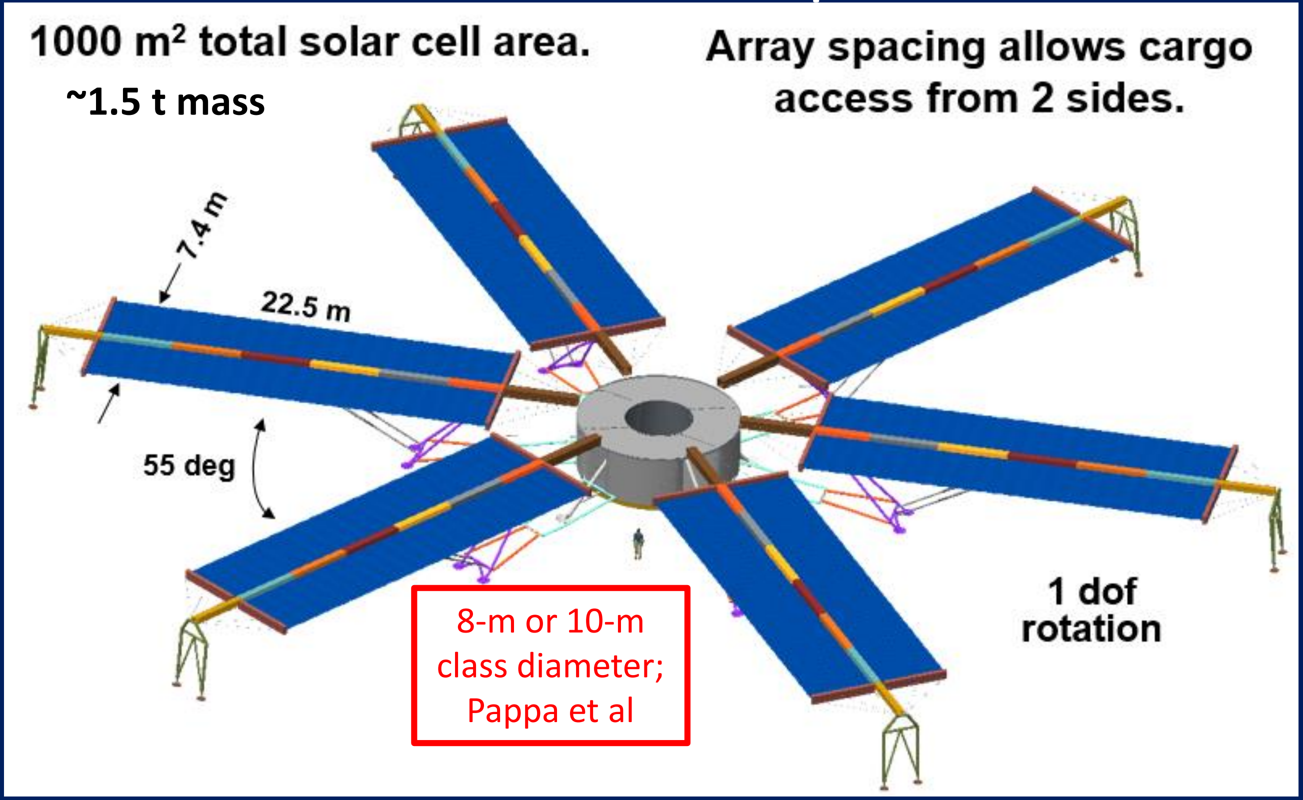
- So what to do?
  - Just accept the lost factor, ~10% (for TJ and IMM cells)
    - Size a ~10% larger solar array area (mass, cost increases)
  - Could redesign the cell for better sub-junction current matching (for target OD, z)
    - A tuned “Mars Cell” could recover ~1/2 the loss
    - But a Mars Cell may introduce cost penalties, production challenges, increased risk
  - Could use single junction silicon solar cell
    - Very little spectral loss or even a spectral gain, but ~2X more area needed because of the low conversion efficiency

Mars Surface Solar Array Power Performance Depends on Many Things…

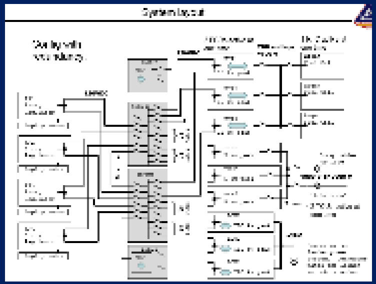
- Mission *(most factors covered in prior charts)*
  - Date, landing site lat/long, duration, time of day, OD, dust storms
  - Affects solar intensity/spectrum, sun angles, albedo flux, sol day/night periods, environmental temperatures, amount of degradation
- Solar array configuration *(in part covered in prior charts)*
  - PV cell type, solar cell string length, number & azimuth/tilt angles of solar panels (per design & from surface irregularities), articulation of solar panels
  - Affects solar panel solar flux intensity, shadowing (self, terrain masking) losses, operating temperatures/currents, day time power hump
- Energy storage subsystem
  - Regenerative Fuel Cell (RFC), Battery
  - Affects required solar array size (>50% different), charge rates/periods
- Power management system
  - Voltage regulation (fixed, peak power tracking), day time and night time user load level/profiles, RFC recharge period, power cable lengths (m's or 1 km?)
  - Affects solar panel level operating currents, voltages losses and IV curve operating point

SAWS Module Concept

- IMM-populated CTAs, PEM H2/O2 gaseous RFC, 120 VDC regulated PMAD, 10 kW class user power module sizing



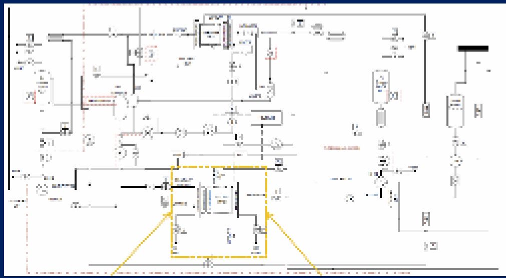
PMAD (1 t class)



F. Davies

RFC (1.9 t)

Araghi & Jakupca

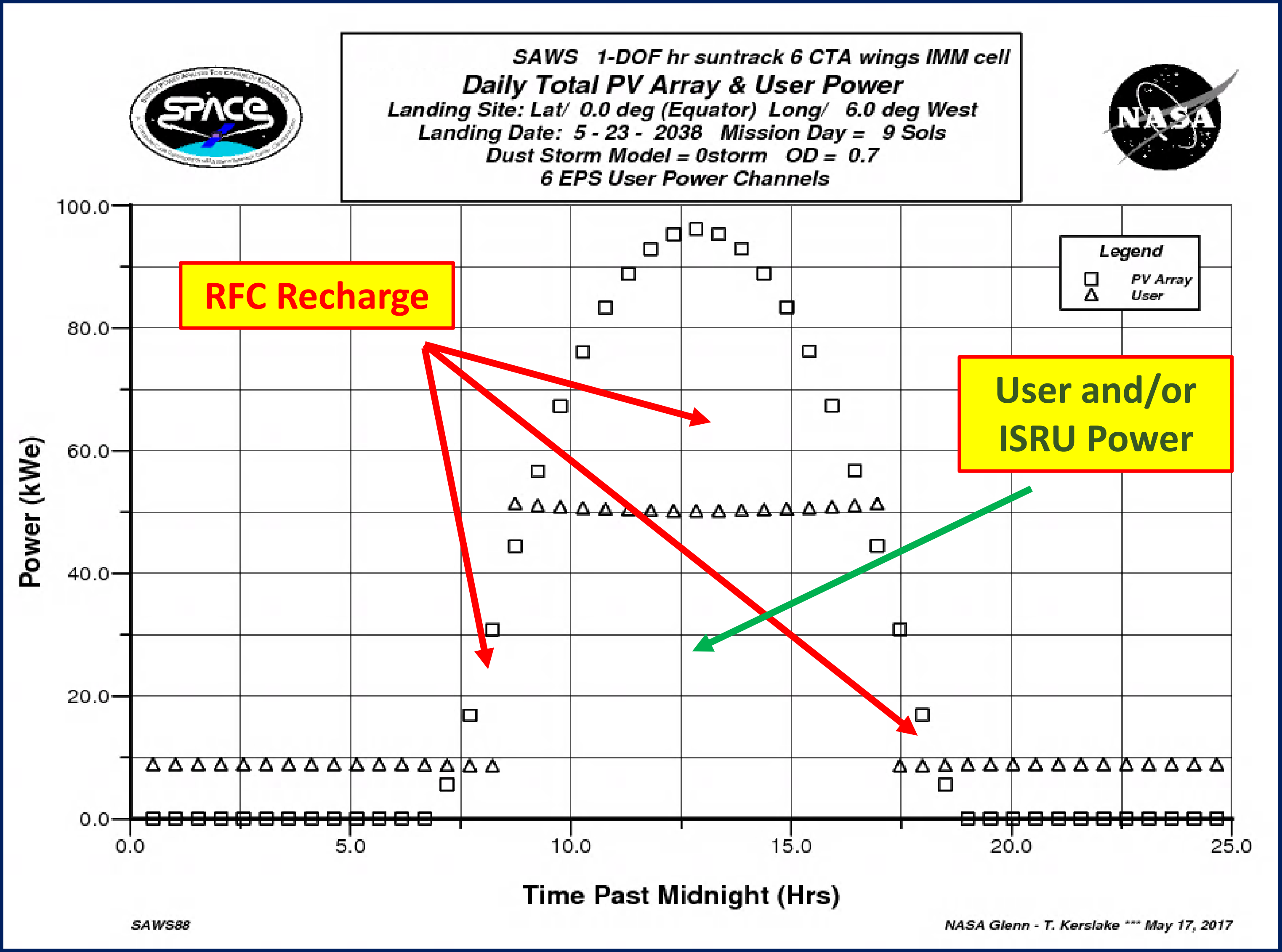


“SAWS” Module Day-Night Power Flow*

- For Mars base power management conops:
  - Desire near constant user power during the day and the night
  - Managed by base computer and/or crew; Updated week to week and seasonally
  - If ISRU plant is present, it desires constant power for constant ops
- This presents challenges for solar power system
  - Makes power only during the day; power generation has a hump profile
  - Effective day period for user power is shorter than solar day
    - Fuel cell must discharge during the early/late day times when solar array power is low
    - Day faction for day time user power is a selectable parameter
  - Solar power profile changes sol to sol through the mission
  - RFC reactants should be fully used while RFC must be fully recharged sol to sol (nominal ops)
  - So the daily power flow values <u>require an iterative solution for each sol</u>
- Solar power system must be designed for a wide range in daily/yearly power gen operations (mass penalty)
  - Base loads, like ISRU (if present), must also be designed for wide range in power consumption or reduced operating fraction (both, mass penalties)

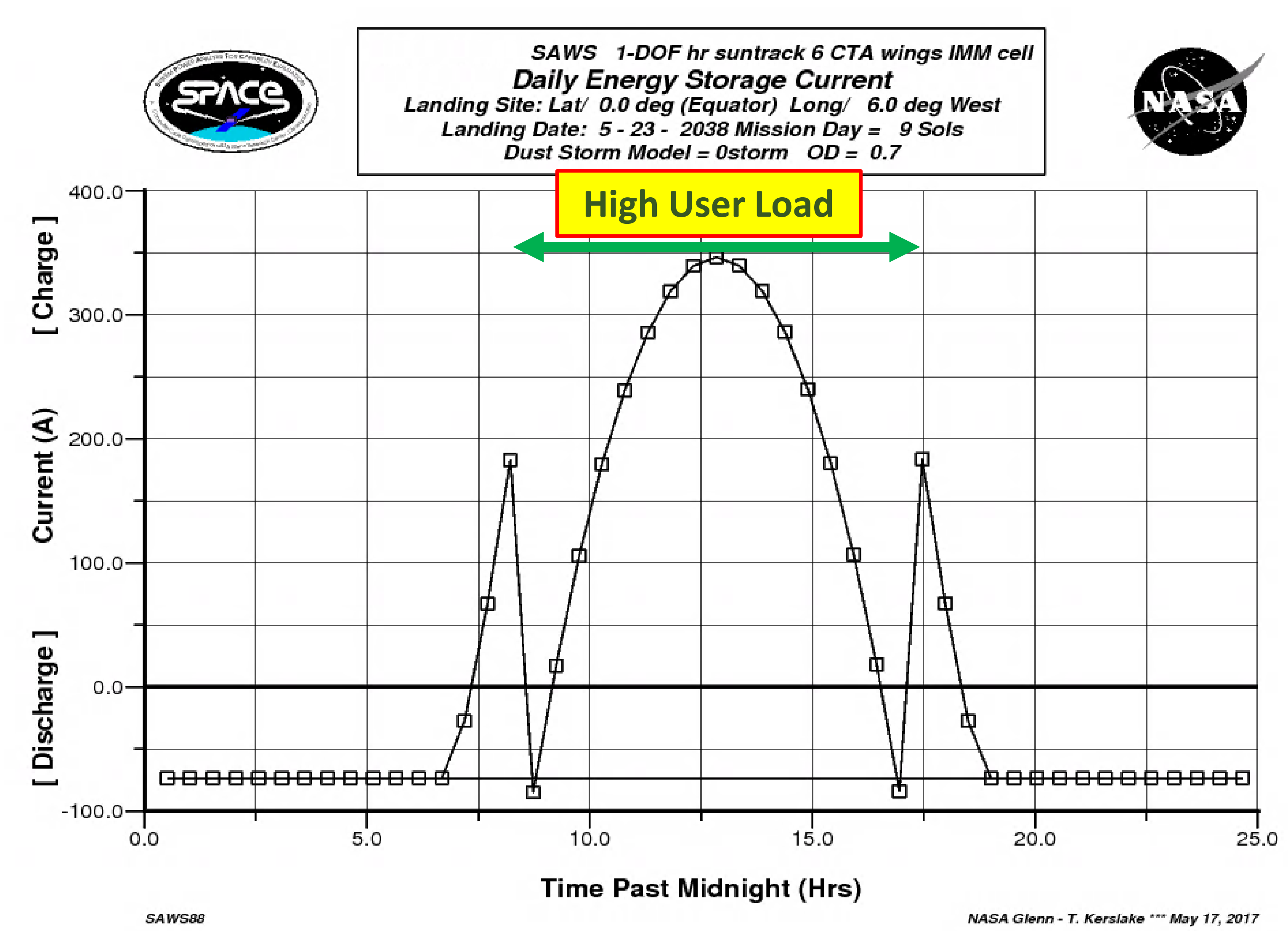
“SAWS” Day-Night PV, User Power Flow*

- 60% day time user power factor input, min continuous user power



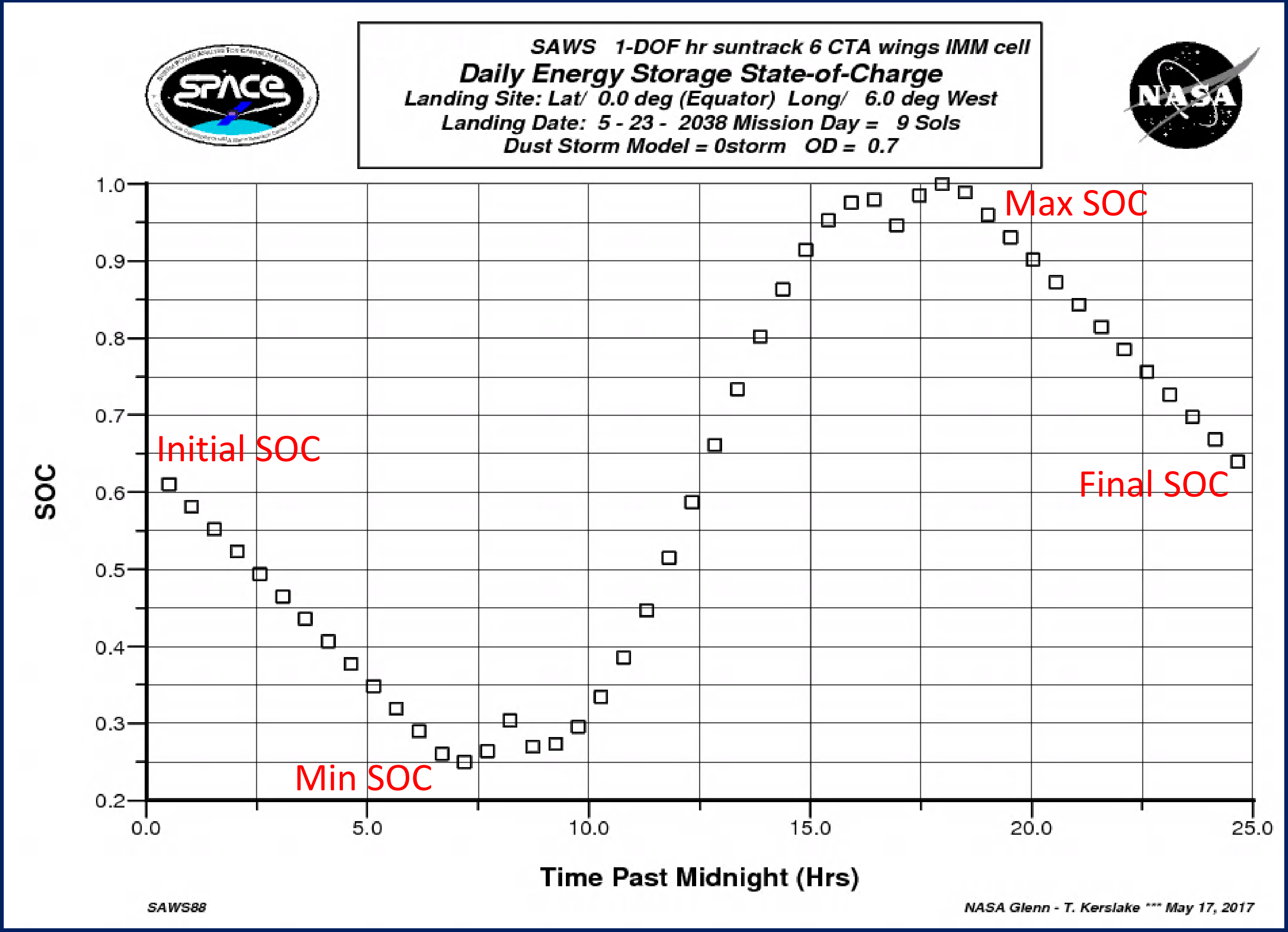
"SAWS" Module RFC Power Flow*

- RFC undergoes 3 charge/discharge cycles per sol



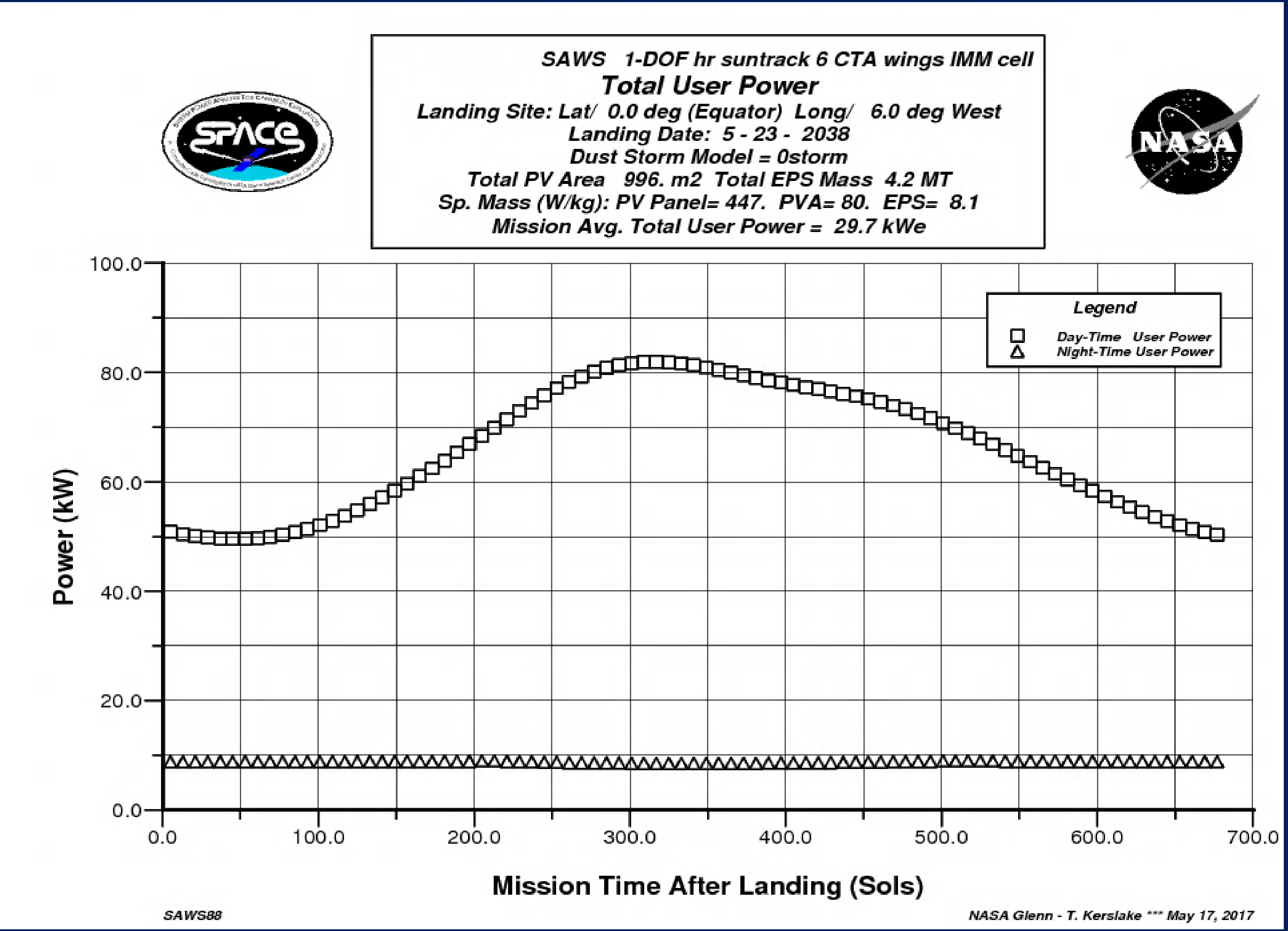
"SAWS" RFC Day-Night SOC*

- RFC fully utilized (0.25-1.0 SOC) & recharged (SOCi =SOCf)



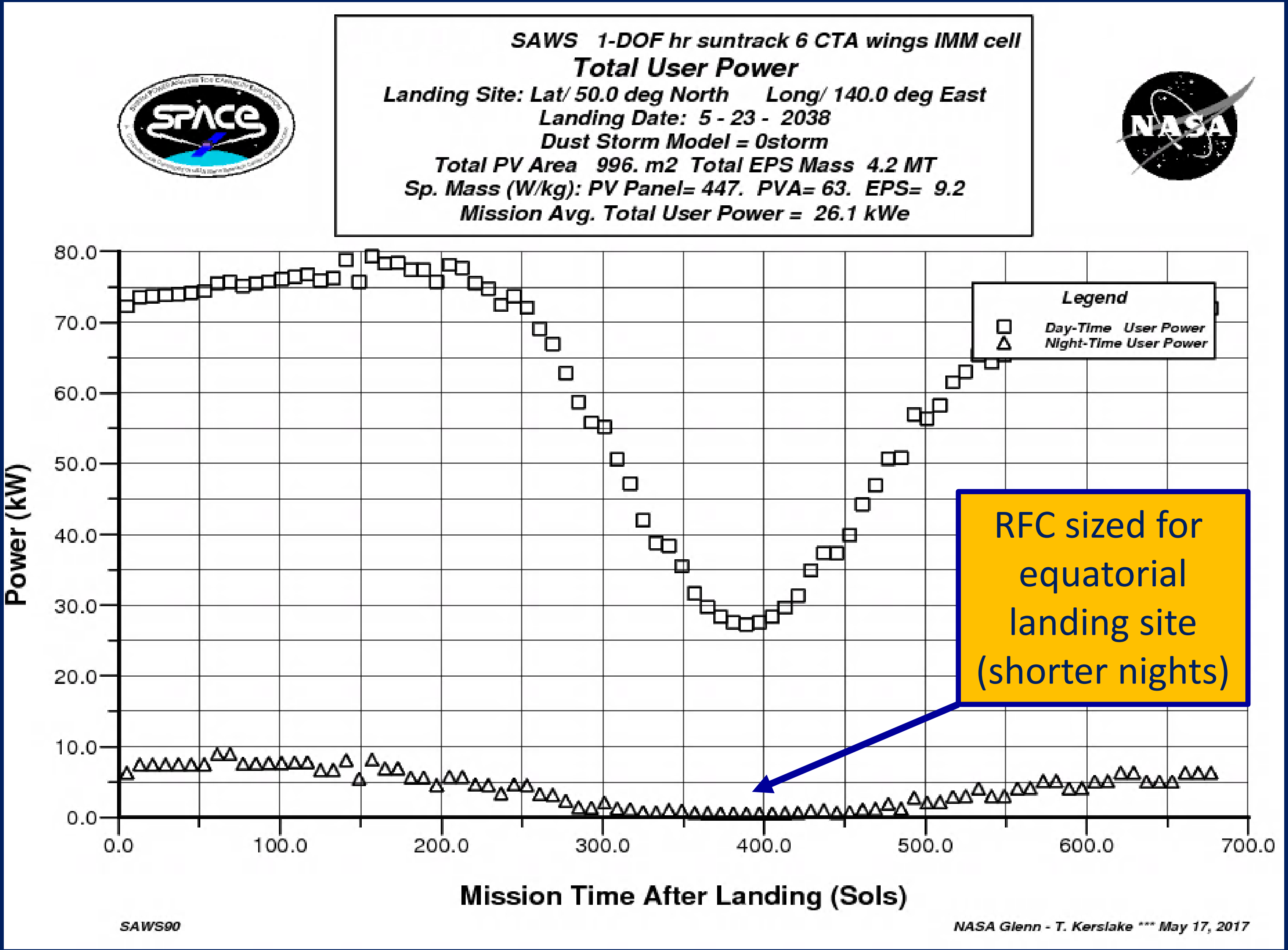
“SAWS” Module Mission Power

- Equatorial landing site



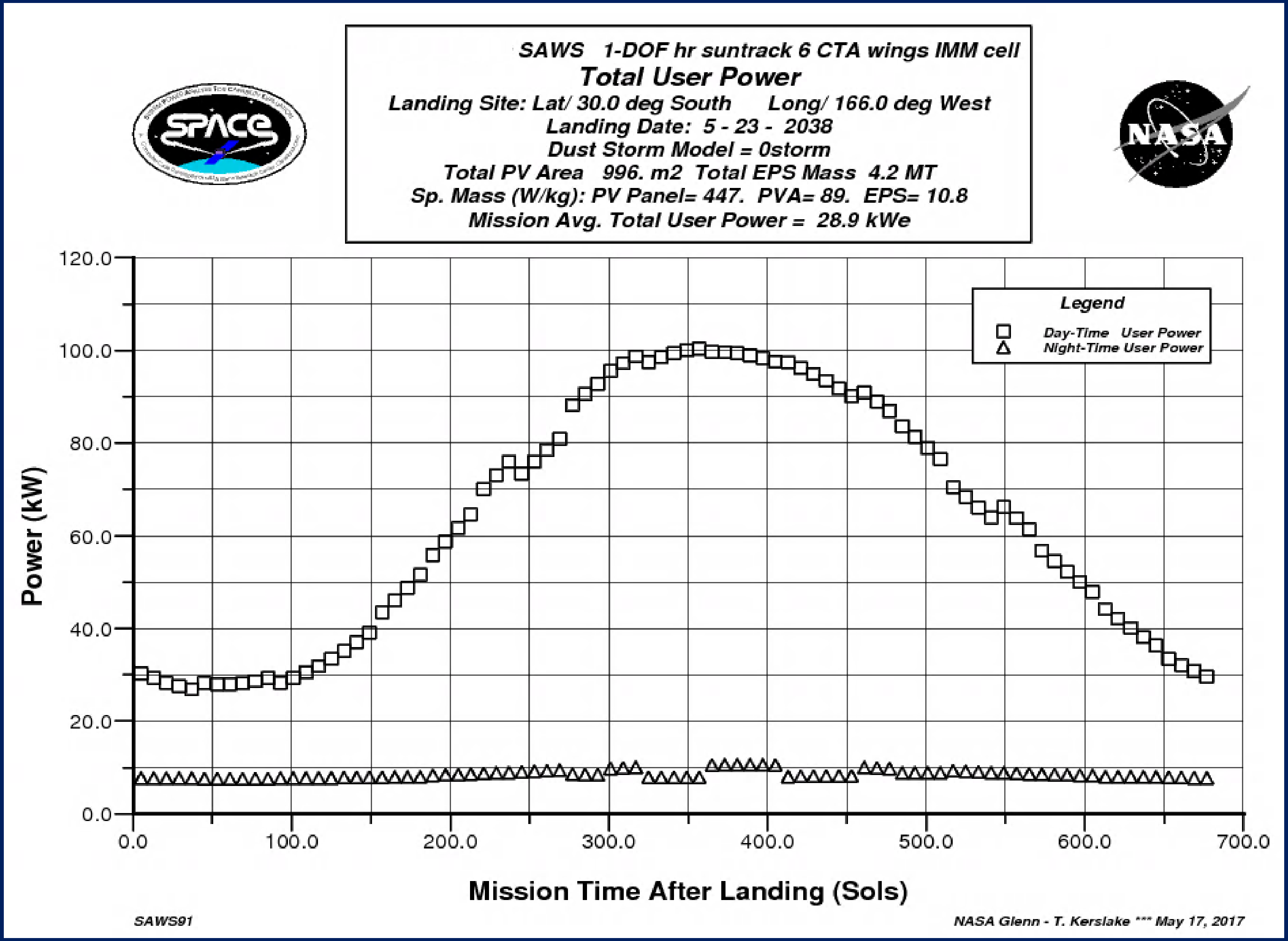
"SAWS" Module Mission Power

- 50° North latitude landing site



“SAWS” Module Mission Power

- 30° South latitude landing site



Closing comments

- Solar powered Mars surface human base is feasible
  - Base design and conops will have to reflect solar power system variable power output; equatorial and mid-latitude landing sites only
  - Significant power down required for major dust storm ops
  - The base design and conops will be different from that powered by a fission reactor nuclear power system (i.e., rover/suit recharging, aborts)
  - kW's solar power will be required regardless of primary power system technology choice (nuclear or solar); deployment, emergency power
- Mars surface solar array performance predictions are complex, but amenable to accurate analysis/verification
  - Fortran (type) time-marching, iterating computational analysis tools required
  - Predicts can support system design / component tech-dev planning
  - Simple power estimates have little value (could be >5X in error)
- Acknowledgements
  - SAWS colleagues across NASA (including LaRC/Richard Pappa)
  - NASA GRC/Geoff Landis & Univ. of Tel Aviv/Joe Appelbaum
    - Mars surface solar flux, dust storm modeling; Mars surface solar array data (MER)

Backup material

Bibliography

- Pappa, R. et al, “Mars Surface Solar Array Structures,” Space Power Workshop, April 26, 2017
- Landis, G. “DUST-INDUCED DEGRADATION OF SOLAR ARRAYS ON MARS“ **First** WCPEC; Dec. 5-9, 1994; Hawaii
- **Landis. G. et al**., “THE SOLAR SPECTRUM ON THE MARTIAN SURFACE AND ITS EFFECT ON PHOTOVOLTAIC PERFORMANCE”, IEEE, PVSC, 2006.
- Manson. J. “Solar Array Dust Removal System,,” ATK, July 2011
- Rucker, Michelle, “Integrated Surface Power Strategy for Mars” Paper 5074, Nuclear & Emerging Technologies for Space (NETS) 2015 Albuquerque, NM, February 23-26, 2015
- Kolecki & Hillard, “The Interaction of High Voltage Systems with the Environments of the Moon and Mars,” NASA-TM 106107, 1993.
- Montabone, L., et al., “ON THE DUSTIEST LOCATIONS ON MARS FROM OBSERVATIONS,” 2017.
- Stella, P., “MARS OPTIMIZED SOLAR CELL TECHNOLOGY (MOST)” IEEE PVSC 2008.

Bibliography – con't

4. Landis, Geoffrey A.., "Solar Cell Selection For Mars." 2nd World Conf. on Photovoltaic Solar Energy Conversion, Vienna, Austria, Vol. 3, Jul 6-10, 1998, p. 3695-3698.

5. Perez-Davis, Marla E., et al., "Lunar and Martian environmental interactions with nuclear power system radiators," NASA-TM-105747, Aug 01, 1992.

6. Zurek, Richard W. and Martin, Leonard J., "Interannual Variability of Planet-Encircling Dust Storms on Mars," J. Geo. Res., Vol 98, No E2, 1993, p. 3247-3259.

7. Martin, Leonard J., and Zurek, Richard W., "An Analysis of the History of Dust Activity on Mars," J. Geo. Res., Vol 98, No E2, 1993, p. 3221-3246.

8. Appelbaum, Joseph and Landis, Geoffrey A., "Solar Radiation on Mars—Update 1991," NASA TM 105216, 1991.

9. Pollack, James B., et al., "Simulations of the General Circulation of the Martian Atmosphere: 1. Polar Processes," J. Geo. Res., Vol 95, No B2, 1990, p. 1447-1473.

10. Landis, G., "Dust Obscuration of Mars Photovoltaic Arrays," paper IAF-94-380, Acta Astronautica, Vol. 38, No. 11, 1996, p. 885-891.

11. Appelbaum, Joseph, et al., "Verification of Mars Solar Radiation Model Based on Pathfinder Data," NASA TM 113167, 1997.

12. Jenkins, P., et al., "Materials Adherence Experiment: Technology," 32nd Intersociety Energy Conversion Engineering Conference, paper 97339, Aug 1997.

13 Scheiman, David A., et al., "Low Intensity, Low Temperature (LILT) Measurements on New Photovoltaic Structures," 30th Intersociety Energy Conversion Engineering Conference, paper 95353, Aug 1995.

14. Kaplan, David I., "Environment of Mars, 1988," NASA TM 100470, Oct 1988, pp. 2-10.

15. Ryan, J. A. and Henry, R. M., "Mars Atmospheric Phenomena During Major Dust Storms, as Measured at the Surface," Journal of Geophysical Research, Vol 84, No B6, Jun 10, 1979.

16 Kolecki, Joseph C., "Electrostatic Charging of the Mars Pathfinder Rover and Charging Phenomena on the Planet Mars," 32th Intersociety Energy Conversion Engineering Conference, paper 97344, Aug 1997.

17. Simonsen, Lisa C., et al., "Radiation Exposure for Manned Mars Surface Missions," NASA TP 2979, Mar 1990.

18. Simonsen, Lisa C. and Nealy, John E., "Mars Surface Radiation Exposure for Solar Maximum Conditions and 1989 Solar Proton Events," NASA TP 3300, Feb 1993.

19. Colozza, Anthony J., "Design and Optimization of a Self-Deploying PV Tent," NASA CR 187119, June 1991.

19. http://www.aec-able.com/corporate/articula.htm

21. Plescia, Jeffrey B., "Viking 2 Landing Site: Site Description and Material Properties," Jet Propulsion Laboratory, Pasadena, California, circa 1991.

22. Gaier, James R. and Perez-Davis, Marla E., "Aeolian removal of dust types from photovoltaic surfaces on Mars," 16th Space Simulation Conference Confirming Spaceworthiness Into the Next Millennium, Nov 01, 1990, p. 379-396.

23. Landis, G. A., "Mars Dust-Removal Technology," Journal of Propulsion and Power, Vol. 14, No. 1, Jan-Feb 1998, p. 126-128.

24. Landis, G. A., et al., "Dust Accumulation and Removal Technology (DART) Experiment on the Mars 2001 Surveyor Lander," 2nd World Conf. on Photovoltaic Solar Energy Conversion, Vienna, Austria, Vol. 3, Jul 6-10, 1998, p. 3699-3702.

36. Appelbaum, Joseph, et al., "Solar Radiation on Mars: Tracking Photovoltaic Array, NASA TM 106700, Sep 1994.

37. George, Patrick, "Space Solar Power Technology Plan FY 99: Power Management and Distribution," NASA Lewis Research Center, 1998.

38. Katzan, Cynthia M. and Edwards, Jonathon L.., "Lunar Dust Transport and Potential Interactions With Power System Components," NASA CR 4404, Nov 1991.

39. Hojnicki, J. S., et al., "Space Station Freedom Electrical Performance Model," 28th Intersociety Energy Conversion Engineering Conference Proceedings, Atlanta, Georgia, 1993.

40. Pollack, James B., et al., "Properties and Effects of Dust Particles Suspended in the Martian Atmosphere," J. Geo. Res., Vol 84, No B6, Jun 10, 1979, p. 2929-2945.

41. Zurek, Richard W., "Martian Great Dust Storms: An Update," Icarus, Vol. 50, May-Jun 1982, p. 288-310.

42. Appelbaum, J., et al., "Solar Radiation on Mars: Stationary Photovoltaic Array," NASA TM 106321, Oct 1993.

43. Hansen, James E., "Radiative Transfer By Doubling Very Thin Layers," The Astrophysical Journal, Vol. 155, Feb 1969.

44. Hansen, James E., "Multiple Scattering of Polarized Light in Planetary Atmospheres: Part I. The Doubling Method," Journal of the Atmospheric Sciences, Vol. 28, Sep 1970.

45. Scheiman, David A., et al., "Mars Array Technology Experiment (MATE) For the Mars 2001 Lander," 2nd World Conf. on Photovoltaic Solar Energy Conversion, Vienna, Austria, Vol 3., Jul 6-10, 1998, p. 3675-3678.

46. Matz, E., et al., "Solar Cell Temperature on Mars," Journal of Propulsion and Power, Vol. 14, No. 1, Jan-Feb 1998.

47. Burger, Dale R., "Mars Solar Array Program," Jet Propulsion Laboratory, NAS7-918, 1993.

Mars surface winds

Wind speed on Mars		R. Pappa	"Feels like" wind speed on Earth (at STP)	
mph	m/s	dynamic pressure (Pa)	m/s	mph
10	4.5	0.2367	0.6	1.4
50	22.4	5.9169	3.0	6.8
67	30.0* +	10.6587	4.1	9.1
100	44.7	23.6677	6.1	13.5
150	67.1	53.2523	9.1	20.3
200	89.4	94.6708	12.1	27.1
224	100.0	118.4304	13.5	30.3
447	200.0	473.7216	27.1	60.6
500	223.5	591.6924	30.3	67.7

* Highest measured wind speed from Viking Lander (1.6 m sensor elevation) **-VL1, sol 209, gusts**

+ 2X higher wind speed at 5 m surface elevation up into boundary layer (60 m/sec class)

Near surface, horizontal dust devil wind speeds of 75 m/sec (<50 m/sec vertical wind speeds)

NESC-RP- 13-00917, "Ground Wind Loads Uncertainty for Mars InSight Lander"

SAWS parametric landing sites

- Landing sites (site longitude affects albedo solar flux levels)

Parametric Landing site #	Landing Site Regioanl Name	Parametric Pos -> N lat, deg	Free Choice Pos -> E long, deg	Likely Power Performance
1	Utopia Planitia, very small subsurface ice depth for ISRU (near VL2)	50	140	lowest under clear skies
2	Mawrth Vallis	30	-20	
3	Jezero Crater (COMPASS study)	19	77	
4	Ares Vallis (near Pathfinder, ExoMars2018)	15	-30	
5	Meridiani Planum	0	-6	medium under clear skies; design point
6	Gusev Crater	-15	176	
7	Columbus Crater	-30	-166	highest under clear skies; **lowest durnig major dust storm**

Mars surface albedo

Mars Surface Albedo, 3:1 variation
(most important for polar latitude landing sites)

albedo.in KWrite

File Edit View Tools Settings Help

New Open Save Save As Close Undo Redo

TABLE 1. - MARS SURFACE ALBEDO (Christenen 1988)

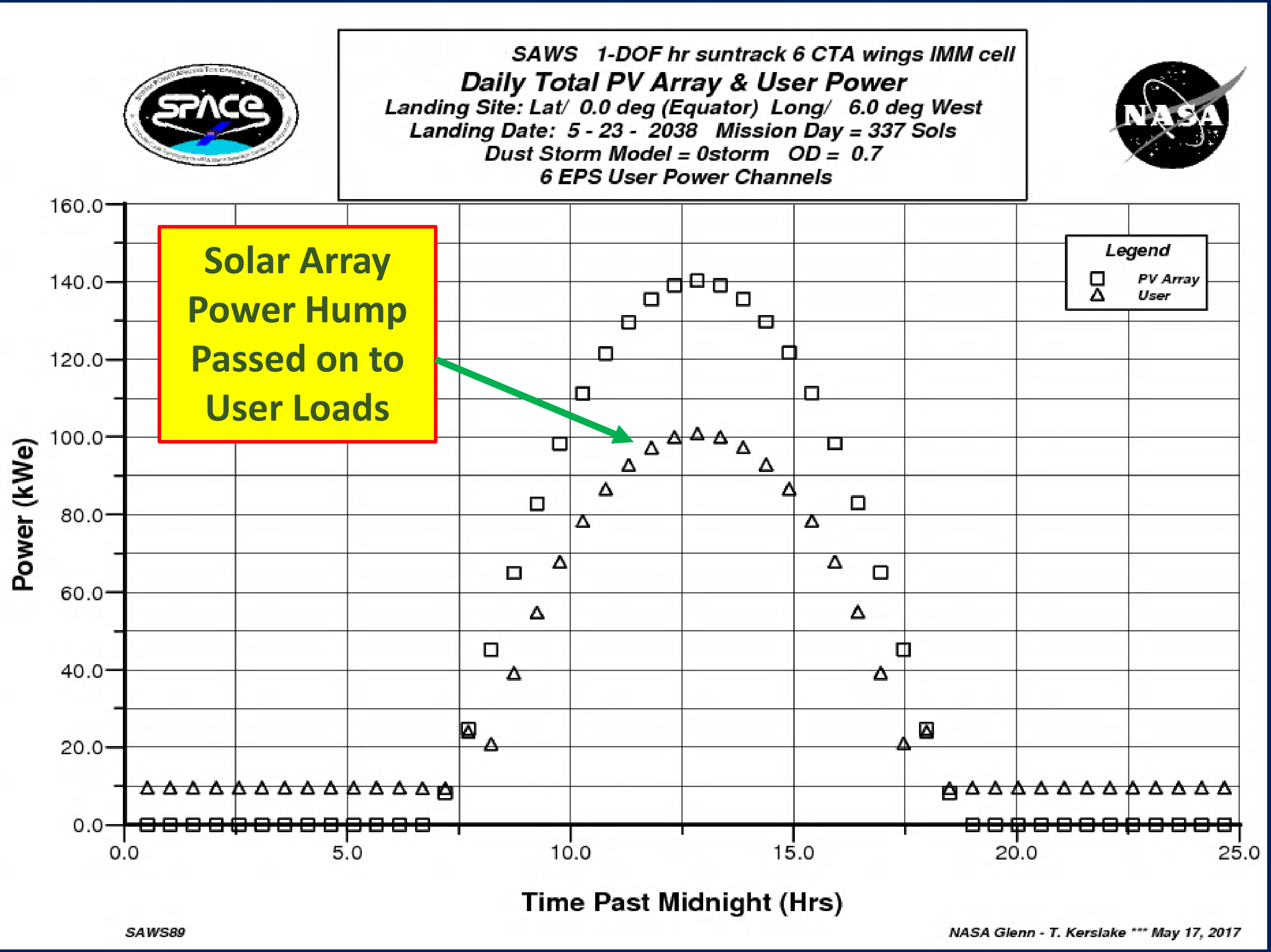
Longitude, deg | Latitude, deg

East	-90.	-80.	-70.	-60.	-50.	-40.	-30.	-20.	-10.	0.	10.	20.	30.	40.	50.	60.	70.	80.	90.
180.	.375	.245	.230	.175	.200	.200	.200	.225	.255	.275	.275	.275	.265	.255	.235	.210	.230	.340	.400
170.	.375	.245	.230	.175	.200	.200	.195	.210	.250	.270	.270	.270	.270	.260	.235	.200	.230	.340	.400
160.	.375	.245	.230	.175	.205	.200	.190	.195	.240	.265	.270	.270	.270	.265	.235	.200	.230	.340	.400
150.	.375	.245	.230	.180	.210	.210	.185	.180	.225	.255	.265	.265	.275	.270	.235	.200	.230	.340	.400
140.	.375	.245	.230	.185	.220	.225	.185	.175	.200	.250	.260	.260	.275	.270	.235	.210	.235	.365	.410
130.	.375	.245	.230	.185	.225	.230	.190	.175	.190	.235	.250	.255	.265	.265	.230	.200	.250	.425	.425
120.	.375	.245	.230	.190	.240	.235	.195	.175	.185	.225	.240	.240	.250	.260	.225	.190	.250	.430	.425
110.	.375	.245	.230	.190	.240	.235	.195	.175	.180	.220	.235	.235	.250	.255	.220	.185	.250	.430	.425
100.	.375	.245	.230	.195	.230	.225	.190	.175	.175	.210	.230	.235	.255	.250	.205	.180	.250	.430	.425
90.	.375	.245	.230	.195	.230	.225	.190	.175	.175	.200	.225	.230	.250	.248	.190	.175	.250	.430	.425
80.	.375	.245	.230	.200	.245	.250	.200	.175	.170	.175	.175	.210	.240	.245	.200	.175	.250	.430	.425
70.	.375	.245	.230	.200	.250	.265	.225	.175	.160	.150	.150	.185	.230	.248	.210	.185	.250	.430	.425
60.	.375	.245	.230	.200	.250	.265	.225	.180	.170	.175	.180	.210	.245	.250	.225	.190	.250	.425	.425
50.	.400	.245	.230	.195	.240	.250	.200	.180	.185	.220	.240	.250	.255	.255	.227	.200	.235	.400	.420
40.	.450	.250	.230	.190	.225	.225	.190	.180	.200	.250	.265	.270	.260	.250	.230	.210	.230	.365	.410
30.	.450	.300	.230	.185	.215	.220	.190	.190	.210	.250	.275	.275	.265	.250	.230	.210	.230	.340	.400
20.	.450	.300	.230	.180	.205	.215	.195	.200	.210	.245	.270	.275	.265	.250	.230	.210	.230	.340	.400
10.	.450	.300	.230	.175	.200	.210	.195	.205	.200	.220	.250	.265	.252	.250	.225	.210	.230	.340	.400
0.	.450	.300	.230	.175	.200	.205	.190	.190	.185	.200	.230	.245	.235	.220	.200	.200	.230	.340	.400
-10.	.450	.300	.230	.175	.200	.205	.185	.182	.180	.200	.220	.230	.220	.185	.160	.175	.230	.340	.400
-20.	.450	.300	.230	.180	.200	.200	.180	.175	.175	.200	.220	.210	.185	.150	.135	.160	.230	.340	.400
-30.	.450	.300	.230	.180	.205	.200	.175	.170	.175	.200	.225	.210	.175	.135	.125	.150	.230	.340	.400
-40.	.450	.300	.230	.180	.205	.200	.170	.170	.175	.210	.230	.225	.185	.150	.135	.150	.230	.340	.400
-50.	.400	.250	.230	.180	.205	.200	.175	.170	.175	.215	.240	.225	.210	.200	.175	.170	.230	.340	.400
-60.	.375	.245	.230	.175	.200	.195	.175	.175	.190	.225	.245	.235	.230	.235	.225	.190	.230	.340	.400
-70.	.375	.245	.230	.175	.190	.195	.185	.180	.205	.250	.260	.255	.255	.265	.250	.210	.230	.340	.400
-80.	.375	.245	.230	.175	.185	.195	.185	.180	.215	.270	.285	.277	.277	.275	.255	.225	.235	.340	.400
-90.	.375	.245	.230	.175	.180	.190	.185	.190	.225	.285	.300	.285	.280	.275	.262	.230	.235	.340	.400
-100.	.375	.245	.230	.175	.175	.190	.185	.200	.250	.300	.300	.290	.287	.275	.270	.235	.235	.340	.400
-110.	.375	.245	.230	.175	.175	.190	.185	.200	.260	.295	.295	.288	.285	.275	.275	.240	.235	.340	.400
-120.	.375	.245	.230	.175	.175	.190	.180	.215	.270	.290	.290	.285	.282	.275	.270	.235	.230	.340	.400
-130.	.375	.245	.230	.175	.185	.200	.190	.230	.275	.280	.285	.280	.280	.275	.262	.225	.230	.340	.400
-140.	.375	.245	.230	.175	.195	.200	.200	.240	.275	.280	.280	.280	.277	.275	.255	.220	.230	.340	.400
-150.	.375	.245	.230	.175	.200	.200	.200	.235	.275	.275	.280	.280	.272	.270	.250	.220	.230	.340	.400
-160.	.375	.245	.230	.175	.200	.200	.200	.225	.265	.275	.275	.275	.265	.265	.250	.215	.230	.340	.400
-170.	.375	.245	.230	.175	.200	.200	.200	.225	.260	.275	.275	.275	.265	.260	.240	.210	.230	.340	.400
-180.	.375	.245	.230	.175	.200	.200	.200	.225	.255	.275	.275	.275	.265	.255	.235	.210	.230	.340	.400

West

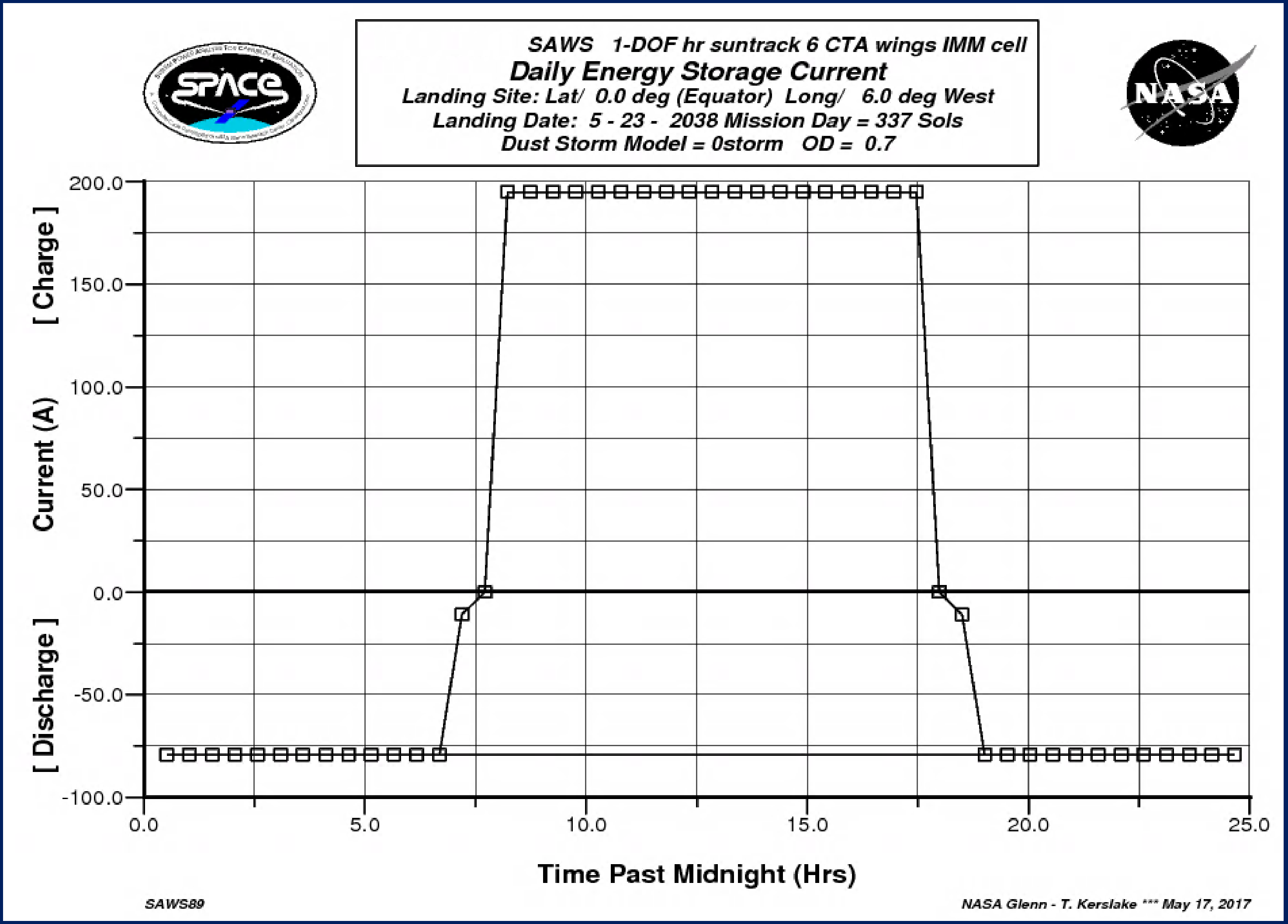
"SAWS" Module Day-Night Power Flow

- 60% day time user power factor input, variable user (ISRU) power

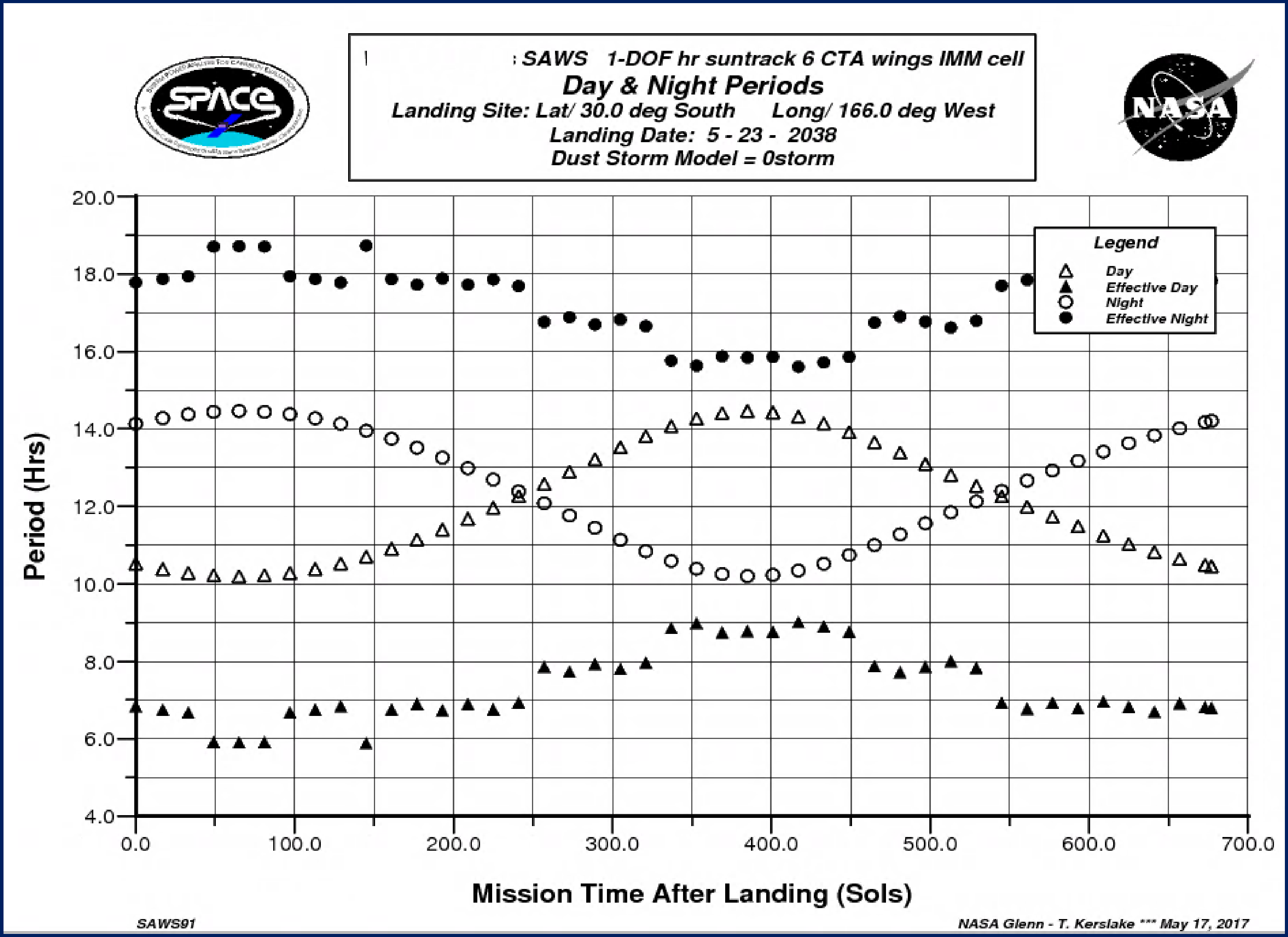


“SAWS” RFC Power Flow

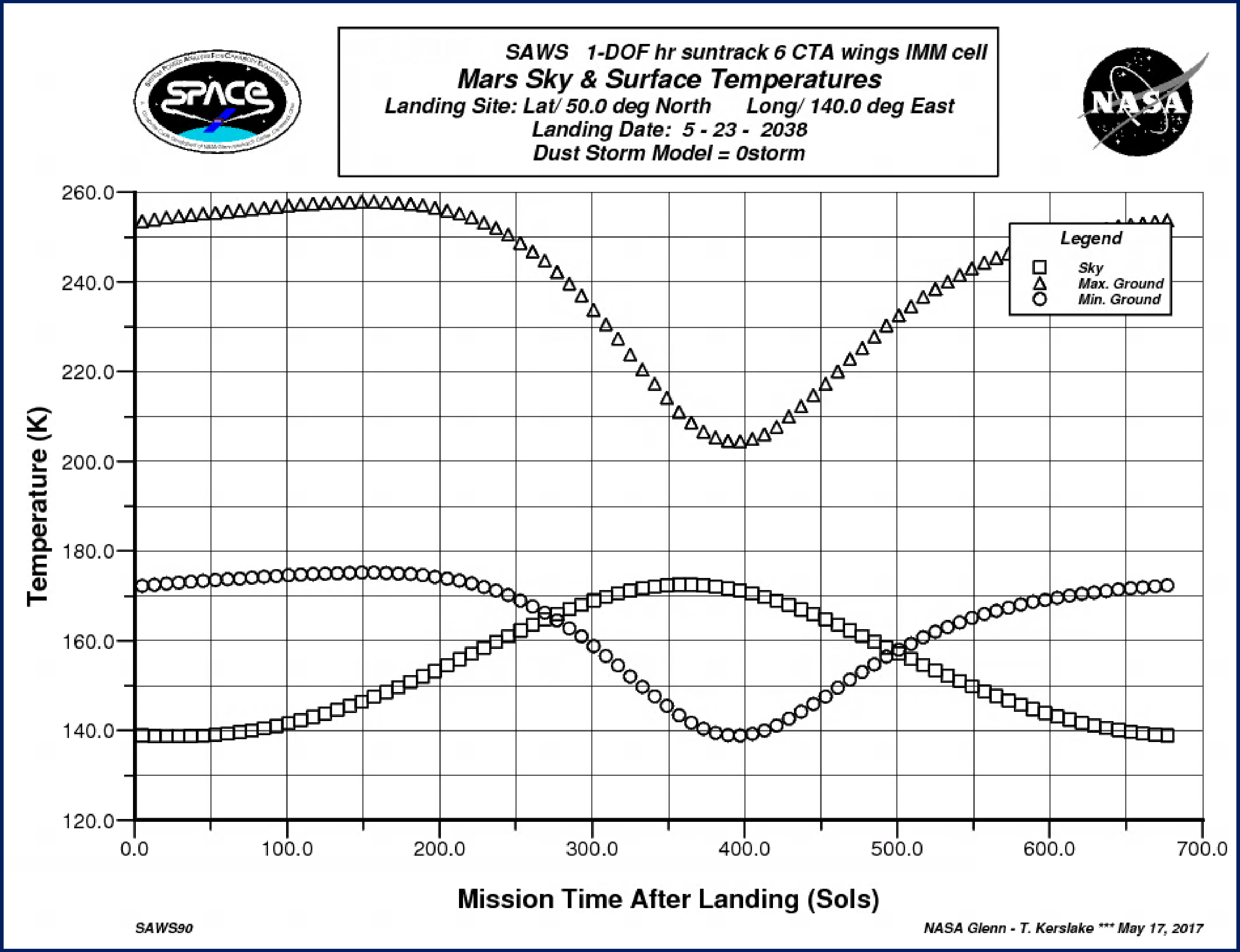
- 70% day time user power factor input, variable user (ISRU) power
- Simpler, monotonic RFC charge discharge operation



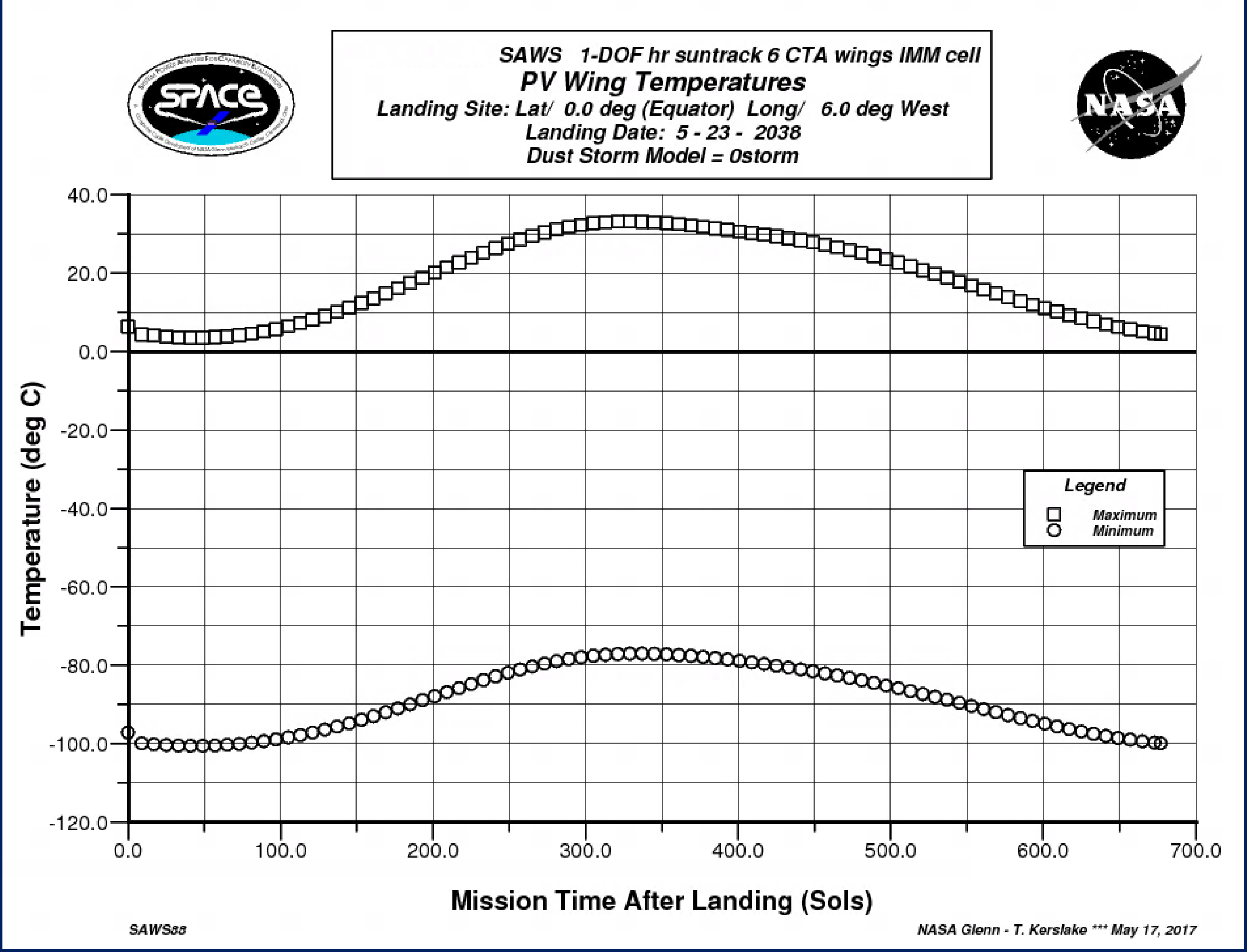
Mission Day Night Periods



Mission Environment Temperatures



Mission Solar Array Temperatures



Mission Solar Array Operating Voltage