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, 1.5m², 0.25 m²/<20 W)
  - MER Spirit & Opportunity (15°S/2°S, 2m², <200 W)
  - Phoenix (68°N, 3m² 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)
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

No Global Dust Storm  During Dust Storm

Dust Haze Hiding the Martian Surface in 2001
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 $f(\text{season, latitude, time})$
    • Highest OD in the South, lower in the North
• Historically, $\sim 1/3$rd 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

- Higher OD values, if a 2\textsuperscript{nd} major storm occurs

![Graph showing single major dust storm event optical depth]

1/15/2034 BOL landing date

OD at a 19\textdegree N site

MES, sols
Major Dust Storm Loss in Solar Flux

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

Max Horizontal Surface Solar Fluxes

Flux, W/m²

0 100 200 300 400 500 600 700

MES, sols

1/15/2034 BOL landing date

Dust Storm

AM0, 30° S, 0°, 50° N
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  \hspace{1cm} z = solar zenith angle
al = surface albedo \hspace{1cm} 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

Graph showing Daily Solar Fluxes on PVA #8 with 6 CTA wings IMM cell.
Legend:
- Front - Total
- Front - Beam
- Front - Diffuse
- Front - Albedo
- Back - Total
- Back - Beam
- Back - Diffuse
- Back - Albedo

Flux (W/m²) vs Time Past Midnight (Hrs)

All Diffuse Sunlight
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 H₂O?)
  - 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, $\tau = 0.94$). 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

<table>
<thead>
<tr>
<th>OD</th>
<th>0</th>
<th>0.25</th>
<th>0.5</th>
</tr>
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<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1.000</td>
<td>0.989</td>
<td>0.944</td>
<td></td>
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<tr>
<td>0.899</td>
<td>0.818</td>
<td>0.750</td>
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</tr>
<tr>
<td>0.694</td>
<td>0.647</td>
<td>0.608</td>
<td></td>
</tr>
</tbody>
</table>

Zen, deg: 0
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

1000 m² total solar cell area. Array spacing allows cargo access from 2 sides.

8-m or 10-m class diameter; Pappa et al
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 require an iterative solution for each sol

- 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

**Legend**
- □ PV Array
- △ User and/or ISRU Power

**Daily Total PV Array & User Power**
- Landing Site: Lat/ 0.0 deg (Equator) Long/ 5.0 deg West
- Landing Date: 5-23-2038 Mission Day = 9 Sol
- Dust Storm Model = 0; storm OD = 0.7
- 6 EPS User Power Channels

**Power (kWe)**
- Time Past Midnight (Hrs)
“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

RFC sized for equatorial landing site (shorter nights)
“SAWS” Module Mission Power

- 30° South latitude landing site

![Graph showing power output over mission time](https://example.com/graph.png)
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
• Landis, G. “DUST-INDUCED DEGRADATION OF SOLAR ARRAYS ON MARS” First WCPEC; Dec. 5-9, 1994; Hawaii
• Manson, J. “Solar Array Dust Removal System,” ATK, July 2011
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”

<table>
<thead>
<tr>
<th>Wind speed on Mars</th>
<th>R. Pappa dynamic pressure (Pa)</th>
<th>&quot;Feels like&quot; wind speed on Earth (at STP)</th>
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<tbody>
<tr>
<td>mph</td>
<td>m/s</td>
<td>m/s</td>
</tr>
<tr>
<td>10</td>
<td>4.5</td>
<td>0.2367</td>
</tr>
<tr>
<td>50</td>
<td>22.4</td>
<td>5.9169</td>
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<tr>
<td>67</td>
<td>30.0*</td>
<td>10.6587</td>
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<tr>
<td>100</td>
<td>44.7</td>
<td>23.6677</td>
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<tr>
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<td>67.1</td>
<td>53.2523</td>
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<tr>
<td>200</td>
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<tr>
<td>500</td>
<td>223.5</td>
<td>591.6924</td>
</tr>
</tbody>
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* Highest measured wind speed from Viking Lander (1.6 m sensor elevation) + 2X higher wind speed at 5 m surface elevation up into boundary layer (60 m/sec class)
SAWS parametric landing sites

<table>
<thead>
<tr>
<th>Landing site #</th>
<th>Landing Site Region Name</th>
<th>Parametric Pos -&gt; N lat, deg</th>
<th>Parametric Pos -&gt; E long, deg</th>
<th>Likely Power Performance</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Utopia Planitia, very small subsurface ice depth for ISRU (near VL2)</td>
<td>50</td>
<td>140</td>
<td>lowest under clear skies</td>
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<tr>
<td>2</td>
<td>Mawrth Vallis</td>
<td>30</td>
<td>-20</td>
<td></td>
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<tr>
<td>3</td>
<td>Jezero Crater (COMPASS study)</td>
<td>19</td>
<td>77</td>
<td></td>
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<tr>
<td>4</td>
<td>Ares Vallis (near Pathfinder, ExoMars2018)</td>
<td>15</td>
<td>-30</td>
<td>medium under clear skies; design point</td>
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<td>5</td>
<td>Meridiani Planum</td>
<td>0</td>
<td>-6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Gusev Crater</td>
<td>-15</td>
<td>176</td>
<td>highest under clear skies; lowest during major dust storm</td>
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<tr>
<td>7</td>
<td>Columbus Crater</td>
<td>-30</td>
<td>-166</td>
<td></td>
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Mars Surface Albedo, 3:1 variation (most important for polar latitude landing sites)

<table>
<thead>
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<th>Latitude, deg</th>
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<td>West</td>
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<tr>
<td>20°</td>
<td>200°</td>
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<tr>
<td>10°</td>
<td>190°</td>
</tr>
<tr>
<td>0°</td>
<td>180°</td>
</tr>
</tbody>
</table>

Mars surface albedo is critical for polar latitude landing sites. The table above shows the variation in albedo across different longitudes and latitudes.
“SAWS” Module Day-Night Power Flow

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

Solar Array Power Hump Passed on to User Loads
“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

SAWS 1-DOF hr suntrack 6 CTA wings IMM cell

Day & Night Periods
Landing Site: Lat/ 30.0 deg South   Long/ 166.0 deg West
Landing Date: 5-23-2038
Dust Storm Model = None

Legend
- Day
- Effective Day
- Night
- Effective Night

Period (Hrs)

Mission Time After Landing (Sols)

SAWS91
Mission Environment Temperatures

SAWS 1-DOF hr suntrack 6 CTA wings IMM cell
Mars Sky & Surface Temperatures
Landing Site: Lat/ 50.0 deg North   Long/ 140.0 deg East
Landing Date: 5 - 23 - 2038
Dust Storm Model = 0storm

Temperature (K)

Mission Time After Landing (Sols)

Legend
- Sky
- Max. Ground
- Min. Ground

NASA Glenn - T. Kerslake *** May 17, 2017
Mission Solar Array Temperatures

SAWS 1-DOF hr suntrack 6 CTA wings IMM cell
PV Wing Temperatures
Landing Site: Lat/ 0.0 deg (Equator) Long/ 6.0 deg West
Landing Date: 5 - 23 - 2038
Dust Storm Model = 0storm
Mission Solar Array Operating Voltage

SAWS 1-DOF hr suntrack 6 CTA wings IMM cell
Cell Voltage Ratio (Vop/Vmp)
Landing Site: Lat/ 0.0 deg (Equator) Long/ 6.0 deg West
Landing Date: 5-23-2038
Dust Storm Model = 0storm

Legend
- Maximum
- Minimum

Mission Time After Landing (Sols)