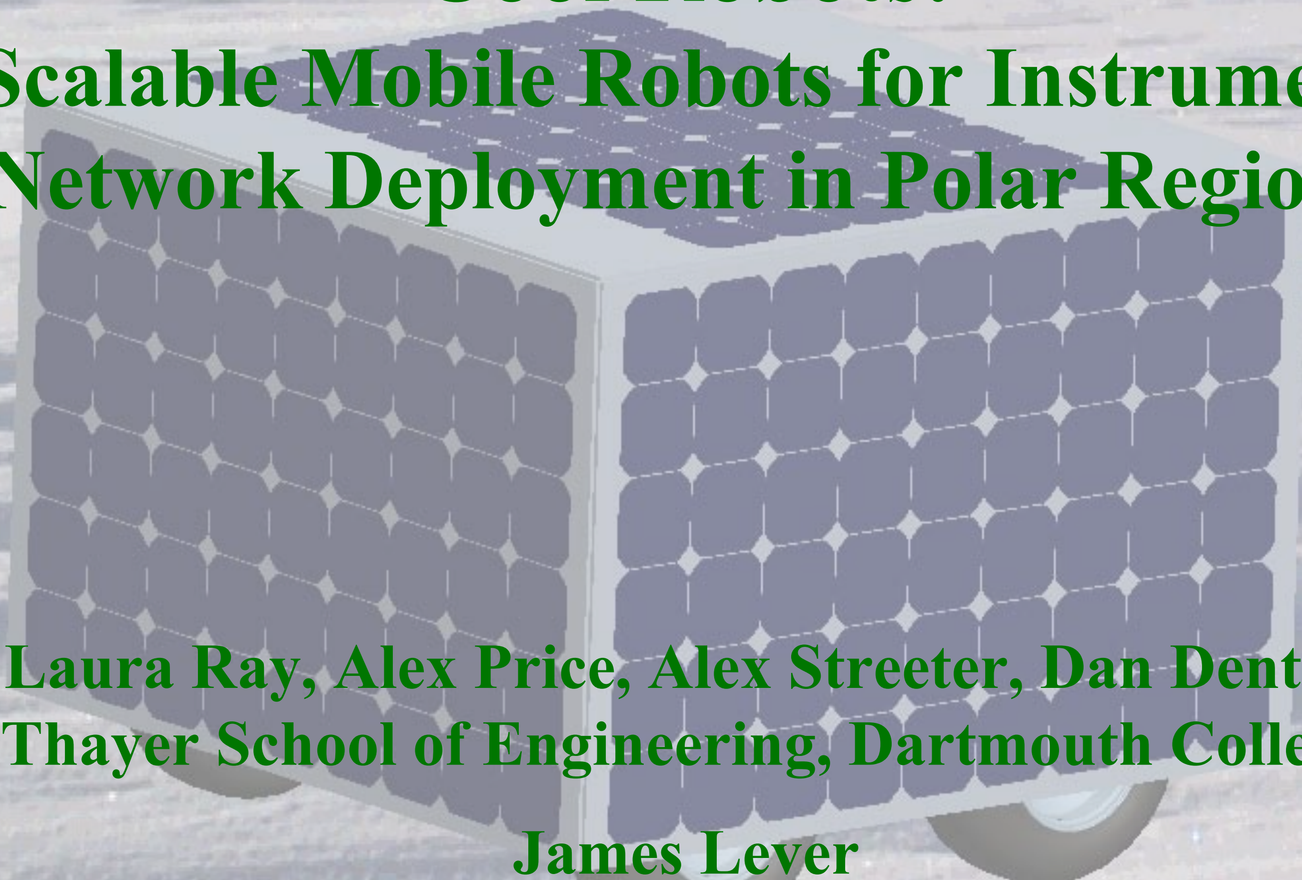
# Cool Robots:
## Scalable Mobile Robots for Instrument Network Deployment in Polar Regions



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**National Academy of Engineering**
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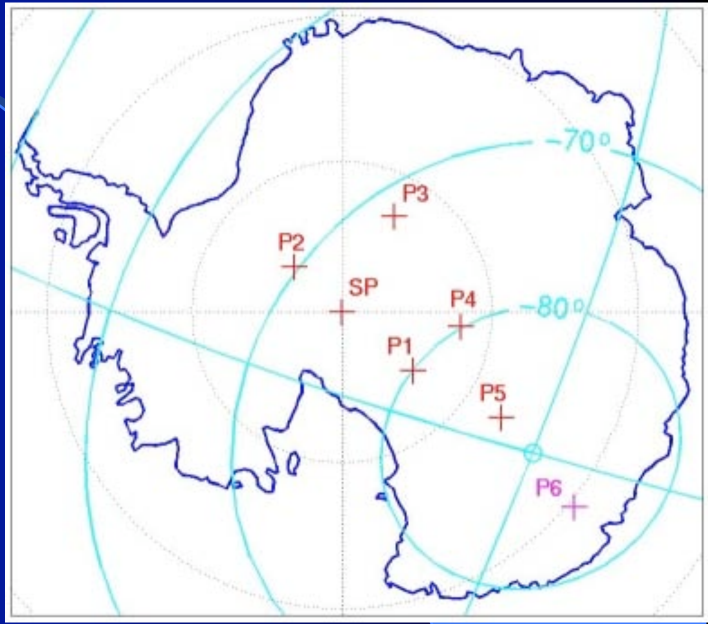
# Antarctic Plateau

- Area >5M km$^2$, high altitude plateau
- -40° to -20° C in summer (Nov-Feb)
- Winds avg. 2 m/s, max 20.5 m/s
- Firm snow
  - <50 mm annual precipitation
  - Flat, w/ wind-sculpted sastrugi

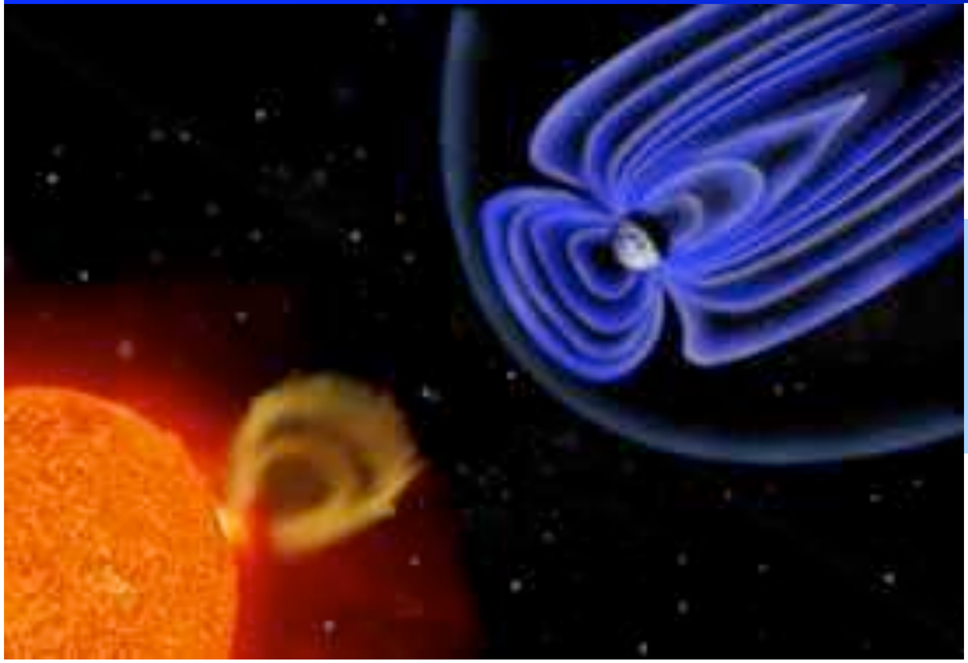

# Science on Antarctic Plateau

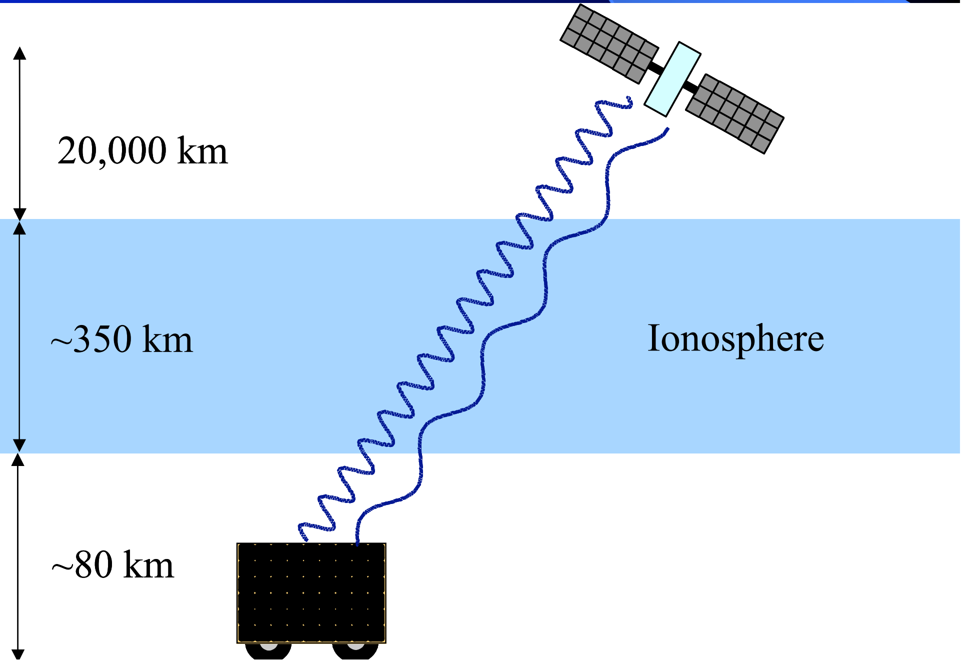
- Field Science
  - Aeronomy and astrophysics: "window to space"
  - Soil and snow biology and ecology
  - Geology, geophysics, glaciology
  - Climate studies
- Six Automatic Geophysical Observatories (50 W, 8'x8'x16'):
  - Magnetometers
  - Radio receivers, riometers
  - Sky cameras
- Transport/maintenance via C-160 cargo aircraft (AGO) and Twin Otter




# Role of Autonomous Robots

- Dense magnetometer networks - ground-based observation of solar-terrestrial physics
- Distributed GPS - mapping ionospheric disturbances
- Field studies - power and high bandwidth communication for environmental science, ecology, geophysics
- Antarctic traverse - navigation support, crevasse free route planning
- General benefits - frees scarce, costly air transport resources





# Project Goals

- Design and construct a robot for autonomous traverse of Antarctic plateau during austral summer
  - Inexpensive (< $20,000)
  - 500 km in under two weeks (avg 0.4 m/s)
  - < 75 kg (90 kg, including payload)
  - Maximum ground pressure < 3 psi
  - Fits inside Twin Otter aircraft
  - No tipping in wind up to 21 m/s
  - Renewable or HED power source

- Demonstrate value of robots to polar science
  - Magnetometer deployment
  - Ionosphere density mapping using GPS
  - Traverse navigation support
  - Mobility and solar power availability


# State-of-the-Art

- Nomad (CMU) – Internal combustion 725 kg, 2.4 x2.4x2.4-m, 0.5 m/s
  - good mobility viable
  - cameras do not work in low contrast terrain
  - Non-renewable energy
- Hyperion (CMU) – “Sun navigation” 157 kg, 2 x 2.4 x 3-m, 0.3 m/s
  - Solar power viable
  - Not rugged enough for Antarctica
  - Commercial panels too heavy
- NASA/JPL – Spirit and Opportunity, 174 kg, 2.3 x 1.6 x 1.5-m, 0.05 m/s
  - Well-engineered for extreme climates
  - Expensive

# Design Specifications for Antarctic Mobility

- Tractor test: 8-9 psi ground pressure → 2-3” sinkage. No boot prints.

- Pull test: 6 and 8 psi ground pressure → 3-4” sinkage. Boot prints for 5-7 psi ground pressure at 1”.

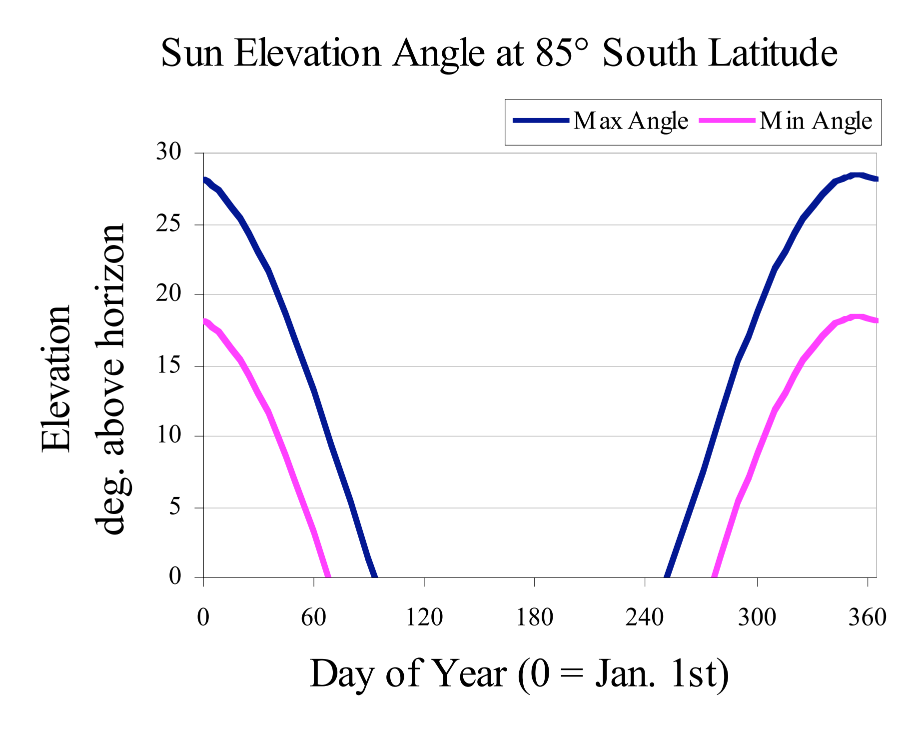
# Design Specifications (cont)

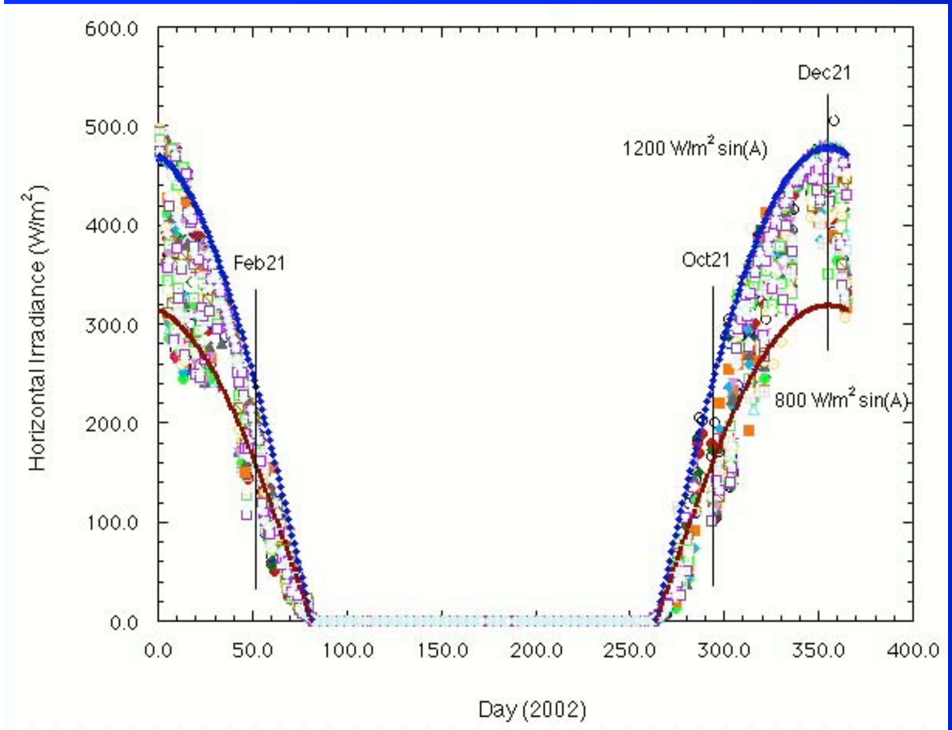
- Minor surface roughness
- Typical sastrugi scale ~ 15 cm
- Firm snow on plateau
- Lack of contrast
- Katabatic winds near coast only



# Solar Power in the Antarctic

- Constant, low angle summer sun
- 'Brighter' sun in high, dry climate
  - Insolation up to 1200 W/m$^2$
  - Few cloudy days on plateau

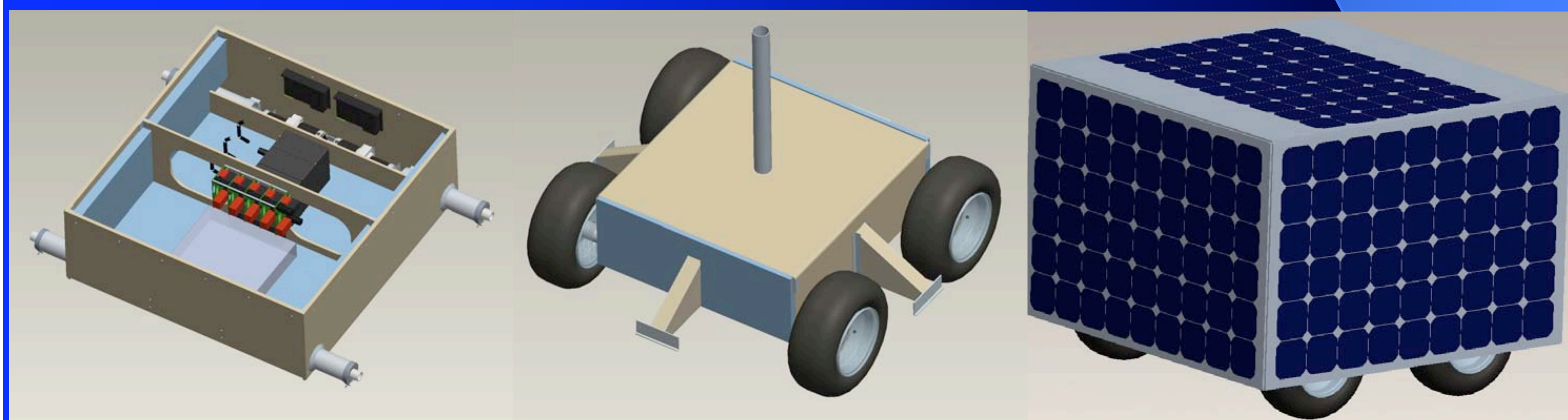


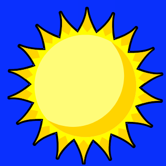

- Significant reflected light
  - albedo up to 0.95, proportional to sun elevation
- Diffuse insolation by atmospheric scattering up to 100 W/m$^2$

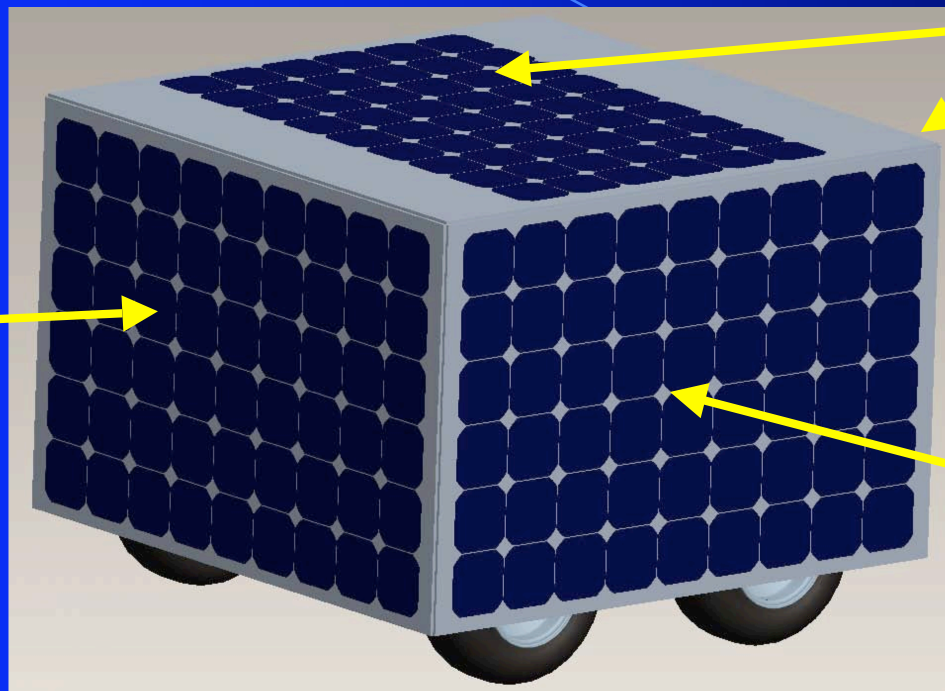
# Cool Robot Design Concept

- Solar panels over chassis box attached by support arms
- Scalable design
- Custom power system, solar panels, and MPP trackers
- LI batteries for “backup” power
- Iridium communication
- Lightest ATV tires and custom rim/hubs
- High efficiency motors/geartrain
- Lightweight honeycomb composite chassis
- 2.5 cm foam insulation sufficient



# Solar Capacity - Average Summer Sun





Top (direct sun only)
34%

Back (in shadow)
11%

Front
128%
(direct + reflected)

Sides
34%
(reflected light only)

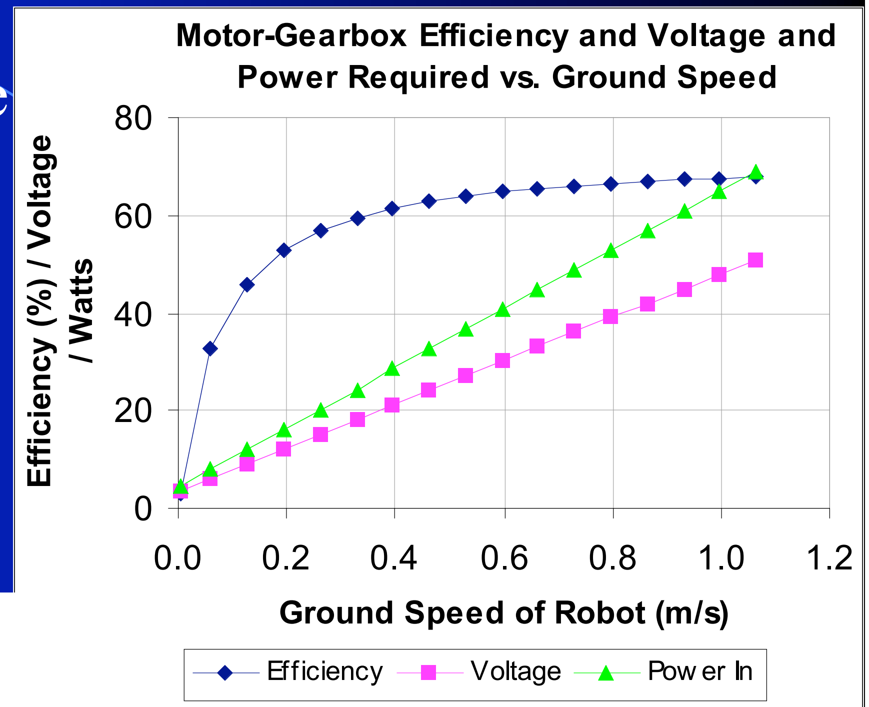
- 1 Sun - 1000 W/m$^2$ insolation w/ 20° sun elevation (avg. for Nov-Feb)
- Robot facing front towards sun (worst case) ; Snow albedo 90% (conservative)
- Required power to meet specs+housekeeping and payload power:  250 W

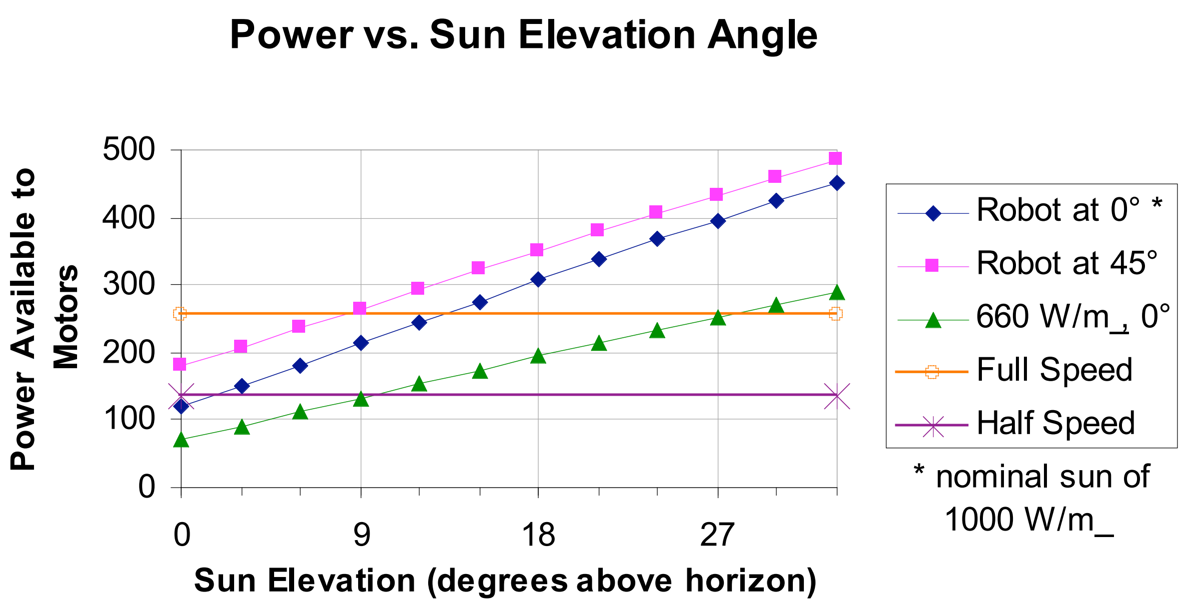
# Solar Cells - Sunpower A-300

- 20% efficient @ 25 C, 12.5 x 12.5 $cm^2$ cell
- 3 W/cell @ 1000 $W/m^2$, \$9-\$12 per Watt
- All back contact
- Efficiency increases w/ temperature decrease
- Compare to space rated cell – 23.5% efficient @ \$52 per Watt
- Bare cells available late 2003, panels mid-2004

# Power w/ Sunpower A-300 Cells

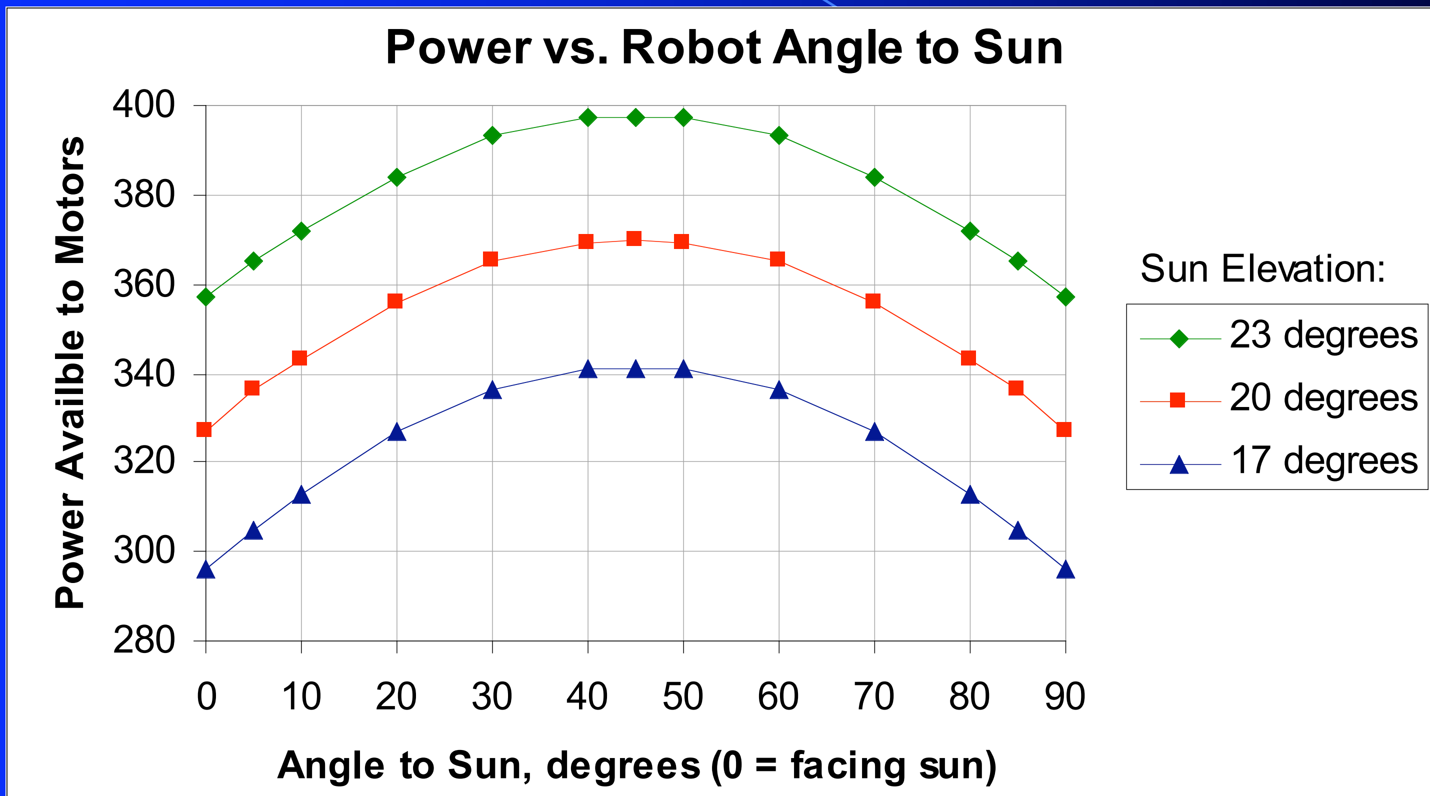
- Drivetrain sized for rolling resistance factor of 0.25
- Flat efficiency curve in speed range
- Cold room tested to -50 C
- Excess power available on average (over summer months)




- Robot can move slowly – 0.2 m/s – under solar power only even in “worst case” conditions

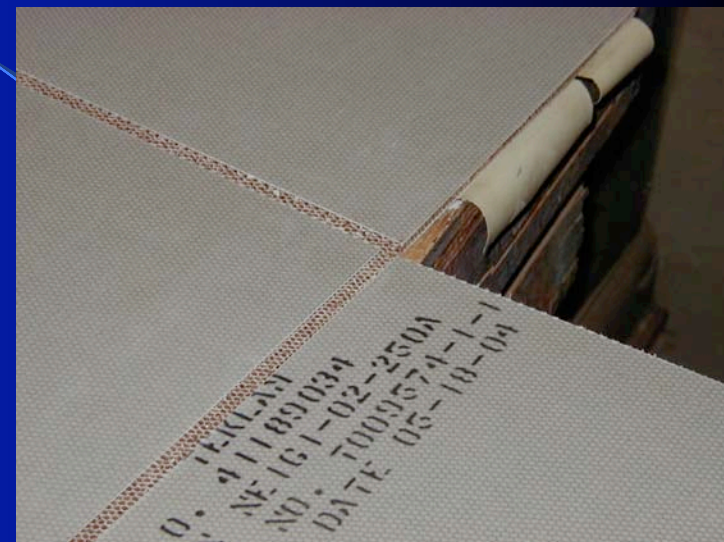
# Power w/ Sunpower A-300 Cells (continued)

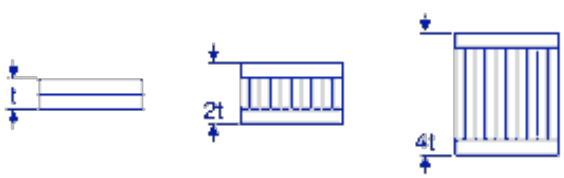



- For portable field power, robot can be rotated to maximize power – 300 to 400 W available over most of the summer

# Chassis Design and Fabrication

- Chassis material - Teklam honeycomb composite: fiberglass face sheets with Nomex core
- Excellent strength-weight ratio: 9.5 mm thick, 1.6 kg/m$^2$ (compare to 3.8-mm thick aluminum plate, 10 kg/m$^2$)
- “Slit and fold” construction w/ light angle brackets, epoxy, and fasteners

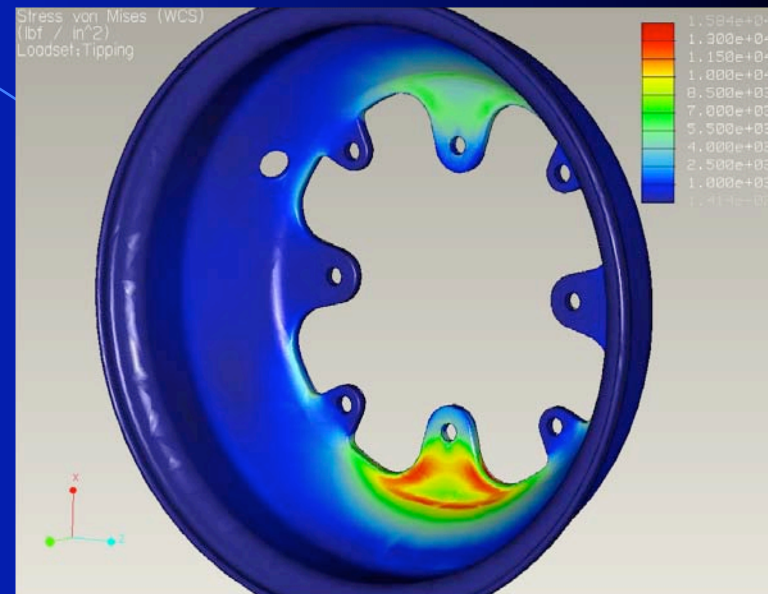


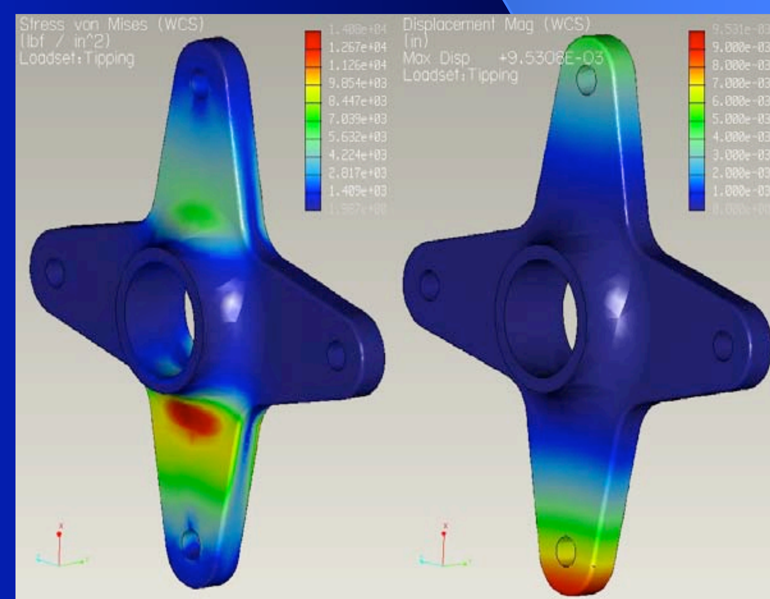

| | Solid Material | Core Thickness t | Core Thickness 3t |
|---|---|---|---|
| |  | | |
| Stiffness | 1.0 | 7.0 | 37.0 |
| Flexural Strength | 1.0 | 3.5 | 9.2 |
| Weight | 1.0 | 1.03 | 1.06 |



# Wheels and Hubs

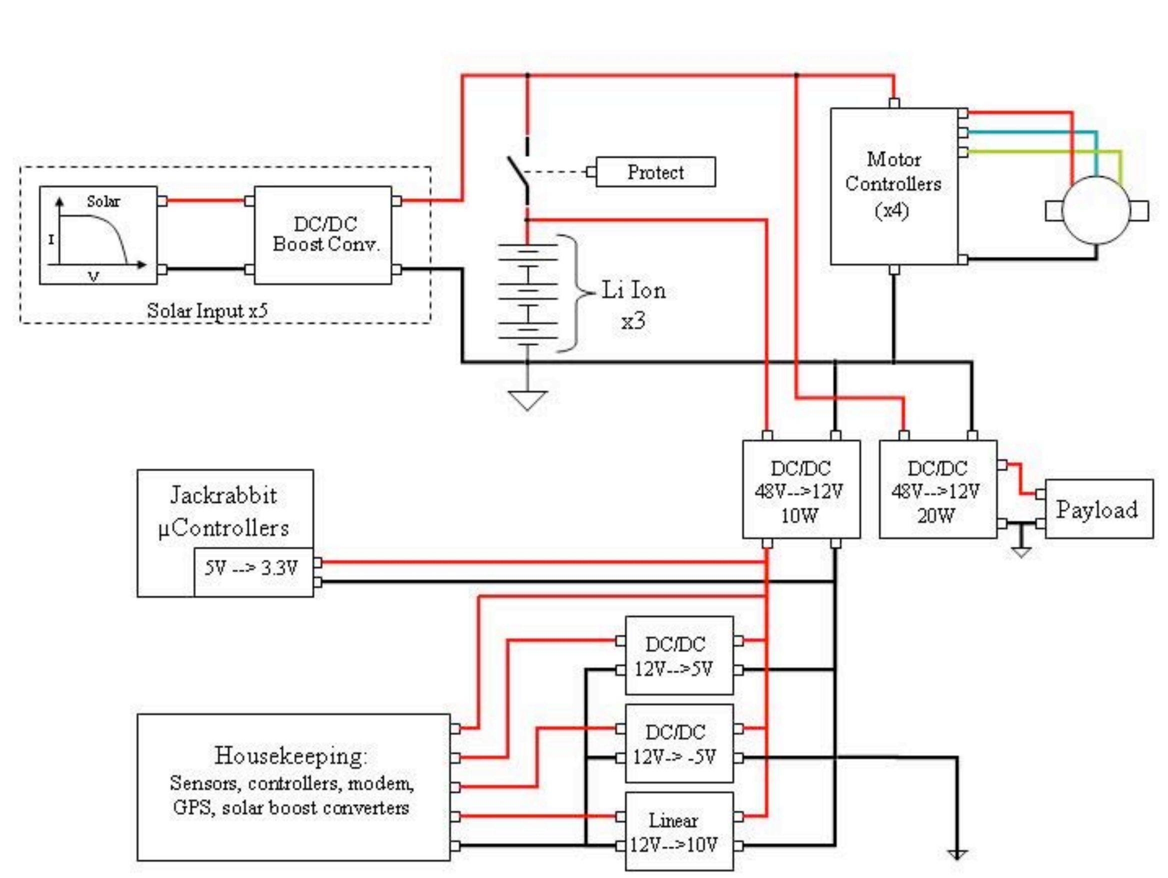
- Rim accepts 20x6-8 or 16x6-8 ATV tires
- Wheel assembly:   1.1 kg/wheel
- Savings of 8-9 kg over commercial rim/hub



# Power System Design and Fabrication

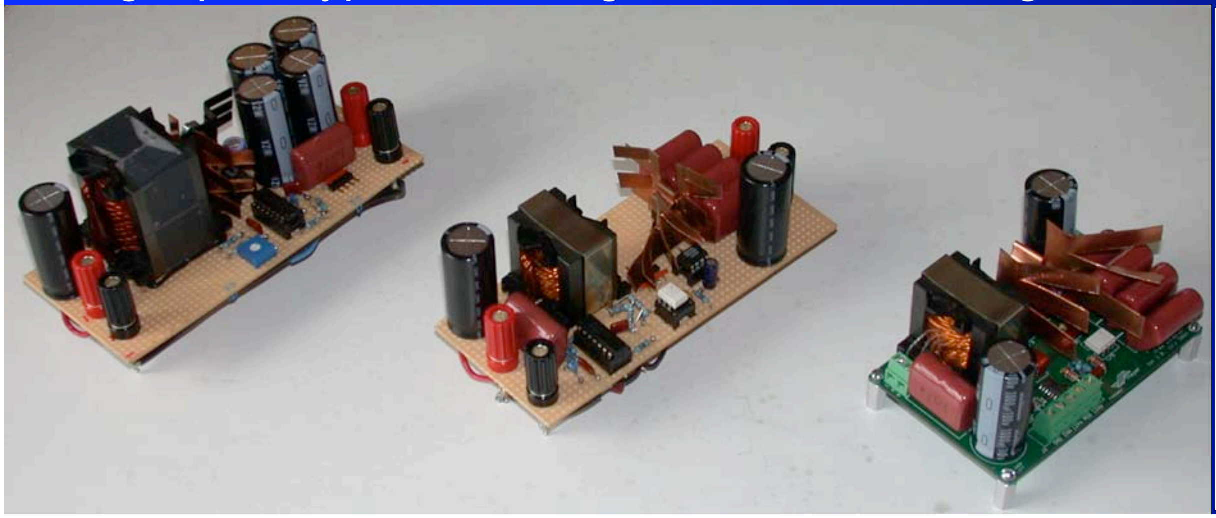
- Architecture/control for all solar operation
- Major components:
  - Li-ION batteries (12 Ah)
  - solar panels for primary power and battery charging
  - Custom DC-DC converters fuse panel power to bus at 48 V
  - Commercial DC-DC converters for housekeeping power
  - Slave microcontroller for power

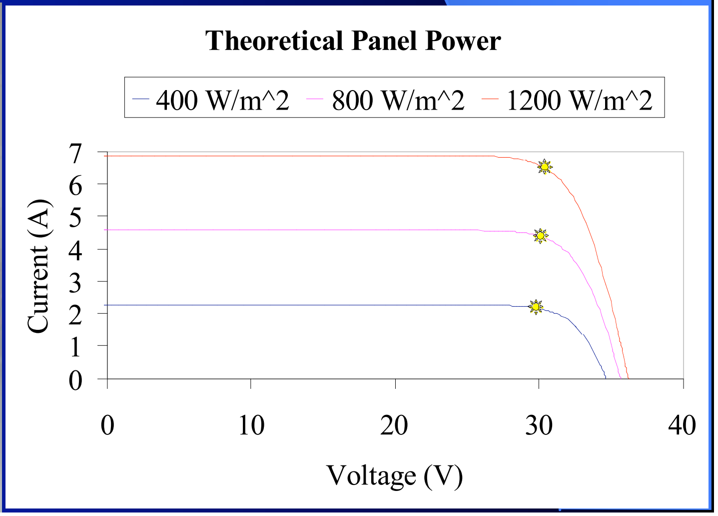


# Custom DC-DC Boost Converters

- Fuse power from five panels operating at different voltages to common bus @ 48 V
- Can operate at Maximum Power Point with input from microcontroller
- Design cycle: 350 gm prototype to 200 gm PCB layout through careful choice of operational frequency and inductor
- > 97% efficiency measured

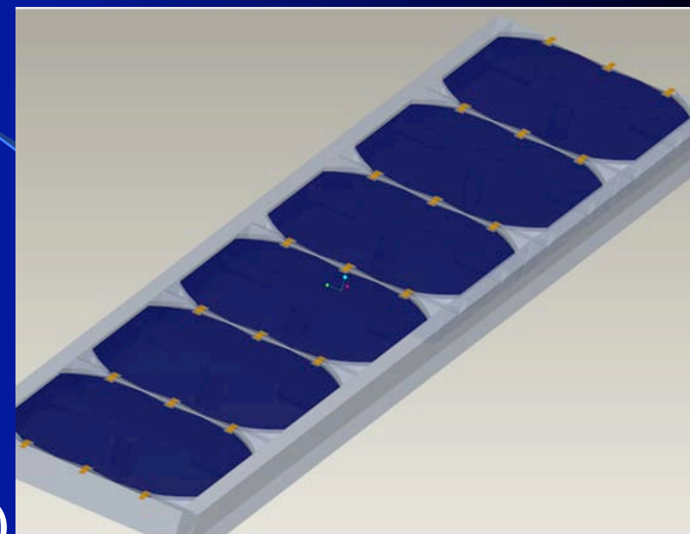
350 gm prototype 250 gm revision 200 gm PCB

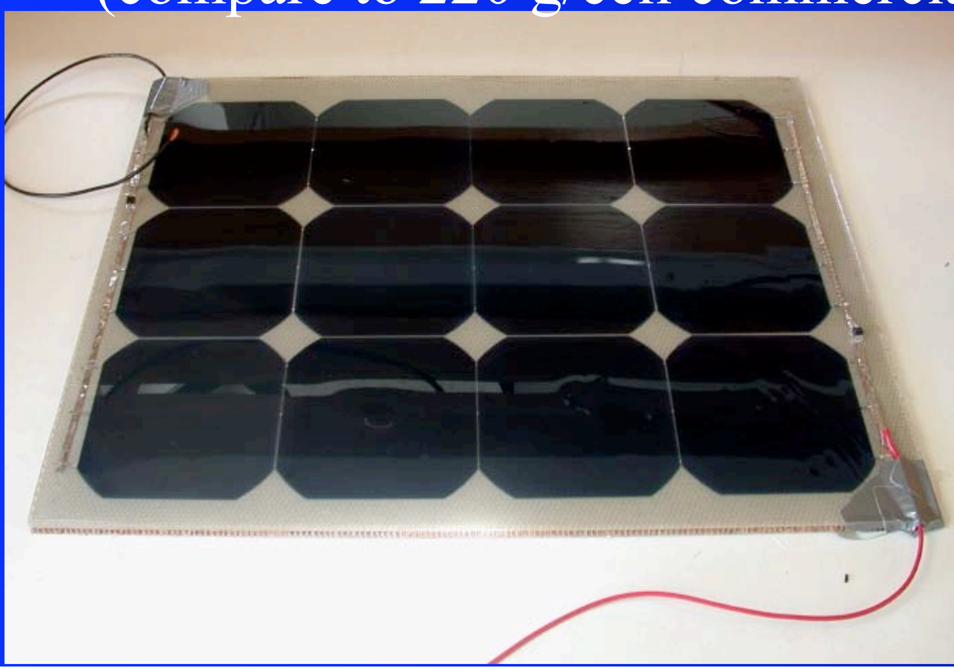


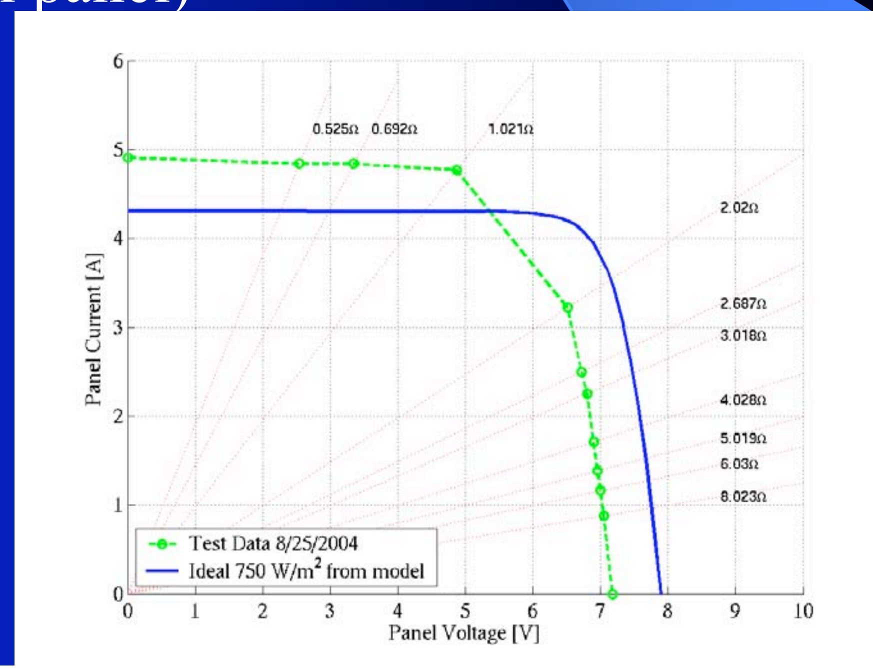


# Panel Fabrication and Testing

- Panel construction: plexiglass soldering jig, silicone encapsulation on ¼" honeycomb composite backing, fabric stippling.
- 18-19% panel efficiency
- 80 g/cell - 4.32 kg for 9x6 panel (compare to 220 g/cell commercial panel)

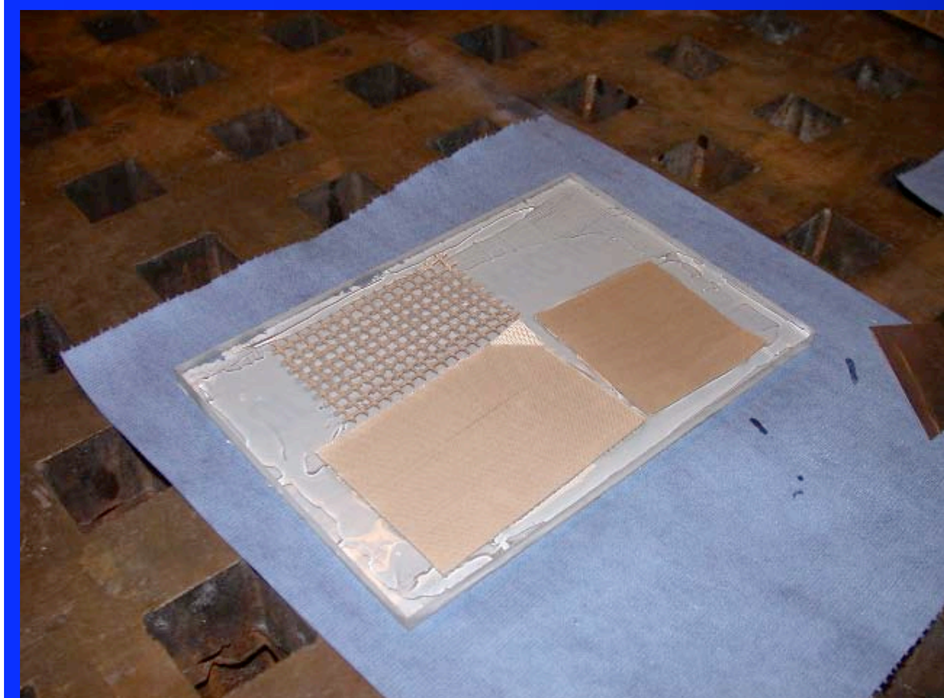


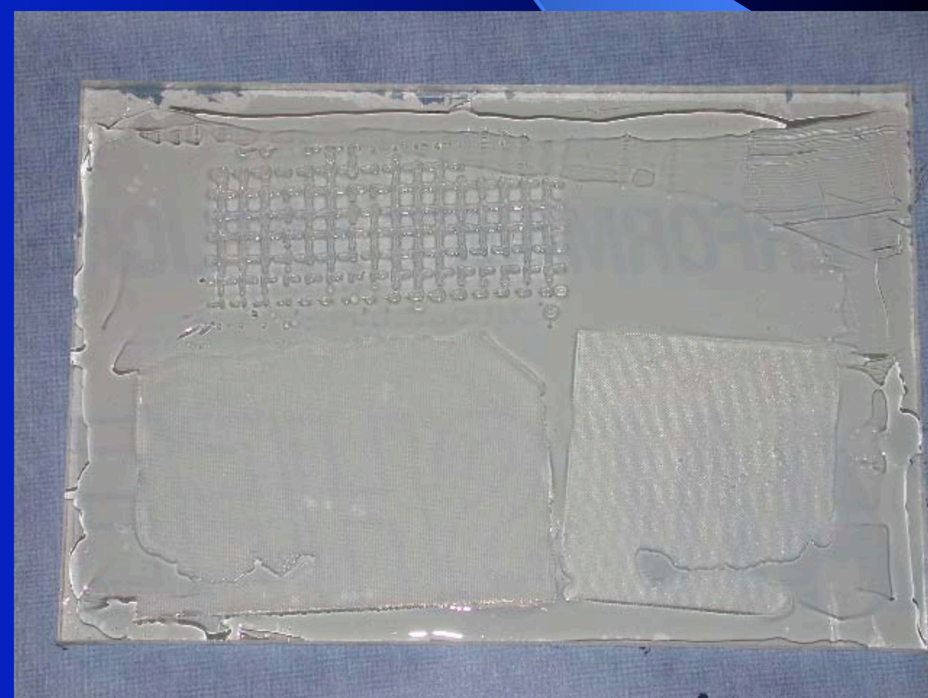




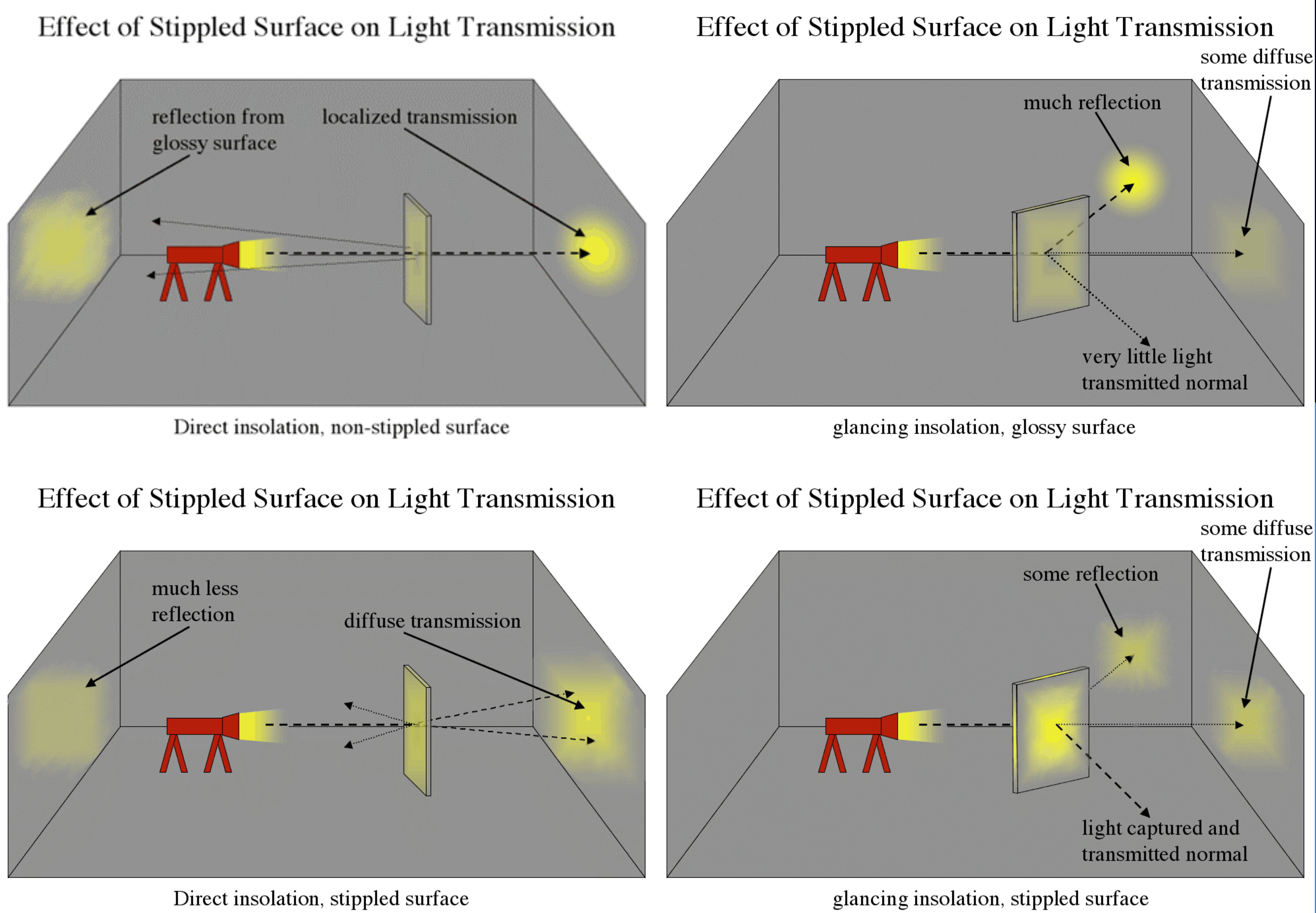
# Panel Reflectivity

- Stippling by overlay of course-woven fiberglass on silicone topcoat



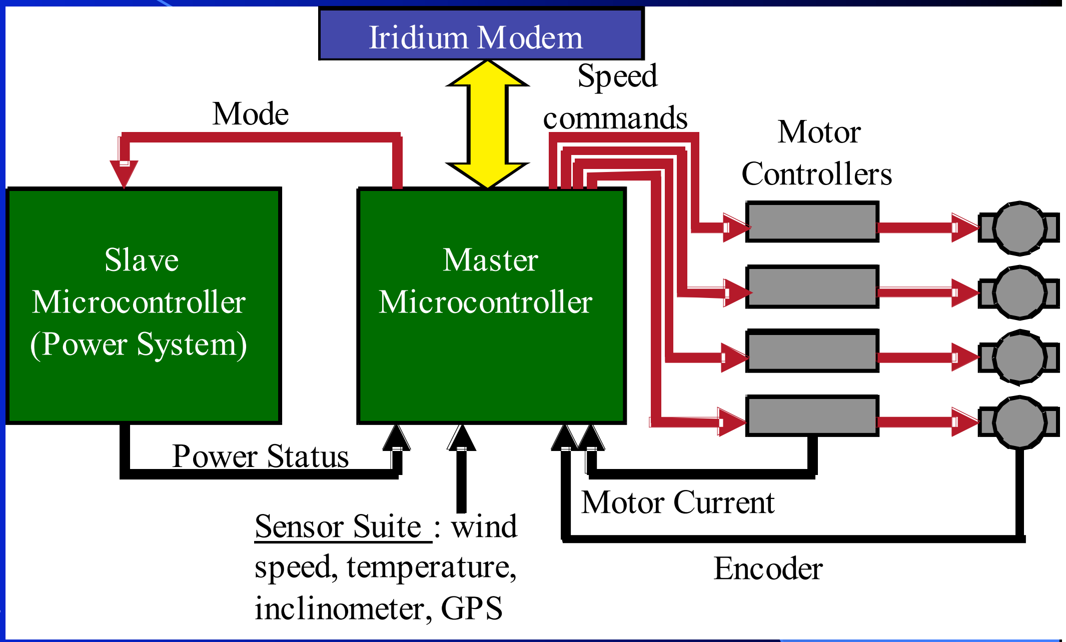


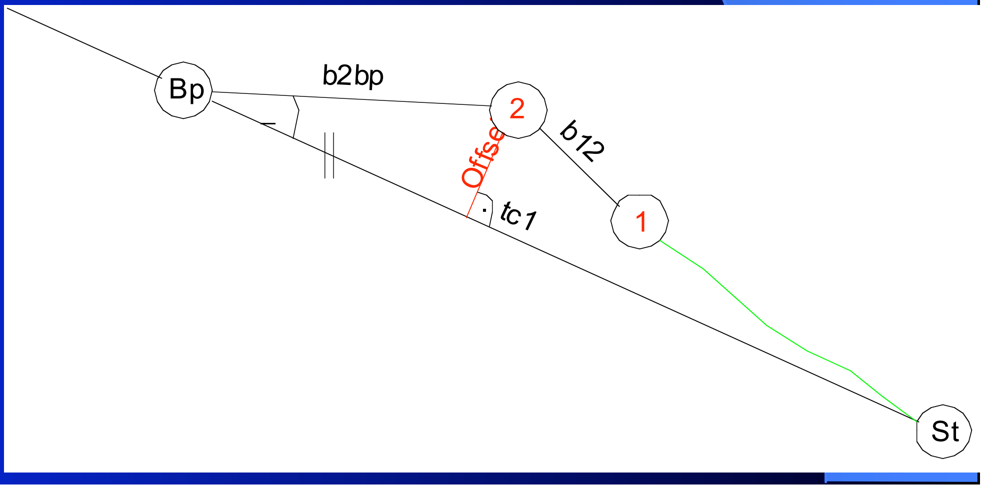
# Reduced Panel Reflectivity by Stippling



# Navigation and Control

- Motor controllers provide closed-loop wheel speed control
- Microcontroller varies speed command to prevent slip
- GPS provides position and bearing
- Low bandwidth path planning and course correction
- Iridium communication of waypoints and data
- Under low power or high winds, robot moves enough to prevent snowdrift



# Cost and Mass

| Item | Cost | Mass (kg) |
|---|---:|---:|
| Motors, encoders, gearheads, controllers (4) | $4,650 | 7.3 |
| Chassis (honeycomb) and insulation | $200 | 7.5 |
| Fasteners, epoxy, and reinforcement | $1,200 | 1.5 |
| Batteries | $1,000 | 4.3 |
| Microcontrollers, electronics | $1,000 | 0.5 |
| GPS, Iridium modem | $1,300 | 0.8 |
| Wheels - rims, hubs, tires (material only) | $550 | 17.3 |
| Solar panels (material only) | $4,500 | 22 |
| Power converters | $500 | 1 |
| Drivetrain materials and bearings | $100 | 8 |
| Misc. - wire, sensors, DC-DC converters, fuse box | $400 | 2 |
| Total | $15,400 | 72.2 |

# Timetable

- Fabrication and software completion by 12/04
- Winter testing in NH 12/04 – 2/05
- Greenland mission Summer ’05, Antarctic mission Nov-Dec ’05
  - Mobility and solar power measurements
  - GPS-based ionospheric density measurement
  - Magnetometer deployment
  - Ground penetrating radar support for traverse

# Acknowledgements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- Participants:
  - Guido Gravenkötter and Gunnar Hamman, Univ. Armed Forces, Hamburg Germany, *Mechanical and navigation system design initiation*
  - Alex Price '04, Th05, *Mechanical design completion and fabrication*
  - Ben Kasdon, Ian Kahn, Xianghui Weng, Th04, *Power system analysis*
  - Daniel Denton '08, *Navigation, control, and fabrication*
  - Alex Streeter '03, Th04, M.S. candidate,  *Power System Design and fabrication*
  - Jim Lever (CRREL), Laura Ray, *Project investigators*
  - Marc Lessard, Research Associate Prof., Thayer School

- Thayer School Machine Shop and Technical Staff


http://thayer.dartmouth.edu/other/crobots/

# Resources

p. 2  USGS Satellite Image Map of Antarctica,
http://terraweb.wr.usgs.gov/TRS/projects/Antarctica/AVHRR.html,
Small Map of Antarctica, http://www.lib.utexas.edu/maps/polar.html

p. 3  http://www.polar.umd.edu/ago.html

p. 4  http://www-istp.gsfc.nasa.gov/Education/Intro.html

p. 6 Robotic Antarctic Meteorite Search: The NOMAD Robot,
http://www.frc.ri.cmu.edu/projects/meteorobot/Nomad/Nomad.html#Mechanical,
accessed June 2004, used by permission

p. 6 Hyperion: Sun Synchronous Navigation, Carnegie Mellon Univ.,
www.ri.cmu.edu/projects/project_383.html, accessed June 2004, used by permission

p. 28 http://www-star.stanford.edu/~vlf/Antarctica/AGO/agoscience/wave_cartoon.gif