Options for Lunar Power Beaming

A presentation to the FISO group

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Outline

- Introduction
- Lunar applications
  - Equatorial
  - Polar
- Mars
- Summary

Introduction

- U.S. Space Exploration Policy – past…
  - Envisions NASA exploration progression from lunar to Mars
    - Moon is challenging due to:
      - ~2 week night time – solar energy is an issue (nuclear?)
        - South pole location for sunlight plus H_2O possibility
      - Hazardous dust – abrasive, health issues, contamination
      - Extreme temperature cycling
    - Mars is challenging due to:
      - Thin CO_2 atmosphere plus dust (limits sunlight, shifts spectrum)
        - However, dust is much less abrasive, cleared by wind/dust devils
      - High iron content, may impact fission reactor option
      - Reduced level of sunlight (~36 – 52% of earth AM0)
- But the plans are all in turmoil right now
  - Evolving and dependent upon appropriations
  - Past options may be relevant
- Power beaming has been a topic of discussion for several decades
  - Let's look at its applicability to lunar exploration (and a bit on Mars)

Lunar (and Mars) Orbital Operations

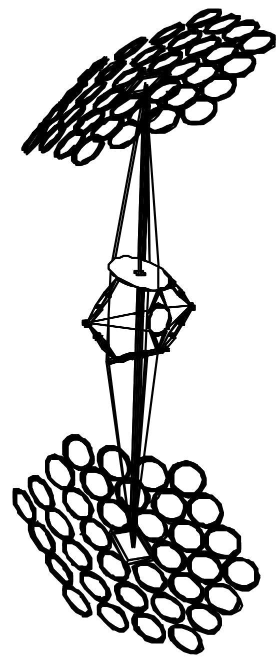
- Lunar options
  - L1 location (~56,000 km) (L2 for the rear side)
  - Equatorial circular or elliptical orbits
    - Limited view time to N and S and to site location
    - Precession
  - Polar elliptical orbits
    - Excellent for N or S polar landing site
    - Largely "frozen" orbits
- Mars options
  - Areosynchronous orbit (17,000 km)
    - Equivalent to GEO – stationary over equator
    - Views ~1/3 of Mars surface

Power Beaming Options

- Lunar options
  - Microwave
    - 5.8, 10 and 35 GHz wavelengths
  - Laser
    - 830 – 850 nm laser wavelength
    - Optimal for GaAs SJ cells (TJ won't work)
    - Other wavelengths are feasible, but must match with solar cell response
- Mars options
  - Microwave
    - 5.8, 10 and 35 GHz wavelengths
  - Laser
    - 1060 nm and 10.6 μm wavelengths
    - 1060 limits solar cell options, but 850 nm case is similar

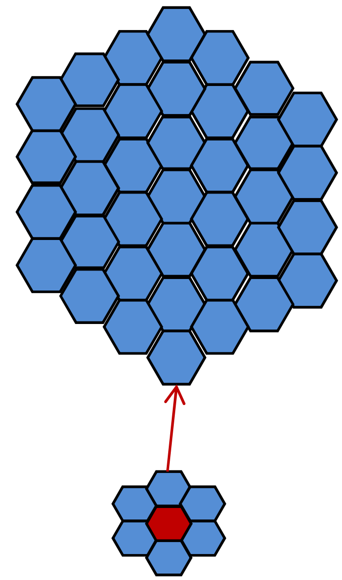
Lunar Power Beaming from L1

- Microwave option (10 MW)
  - Transmitter – 1.5 km dia.
  - Rectenna receiver – 4 km dia.
  - Transmitted power – 17.6 MW
    - 20 W/m^2 at beam center
  - Satellite power - ~50 MW
- Laser option (10 MW)
  - Constellation of 14 – 2.7 MW satellites in halo orbit at L1
    - Each with 55 48 kW building blocks with laser
  - Transmitters – 770, each 1 m dia.
  - Receiver dia. – 50 m
  - Transmitted power – 14.6 MW
  - Total satellite power – 90 MW
- Ambitious design – not practical due to large beaming distance



10 MW microwave satellite concept

2.7 MW laser satellite concept



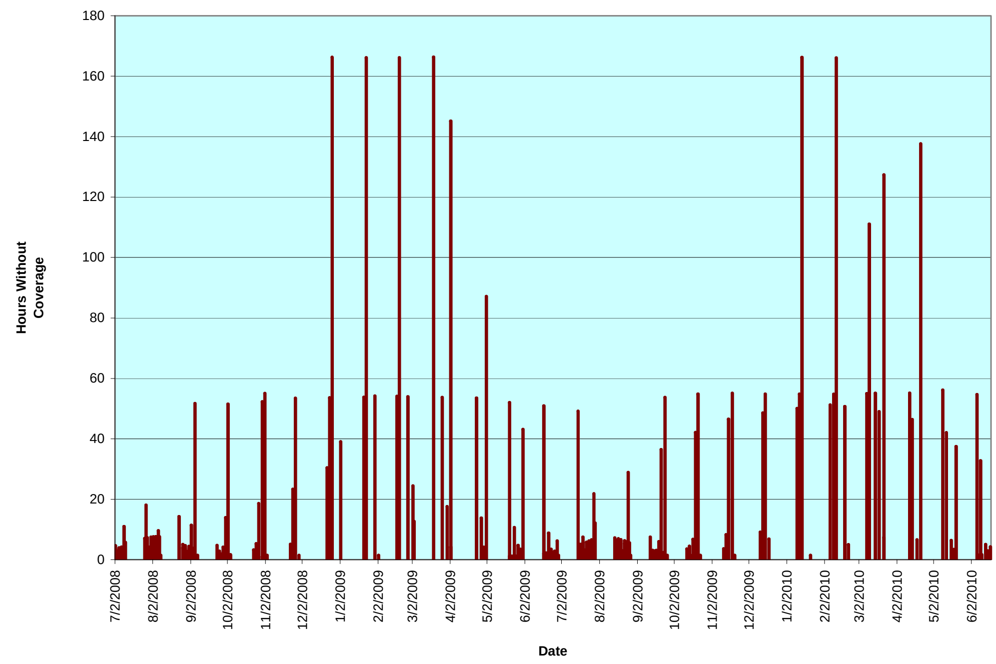
48 kW building block plus laser

Lunar Laser vs. Microwave Beaming

- Microwave beaming
  - Beaming from L1 is best situation
  - Requires large transmitter area which limits size of satellite
  - Or a very large surface rectenna
    - Need to pay careful attention to excitation of rectenna diodes
    - Limits orbital choice, not considered further
- Laser beaming
  - Distance from receiving site is not a major issue
    - Opens door to other types of orbits
  - Aperture in space will set the system design
  - Lower end-to-end efficiency at this time
    - With no atmosphere on moon, adaptive optics unnecessary, tbd Mars
  - Pilot beam control necessary

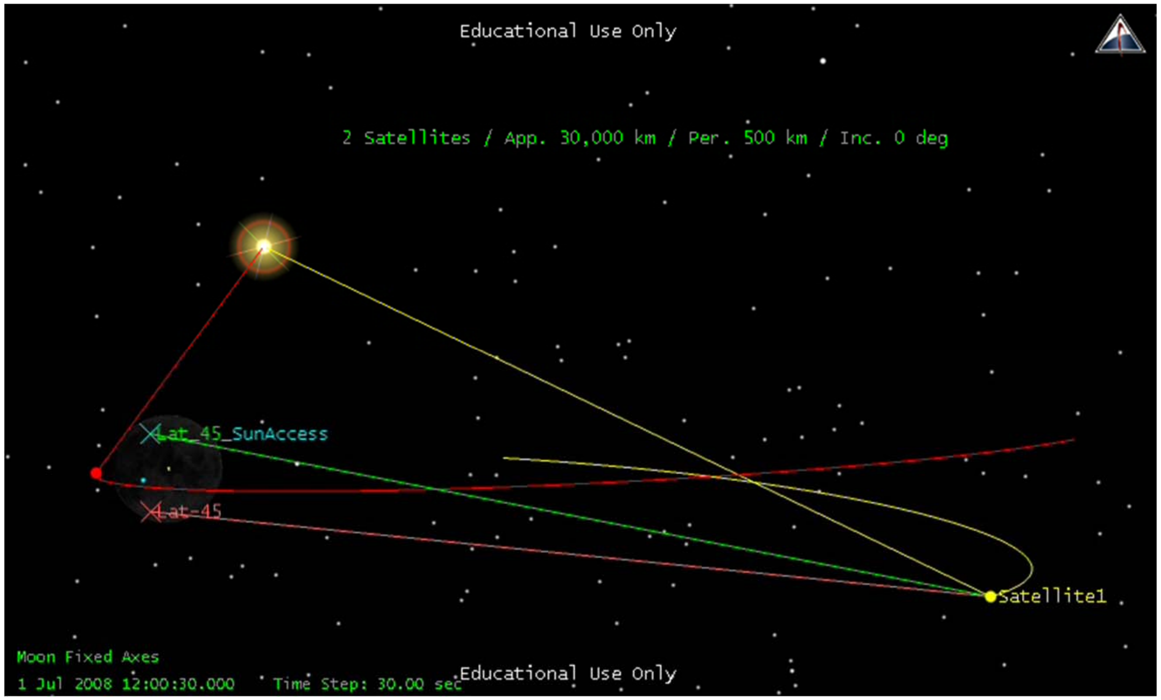
Lunar Equatorial Elliptical Orbit

- Wide range of orbits examined
- Chose 500 x 30,000 km orbit
  - Generally good coverage
  - Beaming distance a concern
  - Microwave beaming not considered due to sizes
- Ran STK 7.1 for 2-year period
  - July 1, 2008 to June 30, 2010
- Beamed to surface sites 45°
  - When in view of satellite
  - **AND** satellite was in sunlight
- Times when no satellite power beaming possible:
  - Up to 164 hours (~7 days) with single satellite

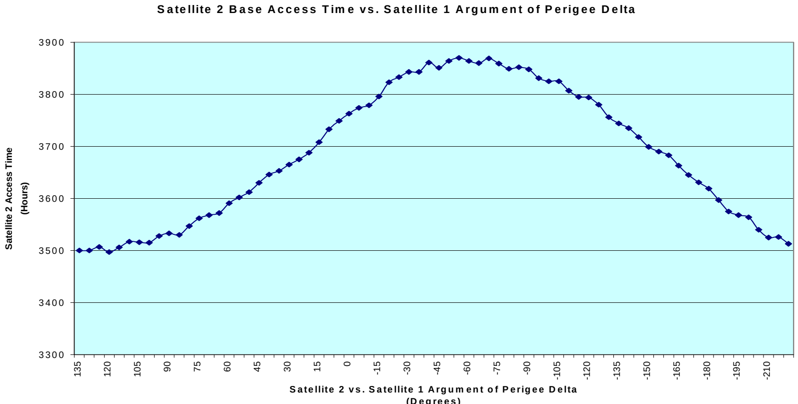


Lunar Equatorial Orbit – Two Spacecraft

Satellite orbits around the moon with beaming

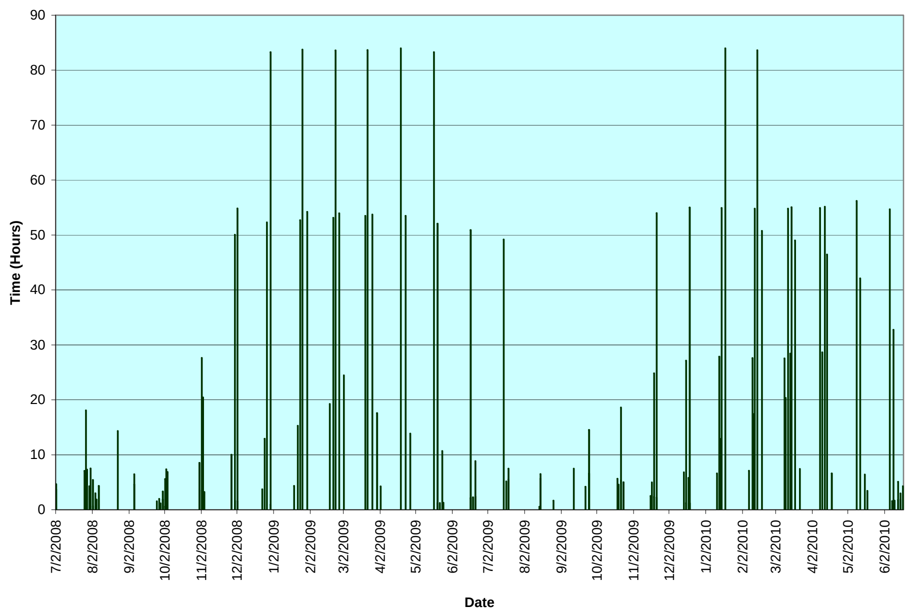


2nd satellite access times with orbital location



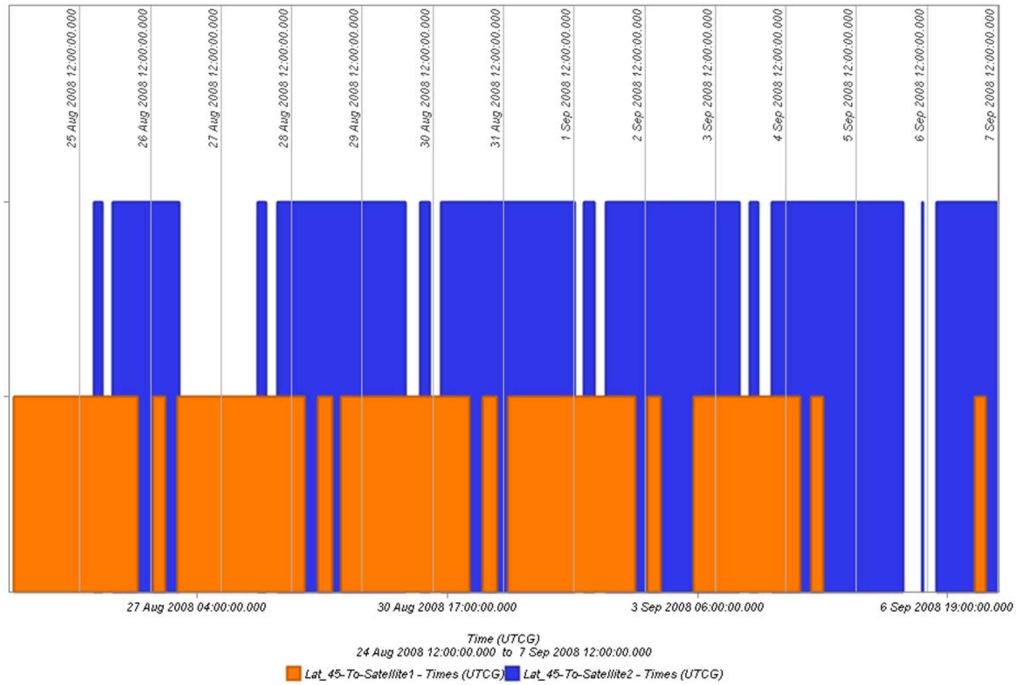
Equatorial Two Satellite View Times

- 2nd satellite improved view times
  - » Adjusted orbital angular offset
  - » Power beaming times increased
- Times with no beaming decreased substantially
  - » Only 8 periods of 84 hours (3.5 days)
  - » Rest of the time it's lower than 54 hours (2.25 days)
- Will reduce the mass of surface storage system
  - » For equatorial ±45º inclinations



Overlapping Coverage - Equatorial

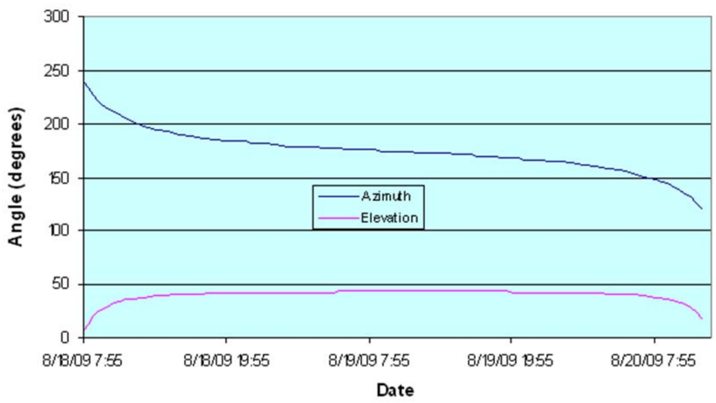
- Satellite view times often overlap
- Is an opportunity for substantial power increase
  - » Laser power to surface PV array
  - » Requires a non-tracking planar array with 1J GaAs cells
    - Monochromatic laser beam cannot be used with MJ cells
    - Did not compute this option
  - » Can't use tracking concentrator array to view dual satellites
- Many opportunities for increased power to surface location

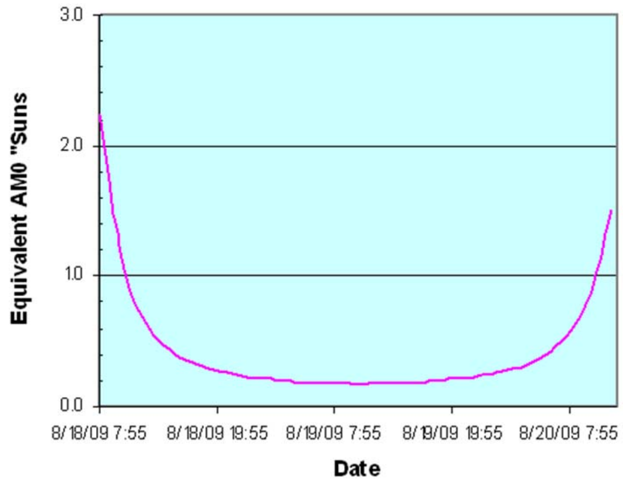


Laser Power Beaming - Equatorial

- Uses 850 nm diode pumped laser, 4 m diameter beaming aperture
  - » 90 kW satellite power available
- Laser beam incidence angles determined by satellite orbit
  - » Surface array tracks E-W
- Laser intensity varies due to view angles and orbital elevation
  - » Satellite near moon when beaming starts - ~2 AM0
  - » At 30,000 km, beam intensity ~0.2 AM0 sunlight

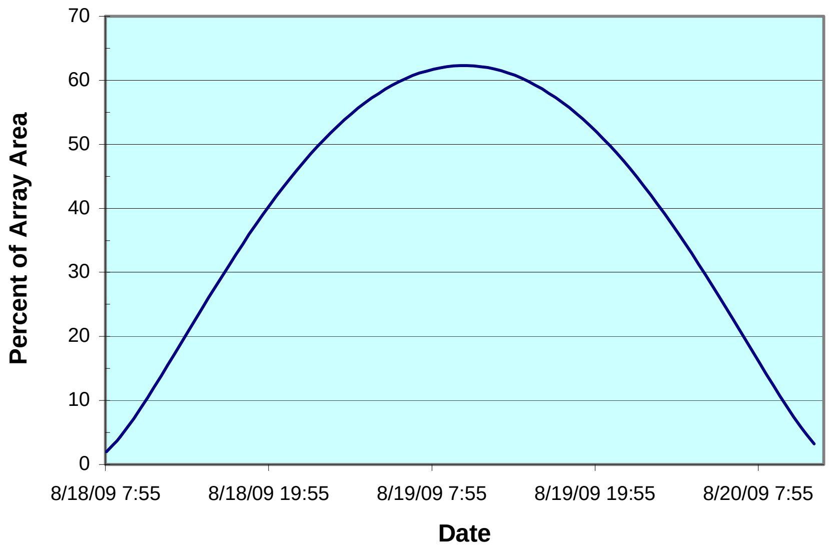
Laser beam incidence angles





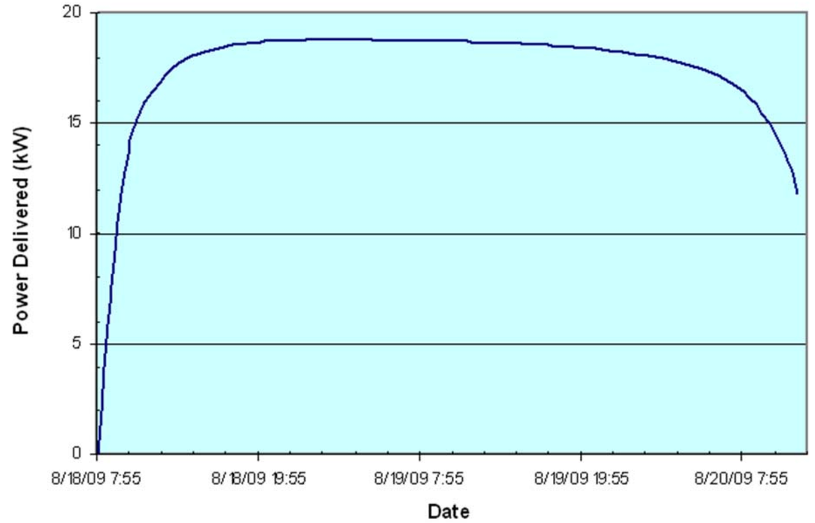
Surface Solar Array/Laser Beam

- GaAs surface array
  - Nominal 60 kW
  - ~18% efficient GaAs cells
  - Temperature corrected
- Size of laser spot on surface array
  - Must be less than total array area
  - Largest spot size is at 30,000 km elevation
    - ~60% of GaAs surface solar array illuminated



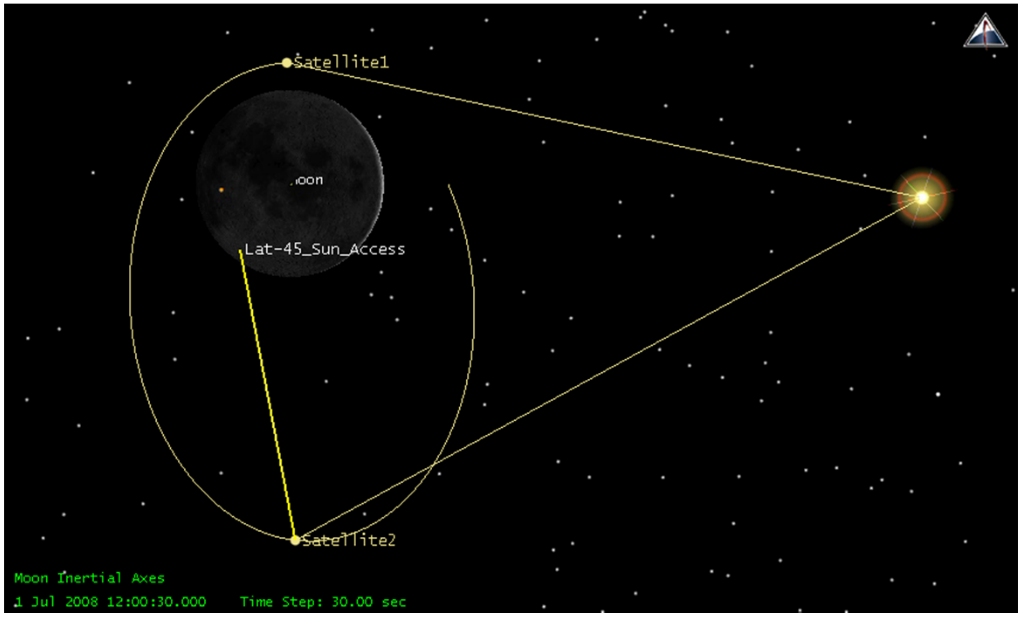
Lunar Power Produced by Laser

- Chose 45º N site for calculation
  - Most difficult case
- Calculated laser beam power from satellite
  - ~90 kW, 50% conversion of orbital electricity into laser beam
  - 12% mirror losses
- Calculated surface GaAs solar array as laser receiver
  - 45% conversion of laser beam into power
- 18 kW power delivered to site
  - With tracking array on surface
  - Further increase with planar array and dual satellite beams

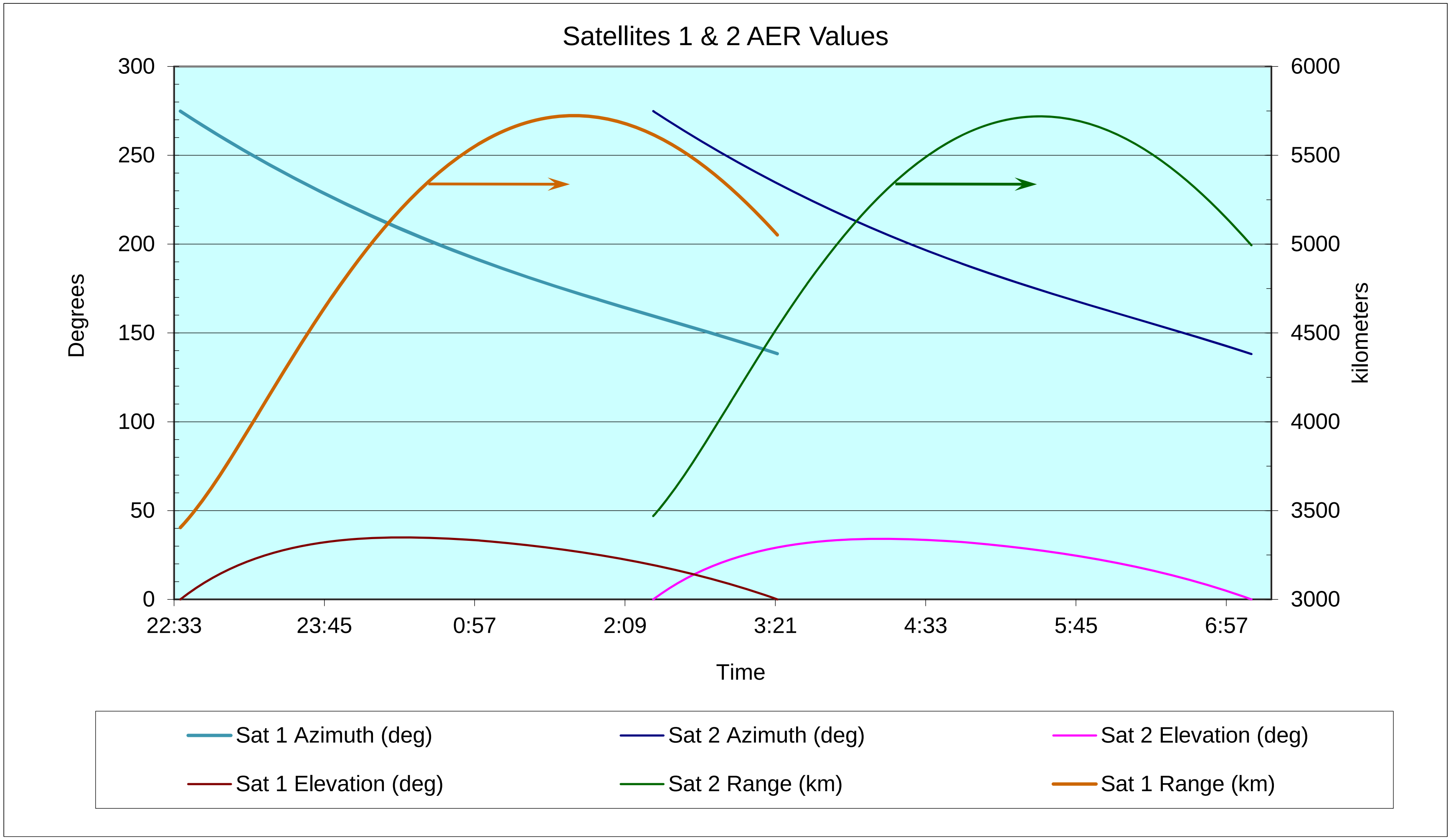


Polar Power Beaming Satellites

- Two satellites in polar elliptical orbit – "frozen" orbit
  - » Offset by ~180º
  - » 500 x 5,000 km orbit
  - » ~7.5 hr. orbital time
  - » Apogee over the south pole
- 850 nm laser beam
  - » 1.5 m^2 aperture (1.38 m dia.)
    - Increases beam size on surface vs. previous case
- Uses 1-J GaAs tracking array on surface
  - » Can track one satellite
  - » Or can use fixed array
    - Receive power from two satellites

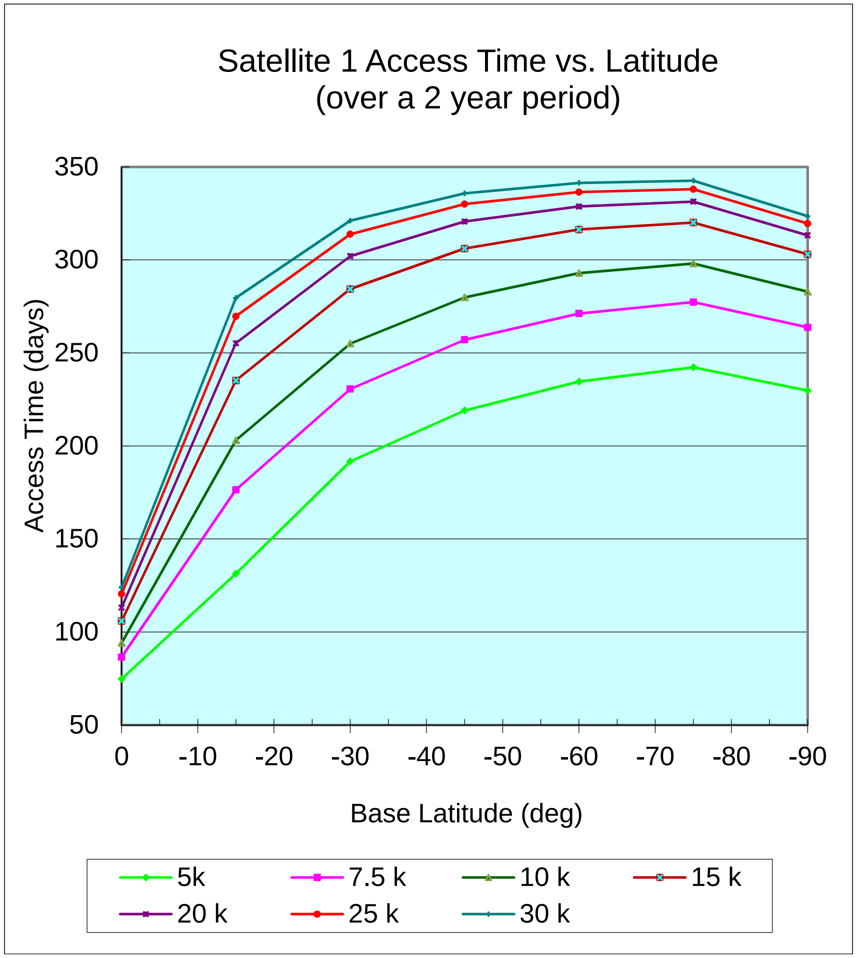


Satellite Parameters – 8/23-24/08
(500 x 5,000 km Polar Orbit)



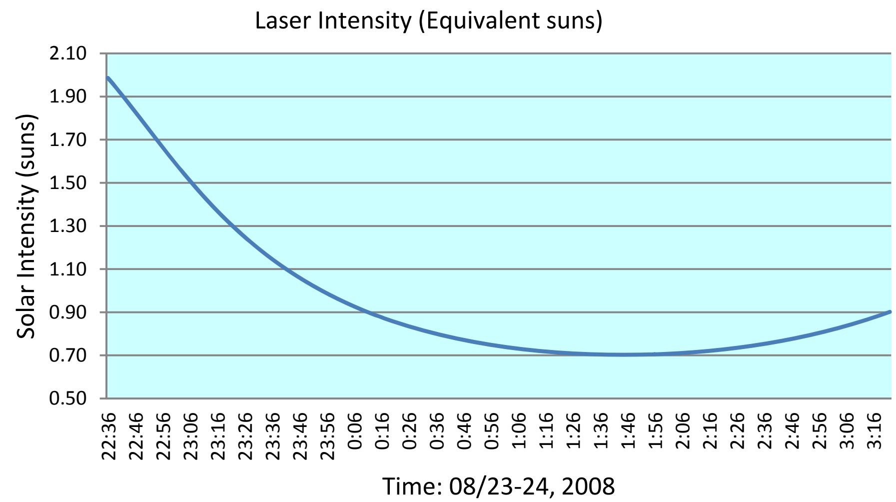
Surface Access Times for Polar Orbits

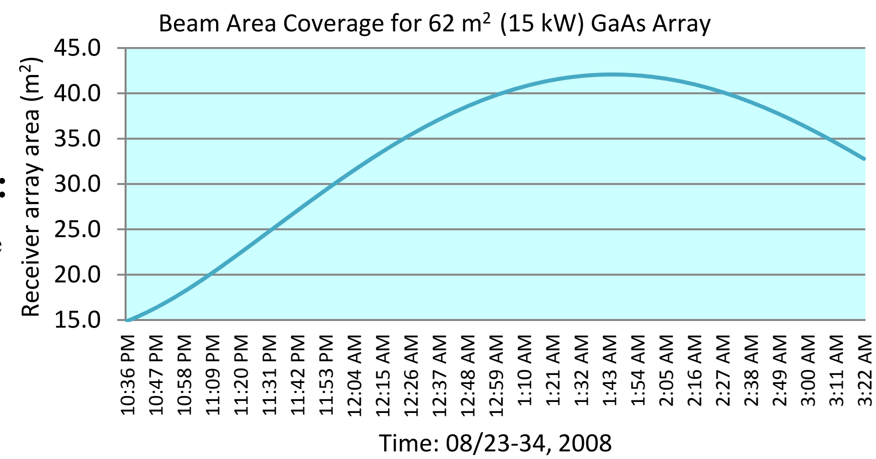
- Polar orbits give excellent access times
  - » From the pole to ~30º
  - » 5,000 km apogee has least view
    - Two satellites required
    - Both satellite access times are comparable
- Access time depends on satellite altitude
  - » Higher provides more access
    - Longer beam distance reduces power received
  - » Second satellite can provide more power
    - If it can also be tracked
    - Or use fixed planar array



Power Delivered to Lunar Surface

- With a tracking array, power to the surface is essentially constant
  - » **~16.8 kW** per satellite
  - » 50% power conversion to laser beam
  - » 45% conversion of laser into power
    - Includes other losses as well
  - » Assumes a **15 kW** surface array (in sunlight, 62 m^2 in area)
    - Neither receiving array area nor laser beam intensity is excessive
    - Can also adjust beaming parameters
- With two satellites, the longest time a receiver at 45° does not receive power is:
  - » Only 1.5 hours maximum, less for a polar site
  - » <u>Substantially</u> reduces storage!
- Laser beaming is a very plausible option!



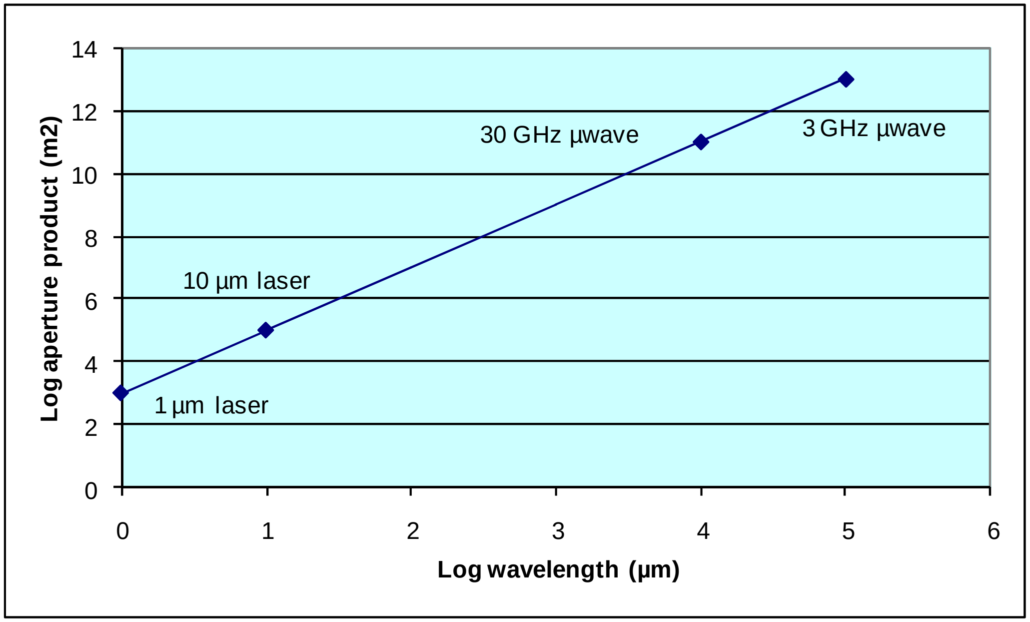


Lunar Power Beaming Summary

- Three cases of lunar power beaming were studied
  - L1 orbit – microwave and laser
    - Extremely large 10MW satellites, mainly for microwave aperture
    - Both feasible, but laser more amenable to smaller satellites
  - Equatorial orbit, ±45° N-S, two satellites, 500 x 30,000 km (2 year), 90 kW
    - 850 nm laser, 4 m^2 beaming aperture, ~18 kW with two satellites, GaAs array
    - Eight times with storage times of 84 hours, rest of time <54 hours
  - Polar orbit, -90 to 45° S two satellites, 500 x 5,000 km (same for N), 90 kW
    - 850 nm laser, 1.5 m^2 beaming aperture, ~16.8 kW with either satellite
    - Maximum dark time of only 1.5 hours
- Laser power beaming to lunar surface seems feasible
  - Multiple orbits are possible, no adaptive optics
  - Substantial reduction in energy storage times for any location
  - Can yield significant mass savings for exploration architecture

Power Beaming Options for Mars

- Power beaming options
  - » Microwave – 2.45 and 35 GHz
  - » Laser – 10.6 and ~1.0 µm
  - » Sized receiving station
    - 95% effic. – $(2\lambda D)^2 = (A_R A_T)$
- Summary of analysis
  - » Microwave **impractical** because:
    - Transmitter area limited
    - Rectenna area huge, therefore:
    - Diodes not fully activated
  - » Lasers have lowest areas
    - But lower efficiency – thermal
      - > 0.9 µm diode laser, >45%
    - PV receivers for <1µm – dust?
    - 10.6 µm dismissed due to CO_2



Summary/Conclusions

- Lunar power beaming
  - Microwave option – L1 is only realistic point (L2 is the same)
    - Requires a large A_T – higher power satellites and higher frequency
    - Diode activation in rectenna a large concern
  - Laser option – most flexible option
    - Satellite size flexible, equatorial (±45º) and polar “frozen” orbits – two satellites
    - Pilot beam desirable, GaAs cell receiver with ~850 nm laser best (~50% conversion)
    - Laser efficiency needs to increase (thermal)
- Overall, power beaming is a realistic option for lunar (and perhaps Mars)
  - Lunar option reduces need for energy storage, but requires two satellites
  - Mars areosynchronous orbit, but dust and atmosphere may be issues