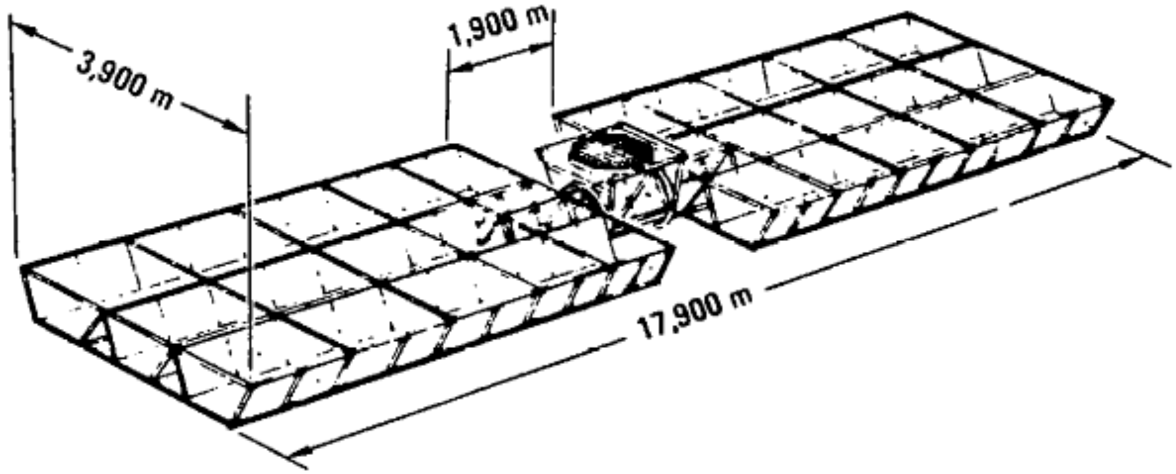
Solar Power Satellites



PHY4422 – Optics I
Michael Chin

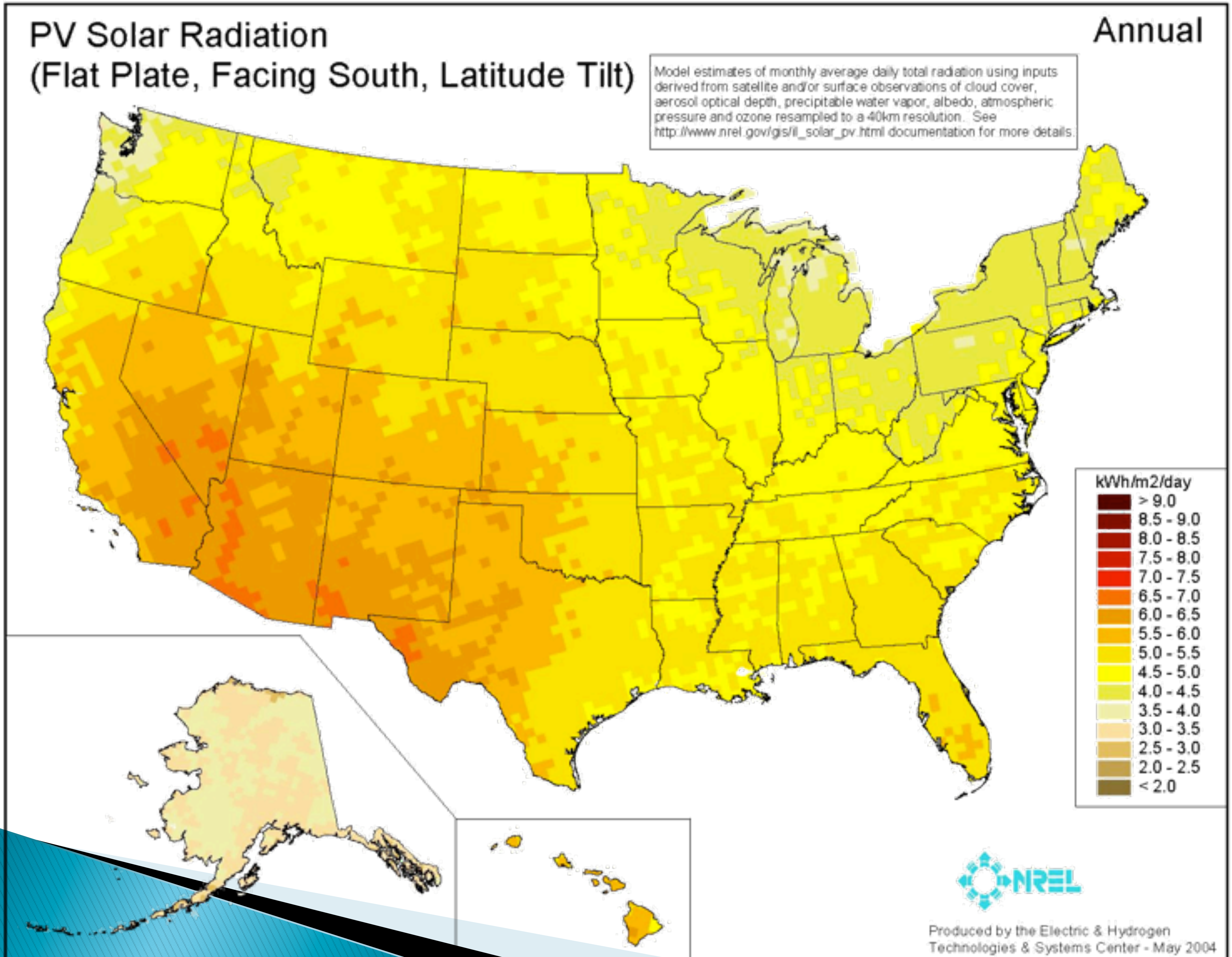
Overview

- What are solar power satellites?
  - Conventional Photovoltaic (PV) arrays in orbit.
  - Wireless power transmission to surface receivers through the microwave band.
- Theory and Operation
  - Solar insolation on Earth's surface compared to irradiance on PV arrays in orbit.
  - Orbital and altitude selection.
  - Frequency selection.
- System Design

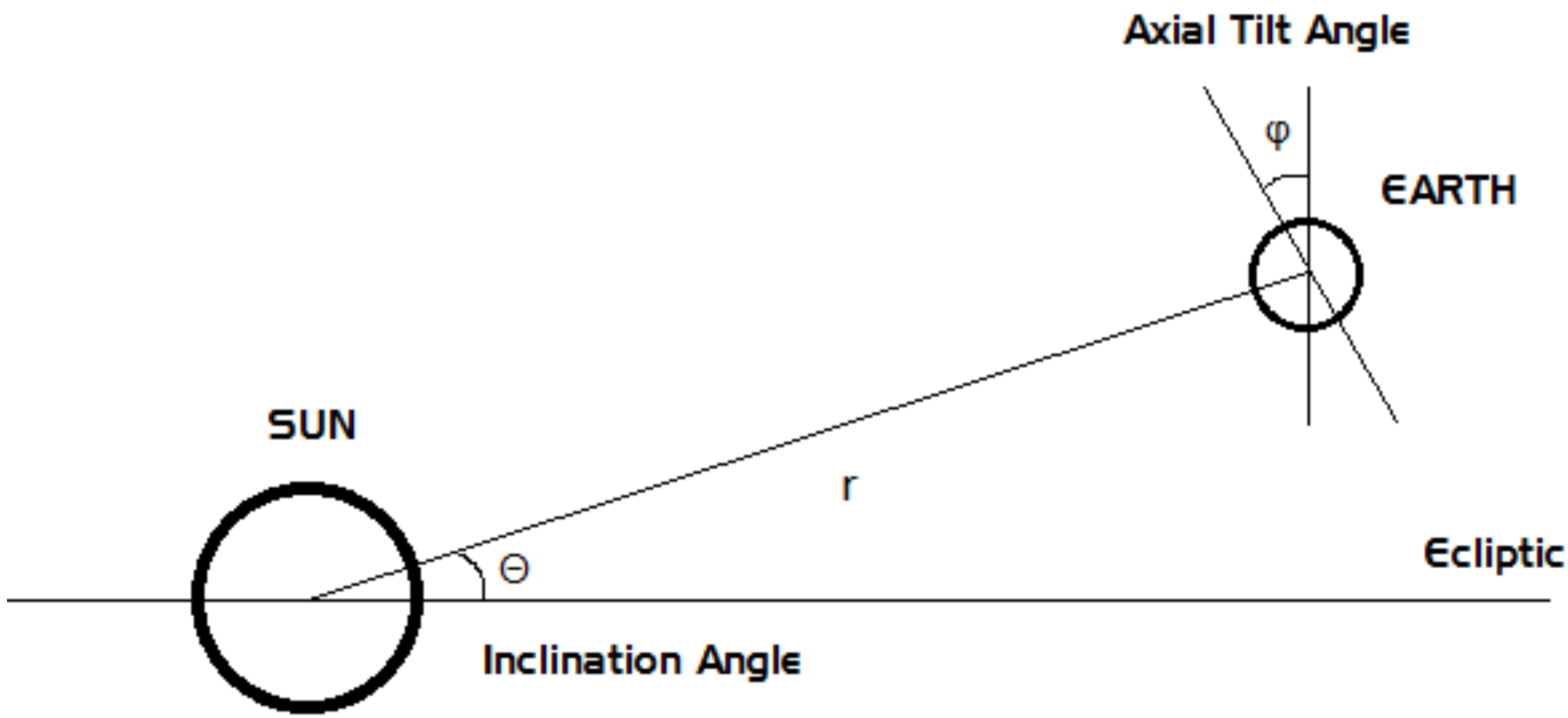
Theory and Operation

- Efficiency of terrestrial solar power limited by latitude and weather.
- Regions of high insolation usually not close to major population centers.
- Terrestrial solar irradiation can be modeled as:

$$I = \frac{I_o C}{4\pi r^2} e^{-\left(\frac{\mu}{\rho}\right)\rho x} \cos\left(\theta - \varphi\right)$$


PV Solar Radiation
(Flat Plate, Facing South, Latitude Tilt)
Annual
Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/il_solar_pv.html documentation for more details.
kWh/m2/day
> 9.0
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2.0
NREL
Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004

Theory and Operation (cont.)



Theory and Operation (cont.)

- Space-based solar power does not have attenuating factors, simplifying the former to

$$I = \frac{I_o}{4\pi r^2}$$

- Orbital selection
  - Sun-synchronous
  - Geosynchronous
- Orbital altitude (dependent on cost, probability of collision with space debris in low-Earth orbit).

Theory and Operation (cont.)

- Frequency selection
  - 2.45 GHz microwave band selected for previous designs. High transmissivity of signal through atmosphere.
  - Interference with communication devices such as cell phones, microwave ovens, and cordless phones.
  - Poses a health risk if intensity is too high. Care must be taken to ensure that microwave beam properly aligned to receiving station.

Theory and Operation (cont.)

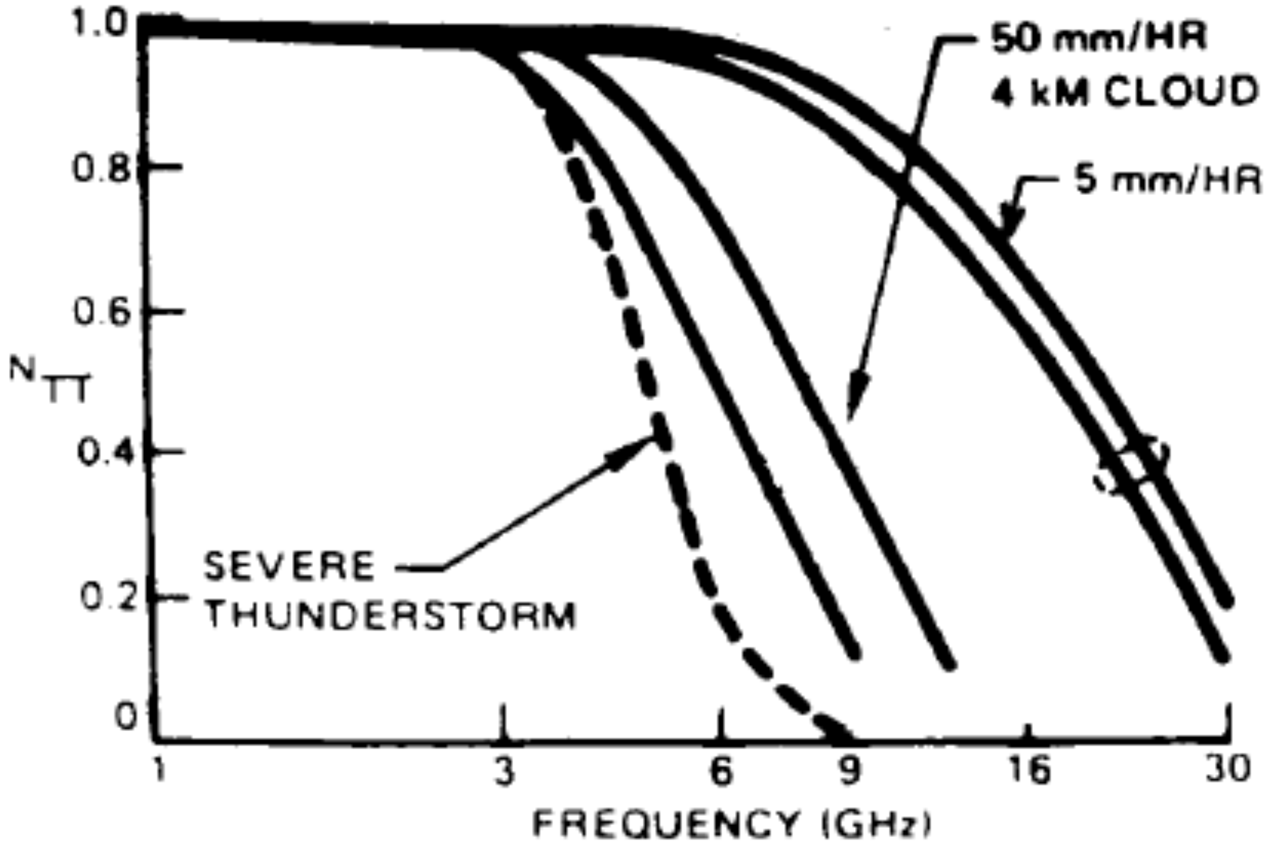


Image adapted from Brown and Eves (1992).

System Design

- Selection of PV cell material
  - GaAs or GaAsAr preferred over silicon-based cells.
    - Higher conversion efficiency (29%).
    - Radiation resistant.
    - Expensive.
- Selection of structural material
  - Aircraft-grade aluminum (7075-T6)
  - Graphite composites
- Altitude control
  - Argon-ion thrusters

System Design (cont.)

- Transmitter design
  - High-gain directional array of dipole antennas.
  - Centrally located antenna bay.
- Receiver design (rectenna)
  - Omni-directional array of dipole antennas.
- Satellite size
  - For a 5 GWe system (71.3 GWs), satellite size on order of 17 km $\times$ 3.9 km.
  - Total system efficiency of approximately 6.5%.

System Design (cont.)

- SPS systems consist of three primary energy conversions
    1. Solar energy converted to DC current. Efficiency primarily dependent on material parameters.
    2. DC current from PV arrays to microwave energy. Typically accomplished using cavity magnetrons.
    3. Microwave radiation to DC current.

System Design (cont.)

- Safety considerations
  - Food and Drug Administration standards for microwave exposure for conventional microwave ovens are 5 mW cm^{-2} at 5 cm from surface of the oven.
  - The SPS satellite emits a 5-6 GW beam, so the ground rectenna must be 130 km^2 in order to meet these regulations.
  - Even with such a large rectenna, feedback mechanisms should be implemented in case of accident scenarios (misaligned beam).

Economic Considerations

- Cost of GaAs cells
  - $\$1.0 \times 10^{10}$ USD per km^2 * 55.12 km^2 = \$551.2 billion USD
- Cost of orbital launches
  - \$10,000 USD per kg * 3.4×10^7 kg = \$340 billion USD
- Total cost for a 40 year loan with 5% annual interest
  - \$1.57 trillion USD
- In order to recoup these costs, a price of \$26.15 per kWh is needed. This is presently not competitive with terrestrial solar power (\$0.20 per kWh), natural gas (\$0.09 per kWh) or coal (\$0.03 per kWh).

Conclusions

- Solar powered satellites viable from a theoretical standpoint.
- Practical considerations such as the cost of the system and complexity of construction inhibit near-term viability of large-scale (5 GWe) systems.
- The Japanese government plans on a 100 kW proof-of-concept SPS system by 2040.