CIVILIAN POWER FROM SPACE IN THE EARLY 21ST CENTURY:

Technologies, Paths and Implications

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WHY-&-HOW DO YOU GET POWER-FROM-SPACE?

- WHY?
  - Because you don't like getting it from terrestrial sources
    - Generation and/or transport 'side-effects' are deemed tedious
  - Because space-derived power *looks* more attractive
    - A *presently-preferred* profile of the various cost-types
      - "The grass is always greener…" syndrome?
  - There's *lots* of it out there – and it's all free, forever
    - We only use ~10^{-4} of the sunlight falling right on the Earth
- HOW?
  - With a *long* extension cord – made of 'jiggled ether'…
    - Electromagnetic radiation beams – shafts of polarized vacuum
  - …connecting Earthside loads to…
    - Power stations-in-Earth orbit!
      - Getting their energy from…
        - Nuclear (*fission*, now; *fusion*, later) reactors?
        - Solar photovoltaic arrays (PVAs)? [Peter Glaser, ~1978]

WHY NOT?

- After all, the basic idea's a quarter-century old…
  …and we've been orbiting things for a half-century..
  …and technology has never been advancing faster…
  …and we've never been as wealthy as at present…
- *BUT* the proposed classic 'first step' is a dilly
  - >10 km^2 arrays of microwave radiators in GEO
  - >10 km^2 arrays of microwave rectennae Earthside
  - Multi-GWe stations are smallest-economically-practical
  - *Proponent*-estimated "switch-on cost" of \$N x 10^{10}, N>>1
    - These are "Only <u>really</u> big-&-rich governments need apply" scales
- U.S. Government becomes ever-more-modest about its abilities to <u>accomplish</u> *any* big new things in space
  - *"He's a modest man, with much to be modest about."*
- Thus, ~25 years later, this *remains* "a bridge too far"
  - <u>No</u> key feature is becoming easier, cheaper, safer,…

WHAT'S TO BE DONE?

- Replace the thus-far-show-stopping features
  - Systematically re-engineer all problematic features
  - Too big-&-costly? Trim by required factors!
    - E.g., by invoking physics-&-technology alternatives
    - E.g., by leveraging new, mass-market technologies
      - E.g., GPS, Internet/GDN, automated transaction-clearing,…
  - USG hesitancy? Make attractive to private sector!
    - Has to happen eventually (at least in the U.S.A.)
      - USG didn't elect to pursue the TVA & BPA models
        - Current policy-trend is to fully-liberalize energy markets
      - Why not sooner-than-later?
    - Figure out if the 'minimum Governmental lead-in' can be stretched to meet what the USG *may* do anyway
      - E.g., can technology-legacies of mil-space efforts be re-engineered to "do the job" re power-station-prototyping?
      - Can future USG requirements be met with space power station capabilities to telling extents?
        - USG as 'anchor tenant' of nascent space power station(s) or 'salvage buyer' of their (surplus) outputs?

HOW'S THIS TO BE DONE? I.

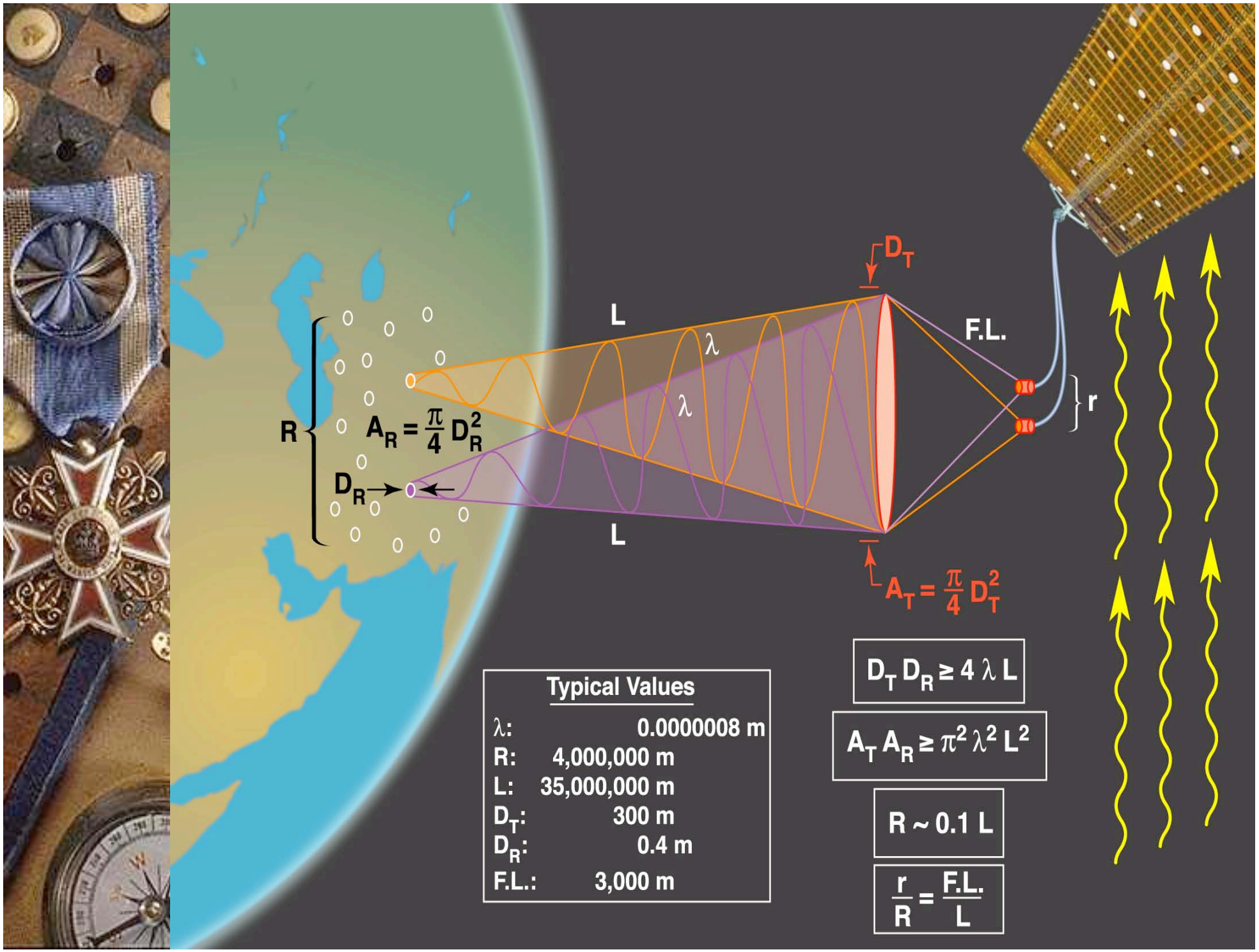
- Modernize PVA choice: Slash prime-mover's mass
  - ***Mass***-in-space is ***cost***-in-space, for very nearly everything
  - Crystalline Si was baselined – "That was then;…"
    - 4-mil slabs – 100 μm thickness of Si
  - But now-COTS a-Si is *far* more mass- (hence cost-)efficient
    - 0.3 μm a-Si, on 5 μm plastic-film (40X lower areal mass)
      - a-Si is now the Earthside *market*-dominating COTS solar PVA technology
    - >0.5 the sunlight-to-DC conversion efficiency:>20X power-to-mass
      - Space-performance-proven on MIR's *Kvant* module, for 18 months
    - Mass- & dollar-budget-gains are of logjam-breaking magnitudes
- Shrink the transmitter/receiver sizes – *drastically*
  - Chop projected beam's wavelength: the *only* (physics) alternative
    - Go from λ of 2-12 cm (μwave) to <0.0001 cm (near-optical)
  - T/R antennae areas *each* shrink by λ-ratio: ~10^5 X (!!)
    - 10 square kilometers ⇒ 100 square meters (if T&R are symmetric)
    - Pick in-GEO transmitter area of 10,000 m^2: receiver's is ~1 m^2 (!!)
  - Improvements in T/R areas are of *fundamental* importance
    - Associated cost reductions are crucial enough
    - But scale-size reduction is enabling for getting *there* from *here*!

HOW'S THIS TO BE DONE? II.

- Issues-&-alternatives
  - Minimize power-station's $/W: the ***fundamental*** FoM
    - Optical-vs.-μwave ~ 2X inferiority in DC ⇒AC is minor concern
    - More than offset by
      - a-Si's >20X advantage in power/mass efficiency
      - Huge T/R area-reductions enabled by optical waveband transmission
  - Minimize the initial power-station size
    - Big beam-projectors are ~ N *meters* diameter, N the transmitter-receiver range in *thousands* of km
      - 1-2 meters is the practical range for LEO power stations
    - Thus may have LEO *constellations* of sub-tonne power-stations
  - Generate and project optical-wavelength photon beams
    - Use laser diodes to optically pump fiber-lasers
      - Leverages 2 decades' advances in huge telecommunications tech-base
      - Allows areally-distributed (not point-concentrated) entropy rejection
    - Use large-area Fresnel lens main beam-projectors
      - Low areal-mass technology: Lens is thin, flat, polyimide film
        - ~10 gm/m^2 asymptotic mass-budgets
      - Far looser tolerances than reflectors: e.g., tolerates ~10^{4}X surface errors

HOW'S THIS TO BE DONE? III.

- Issues-&-alternatives, cont'd
  - (Finely) partition the power station's transmitted beam
    - Radiate <u>many</u> lower-beams through one *shared* primary projector
      - More leveraging of far-shorter transmission wavelength
      - Servicing many small customers, rather than just one mega-customer
    - Readily done: PVA's optical fiber 'power-harvesting' network
  - Send these myriad beams in different directions all over the field-of-regard, each to a distinct Earthside receiver
    - Thereby servicing a continent-sized area of receivers…
      - Eliminating all transmission and distribution costs of POES (cf. 'POTS')
    - ..at different power levels, for different dwell-durations,…
      - Leveraging the differentially-pumped laser-diode modules on PVA…
      - …as well as individually-steered beamlet-lensette modules in the focal plane of the station's primary projector
      - ~3-30X sunlight intensities likely hit 'sweet spot' of mass markets
        - ~2.5-25 kWe/m^2 of customer's receiver (≥60% receive-efficiency)
      - Beams' 'soft edges' and *real-time* closed power-loops <u>assure</u> safety
        - Beams' perimeter intensity-meters & 'coding' foil defeat-attempts
    - ..energizing myriad loads, just-as-ordered: ***spacetime beam-agility***
      - Purchasing done in real-time, via the Internet/Global Digital Network
        - Tiny comm-&-Xaction costs: c < \$10^{-10}/bit, world-wide; -c′>2X/yr.
      - To GPS-cued {***x***,***v***,***a***,θ,φ} precision locations/motions/orientations
        - Thus enabling *precision* servicing of <u>*moving*</u> customer-receivers
        - <u>***No***</u> major prime mover-type goes unserviced by space powerbeams!


R
$A_R = \frac{\pi}{4} D_R^2$
D_R
L
λ
λ
L
D_T
F.L.
r
$A_T = \frac{\pi}{4} D_T^2$
Typical Values
λ: 0.0000008 m
R: 4,000,000 m
L: 35,000,000 m
D_T: 300 m
D_R: 0.4 m
F.L.: 3,000 m
$D_T D_R \geq 4 \lambda L$
$A_T A_R \geq \pi^2 \lambda^2 L^2$
$R \sim 0.1 L$
$\frac{r}{R} = \frac{F.L.}{L}$

HOW'S THIS TO BE DONE? IV.

- Issues-&-alternatives, cont'd.
  - Leverage upcoming advances in space-transport costs
    - 'Space tugs' using big solar PVAs and COTS plasma-jet engines
      - 'Motor around' cislunar space at milligee acceleration-levels
        - "From anywhere to anywhere" in a matter of weeks
    - No more expensive to transit from Earthside-to-GEO than from Earthside-to-LEO
      - 'Overhead': 5-10% of payload mass, used as 7000-3500 sec I_{sp} jet-mass
      - Vs. ~3-4X more expensive 'classically': GTO-insertion-&-apogee-kick
    - *Big* economic 'win'
      - On top of ~2X gain in costs-to-LEO (current space-launch 'glut')
  - Maximize use of lunar materials-as-available
    - Likely 3-10X cheaper-in-GEO than Earth-sourced equivalents
      - For Mg, Al, Si, Ti, Fe – and O; possibly for H, C & N, as well
    - Feedstocks for in-orbit robotic manufacturing plants
      - E.g., for making PVAs; low-fractional-mass 'smarts' come up from Earthside

WHY NOT PROCEED? I.

- Economics are daunting
  - Start-up ones are completely show-stopping
    - Huge amounts of technology development/demonstration required
    - USG is only likely performer
      - But may well perform, for its own purposes, in the coming decade
  - Initial system economics are sharply challenging
    - Market-required ROIs are huge: 30-40% per annum
      - Risk discounts are necessarily huge
    - Limits on initial capital investment dictates system/orbital design
      - Place power-stations in LEO, not GEO
        - Shorter range permits smaller, 1st-generation transmitters
        - Need constellation of power-stations to assure customer coverage
      - Start with small (sub-tonne) power-stations : Servicing few customers
        - More (or larger) power-stations are added as customer-base grows
  - Full-sized, mature system economics 'look sweet'
    - But so did the "square miles of microwave antennae" ones
    - Maturity and scale advantages are huge
      - Customers are 'always there'
      - Capital market-required ROIs are down to ~10-15% per year
  - Crucial issue: how to survive 'infant' & 'youth' periods
    - It's simply idle to "wish them away"
    - Must be able to survive 'birth' and bootstrap up to 'adulthood'

WHY NOT PROCEED? II.

- Meteorology?
  - Water droplets (fog, clouds, rain) get in the beam's way
    - All beam-types; some suffer more than others…
  - Classic responses
    - Beam-around patchy obscuration (many stations in all skies)
    - Punch-through thin, wall-to-wall obscuration ($\tau \leq 3$)
    - Work-around really thick, wall-to-wall stuff (ground reserves)
      - Thunderstorm-centers: ~10 hours/year, in most (U.S.) places
      - Live with such outages: Like 'standard' electrical utilities do
        - E.g., rely on Earthside 'baseload' system, via price-rationing
- Safety?
  - Ground-level issues
    - Injuries precluded by intensity-sensors on receivers' perimeters
      - Leveraging physics features of beams' "soft edges"
      - Receiver's computer must be 'happy' at all times, re <u>all</u> conditions
        - Ditto for power-station's computer, re each-&-every powerbeam
        - Receiver must 'echo *unknown* song' encoded on its power-beam to the power-station, continually – or the beam goes off instantly
      - System fails-<u>safe</u> *by design* if beam-control loop isn't <u>*actively*</u> closed
        - E.g., any comm failure cuts beam's power at lightspeed: 0.2 sec.
  - Issues at altitude
    - Injuries precluded by varying-intensity sensors at beam's receiver
      - 'Fast flyers' pass through highest-intensity beams 'without knowing it'
      - Birds not burned by *any* time-intensity flight-history

EXEMPLARY SYSTEMS

- Near-term (first-generation)
  - Customers
    - Small set (100s at any time) willing to pay premium (~$10/kW-hr)
    - Each needs small (≤10 kW) amounts of power, but located far off-grid
  - LEO-based system
    - Short-range dictated by use of small (~2 meter) beam-projectors
    - LEO constellation of ~250 power-stations
      - Each uses 50 kWe from 300 m^2 PVAs to project single 20 kW beams
      - Constellation of ~80 kg power-stations launched on single EELV
  - Economics
    - Deliver 0.62 MWe at ~$10/kW-hr : generate ~$55 M/yr. of revenue
    - 30% annual return on $180 M investment ($90 M launch; $90 M fab)
- Far-term (a few decades out)
  - Customers
    - Large set (50 M) paying low rates ($0.05/kW-hr)
    - Need small (~ 10 kW) amounts of power, delivered wherever they are
  - GEO-based system
    - Long-range demands use of large (~300 meter) beam-projector
    - Constellation of ~1000 power-stations to service a continent
      - Each uses 5 GWe, 20 km^2 PVAs to project many beams (~ 50,000 @ 40 kW each)
      - Each station has ~1500 ton (mostly PVA) mass; ~90% from lunar materials
  - Economics
    - Each station delivers 1 GWe at $0.05/kW-hr : ~300 M$/yr of net revenue
    - 15% annual return on $2 B investment ($0.5 B launch; $1.5 B fab)

SUMMARY

- ***Big*** changes are required, in order to 'move out' on large-scale power supply from space
  - Basic challenge is economic: must make commercial sense
    - Eventual, mature system-set looks great
      - Provides non-hydrocarbon-based energy from GEO directly to users
        - Wherewhen & as-much-as desired: ubiquitous *utility-grade* power
      - Economically viable : Service large, non-baseload market
        - Locally-delivered (mobile!) energy commands price-premium
        - Mature systems/technologies attract low ROI-demanding investors
    - Getting *there* from *here* (i.e., zero) remains the crucial challenge
      - First-step capital-investment must be affordable: 10s of B$ are not!
      - New system/technology is risky: investors always demand high ROIs
      - Start by servicing small set of high $/kW-hr customers; then bootstrap up
- Recent technology advances offer titanic leverage, e.g.,
  - High W/gm a-Si PVAs: greatly cuts system mass (cost)
    - Allows system to sell power at economically-viable $/kW-hr
  - Optical power transmission: drastically cuts T/R sizes
    - Allows smaller-scale power-stations (cutting initial investments)
    - Allows sales to small (mobile!) end-users : not just mega-users
- Near-term USG programs *may* provide crucial tech-bases
  - In-space tech-demos/uses; technology legacies "for free"?
- Hydrocarbon energy economy *may* recede 'naturally'
  - *Technology-enabled* **market forces** – vs. government decrees