OPTICAL POWER-BEAMING FROM SATELLITE POWER-STATIONS:
Economic Imperatives and Provision of High Value-Adding Electrical Power*

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Abstract

Solar-energized powerbeaming satellites have not advanced discernibly during the past quarter-century, although total economic growth, electrical power demand, energy generation-centered environmental concerns and the overall technology base each have advanced far more rapidly in absolute terms than within any comparable interval in history. An impossibly-large 'first step' and doubtful economic viability, even in asymptotically long time, are identified as the independent root causes of solar-derived power microwave-beamed to terrestrial use-points from Earth-orbiting satellites failing to participate at all in this growth. Moreover, these challenges may be 'show-stopping' ones, into the forseeable future. In this paper, exemplary ways-&-means are identified to obviate these basic deficiencies. Reducing start-up cost-scales from hundreds of billions down to hundreds of millions of dollars by minimal-sized in-space systems is seen to be crucial to enabling commencement of servicing of the highest value-added, most power-cost-insensitive terrestrial loads, ones having ~1 kWe service-requirements for which ~$10 kWe-hr total unit energy cost (TUEC) is sustainable; dozens to hundreds of megawatts of such very high value-adding electricity demand is projected. Global service capacity expansion into multi-GWe scales may be expected when the ability is attained to deliver spot-beams of ~10 kWe capacity to mobile (e.g., vehicular) loads at TUECs of ~$1/kWe-hr, and ultimately into TWe scales as economies-of-scale of GEO-based solar power stations enable delivered-power TUECs of ~$0.1/kWe-hr to stationary loads of all natures to become competitive. The essential points are that it's likely necessary to 'wedge' incrementally into electricity markets by maximally leveraging all of the intrinsic advantages of space-sourced power beams, and to strategically select a sequence of markets most congenial to power beamed from space power stations. Representative enabling technologies centered on powerbeaming at optical frequency and with notably high spatio-temporal agility are surveyed, and some possible developmental paths are sketched. Key to most of these are synergistically leveraging other modern technologies, including the Global Digital Network, the Global Positioning System and very large-aperture space optics, which together can support safe-&-reliable maintenance of 10-100X sunlight power-beam intensities on the photovoltaic converter-bearing upper-surfaces of vehicles, thereby accessing a huge, hitherto under-appreciated mobile-load market for electric power. Such paradigm-shifts in implementation technology and market-penetration strategy may be pivotal with respect to powerbeaming from space power stations – either solar- or nuclear-energized – becoming a significant player in the 21st century's large-scale energy supply-mix.

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Introduction. Peter Glaser joined the company of the Great Visionaries of humankind when he first proposed large-scale power-beaming from space for Earthside baseload electricity generation [1]. This was the first specific proposal toward humanity's realization of a Dyson Sphere about its own star, and thus must be regarded as a signal landmark in the technological history of our kind.

However, a third-century hence – during which time more overall technological advance undeniably has taken place than in all previous human history – there is as yet no discernible, "bootprints in the sands"-quality progress that has been made in this direction. Most peculiarly, in the meantime, great concerns have been raised regarding each-&-every type of extant Earth-based means of power generation. How is this "great contradiction of our times" to be understood, and what's to be done about it? These issues are the subject-matter of this paper.

Why Space-Sourced Beamed Power? Space-sourcing power for the full spectrum of human activities is so obviously advantageous – so ubiquitous in nature, so abundant in magnitude, so regrets-free in capturing and transmitting – that it's *deeply* surprising that it's not already being done in this, Year 46 of the Space Age. To be sure, radiant power beamed from a nearby star – indeed, from the proximate star – has powered most things terrestrial (volcanoes, earthquakes, hydrogen bombs and nuclear power reactors being notable exceptions) from The Beginning. [However, this flavor of space-sourced power-beaming is free, natural – and unavoidable – and so, in the finest modern physics tradition, we unapologetically subtract this (near-)infinitude from present considerations, and solemnly proceed with analysis of the four orders-of-magnitude-tinier matters of present interest.] In acute contrast, in the 46th year of the Air Age, humankind – far poorer economically and much more impoverished technologically – had advanced technically from powered gliders that could barely transport a single person a couple hundred meters to bombers that could carry city-busting bombs half-way around the planet. In further contrast, in Year 46 of the Radar Age, signals were being employed routine to map the mesoscale surface features of planets hundreds of millions of kilometers distant, moreover in the face of fourth-power-of-the-distance propagation losses, and the associated antennae also were being used to receive watt-level spacecraft telemetry signals beamed across an entire stellar system (that of Sol). Finally, in Year 46 of the electronic digital computer age, such devices already had become huge foundation-stones of modern civilization, utterly ubiquitous in human affairs. *How*, then, after nearly a half-century of spacefaring – and, at least as importantly, *why* – have we fallen so short in space exploitation endeavors generally and most particularly in the purposeful utilization of space-based means for addressing our energy-supply needs – and what's to be done about it?

Prime Mover Problems: Fuels, Ashes, Entropy, Etc. It's assuredly not that the main prime movers presently powering human civilizations are ideal in all respects – or even in any major one. Supplying their demands for hydrocarbon fuels not only distorts much of contemporary international affairs – to the extent of underlying at least two major conflicts in the past dozen years and several other less intense but far more bloody mass homicides over the same interval – but likely will do so at an ever-accelerating pace over the next few decades, as these fuels become ever more scarce and thus more valuable (at least in the surprise-free scenario). Sourcing fuels to nuclear power plants isn't so pervasively problematic, but such fuels seem to be in remarkably short supply relative to presently employed means – light-water reactors (LWRs) – of generating nuclear power in usefully large scales, and alternate means haven't surfaced meaningfully despite a half-century of various fitful efforts, all over the industrialized world. Supplying 'renewable' energy sources in usefully-large quantities to the principal engines of civilization has proven to be persistently expensive, in spite of decades of governmental nurse-maiding of their development, and the present-day outlook for their becoming truly economically competitive on usefully-large scales isn't confidence-inspiring to any reasonable skeptic known to us.

The *consequences* of powering large-scale prime movers of the present energy era are even less happy. Generating heat by oxidation of hydrocarbons produces oxides – surprise! – not only of carbon and hydrogen, but even of the nitrogen component of the air typically used to supply everyone's favorite electron-acceptor, molecular oxygen. Now thereby creating *hydrogen* oxide – water – is still politically correct, but the resulting *carbon* and *nitrogen* oxides, though dearly-beloved by all plants, are viewed with ever-increasing alarm by those resolutely committed to at least the atmospheric aspects of the *status quo ante* of contemporary human civilization. Moreover, imperfect oxidation of hydrocarbon fuels – e.g., generation of carbon monoxide – is disfavored generally (albeit not for efficiency reasons), and oxidation of minor and trace components of hydrocarbon fuels – e.g., sulfur and heavier metals, respectively – is quite widely viewed with dismay, if not outright alarm. Quite recently, intensive-but-imperfect oxidation of hydrocarbon fuels has been blamed in the technical literature for mesoscale climatic anomalies – multi-year droughts and floodings – in China and in India, via largely independent atmospheric mechanisms, and oxides of sulfur and heavier metals have been blamed by experts for remarkably widespread albeit mostly subclinical respiratory illness in urbanized China; ground-level ozone resulting from hydrocarbon-based power production has been authoritatively blamed for oxidative-stress-engendered crop-losses amounting to 10% of China's total cereal-grain production, equivalent to 200 calories/day per capita of human food in that most populous of countries. Finally, it's become enormously fashionable during the past decade to forecast amazing changes in climate a century hence, due to an increase of the order of 1% in atmospheric radiative forcing arising from continually-increasing inputs to the atmosphere of carbon dioxide and methane – the latter being a presently-favored hydrocarbon fuel which inevitably leaks to some extent into the air – and many such forecasters have chosen to dwell on the forecasted downsides of such anticipated changes, so that the 'ashes' from hydrocarbon-based energy production have come to be regarded – at least in the more politically correct circles – as shadowing humanity's long-term future.

The 'ashes' from nuclear fission energy generation aren't regarded much more warmly by many involved in the energy forecasting business, in spite of their million-fold smaller mass per unit of energy generated. While one possible interpretation of this might be that these folks just don't care for large-scale energy production of <u>any</u> nature, the more conventional view is to the effect that even relatively very small masses of nuclear fission 'ash' may be quite problematic. To be sure, open-ocean disposal of all of the nuclear power-plant waste that human activities could possibly produce during the entire 21^{st} century wouldn't increase the total radioactivity of the ocean by even 1%, and moreover this increase would inevitably die away in a few decades' time; however, quantitative considerations generally aren't warmly regarded in these discussions, which instead tend to focus on favored nightmare scenarios involving the undeniably-substantial mass-flows of fissile isotopes internal to various interesting nuclear fuel cycles, and the possible use of even tiny fractions of such flows in nuclear fission explosives. The bottom line is that nuclear fission energy generation doesn't enjoy even as good public reputation regarding its side-effects as does that based on oxidation of hydrocarbons, in spite of the objectively far smaller loss-of-life from the former vs. the latter per unit of useful energy produced – proving once again that humanity does indeed stick with the devil that it knows. Nuclear *fusion*-based civilian energy-production, if-&-when it ever occurs on large-scale, is authoritatively predicted to be greeted with comparable levels of dismay regarding its radioactive and weapons-related 'by-products' [2], though the technical details of such discussions will apparently be very different from the present ones centered on nuclear *fission* power.

Renewable energy sources are renowned for generally not having ashes-of-significance, but the consequences of extracting energy from wind, water, sunlight – or chicken manure – somehow come to be regarded as unacceptably severe whenever one or another of these sources even bids to attain to significant scale. Bird losses from operation of wind farms – to say nothing of currently-contemplated scenery-desecration by sea-based windmills proposed to be located off of Cape Cod – apparently can't be abided, nor can hydroelectric dams and their asserted depression of wild fish runs and/or canyon sedimentation fine-structures be tolerated, nor can land-use losses from large-scale solar photovoltaic 'farms' be accepted. In short, using land, scenery or even 'free air' for large-scale energy generation involving 'harvesting' of energy recently sourced into the fluid envelopes of the Earth by the Sun seems to not be qualitatively less problematic than does liberating energy long-ago sent to Earth from the Sun – or even that deposited on the Earth during the Solar system's birth, in the form of long-lived isotopes of the actinide elements.

As if these problematic supply and ash-disposal issue-sets weren't sufficient by way of 'show-stoppers' for large-scale energy production, increasing concern is expressed regarding the low-temperature waste heat invariably generated as energy is produced in support of human activities. 'Urban heat islands' are viewed with increasing alarm as generators of microclimatic shifts, and the loss in the form of 'waste heat' of 2-4 times the energy put to use – in conventional Rankine-cycle electric power-plants and in typical automotive engines, respectively – is increasingly decried as unacceptable. 'Entropy pollution' seems likely to enter the jargon of those opposed to large-scale energy production/utilization, to the extent that it hasn't done so already. In short, humanity – or at least the current preponderance of the chattering classes and the politicians who are specially receptive to the wisdom that they dispense – seems ready – if not downright eager – in several independent respects for qualitative improvements in the human race's large-scale energy supply system.

Space-Originated Beamed-Power As The 'Electric Ideal.' Electric power – and, derived readily from it, most all other desired forms of energy – that leaps exactly when bidden, like a genie from a lamp, from a container of low mass, volume and cost to serve human needs seemingly is the ideal for energy supply on all scales. Realizing a petite, inexpensive, side-effects-free "black box" that sources any desired quantity of electricity-on-demand seemingly would be a great advance. Power generated in space and beamed to points on/about the Earth's surface, there to be converted by cheap, compact equipment into the desired electrical forms with no material by-products and at high efficiency, seemingly would do just this. Why, then, isn't it being done – or, indeed, why isn't it already in widespread use?

Why *Not* Space-Sourced Beamed Power? Consider just what stands between us and large-scale use of power beamed to use-points on-and-about the Earth's surface from space sources thereof.

Buy-In Costs. First of all, of course, there are the 'buy-in' costs, those associated with preparing to do something for the first time. We have neither power stations of even remotely interesting scales in space, nor equipment or facilities on the ground for receiving power beamed from them, nor means for getting power so generated at ground-points to use-points. Furthermore, it's not clear what fraction of the basic technologies – the building-blocks from which such systems could be assembled – even exist, or how hard it will be to perform such integrations for the first time. Non-existent technologies may have costs-to-realize that are difficult to estimate reliably. Such overall space power system cost estimates as do exist generally have been generated in what might most delicately be characterized as "cost-unfamiliar circumstances" – i.e., in government-sponsored studies performed largely or totally by either *de facto* or *de jure* academics – and are often criticized as being either out-of-this-world optimistic or so programmatically grand and inclusive as to be intrinsically quite decoupled from real-world economics. At that, the plans associated with these cost-estimates almost invariably involve expenditures of tens of *billions* of dollars prior to attainment of positive cash-flow from power sales in real markets. The capital markets of humankind just don't support such first-time, up-front costs – *ever, anywhere, for any purpose*. Market capital flows to highest-&-best uses, i.e., to where risk-discounted returns are the greatest. Risk premiums on doing even moderately large-scale things for the first time are generally of prohibitive magnitudes, as the English Channel Tunnel and IRIDIUM satellite telephony experiences recently underscored. Even today, only very rich governments ever throw ten billion dollar chunks of capital at a "good idea" with no real thought for getting it back with market interest – and they don't do this very often at all. Thus, merely "getting off the ground" with space-based power beamed-to-Earth is a real challenge – <u>if</u> $\geq\$10^{10}$ up-front capitalization is truly required.

<u>Continuing Costs</u>. We live in a world in which the most modern, pollution-controlled, coal-fired electric power plants deliver electrical energy to the transmission system in the American Midwest at a total unit energy cost (TUEC) of $10/MWe-hr – $0.01/kWe-hr – while modular combined-cycle natural gas-fired units currently produce it in American urban-industrial load-centers for a TUEC of ~$0.05/kW-hr (nearly 75% of which is fuel cost). While such real-world sales prices might be claimed to involve all sorts of hidden subsidies, unfunded externalities, etc., etc., all such claims are termed "whining" in the world of power politics, and are regarded as tantamount to a demand for preferences, overt subsidies, minimum capacity mandates, etc. for some whiner-favored alternative electricity source. It is this world into which space-derived power must be sold, and the price-competition is daunting to contemplate. Four megajoules of electrical energy put onto the transmission grid for a penny, or an electrical megajoule delivered directly to an urban load under acceptable environmental conditions for roughly the same penny, is a *very* fine deal – and it's undeniable that space-based power will find it quite challenging to offer comparable terms, even when it's highly mature. How it could ever *commence* to sell into such energy marketplaces – when its technologies will be least mature, its scales will be smallest and thus its TUECs highest – isn't <u>at all</u> obvious.

<u>'Accidents-&-Incidents'.</u> It's undeniable that we humans have very strong preferences for the devils that we know. Furthermore, we're massively documented to be far more risk-adverse when the risks are unfamiliar, for the same overall objective risk-level. For example, we Americans currently lose ~100 of our fellow citizens to fatalities involving Government approved-&-licensed automobiles operated on Government roadways by Government-licensed drivers every day and generally think about this very little, but we still go into prolonged national fits of introspection and fault-finding over an astronaut loss-rate averaging less than 1 per year; after a century of bearing automotive losses, the former type of tragedy is a commonplace, while the latter one is still quite novel and thus perceived-terrible. So it will be with any novel form of power generation, as the history of nuclear fission power makes abundantly clear: mountains of uncontroverted statistical evidence establish that the life-lost per

kWe-hr of nuclear electricity is less than 10% of that lost due to coal-derived electricity generation, but nuclear electric power development has stalled out worldwide in favor of more intensive development of coal-derived electricity, largely on the basis of *perceived* risks.

Space-based electrical power will be no different. Power beams from space – regardless of the details of their nature – will be accused of everything noxious from causing cataracts on bird-eyes to inducing cancer and birth-defects in those humans conceivably exposed to the fringes of the descending beams, despite their likely being comprised of the same photons as sunlight. Beam-steering accidents – and they will occur, although their frequency and severity may be exceedingly low – will be featured luridly in song-&-story by opponents, skeptics and critics, who assuredly will exist-in-abundance, even for such comparatively benign energy supplies. Thus, the political costs of such accidents certainly won't be negligible – and may not even be all that small. Whether such costs can be sustained must be considered to be an open question, likely for decades to come.

Beam Obstacles, Bad Weather And Contingencies. Depending on physical characteristics of the space-originated power-beams, they will be subject to attenuation – and possibly effectively-complete obscuration – by obstacles both natural and man-made interposed in beam-paths. Obvious example includes optical-frequency beams in heavily-clouded circumstances, or failure of any type of beamed power-delivery to vegetation- or tall building-occluded receivers. Depending on the quality of work-arounds, these may range in significance from minor annoyances in unusual circumstances to frequently-encountered, serious-quality impediments. If space-derived power is to become regarded as quality-comparable to electricity from the wire mains of electrical utilities, it must comparably reliable and at least as ubiquitous; space-originated power-beams of various types may find one or another of these qualities difficult to attain, necessitating back-ups having significant costs (economic or otherwise). Finally, all-causes outages of space-originated power must be graceful, i.e., not much more customer-inconveniencing in the time-average than the ~10 hours/year of (generally weather-related) utility power outage which is the *de facto* U.S. standard for service reliability.

'Last Mover' Disadvantages And Intellectual Inertia. It's fashionable in high-tech circles to speak of 'first mover' advantages, the (widely perceived, if not altogether real) edge enjoyed by the first entity to commence servicing a new market. In this general context, electricity delivery-service has been around on large-scales for about a century now, and there are lots of folks who presently supply electrical power in various forms, locales, scales, price-ranges, etc. They know their markets, they have their customers, they understand and 'work with' their regulators, they support the successful politicians who govern their marketplaces – and they're more-or-less firmly resolved to stay in business, and perhaps even plan to expand their market-share. They'll likely not willingly surrender market-share to newcomers, and they'll use all means – economic and non-economic – at their disposal to avoid doing so.

In their efforts to retain market-share, they'll enjoy the fundamental advantage that humans are not only risk-adverse and moreover are exceptionally adverse to novel risks, but also are change-wary, even when stay-or-switch risk-differentials are perceived to be small. Thus, if space-originated beamed power is to succeed in the real world, it must be *significantly* advantaged over the incumbents in the markets which it attempts to penetrate, if such penetration is succeed at all, let alone in an economically-timely manner (recalling that, in the real world, "Time is money").

It's likely worth considerable intellectual effort to understand just why space-originated power-beams can rationally be *expected* to succeed in accessing markets of interesting scales, all of the foregoing considered. When doing so, it's necessary to recall that contemporary energy ventures that entail significant risk – e.g., opening up new oil fields – are required to have credible business plans exhibiting returns-on-investment (ROI) of the order of 30%, or investment payback times of 30-36 months. Since it seems likely that any non-governmental capitalization of space-based power plants will be competitively accessing the same type of capital pools, it's necessary to plan realistically to attain comparable ROIs. Much later, when space power technology is far more mature and its workability no longer doubted by anyone, it may be feasible to capitalize additional space-based power-plant capacity on the basis of 20-40 year service lifetimes, with comparably leisurely amortization schedules. However, the past two centuries of history of new types of utilities – rail transportation, electricity, gas, telephony, etc. – quite uniformly informs the student that few-year-duration payback-intervals are demanded almost invariably by private investors in novel utility enterprises.

Key Technical Ways-&-Means. We now consider a set of specific technical approaches to space power plants that we believe, if innovatively employed, can satisfy the rather stringent set of 'practical' requirements just sketched.

Primary Energy Sources. From a purely technical-economic standpoint, it's not entirely clear what are the most preferred prime movers – the primary energy sources – for space-based power plants. Nuclear fission reactors, in principle, have the two great advantages of arbitrarily high power density (e.g., >>100 W/gm specific thermal power, in practical designs) and very high temperature (≥1500 K, employing special structural alloys) long-term operation, so that they can at once be very compact (i.e., of comparatively very small mass and volume, in the context of facilitating space launch) and operate with high-temperature (and thus area- and mass-efficient) waste-heat-rejecting radiators. Thus, we consider the type of automatically self-regulated, thorium- and natural uranium-burning, unrefueled power breeder reactors that we first discussed several years ago for long-term untended operation deep underground [3] to be outstanding candidates for the prime mover function in similarly long-term untended space power plants. Because we outlined their design and performance characteristics previously, we discuss them no further here, but merely point to their high-pressure helium-cooled Brayton 'topping' cycle variant (without an associated Rankine 'bottoming' cycle) as the likely-preferred embodiment for space applications, since the resulting high-temperature waste heat could be readily rejected from 800±100 K radiators into vacuum without significantly burdening the station's overall mass-budget.

At the other pole of parameter space with respect to compactness and temperature of waste-heat rejection is the set of solar photovoltaic (PVA) options. If mass-economized to within several-fold of pertinent physics limits – i.e., to levels likely to be technologically accessible reasonably readily – thin-film photovoltaic materials surfacing loading-bearing and heat-sinking/-radiating sheet-assemblies suitable for in-space operation can be realized for of the order of 1 gram/m^2, and provide whole-solar spectrum conversion efficiencies to electricity of ≥10%. [Such thin-film amorphous-semiconductor PVAs operate with somewhat different photophysics than do the far more familiar 'thick'-slab crystalline-semiconductor ones; one of the crucial technological implications of this difference is that photoelectric conversion of sunlight occurs in active amorphous material (e.g., Si/Ge) thicknesses of ≥10^{-5} cm, while the thickness of the 'standard' Si crystal-based photocell is ~10^{-2} cm. While such thin-film converter-layers generally have been mounted on backing-films of at least an order-of-magnitude greater thickness for transportation-convenience (i.e., acceleration loadings during launch-into-space) with respect to space applications, such backings are photovoltaically inert – i.e., have only a mechanical-support function – and may be made as thin as in-space stress-levels indicate, if such thin-film PVAs are space-manufactured. Thus, while really thin-film PVAs of $<10^{-4}$ cm thicknesses may be limited to space applications in which gravity-gradient, wind-&-water (and all other high-stress-inducing) loadings don't exist, in all such environments they offer $\sim10^2$-fold specific power (We/gm) advantages over classic crystalline PVAs, as they are already demonstrated to have within two-fold of the same areal efficiency in sunlight-to-electricity conversion.]

We consider it especially notable that thin-film solar PVA systems have enjoyed extensive penetration of the commercial marketplace for alternate electric power supply (e.g., in residences and small businesses) during the past several years with conversion efficiencies of $\geq10\%$, specific powers of the order of 1 We/gm, and prices not greatly in excess of \$1/We [5]. Indeed, the global market for such PVA technology is currently of the order of 100 MWe/year, and single manufacturing lines of 1 We/second sustained production-capacity are in commercial operation, laying down amorphous silicon thin-films onto 14-inch-width stainless steel sheet of 7 micron thickness and lengths up to 7000 feet at >1 We/gm specific power [6]. Quite notably, early forms of this technology have been space-qualified, serving as the primary power source on the KVANT module of the MIR space station [7].

<u>Energy Conversion and Beam Generation Systems And Entropy Rejection</u>. When considering the type of beam to use for transporting power from space to Earth, one swiftly realizes that only electromagnetic radiation is suitable for beam-forming, and only small fractions of the electromagnetic spectrum at that; the requirement to penetrate the Earth's kilogram/cm^2 blanket of air precludes everything else.

The basic properties of beams of electromagnetic radiation are circumscribed by the Rayleigh criterion, which specifies that, if it's formed as carefully as ever possible, a beam comprised of photons of free-space wavelength λ and launched from an aperture of diameter D_1 can be almost entirely intercepted by a distant aperture of diameter D_2 if and only if the free-space propagation between the two apertures involves a distance not greater than L, where $D_1D_2 \approx 4\lambda$ L. This is a theorem of wave physics, not a technological rule-of-thumb; it can't be side-stepped or somehow 'worked around.' It's a remarkably simple statement of how well you can *possibly* do when forming and propagating a beam of any specified wavelength over any specified distance between 'sending' and 'receiving' apertures, e.g., transmitting and receiving antennae. [The physical limit to project a 'soft-edged' beam from one aperture into another is twice the wavelength-distance product, but our requirement for a relatively 'sharp-edged' beam at the receiver – one whose intensity falls off swiftly near its outer edge – imposes another ~2-fold 'cost' in aperture-product; we impose this value-adding 'cost' uniformly on all of the designs that we discuss.]

Since the cost of creating an aperture rises at least as rapidly as its area – i.e., rises as D^2 – one is strongly motivated to keep both D_1 and D_2 to as small values as may be feasible. [True, economics-of-scale might be argued to somehow make costs of large apertures rise somewhat more slowly than D^2 scaling, but 'optical figure'-maintaining stiffening requirements and the awkwardness of working at large scales can be argued at least as readily to make large aperture costs rise faster than D^2 scaling would indicate.] If the beam-propagating distance is more-or-less lower-bounded – as it assuredly is, in the space power-beaming-&-projecting context – then the only free parameter is the wavelength of the radiation to be beamed. For that reason, exploitation of the relatively few atmospheric transmission windows that exist automatically directs attention to the shorter wavelength portion of the electromagnetic spectrum. These are the L-to-X-band microwave band, between ~15 and ~2 cm wavelength, and the near-visible spectrum, between ~0.3 and ~1.5 microns wavelength. These are the essential physical constraints within which lie the technical possibilities for power-beaming to Earth from space.

Glaser, in his historic proposals of a third-century ago, chose the microwave band, for well-understood reasons of (then, far-)greater technological maturity and thus more feasible economics-in-large-scales. His specific initial choice of 12 cm wavelength radiation adroitly side-stepped many regulatory issues, as this waveband is a largely unregulated one given to both industrial and residential uses (e.g., industrial processing and kitchen microwave ovens), and also accessed a very widely deployed – and thus very economical – microwave technology-set. However, propagation of such radiation over distances of even 1000 km – about the minimum that's feasible to consider seriously for any wide-applications space-originated power-beaming system – involves an aperture diameter product of $\sim 4 \times 10^9$ cm^2, e.g., Rayleigh criterion-specified symmetric transmitting and receiving apertures each of 600 meters diameter(!). If the transmission-distance is greater – and Glaser's baseline system was proposed to be located in geosynchronous equatorial orbit (GEO), at 35 megameters altitude – then the product of the transmitting and receiving aperture-diameters grows proportionately; Glaser's proposed transmitting and receiving antennae were each ≥10 km^2 in area – and their estimated costs-to-implement (tacitly ignoring then-prevailing space-launch expenses, at that) were denominated in billions of dollars each. In order to not be of completely unreasonable size from an economic perspective, each of these apertures had to process time-averaged gigawatts of power, and thus had to be closely associated with either very large terrestrial loads or very high-capacity transmission lines; their notably large real estate requirements generally precluded the former, so the various substantial (economic, environmental, time-delay,…) costs of the latter necessarily were placed 'in series' with those of the space power-beaming system itself.

Though economically burdened by its exceptionally large minimal scales, Glaser's microwave-based proposal had the notable virtues of leveraging vigorously the COTS microwave-generating and – rectification technologies then already well-developed. The former could generate microwave power from the DC power available from solar PVAs (or space nuclear reactors, or whatever) with ~70% efficiency, and could reject waste heat at intermediate temperatures with acceptable (if not really excellent) radiator-mass efficiency; the klystron and magnetron designs were well-suited to exploitation of the abundant vacuum environment. The rectenna elements proposed for converting received microwave power at Earth's surface to DC (preparatory to exciting AC transmission lines) offered >50% efficiency, and could be cooled acceptably with ambient air. In-space power manipulation prior to microwave generation sourced several percent of low-temperature waste heat, but this could be radiated into space readily within the already-huge mass-budgets of the ~10 km^2 transmitting antenna.

Indeed, in-space power-manipulation efficiency was important to both controlling the physical scale and the economic cost of Glaser's proposal, as the only then-extant solar PVA technology – that based on relatively thick slabs of crystalline Si – had a high per-watt Earthside cost and comparatively low watt/gm mass-efficiency, so that lifting it into orbit also had high per-watt costs; it was therefore economically necessary to handle each electrical watt-generated very efficiently.

That Was Then; This Is Now. In considering what may be the preferred form of space-based power-beaming systems for the early 21st century – essentially, in updating Glaser's proposal in the light of humanity's present technological posture and associated economics – we first-of-all must note that the constant-value-dollar cost of space-launch hasn't fallen nearly as rapidly as most everyone projected, a quarter-century ago; this surely accounts to some extent for the continuing failure-to-materialize of space-sourced power. Indeed, were it not for the currently severely-depressed market for space-launch services, the per-pound cost of putting mass into the 'standard' low Earth orbits would not be sensibly lower now than it was back then. However, thanks to the very recent advent of government-sponsored EELV-based space-launch capability in the U.S., albeit without any really substantial demand for the space-launch services thereby made available, space-launch to low-latitude LEO presently currently can be purchased at a per-pound cost of perhaps $2500, about half of what it was a half-decade ago, and likely not much more than half of what it'll cost at the end of the present decade (all in then-year dollars). [Contemporary space-launch costs to GEO remain 'stuck' at nearly 4 times that to low-latitude LEO. However, ongoing technological advance may change this drastically – and fairly soon – as is discussed further below; this, in turn, may correspondingly impact the cost-efficiencies of almost all types of space-originated power-beaming architectures.]

The impetus to reduce the 'buy-in' costs of space power systems strongly motivates reduction in the mass launched into space – wherever they may eventually end up being operated, for space-launch costs thoroughly dominate total system costs in all known and contemplated space power-beaming architectures of the present era. This basic economic consideration, in turn, not only impels use of the highest specific power technologies – those capable of processing the most (system efficiency-weighted) watts per gram of component or sub-system – but *also* the initial creation of the smallest, i.e., lowest-mass space power stations that make technical and economic sense. As is discussed further below, relatively small stations – ones sourcing megawatt- vs. gigawatt-scale (collections of) beams – may be eminently useful along an entirely different programmatic axis: 'wedging' into marginal markets at the commencement of the space power-beaming era.

Crucially, however, the optical telecommunication revolution-driven advent of high watt/gm solar PVA and DC-to-optical power-conversion technologies have shifted fundamentally the outlook for power-beaming in other-than-microwave wavebands. **The basic feasibility-driver of all types of space-originated power-beaming is the per-watt cost putting electricity into the possession-for-use of customers on/near the Earth's surface**; per-step efficiencies in the energy-cascade from sunlight (or nuclear fission, or…) through DC power-in-space on through power beam-generation and –projection are all divided by the mass-efficiencies of the technology in that cascade-step, since the unit-mass costs-to-orbit continue to be large compared to associated ground-based manufacturing costs. Thus, relatively power-inefficient technologies will be preferred in space power stations if-and-only-if their relatively high mass-efficiencies overweigh their power inefficiencies: **the only thing that matters at the bottom line is the total in-space economic cost to generate and project to Earth use-points power-beams that put a unit of electrical power into the hands of a paying customer.** *If the (externalities-included) economic value of the electricity thereby delivered constitutes an attractive risk-discounted rate-of-return (ROI) of a total capital investment of feasible overall scale, then space-originated power-beaming for civilian applications will come to pass; otherwise, it very likely will not, as the economic scales of civilian electricity are so large that not even very rich governments could afford to significantly subsidize a mass-market for it.* [To be sure, governments have been politically quite successful at mandating electricity price-subsidies for favored constituencies, e.g., residential customers, but the titanic economic dislocations of such cost-shiftings have driven substantial (if sometimes fitful) liberalization of electricity markets, at least in the U.S., during the past decade.]

For all of the above reasons – as well as other which will become apparent – we expect that beamed space-sourced power will become useful with lowest overall programmatic risk if the near-optical wave-band is employed in lieu of the microwave one, under presently-prevailing circumstances. The corresponding 5 order-of-magnitude reduction in wavelength confers a intrinsic 10 order-of-magnitude reduction – a 10 *billion*-fold drop – in the minimum area-product of the transmitting and receiving apertures of the product, a factor so huge that it permits entirely novel technical solutions to space power station implementation challenges be exploited, as we'll discuss below. The totality of such exploitations, we believe, may make all the difference – e.g., between futures that continue to be devoid of space-sourced power and ones potentially rich in it.

Beam-Forming And -Projection Means. We therefore invite attention to prospects for converting solar PVA power into optical-wavelength power and then projecting beams of thereby-realized coherent light to Earthside PVA receiver-converters. This can be accomplished with minimal mass, and thus maximum economic efficiency, by conducting the optical power generation in a manner tightly integrated into the PVA system itself, both in order to minimize long-haul, high-power DC transmission within the space power station and – at least as importantly – to reject the waste heat of DC-to-optical conversion with maximum mass-efficiency. Specifically, we consider the use of telecommunication-optimized laser diodes to convert DC power *in situ* from each tiny (~1 m^2) segment of the photovoltaic array into (largely) incoherent optical power with slope efficiencies of ~60%, and then use this optical power to pump in parallel a huge multiplicity of fiber-optic lasers, with marginal efficiencies of ~70%, thereby realizing overall DC-to-coherent light conversion efficiencies of 35-40%.

The essence of this approach is to leverage the last two decades of advances in optical communications technologies to 'harvest' PVA power locally, converting it within ~1 meter of where it was generated via sunlight-absorption into optical fiber-embedded coherent optical power (so as to circumvent long-distance transport losses and mass penalties), employing millions of near-microscopic laser-diodes conducting in-line pumping of doped optical fibers. The lightwave intensity in each member of the network of optical fibers then grows continually as the very many individual fibers thread their respective individual paths from the extremes of the total power-station PVA into the station's central beam-forming region. Quite usefully (as will be seen below), the coherent radiation thereby gathered into the station's beam-former is monochromatic. The PVA-generated DC power flowing into each laser diode would be on-off-switched by a control-line from the power-station's central computer. Such a power-control system might be conveniently implemented with different-wavelength optical signals counterpropagating along the same optical fiber which is being pumped by the thereby-controlled set of laser diodes.

The waste heat from the laser-diode pumping – amounting to ~60% of the total electrical power of the PVA – must be radiated back into space, for there's no other place for it to go, anymore than there was for the microwave generators proposed by Glaser; moreover, this waste heat must be so rejected from the space power station at/about 300 K temperature, as these COTS diode-stacks have been intensively engineered by telecommunications technologists for near-room temperature operation. The corresponding radiator area required is obviously several percent of that of the PVA that sourced the power fed into the diodes, naturally suggesting that roughly this fraction of the PVA itself be pressed into second-use as the power-station's ~300 K thermal radiator. [However, it's clearly quite feasible from overall mass and cost budgets to have a dedicated thermal-radiator system, even one having significantly higher mass per unit area, if this is markedly more convenient, as the mass-expense will still be only ≤10% of that of the PVA itself.] This in turn motivates the proposed use of highly-distributed, intimately-integrated tiny diode assemblies all over the PVA itself, so that the required room-temperature heat-transport – the 'spreading' of the dissipated heat from diode junctions into adjacent thermally-radiating sheet – will involve as little dedicated mass as ever possible.

It appears that such dedicated mass may be reduced to *de minimus* levels by implementing the power-station's PVA as thin-film photovoltaic material carried on a thin *sandwich* comprised of a pair of ~1 micron-thickness metal sheets patterned on their facing surfaces with an interposed lacework of microscopic dimensions partially loaded during manufacture with a suitable fluid, e.g., water, so as to function when pressed together in vacuum as a sheet heat-pipe (actually, a huge interlaced community of tiny, slender, mutually-vacuum-tight and thus functionally-independent "heat-pipettes", in order to assure long-term in-space operability). Such sheeting will function as a thermal superconductor for ≥100 Watt/cm^2 local thermal inputs, spreading room temperature-inputted heat over >10^3-fold larger areas for radiative rejection with few degree-scale temperature-drops. See Figure 1.

Incident solar energy thus may be converted into DC power with 10-20% net efficiency (the remainder going directly into uniform PVA heating and thus thermal radiation back into space). After this DC power is transported over short metallic lines heat-sunk directly into the PVA, it's expended in a local laser-diode stack that side-pumps an optical fiber-laser which is passing-through the area with ~60% slope-efficiency, and the waste heat is sunk back into the thin metallic sandwich-sheet comprising the structural support for the thin-film PVA material; the total distance-traveled by the {DC+thermal} power within the space power station thus is kept to ≤1 meter. Something of the order of 4-8% of the total radiant power of the sunlight incident on the power-station's PVA thus has been converted into optical fiber-enveloped coherent radiation – crucially, within quite acceptable parameters of power conversion and heat rejections.

Optical fibers implemented in modern technology are famously low-loss power-conduction media; nonetheless, they must be more-or-less continually heat-sunk onto the PVA during their transits across the entire station to the beam-forming sites, as their tiny sizes make them effectively incapable of shedding any useful power into thermal radiation. Very notably, the best of them are capable of continuously transporting exceptionally high optical intensities – hundreds of megawatts/cm^2 – so that modern single unimodal fibers of the order of a tenth the diameter of a human hair can transport a few dozen optical watts. Even with their rather 'bulky' tapered-index jackets, the best modern fiber-optic *bundles* thus can transport in excess of 10 MW/cm^2; a 5 cm^2 set of bundles could carry the output of a 12% efficient PVA with 40% photodiode-to-fiber laser efficiency – 5% overall conversion efficiency – when the PVA is a kilometer in diameter. [The impending commercial advent of vacuum-cored optical fibers apparently will be capable of transporting far higher peak optical flux levels without non-linear processes supervening, as only the radial fringes of the unimodal optical electric fields will 'touch' even very low-loss, highly-linear dielectric. The use of these in transporting coherent optical power likely will bring the station's entire optical fiber-bundle size down below 1 cm diameter, even for stations radiating GW levels of power-beams.]

The exceedingly high spectral brightness – combined with the very large radiance (i.e., the intensity per unit of solid angle of uncorrectable beam divergence) – available from contemporary fiber-optic technology enables especially simple – and thus early-time feasible – beam-forming. For example, a set of fibers selected for serving a single Earth-based load may be coaxially-positioned behind a projection-lensette, which in turn illuminates with the (suitably mutually phase-controlled and overall soft-apodized) outputs of the fiber-set that it subtends a distant, main projection aperture. See Figure 1. This distant main aperture – situated of the order of several kilometers distance from a large set of beam-emitters – would be use-shared by all of the projection lensettes of the entire power-station, since they could all be focused comparably well by one-and-the-same main beam-projecting aperture, their extraordinary spectral brightness and the intrinsic linearity of (low-intensity) electromagnetics considered.

We contemplate a main projection aperture comprised of a single mass-optimized Fresnel phase-plate lens, likely implemented as a few-microns thickness of a suitable dielectric (e.g., a space-environment-compatible polyimide). Its diameter would be a few times that indicated by the station's Rayleigh range to a minimum-diameter receiving aperture Earthside, so that it would be able to project suitably formed beams with 'boxcar' intensity profiles onto distant receiving apertures, moreover even at significant off-zenith illumination geometries, i.e., so that there would be strictly-minimized 'spill-over' of the projected beam beyond the edges of even the worst-case Earthside receiving antenna-geometry. For instance, the Rayleigh criterion indicates a space power-station located in any geosynchronous orbit could project 0.8 micron-wavelength – i.e., near-infrared – beams to Earthside receiving antennae of 1 meter diameter by use of a main projection aperture of ~100 meters diameter; however, we contemplate use of a main projection aperture for this application of 200-300 meters diameter, to more fully enable projection of 'tight' beams to Earthside receiving sites in all geometries. This particular main projector would have a f-number of the order of 10-15, or a focal length of roughly 3 km, so that it would magnify motions in its beam-forming region by a factor of $\sim 10^4$, if it were situated at geosynchronous distance and beam-projecting to Earth-based receivers. A ground-step of a km would correspond to a ~10 cm step in the beam-forming region, and a ground-speed of 30 m/sec – roughly 60 MPH – would correspond to a speed of ~3 mm/sec in the beam-forming region. The effective instantaneous field-of-regard of such an aperture would be ~4000 km from side-to-side, roughly the east-west distance across the United States. In other words, this main projection aperture could project optimally-focused power beams within a meter-diameter aperture anywhere across a disc on Earth which would cover the continental U.S., moreover *without moving the aperture at all*; all that would be required to move would be the sub-mm-scale optical fiber-lensette sets in the ~0.3 km-diameter beam-forming region. See Figure 2.

The Baseline-Design Space Power-Station. The space power-station that we expect may be the "preferred embodiment" of the basic Glaser concept in the early 21st century thus consists of four modules: the solar PVA, the beam-former, the main projection aperture, and the control computer system. The km-scale PVA is connected to the beam-former by bundles of fiber-optics aggregating to a few cm in diameter, which carry the entire optical power to be beam-formed- &-projected. The beam-former is defined by a (likely-mostly virtual) space-frame upon which the optical fibers are subdivided into sets of various fiber-populations, corresponding to various classes of load-sizes to be serviced. Each such set is interfaced to a projection-lensette, which initially beam-forms and directs the outputs of the fiber-bundles toward the major projection aperture near whose axis the lensettes are all located. The many individual beams thereby formed each impinge on the main projector aperture – each just filling it

– and are thereby individually projected toward their respective Earthside receivers. The control computer system, in continuous, high-bandwidth communication with the Earthside customer-community, acts to switch on-&-off the laser diode-stacks exciting each fiber-optic line and also command-controls the positions and velocities of each of the projection lensettes, so as to keep them all precision-aligned in close-to-real-time with their respective designated Earthside receivers. In the 'baseline design,' the entire system is located in a geosynchronous equatorial orbit, rotates as a unit once per day, and thus services a continental-scale set of customers from an apparently-fixed-point in their sky. See Figure 2.

<u>Beam Transport</u>. Electromagnetic radiation beams transporting through space pose no interesting issues beyond geometric diffractive spreading, which we've already addressed via the Rayleigh criterion as applied to sizing of transmitting and receiving apertures. Beam transport through the atmosphere likewise poses few issues beyond those of molecular opacity (and non-linear breakdown, which doesn't occur at intensities of present interest), which we've addressed in the discussion of wavebands intrinsically suitable for purposes of power-beaming through the Earth's atmosphere. However, meteorological phenomena – clouds, rain, fogs, etc. – pose issues for high-quality beam-transport at both wavebands of present interest, and the more so for the near-optical one. [Microwave beams also are notably weather-modulated, especially at shorter wavelengths, but these are of lesser present interest.]

The basic *physics* point-of-interest is that scattering by water droplets of all pertinent sizes is quasi-isotropic for beams having wavelengths of the order of 1 micron, so that beams heading into Earthside receivers are attenuated by having their constituent photons "blown all over the place," rather than dispersing them close to the axis of beam propagation via preferentially-forward scattering. The effects of meteorological scattering are such that beams-of-present-interest aren't somewhat de-focused, but instead are (nearly-)isotropically diffused. Thus, we don't have to worry about relatively intense beams 'barely spilling over' the edges of receivers due to meteorological scattering of any type. Instead, the photons thereby lost will 'go away' entirely-&-cleanly.

The basic *meteorological* points-of-interest are that while clouds are a frequent feature of the sky most everywhere, dense clouds from horizon-to-horizon are seen only quite rarely in most every locale of interest; furthermore, most clouds are 1-3 optical depths in vertical thickness, with only thunderstorm cores having vertical extents of a dozen optical depths or more.

Thus, our basic response to the 'patchy clouds' issue is that we'll send in beamed energy around them, from space power-stations in the sky whose lines-of-sight to any given ground-based receiver at any moment-in-time aren't significantly cloud-occluded. This is a trivially-implemented feature of any system that effectively exploits the spacetime agility of power-beaming from space sources. [Power stations in LEO are especially well-adapted to sending power-beams in along axes in which significant cloud obscuration isn't found at any particular time – there's likely to be a lot of them, and they will innately sample most if not all major regions of the sky of any particular receiver location, thereby maximizing the likelihood at all times of at least one 'clear shot' to any receiver. Correspondingly, power stations are geosynchronous distances won't necessarily all be in equatorial orbits; some may well be deployed in significantly inclined orbital planes, possibly also of substantial ellipticity and/or eccentricity (e.g., Molniya-like), in order to better service high-latitude loads (which may indeed be comprised of unusually large fractions of 'premium' customers) – with their innate beam-agility obviating possible 'regrets' associated with their apparent motion across local skies with respect to servicing 'ordinary' lower-latitude loads.]

To the issue of horizon-to-horizon cloud-coverage of a receiver calling for power to be beamed to it the response is to simply 'punch through' the obscuration which, as already noted, is likely ≤3 optical-depths in extent. Yes, such punching-through by simply (even automatically) 'turning up' the beam intensity incident at the tropopause will cost more in beam power sent from the in-space power-station, but doing so is side-effects-free -- and this is consistent with space-originated beamed power at least initially being a premium source of electrical energy, one sold at unusually high price in exchange for its novel features. The customer whose power-beam receiver is somewhat cloud-obscured can instruct his/her energy-bot to either manage the electrical load that's being supplied by the receiver to get by with less beamed power until the horizon-to-horizon clouds disappear (e.g., either by reducing its magnitude or drawing from an alternate power source) and a beam-from-space can find its way into the receiver, or else to buy as much more beamed-power (perhaps at a discounted, "weather-compensating" rate) as may be needed to compensate from moment-to-moment for the cloud obscuration-induced propagation losses, thereby maintaining full power output from the beam-receiver for the typically-brief interval while the extensive cloud-system 'blows through' the local sky.

With respect to *really* dense horizon-to-horizon thunderstorm-type cloud systems, we note that it's technically feasible but likely economically uninteresting to punch through nearly all of them. To (near-)optical power-beam propagation, they pose side-effects-free isotropic scattering opacity, not potentially beam-path-distorting absorption opacity, and thus it's altogether possible to simply obviate the attenuation by raising the projected beam intensity appropriately. This likely becomes uneconomically uninteresting for all but the most peculiar receiver-loads when the beam-path becomes of more than ~5 optical thicknesses in total propagation loss. In such circumstances, we observe that such strongly-adverse propagation circumstances occur for of the order of hours per year in most parts of the electrified world, as the most intense storms past through. Thus, we suggest the same basic response as is taken *de facto* to severe storm-induced utility power outages through the present time, which also occur at the level of roughly 10 hours/year, or 0.1% of the time: get by without the lost utility power, either by doing without power entirely or else by providing your own, until utility power-service is restored. Back-up prime movers (small engine-generator sets) and rechargeable chemical batteries (often powering DC-to-AC inverters) are standard features of such interim-power strategies. Because we expect that power-beaming wouldn't be severe storm-interrupted for the usually-extended durations of utility power outages – but might be somewhat more frequent – secondary chemical batteries and mechanical energy-storage (e.g., by advanced flywheels which, though of rather limited energy-storage capacity, offer unusually high charge-discharge power-levels and also have indefinitely-great cycle-capacity, and thus are especially 'friendly' to brief-duration-but-frequent high-power demands) would seem to be preferred 'ride through' technology-choices. [The cowardly option, of course, is to resort to the local utility for 'tide me over' power. This option may be especially tempting to 'old' load, which may well have the 'traditional utility' transmission-&-distribution system "near at hand." While there may not be much 'old' generation connected into this system when power-beaming has matured, it presumably will still be serviceable for importing usefully-large amounts of power from adjacent regions not then covered by the posited intense storm, which is of quite limited (usually, <100 km) geographic extent. Contemporary time-of-use pricing technology-&-practices, adapted to 'circumstance-of-use' pricing, will automatically steer such extraordinary power-imports to their 'highest-&-best' uses, right up to the then-prevailing physical limits of the power-importing system.]

Thus, meteorological complications of all flavors – but typified by clouds and cloud-systems – appear as a minor, readily-addressed complication of propagating beamed energy from space all the way down to ground-based receivers. Just as wind-damage, icing, tree-growth, flooding and equipment-aging occasionally interrupt traditional utility-provided electricity service, so beam-path opacity of various natural origins may be expected to occasionally impair that of space-originated power-beaming – moreover, to roughly the same overall extent in terms of aggregate service-interruption. Moreover, the highly-automated, closed-loop characteristics of power-beaming to customers will lead naturally to ever-smaller meteorological impacts, as beam-seeking behavior of receiver-'targets' becomes ever more agile in spacetime and as transmitted beam-power is automatically adjusted to meet time-varying load demands with ever-smaller latency.

Beam-Reception And Electricity Generation. Earthside reception of space-originated beamed power may take place on a wide variety of scales and locations, across a rich spectrum of higher-value applications for electricity (and perhaps for low/moderate-temperature waste-heat from cooling the PVAs, as well). Since we expect that initial stages of market penetration of space-originated power will involve relatively high unit-cost power-beams – or, at least, for power that is to be sold at comparatively high unit prices – we emphasize the providing of beam-power under circumstances of greatest-possible-convenience to the set of highest-value applications. As already suggested, we anticipate leveraging the intrinsic spatial and temporal agility of space-sourced power beams to put down beamed energy *quite* exactly *where* and *when* that it's desired (and, of course, paid for) – and nowhere else. Presently-available high-precision geolocating GPS receivers suitable for the mass market and real-time, high-bandwidth, low-cost global telecommunications connectivity via the Global Digital Network – along with already-fully-automated global financial transaction-executing and account-clearing services – are regarded as necessary-&-sufficient to enable beam-agile servicing of virtually the full spectrum of markets for on-the-spot-delivered electrical power and energy: ***you get delivered just what beamed energy you contracted for, exactly where-&-when (to within the nearest few dozen centimeters during open-loop initialization-of-delivery and position-slaved to your receiver to within a few centimeters following loop-closing, and always to within the nearest dozen nanoseconds) you specified to have it delivered, at the time-programmed rate(s) that you specified for its delivery (including a 'follow my demand' spec), with at most a quarter-second time-delay between contract-execution and commencement of energy delivery.*** Such heaven-sourced 'fire,' we suggest, is truly of Promethean quality, even for us early Third Millennium folks, and will indeed prove to be "the means to mighty ends" in our times.

We anticipate conversion of beamed power so received into electricity with photovoltaic converter array-material specifically designed for maximally-efficient conversion of the particular spectral characteristics of the beamed radiation, i.e., a reasonably wavelength-optimized converter, for which conversion efficiencies of 50-70% (depending primarily on wavelength, and secondarily on materials choices and implementation approach) have been demonstrated in square-meter-scale modules. [High conversion efficiency is of dual significance: first, it maximizes the desired product – electrical power – and, second, it minimizes the waste heat generated in the array that must be offloaded into ambient air, water, etc. In worst-case, waste heat from the receiver PVA may be dissipated into ambient air with ~3% 'overhead' in electrical power expended in powering a power-economized fan blowing over an optimized finned heat-sink, with <25 K temperature-differential. In more typical instances, it may be employed for space- or water-heating, or for thermally-energizing brine-type chillers.]

Petite Receivers. Quite importantly for some customer use-modes, the exceptional radiance of these space-sourced power-beams may be exploited to focus them to far-higher-than-incident intensity onto appropriately-cooled PVA surfaces. This may be useful for driving to an absolute minimum the mass or volume of such a power converter-assembly, or in high-temperature heat-generation applications (e.g., field-stoves), or…. Such focused-beam considerations make obvious the fundamental irrelevance of the cost-per-unit-area of Earthside PVA materials for use with these types of power-beams, since most all of them can convert to electricity radiant fluxes of ~10 W/cm^2 about as readily as they can those of ~0.1 W/cm^2 'ordinary' sunlight; "dollar-per-watt" concerns pertinent to solar-PVA systems naturally drop (far) below thresholds of real-world interest with respect to processing this class of space-originated power-beams. Since these power-beams also have extraordinarily high spectral brightness – i.e., are monochromatic – the focusing of them by thousand-fold factors can be performed with children's toy-quality plastic-replica Fresnel phase-plates; spectral broadband-edness of the focal qualities of lenses for such applications is utterly irrelevant.

Premium customers presumably will demand that their beam-generated electricity be sourced from as compact and lightweight – and even inexpensive – package as is possibly consistent with reliable, safe operation. We therefore anticipate that the exceptionally high-brightness origin-&-nature of the beamed radiation will often be exploited to deliver beamed power to Earthside receiver at substantial intensity-multiples of that available from Sol-beamed power – ordinary sunlight. We expect that many premium applications will desire to have ~1-10 kW of steady electrical power sourced from a ≤1 meter^2 beamed-power-receiver assembly, i.e., one with the scale – and perhaps the mass and even the portability – of a large umbrella. [Indeed, it's our present estimate that this may even characterize the "sweet spot" of the eventual mass-market for power beamed-from-space. There seems to be no *a priori* reason for customers to wish to have receiving antennae for space-originated power-beams that are any larger – in size, mass, etc. – than technically necessary.]

Operational Safety. Serving such markets will involve beam-intensities of 5-50 times that of sunlight, so that such beams – particularly the ones at the more intense end of the range – will, at least in principle, pose safety risks. The obviously-sufficient response to all such issues is a combination of passive physical barriers – e.g., tight-mesh fencing, so that human body-parts, e.g., fingers, can't be inserted into even the edges of beams without deliberate effort – and reasonably-sophisticated automatic safety devices, such as beam-interruption sensors positioned completely around the perimeter of all Earthside receiving apertures whose associated digital controllers command immediate beam-shutoff when any single such detector senses even momentary diminution of *local* beam intensity.

Given the fifth-second loop-closure time for even the most distant space power-stations of present interest – those at geosynchronous distance – this suffices to ensure that any possible beam-induced skin-damage would be considerably less severe than a first-degree burn, even for 100X-sunlight power-beams, even if a receiver-surrounding physical barrier's sensors and the beam-perimeter sensors both were somehow to be entirely circumvented – by some 'magical' means entirely unclear to us – and full-beam-intensity exposure was sustained at 10 W/cm^2 levels until auto-beam-cutoff occurred 0.2 seconds later. [We note that such systems can be implemented with any desired degree of redundancy and with 'perimeter defenses' of any desired degrees of stand-off distance-&-time, so that risk of any politically-specified extent-of-damage may be made as statistically unlikely as may be politically determined to be necessary – and all this can be accomplished with small-to-negligible economic costs.

Moreover, automatic, asymptotically-zero-cost, millisecond-by-millisecond record-keeping at multiple points – the ground-situated receiver, the Earthside control system, the space power station, etc. – can readily assign the physical bases of liability essentially as precisely in spacetime and as incontestably as may be politically required. Automatic beam-shutoff, followed by automatic low-intensity receiver-occlusion-checking, followed by automatic-&-conditional full-beampower-restoration, should aptly address even the bird-injury issue-set, over-&-above the inadvertent airplane one. For sensitive applications, we expect the corresponding power-beam may be slightly (e.g., amplitude-)modulated with a stochastic time-patterning at the space power-station, such modulation being individualized to the particular receiver to which it's directed, and for the content of this modulation signal to be required to be returned by the Earthside receiver to the space power-station with only speed-of-light delay, in order for power to be continue to be beamed at all. We observe that the digitized bit-stream involved – something of the order of 1 kilobit/second, including full receiver status – can presently be dispatched from most anywhere to most anywhere else via the global digital network for an economic cost <\$0.01/hour, a cost that moreover drops by at least two-fold annually.]

Power-Delivery Flexibility. Finally, we anticipate that (especially!) premium customers will eventually demand that they be provided with just the time-varying amounts of beamed power that they wish to have – no more and (most definitely!) no less. While take-or-pay of fixed levels of beam-power may well be the initial mode-of-service from in-space power-stations, we expect that an increasingly sophisticated market for such power will eventually – perhaps even quite soon – demand the type of electricity-servicing that (they believe that) they purchase from their electric utility: "Just exactly as much power as I want from moment-to-moment, including full servicing of all of my surge and start-up loads." To be sure, surges from such events as motor-starts can be accommodated by small energy-storage devices – e.g., super-capacitors – transiently powering surge-rated inverters operated in parallel with the receiver-powered line, but lower-frequency changes in customer power demand will have to be addressed by corresponding shifts in beamed power. While the basic design for a space power-station that we've sketched elsewhere might not seem to accommodate such 'dialing' of the power-output of a projection-lensette very efficiently, we suggest that there are a number of basic architectures of the power-gathering optical fiber network that can rather readily do so. For instance, a given optical fiber threading its way through N different diode-pumping points might be interlaced with M other fibers, each also having a basically-similar pumping arrangement, with which it shared various (*a priori* known) fractions of the N points at which it is being power-loaded. Commanding the moment-by-moment pumping-instructions given to each of the $\vartheta(N^2)M$ laser-diode pumping-stations so as to power-load each of the M fibers with the desired amount of power is then a well-posed problem, optimal solvable (e.g., by a dedicated-&-specialized module of by the station's control computer system) along the same lines as hash-coding problems are routinely solved in contemporary computer science applications. Importantly, modest internetting of the power busses of near-neighbor laser diode-banks will permit the entire electrical power available from the station's whole solar PVA to be continuously (i.e., maximally-productively) employed in laser diode-pumping of the station's fiber network.

Control And Concept-Of-Operations. A sketch of a few of the basic concepts-of-operation may serve to illustrate how we believe a space-originated power-beaming system might serve the upper-end civilian marketplace for electricity. We sort this by class-of-customers, aligned along the epoch-of-first-use axis.

First Customers. The earliest customer-class for power beamed from space is likely to be found fairly exclusively in out-of-the-way places, generally far away from utility power-mains (or at least plug-in power receptacles) – though occasionally merely unable to access ones near-at-hand (e.g., in a sailboat-in-harbor but not at-pierside). In his/her then-prevailing circumstances, (s)he is quite insensitive to the cost of electrical energy or power; to this customer-set, 1-100 megajoules of electrical energy have a perceived 'here-&-now' worth never less – and often far more – than $1 per megajoule. [E.g., a 'dead' car battery can be induced to crank most automobile engines successfully with an infusion of ~0.1 megajoules of quick-charge energy.] An example of such a customer might be an economic upper-middle-class person with a great fondness for the conveniences of electricity while far-from-homebase but who hates lugging around massive batteries and/or a motor-generator set. [It's useful in this context to recall that we already live in a society nearly all of whose members cheerfully pay ≥$1,000/kWe-hr for the convenience of primary battery-energizing of their consumer electronics.]

Thus, in his/her backpack – (s)he may be a civilian-in-the-wilderness, or a soldier-with-USG-charge-card – (s)he carries an umbrella-like object, which is unfurled at a location-&-time of choice and planted onto the local terrain. (S)he then makes connection via the receiver's communications module and contracts for power to be beamed at a specified intensity-vs.-time onto the geolocation specified by the GPS receiver positioned at antenna-center of the umbrella-esque power-unit, accepts the liability-waiver and executes the funds-transfer as cued by the communicator module. A power-up cycle is then automatically executed: if the low-power beam initially transmitted reaches – or, with auto-executed fine adjustments, is able to reach – all portions of the antenna in the *a priori* expected manner, full-intensity power-beaming is commenced, and is then maintained for just as long as the non-occluded-beam condition-set continues to exist; otherwise, the customer is cued to correct the beam-interruption condition. The contracted-for electrical power flows from the receptacle on the antenna-handle into the customer's local load, for as long an interval as has been contracted, upon to whatever maximum rate-vs.-time may have been contract-specified. This particular customer has executed a take-or-pay contract; when (s)he's got all the power/energy needed, e.g., to recharge a battery-set, to cook a meal, to operate a high-bandwidth comm-set, or whatever – (s)he simply folds up the receiver-unit and moves on; the power-beam 'evaporates' essentially instantly, even if the customer didn't explicitly tell it to do so. [If the customer formally canceled the remainder of the service via his/her communicator, (s)he might get some credit to his/her account for the unused power/time, e.g., if the then-existing 'spot market' for beamed power in his/her general sector of spacetime permitted the beam scheduled for him/her to be re-sold to another 'spacetime-adjacent' customer.] At any given time, there may be 'only' thousands of such customers per million square kilometers – i.e., 'only' tens of *millions* of watts of demand for power beamed from space across all of America, with its half-*trillion* watt aggregate electricity demand – but it's anticipated that space-beamed power service will start with space power stations having power-beaming capabilities of mere megawatts, so this potential customer-base would saturate capabilities, i.e., will *bid*-&-pay 'top dollar' for the power that's initially available – thereby maximizing both ROI and incentives to swiftly expand the aggregate power-beaming capacity. We unhesitantly estimate that this initial market will support sales of time-averaged megawatts of electricity at prices of at least $10/kW-hr, to the USG and/or in the U.S.A. alone.

<u>*Early Adopters*</u>. Market-oriented technologists in the contemporary West are blessed with a class of techno-masochists known as “early adopters,” people who rather joyfully pay-&-suffer for the privilege of living-&-working on what’s colloquially know as “the (b)leading edge” of modern technology. Though generally not individually wealthy, this sub-population in aggregate commands very substantial economic resources, which are reliably thrown at any new, advanced, technically-challenging widgetry that somehow enjoying the repute of being ‘cool.’ [For example, although the authors fancy themselves as more-or-less-normal folks who have similar-type friends, they know of three colleagues who have *elected* to create – out of salary-based income – solar-electric homes, ones whose electrical requirements are met entirely by solar photovoltaic power.] These sorts of folks will reliably commence to buy space-beamed power as soon as it becomes available for of the order of $1/kWe-hr, for ‘special purposes.’ Among these will be recharging of batteries on their while-parked electric cars, so as to enable such presently range-‘marginal’ modes of personal transportation to be used reliably for longer-distance journeys. Since this involves beamed power of specified total time-integrated magnitude but rather indifferent as to time- or (within very wide limits) rate-of-delivery to the receiver, such ‘salvage use’ loads may initially be serviced by space-sourced power-beaming systems with power which would otherwise go unused, e.g., which is ‘abandoned’ unexpectedly by take-or-pay customers. These loads will be enabled thereby to enter the beamed-power marketplace relatively early – to limited extents. These customers will simply purchase *energy* beam-delivered within a specified clock-time-interval to a specified site, with specified minimum and maximum rates – likely with specified not-to-exceed prices for each of two or three blocks of energy-delivered. [For instance, a customer might be willing to run the hydrocarbon fuel-powered engine in the car, in spite of the then-prevailing very high price of its fuel, in order to get to work or to return home, if the price of beamed energy somehow was exceptionally high that day, but would buy beamed energy in various quantities over the next several hours, “if the spot-market’s price is right.” This customer might place a beamed-energy delivery order accordingly, just before leaving the parked vehicle on that particular day – or instead might contract for delivery of energy at a roughly-fixed location, within a specified time-window, days in advance, in order to secure lower take-or-pay pricing for the desired beamed energy-block(s).]

<u>*Mobile Customers*</u>. Roughly contemporaneous in market-penetration epoch with fixed-site ‘early adopters,’ we expect, will be the first mobile customers. The large majority of these will be commercial and personal vehicular transportation-users, buying power beamed to the rooftops of their vehicles. [We observe that power-beaming to moving vehicles involves no waste-heat-disposal issues; the vehicle motion-induced ‘breeze’ is more-than-ample to extract waste-heat from a beamed-power PVA.] Depending on vehicle scales – from small two-seater cars to large commercial freight-hauling truck-tractors – and the speeds at which they’re driven (e.g., urban stop-&-go to high-speed hill-climbing on interstate highways) – such vehicular loads will vary between ~3 and ~150 kWe, and may involve feasible receiving antenna-areas of ~0.4-20 square meters. These mobile, characteristically fairly price-sensitive customers will be ‘inspired’ to buy power beamed from space by high local fuel costs – be they market- or tax-driven – when the price of beamed energy descends through certain thresholds. For example, in Europe at the present time, the fully-taxed cost of motor vehicle fuel is equivalent to a cost of electrical energy-delivered-to-the-vehicle-at-time-of-use of about $0.6/kWe-hr; if the differential capital costs of heat-engine and electrical power-trains and of maintenance thereof are included, this ‘energy-source indifferent’ cost-level rises to $0.9-1.2/kWe-hr delivered-at-use-time, depending on car size and driving modes. Thus, if electricity could be delivered to such vehicle-customers at, say, $0.7/kWe-hr, when-&-as they need it, a Eurocentric energy market of semi-titanic

size – tens of gigawatts – for energy/power beamed from space presumably would open as quickly as automotive power-train retrofits could be performed, driven by pure-&-simple cost-avoidance behaviors.

Due almost exclusively to lower fuel and sales taxes, the 'energy-source indifference' cost of timely-delivered electrical energy to automobiles in America is lower by about two-fold: to ~$0.3/kWe-hr if only energy costs are considered, or ~$0.5/kWe-hr, if all costs-avoided are considered. The notably differing cost-levels between and within these two huge energy markets naturally generate a very attractive growth-plan for space-sourced beamed-power to mobile customers of all types. [*All* types? Yes, even passenger airliners – generally considered to be the quintessential "gotta have hydrocarbon fuels, and nothing else" large-scale energy-market – could potentially be serviced with space-sourced power beamed to their wingtops at 100-400X solar intensity levels: the largest passenger aircraft have wing-areas of ~500 m^2, and per-engine peak power levels of ~65 MW, so that beam intensities of ~500 kW/m^2 will readily suffice to provide peak electric power to engine-pairs. If-&-when generation of 'persistent contrails' by water-vapor-gushing aircraft engines is added to the list of mortal sins against the environment, we humans needn't sacrifice civil air transport on the high altar of atmospheric political correctness – <u>if</u> power-beaming from space is then available: even the largest civil airliners can potentially fly mostly on space-originated power-beams, with thrust generated by high-bypass-ratio hybrid fuel-electric engines burning fuel when below clouds and beam-powered when above them.]

Servicing mobile customers may be considerably easier from technical vantage-points than it might first appear. Most such customer-types may have either limited on-board energy-storage capacity – e.g., a rechargeable, secondary-type battery – or an on-board prime-mover of limited power or energy– e.g., a hydrocarbon-fueled engine(-generator) sufficient to operate the vehicle at reduced speed (or with a modest fuel-tank capacity good only for rather limited unrefueled range). Such customers may enter into a more-or-less dynamic beamed-power-purchasing contract, one 'steered' both by ongoing power-demand from the vehicle's as-commanded power-train and by the GPS-determined time-varying position of the vehicle – and presumably bid price-clamped at some predetermined-to-be-acceptable unit cost of delivered beam-energy. The vehicle operator's on-line 'agent' – the car's motive energy-bot – would then bid from time-to-time for beamed energy delivery, while simultaneously considering the state of the vehicle's battery-charge, the differential cost of battery-energy (appropriately discounted for considerations such as depth-of-discharge shortening of battery-life of known capital cost-to-replace), the estimated remaining duration (in energy units) of the present day's trip, pending beam-obscuration by long tunnels and bad weather, driver reluctance to proceed at reduced speed over significant travel-distances with power sourced by the vehicle's fuel-burning engine, economic costs of engine-generated energy, etc.

Technically, it's quite readily feasible to keep space-originated power-beams centered on vehicle-tops, even as they maneuver in traffic, make emergency stops, etc., as brief consideration of Newton's Second Law makes clear: vehicles are typically equipped with 3-5 times the brake horsepower as they have motive horsepower, and can slow-while-breaking at a maximum of 0.3-0.5 gee, depending on speed, vehicle-type, road surface- and tire-quality, etc. The loop-closing time from the vehicle beam receiver-centered GPS antenna to the power station-in-geosynchronous orbit and back-via-powerbeam is 0.2 seconds, during which time a sustained, unanticipated vehicle acceleration of 0.5 gee (the all-parameters worst-case) – i.e., 5 m/sec^2 – has induced a power beam-center-offset of 0.1 m, much smaller than the meter-diameter-scale beamspot itself; the vehicle's continuous sending of not only its

GPS-provided geolocation and velocity but *also* of its time-varying acceleration would quickly – in ~0.3 second – reduce the beam-aiming error to <<0.1 meter for the remainder of the emergency-braking episode. As already noted, maximum-available-acceleration from the vehicle's powertrain could induce worst-case beamspot-center offsets only 3-to-5-fold smaller than the emergency-braking ones just upper-bounded. The 'bottom line' is that the completely non-intuitively-large value of lightspeed and the relative nearness of geosynchronous orbit, together with the geolocation and signaling capabilities of technologies already universally and inexpensively available at the start of the 21st century, combine to permit *cooperative* Earthside motor-vehicles to be beam-spotted from even geosynchronous-orbit distances with remarkably high precision, even when they're accelerating at their respective 'physics limits.'

Mass Market Customers. The present price of energy delivery to stationary-type mass-markets in the U.S. is $0.06-0.3/kW-hr during peak-use hours, this range generally covering preferred residences (and some farms) and non-preferred commercial customers. These prices are widely understood to not be market-determined ones, but rather are politically prescribed. If-&-when market-rationalized, time-of-use pricing of electricity becomes at all widespread, peak-use energy will sell to end-use American customers for $0.20-0.50/kWe-hr – just as it routinely has done at free-market wholesale, over the past several years. [Servicing peak electrical system loads – necessarily, of *a priori* somewhat-uncertain magnitudes – is remarkably expensive, and relatively economically-liberalized American wholesale electric markets reflect this basic reality, even if the politically-constrained retail ones currently do not.]

Rationalized pricing of peaking electric power in the mass marketplace eventually will bring it into the range at which the American motor-vehicle load already may have 'enticed' ever-more-economical space-originated power-beamed electricity. The stationary-load mass-market of hundreds of GWe (in the U.S. alone) will then be accessed, likely driven by canny individual customers in homes and businesses conducting local, computer-driven arbitrage against the local utility's simultaneous offerings, relative to their internal needs, their energy-storage capabilities and their rooftop beamed-power-receiving capacities. As the time-dependent price of space-originated beamed power drops – and the in-space power-stations become ever more adept at following the solar-phased electricity demand-peak as it sweeps diurnally around the Earth – such free-lance arbitraging will enable ever-deeper penetration by space-beamed power of the mass-market for electricity, until ground-based electricity-supply systems become very high economic efficiency, mostly base-loaded ones. [Their time-&-circumstances-of-use-based electricity sales will rationally price back-up electric power for use during the rare meteorological outages that we've discussed above.] At that, all such currently-conventional electricity-supply systems will always be disadvantaged by the full set of transmission and distribution costs – economic and otherwise – stacked on top of their 'bus-bar', or electricity-generation, costs. [These almost-always-substantial transmission and distribution costs are intrinsically-&-entirely avoided by beamed-to-the-load-upon-demand power technology that we've discussed above.]

'Free' Technologies And Tech-Demonstrations. The many advantages – both quantitative and qualitative – offered by space-sourced power-beaming are even now becoming apparent to key U.S. Government decision-makers, and it seems quite likely that serious programmatic enterprises will commence reasonably soon to beam power through space in usefully large quantities and rates, following the basic path already blazed by space-beamed high-bandwidth information flows.

Unsurprisingly, such moves are likely to be taken first by those responsible for American national security. Such efforts are likely to be unusually purposeful, fast-paced and correspondingly well-resourced, relative to most large-scale National endeavors. It's reasonable to expect that the basic technologies found to enable these enterprises will be made available for other Government purposes soon thereafter; depending on top-level policy determinations, key technologies may be made available reasonably soon for civilian exploitation. The Internet evolving rapidly from the ARPANET base is the salient, potentially-pertinent example of such a dual-*used* technology-set – one that sprang from the U.S. politicomilitary desire, three decades ago, to be able to fight all-out, all-planet nuclear war more effectively through leveraging of highly-survivable, long-range, digitally-based communications.

Large-Scale Solar Photovoltaic Power Supplies. Interestingly high-capacity solar PVAs-in-space may be among the first of the key enabling technologies for large-scale civilian-applications power-beaming to be performance-demonstrated by the U.S. Government. While high-capacity electric power supplies have many potential national security-related uses of rather unrelated natures, the single one which presently seems sufficiently compelling to justify sustained, serious effort in-&-by itself is the 'space tug' one overviewed below.

'Space Tugs' And 'Orbital Homogenization'. One of the first – and certainly one of the highest-leverage overall – applications of space power-beaming may be in the energizing of the in-space analogs of ocean-going tugboats, or 'space tugs.' The past half-dozen years have seen the advent of high-power, high-efficiency plasma-jet engines developing specific impulses of several *thousand* seconds. These can be used to transport payloads through large Δv changes – ones of several km/sec -- with very modest costs in reaction mass, so that orbit-shifting patience denominated in mere weeks can see power-intensive payloads – e.g., space power stations launched into LEO and deployed/assembled there – transported into essentially any other orbit, anywhere in the Earth-Moon system(!). The fraction of payload mass required to transit from GEO to LEO would be ~10% with extant COTS plasma jet-engines, and near-term advances in engine specific impulse (to the neighborhood of 7000 seconds) bid to reduce this orbit-shifting 'overhead' to ~5%; either of these compare exceedingly favorably with the ~200-300% mass overhead in moving from LEO to GEO with present COTS liquid or solid chemical-rocket technologies, respectively. The bottom-line consequence of this reasonably near-term advance is that all orbits in cislunar space then become comparably accessible in energy- (and thus in dollar-)cost. If mere weeks of transit-time delay can be accepted – and if large solar PVAs are available, either carried by the tug itself or else sourcing beamed-power from afar – then all points and all orbits in cislunar space become first-order-equivalent in terms of access. [An additional feature of such 'space tugs' is that, as their name suggests, they're re-usable; once a payload has been hauled into a desired orbit, the engine-fuel tank-embedded PVA 'tug' can detach and swiftly (e.g., in a matter of days) 'fly' to another use-point, there to commence transporting another payload to any destination-of-choice.]

Space-Based Power Beaming. However compelling greatly-enhanced orbit-to-orbit space transportation may be, the beaming of power across space to other space platforms and from space to use-points on/near the Earth's surface may be of greater long-term significance. Transportation from LEO to higher Earth orbits currently imposes costs of known-&-large magnitude, thus making the 'space tug' technology-set of urgent interest. However, the ability to place beamed power where-&-when you want it, in whatever quantities and for whatever durations you may need it, may be of far greater long-term importance. Therefore, the attention – and programmatic emphasis – given to realization of power-beaming *across* and *from* space by thoughtful U.S. decision-makers may not be less than that bestowed on creation and initial use of megawatt-class, in-space solar PVA power supplies.

Lunar Materials Exploitation. Every undergraduate student of orbital mechanics understands that every orbit in cislunar space is 'energetically cheaper' to access from the surface of the Moon than it is from the Earth's surface – and that most such orbits (including those at geosynchronous distance) are 'cheaper' by an order-of-magnitude. Thus, if abundant lunar materials – notably structural metals such as Mg, Al, Ti and Fe, as well as photovoltaic ones such as Si – could be sourced to space manufacturing points in high orbits, the unit cost of systems in such space locations could be expected to undergo comparable, i.e., order-of-magnitude, cost-decreases. Any rational long-term U.S. program to enhance America's posture as a spacefaring nation thus will necessarily include a lunar materials exploitation component – and civilian space power efforts can be expected to benefit correspondingly.

Exemplary Systems, Near And Far. We offer examples of two 'flavors' of space-base power-beaming stations and associated system architectures, one that might be implemented quite soon and an other that might be an example of a mature technology, a third-century later. [Both of these examples are illustrative mostly of how particular technology-choices might be integrated; many other possibilities exist, and some ones quite different from those given here might be far superior to present ones in particular situations.] There are actually significant, *qualitative* differences between these two applications, both in the economics and in the technologies employed. Basic economic disadvantages of early-time systems are highlighted below. With respect to technologies and architectures, the early-time requirement for each station to be very inexpensive requires it to have a small main beam projection aperture, and thus demands proximity of all such space power-stations to Earthside customer receivers. Such deployments in LEO put such stations in Earth-shadow perhaps a third of their total lifetime (in which condition they obviously can't source power-beams), and also give them intrinsically inferior 'reach' to customer antennae located far from directly beneath them (so that their enforced 'absenteeism' from load-servicing duties is relatively large), both as compared to stations positioned in orbital altitudes at ≥1 Earth-radius.

Near-Term. We first consider power-beam servicing of ~10^2 fixed-site customers, each of whom have battery-charging type loads of the order of 10 kW which need to be 'hit' with beams a few times each day for ~10 MJ energy-deliveries, basically at times-of-convenience. [These customer-loads might be essential electrical equipment in obscure locations, or they might be exotic electric vehicles parked far from recharging-points, or…]

The early-technology space power-stations sourcing the ~20 kW beams of interest might be ones carrying ~50 kW of thin-film amorphous silicon-on-film PVA of 12% conversion efficiency and 2 W/gm mass-efficiency (the PVA implemented in this already-demonstrated technology having a total area of ~300 square meters, e.g., a 15x20 meter rectangle). The ~30 kW of waste heat generated during coherent radiation generation in present-generation diode-banks and optical fiber-laser are spread back into the film of the PVA via passive conduction-modules, with the entire assembly having a mass of 40 kg, or ~1.2 We/gm. [We note that 2.2 We/gm PVAs are being prepared for in-space testing at present.] The fiber-bundle carrying the coherent radiative power from the PVA-centered assembly is interfaced with a projection lensette positioned at the focal point of a 2-meter diffraction-limited mirror serving as the main beam-projecting aperture, which then directs the beam Earthward towards one or another of the customer receivers, also of 2 meter aperture (but having no optical-quality requirements). The total spacecraft mass is ~80 kg, and 250 such craft are launched by a 'heavy' version of an EELV (at a cost of ~$90 M).

Deployed in mid-latitude orbits of ~700 km altitude, this IRIDIUM-like spacecraft constellation has the high-population-density portions of the Earth visible to its at least four of its beam-projectors at all times. Roughly 25%, or 62, of these first-generation power-stations, are servicing customer-load at any given time; the rest are over oceans, deserts or other load-poor regions, or else are in Earth-shadow. This constellation of small, first-generation in-space power-stations thus is sourcing, in the time-average, 1.25 MW of power-beams generating an aggregate of 0.62 MWe of power for its customer community, which is assumed to be paying ~$3/MJe, or ~$11/kWe-hr for the electrical energy/power so delivered; thus, ~$6.8 K/hour, or ~$65 M/year, of gross revenue is being realized.

In order for a 30% ROI to be sustained by such operation of such a constellation, the Earthside cost of the spacecraft in the constellation must be no more than ~$90 M, even if Earthside operating costs (system control, account management, etc.) is assumed to be spread over several such constellations. This constellation-build cost demands a spacecraft manufacturing cost averaging ~$360 K. Spacecraft of considerably greater complexity were offered to the DoD in multi-thousand quantities for unit costs ~$400 K a dozen years ago, so that these seemingly very low unit costs certainly aren't out-of-the-question. However, the low manufacturing cost-ceiling aptly illustrates the challenges posed by the high ROIs demanded of innovators bidding for venture capital – and the crucial importance of relatively low costs for space-launch services. Alternately, it may be taken to illustrate the importance of identifying and successfully soliciting patronage by relatively cost-insensitive customers for electrical power beamed from space; e.g., a customer-set willing to pay even 2X more – $22/kWe-hr – would render feasible a spacecraft cost of ~$1 M, higher on a per-pound basis than that of the spacecraft-sans-telecommunications-payload of the IRIDIUM constellation.

Far-Term. We next consider power-beam servicing of 150,000,000 mobile loads averaging 10 kWe, each of which needs to be serviced twice daily to provide energy to be used over transport-intervals 1-3x10^3 seconds (i.e., during the daily commute-intervals, in their hybrid fuel-electric personal transportation vehicles), so that 10-30 MJe of total energy must be provided to each vehicle within an 24-hour interval, across a continent the scale of the U.S.A. or Europe, i.e., within a ~10^7 km^2 area. [There are 130,000,000 personal automobiles currently licensed in the U.S.]

The then-mature technology servicing this customer-set is represented in a constellation of 1000 power-stations at geosynchronous distance, each a nominal 2 GW power-beam projection capability, partitioned into mostly 20 kW beamlets (but spanning the range of 2 kW to 20 MW), and employing 3 main projection apertures of 300 meters diameter and 3 km focal-length. The projected beams in the near-infrared spectrum (e.g., $\lambda \sim 0.8$ μm) have an edge-thickness of ~30 cm on Earthside receivers.

Each such station is assumed to be base-loaded, in that it services the third of the Earth's surface for which it appears well above the local horizon, and thus sees only modest diurnal load-cycling: when it isn't servicing real-time load, its beams are sourcing power to charge energy-storage modules (e.g., secondary batteries) of both stationary and mobile loads, e.g., in homes/businesses and vehicles. Only a modest fraction of its capacity will be employed to service the vehicular load of present interest.

For servicing this geographically-dispersed vehicle load, each of the 1,000 stations directs 10,000 beams with average powers of 20 kWo each toward receivers on the roofs of currently-parked vehicles, this aggregating to a commitment of 10% of its total capacity, most of which continues to service real-time load. The mean dwell-time of each such beam on a vehicle being 'fueled' is 2000 seconds, during which time an average of 17 MJ of electrical energy is delivered into the vehicle's secondary battery. Each 20 kWo beam thus is capable of 're-fueling' ~45 vehicles during an 24-hour mobile-load charging cycle, though the actual mean number of such loads to be so serviced is only 15; the ~3X margin is devoted to peak load-management capability, real-time servicing of mobile vehicular load, dispatching around local meteorological outage-intervals, etc. Unused beam-time naturally is re-directed to 'spot' and 'salvage use' loads, as well as to loads serviced by the other 90% of each station's capacity. This reference constellation of 1000 stations thus would be capable of servicing all of North America a few decades hence.

Each of these 2 GW beam-power – 5 GWe PVA – stations has a mass of 1500 tonnes, most of which is devoted to 4 W/gm advanced solar PVA. Over 95% of the station's total mass – e.g., the entire PVA – was manufactured in high orbit from Al, Ti and Si shipped from robotic processing-sites on the lunar surface at a total unit mass cost (~$1/gm) averaging one-tenth of the present cost of launching the same mass into LEO; the ~3% of total station mass which was sourced from Earthside – mostly pre-integrated high-precision (electro-)optics, optical fibers, switched laser diode modules and control plant – was launched to LEO and space-tug-transported to geosynchronous orbit at only a modest cost-premium over its LEO-launch cost. Thus, the assembly-line-based manufacturing cost (including Earthside-sourced components and sub-systems) of each such station is estimated to be only $2 B (2003 $) – $1/W of power-beam output capacity – and is dominated primarily by the as-delivered cost of the lunar materials required for manufacturing the ~2,000 hectare-area (i.e., ~20 km^2) PVA of 1200 tonnes mass, and secondarily by amortization of the high-orbit robotic manufacturing facility that had produced it and its fellows over the preceding decade.

Each of these stations delivers-to-load 1 GWe electric, continually, at an average billed price of $0.05 per kW-hr-delivered, thereby throwing off $50 K/hour, or ~$440 M/year, of gross revenue. Earthside operating costs per station average $140 M/year – this is a full-service utility operation, by now, with a plethora of overheads – so that its net revenue is $300 M annually, its gross margin is 68%, and it provides a utility-respectable 15% ROI, especially considering its projected 50-year service-life.

'Real World'-alities. There are several features of the 'real world' that impinge on the technology-intensive architecture and design of in-space power-beaming systems. Lacking any particular expertise in these, we merely invite our colleagues' consideration of them.

Economics. It's surpassingly difficult to overemphasize the significance of economic considerations when considering space-originated power-beaming. Only if servicing an intrinsically cost-insensitive customer can such considerations be ignored – but perilously so, as such customers are also notoriously fickle, and their custom is subject to all manner of interference, telling fractions of which are either invisible or unpredictable. Scrupulously respecting the economic realities is a *sine qua non* for all attempts to address markets in the real world – most particularly, the really large-scale ones. In particular, adapting to non-market practices in the U.S.A. is a time-tested recipe for creating a 'bonsai enterprise': it may be quite pretty from some perspectives, but it'll assuredly always be small (certainly, relative to its genetic potential).

Competition. As already noted above, no seller really likes to have competition appear in his/her markets. It's therefore preferable, to the greatest extent feasible, to have space-sourced beamed power initially serve markets that are not merely under-served, but entirely non-serviced, by existing suppliers. There are many economically well-positioned customers who may surprise both the energy punditry and themselves by eagerly congregating to constitute such markets for spacetime-agile, on-demand beamed power from space, just as there were many people who surprised most everyone other than Craig McCaw by swiftly becoming the mass-market for mobile telephone service, barely a dozen years ago. Everyone – notably including traditional wireline telephone companies who happily sold call-completing services for communications originated on cellular phones – benefited from the resulting intensified demand for telephony services (and all of the ones who adapted aptly to cellular telephony's advent continue to prosper).

Regulation. As we noted above, the best that can be hoped for with respect to governmental regulation of space-originated beamed power is rationality and competition-neutrality. However, these ideals are seldom, if ever, attained in the real world. Intelligent students of government regulatory practices who are involved in space power-beaming enterprises will interact with non-idealities accordingly. To be sure, there's genuine ground-for-hope, as the history-to-date of the Internet eloquently attests: if a technology is sufficiently novel and *also* sufficiently promising, virtually all components of the government bureaucracy have real difficulties in "getting their arms around it," and the more perceptive political leaders will actively harry-&-delay these stultification processes.

Juridical Hazards. The *de facto* unwillingness of the American generators of statutes and regulations – legislators and bureaucrats who nominally implement their instructions-in-law – to draw truly 'bright lines' between licit and illicit behaviors is the meat-&-drink of the more 'creative' portions of the tort bar. It's manifestly in the self-interest of those aiming to make power-beams pervasive in society to see to it that they "first do no harm," moreover "beyond the shadow of a doubt." As we've noted elsewhere, technological means for assuring everyone's physical safety relative to all aspects of power-beaming with almost arbitrarily-great reliability are not only already available but are generally of very low cost. Exercising such means in all respects confers self-evident benefits, and doing so is a defining feature of any intelligent power-beaming entrepreneur.

A Way Forward. We now sketch one possible set-of-tracks for moving from the present-day situation to one in which space-originated power-beaming is fully developed for civil purposes. We have no illusions that these are tracks that will actually be followed with any significant likelihood. They are offered only as representative possibilities.

Identification Of Markets. Any realistic business plan – a *sine qua non* for any private business initiative of the type that we posit will be necessary to bring civilian-purposes power-beaming into meaningful existence – will have a very clear-sighted view of its customers: who they will be as a function of time and business development, as well as why they'll more-or-less reliably purchase The Product, in what quantities, willingly paying what price(s) and with what price-demand 'elasticity.'

The USG 'Salvage' Market. We suggest that the single-most-likely initial customer-base will be the "cast-offs" from the U.S. Government's space-based power-beaming programs, which we posit will come into existence in the relatively near-term, in any event. Just as the more far-sighted commercial imagery-from-space companies have very recently gained a toehold – if not yet a full foot-hold – with respect to the U.S. Government's acquisition of imagery from space for somewhat-less-than-absolutely-vital National purposes, so we suggest that, just like the Brothers Grimm's 'Old Woman Who Lived In A Shoe,' the Government will come to have more of its "children" clamoring for power beamed from space than it really wants to service with its own, Government-owned space power-stations. In such circumstances, we confidently predict that at least some entrepreneurs will be able to find at least one very well-heeled, long-term "anchor tenant" for the outputs of their brand-new, Government systems-derived, albeit privately-owned space systems, just as reborn IRIDIUM has done for global cellular telephony-from-space (with DoD as the *de jure* anchor tenant) and as Ikonos and QuickBird have done for high-resolution ground-imagery-from-space (with NIMA as the *de facto* anchor tenant).

As a specific example of such 'children,' we note that American infantrymen going into forward areas already routinely carry <u>much</u> more than 10 pounds of one-time (i.e., primary') batteries with which to operate the various electricity-hungry equipments that so famously turbo-charge their capabilities as "21st century land-warriors." The Bad News for them – and the potential Good News for space-originated power-beaming – is that the *really* big power- and energy-demands of ever-more-modern individual-warrior combat-support technologies are yet to crest, while the large gains in primary battery energy-to-mass-enhancement technologies are already in-hand. Thus, within the next decade, the demand for on-the-battlefield electrical power for the 'dismounted' American land-warrior will soar, and the primary-battery technology's 'answer' to this demand will be literally back-breaking. Given the characteristic American way of doing things, 'Something New-&-Surprising' then will happen – and it just could be the unexpectedly rapid-&-widespread advent of from-space beamed power to myriad kilowatt-scale use-points: dismounted American land-warriors occasionally deploying their beamed-power 'umbrellas' for recharging reasonable-sized secondary batteries, in lieu of toting huge primary battery-packs into action like 21st century pack-mules.

Several other examples of quite different characters might be given of Government-customer demands that seem likely to come into existence during the coming decade in significant quantities, ones in which the Government might be somewhat reticent regarding details of power use-after-reception but not disablingly so with respect to providing to a reasonably-discreet commercial supplier in a just-in-time manner the spacetime loci of beamed-power-for-sale delivery-points.

Initial Non-Government Markets. As we've already noted above, a non-trivial fraction of American motorists will go out and buy beamed power receiving-units for their automobiles, just for peace-of-mind with respect to never having a truly-dead battery somewhere, somewhere. This is another aspect of the same basic market (of quite impressive scale) as is already known-to-exist for emergency-use-only cellular telephones – except that these power-beam-receiving units likely would get plenty of use on camping-&-boating expeditions – and even weekend outings – which could then involve high-luminance TV, abundant electric lighting, etc., initially, at least, for the sheer novelty of it all.

In any case, carefully-&-objectively establishing beforehand that a market of appropriate magnitude *and* price-willingness will reliably and timely arise is a 'no brain-er' requirement for every stage of power-beaming-from-space. [The whitened bones of the first IRIDIUM Consortium lie alongside the Yellow Brick Road to caution those who might be tempted to skip this admittedly-tedious step.]

Initial Technologies Selection. Picking the technologies to employ in the initial implementation of a space-originated power-beaming system is especially easy: one chooses those that exist and are known-to-work, in preference to all other possibilities. Indeed, the risk premium on all flavors of private capital of the requisite magnitudes likely would be forbiddingly large, if all but a very small number of low-risk technologies weren't already space-demonstrated – perhaps in other, quite unrelated applications – before commencing to create the first commercial space-based power-beaming system.

To be sure, initial commercial implementations might be quite different from grand, GW-scale ones based at geosynchronous distances from Earthside users. For example, a Government power-beaming system developing many of the key enabling technologies for follow-on commercial systems might be a modest-sized constellation of (even sub-)MW-scale ones, and might be based in low Earth orbits – LEOs – perhaps ones having a Sun-synchronous character, and might employ single-meter-scale beam-projecting apertures to beam-service at any given moment a relative handful of stationary receivers. [Indeed, such systems might be used *per se* for initial commercial purposes.] Large apertures for long-range beam-projection to tiny Earthside receivers may not come from such Government systems at all, but rather might be 'imported' from other, unrelated Government systems, e.g., high-performance imaging ones.

The bottom line in these respects is that development-&-demonstration of space technologies is an amazingly expensive and time-consuming business – at least as all elements of the American Government have been doing it in recent decades – and attempts to 'prove the Government's stupid' in this area should be selected-for-execution very carefully. Yes, a few privately-funded attempts to revolutionize space-based communications and imagery apparently have more-or-less succeeded, but many others – including nearly all of those in space-launch – have failed quite abysmally. Therefore, picking-&-choosing carefully among *already-demonstrated-to-work* technologies – ancient and 'clunky' though some of them may be – likely is the better part of programmatic wisdom in any youthful space-based power-beaming enterprise. Admittedly, this puts the entire enterprise in series with genetically-related Government undertakings of presently-uncertain advent – but the genuine alternatives are remarkably few.

Capital Sources And Scales. In the present era, capital is raised in the global private equity markets for single new technology-intensive enterprises in the amounts of tens of millions of dollars of the order of a hundred times each year, and it's raised in quantities of hundreds of megabucks for such purposes a few dozen times per decade. However, single-purpose chunks of capital devoted to novel technological undertakings in the billions of dollars range are mustered only about once per decade, cellular and satellite telephony being the two recent examples. It's therefore eminently appropriate to keep in mind the exponential rareness of really big amounts of private capital going to any single purpose when doing the economic and technology 'architecture' work on any space-originated power-beaming scheme. The truly winning approaches will be distinguished, we suggest, by great cleverness and considerable daring in minimizing capital requirements while still penetrating into really large-scale power markets in timely and reliable manners. Specifically, their buy-in cost will be at most $1 B.

Powerfully – both strongly and cleverly – leveraging prior investment by government, as we've suggested above in a little detail, may well be necessary for programmatic success, but it'll likely be far from sufficient. [If opportunities are seized when they're still immature, the path to success will be arduous and fraught with peril; if instead one waits until they're fully matured, one may not only wait for a very long time, but one's competitors then will be numerous, for the enormous marketplace incentives offered for novel success in servicing the multi-*trillion*-dollar-per-year global market for electricity a few decades into the 21st century will be manifest to all.]

Space-Launch Market-Leveraging. Space-launch currently enjoys the romance that aviation enjoyed in the first half-century of its existence: people threw capital, effort, talent – indeed, the full spectrum of human-accessible resources, including lots of what Keynes famously labeled as "animal spirits" – at aviation unrelentingly for the first several decades after the flights at Kitty Hawk, considerably (indeed, often *far*) out of proportion to rational risk-reward expectations. The concept of air flight and then air transport – of "slipping the surly bonds of Earth", if only transiently and incompletely – was so powerful that otherwise-rational folks invested in its realization and elaboration at very small risk-discounted rates-of-return – and they continue to do so. [Indeed, as Warren Buffett – one of the most canny large-scale capitalists of the past several decades – is reported to have remarked ruefully to his stockholders recently about the unhappy history of a large investment he'd made in civil air transportation, "You would have been much better served if I'd spent that evening {that he'd made the purchase of a large block of stock in a famous passenger airline company} in a bar. I'm now a recovering aero-holic."]

Many private enterprises have been re-tracing aviation history in the set of space-focused businesses over the past third-century, and in no portion of this sector as intensively as that of getting other people's payloads delivered into low Earth orbit (LEO) in exchange for services-payments roughly equivalent to the payload's weight in gold. [Very importantly, only the high-tech portions – e.g., specialty electronics, electrooptics, etc. – of typical payloads-in-space have "costs to create on the ground" which are comparable to the traditional ~$10/gm cost of getting it launched into LEO; everything else that's space-launched – structures, tankage, consumables such as propellants, etc. – has a delivered-into-space cost completely dominated by space-launch costs themselves.] This trend shows no signs of abating anytime soon – in spite of very many bankruptcies-&-liquidations and often-huge losses in stockholder equity in large space-launch concerns that are still in business – and the already-cited history of aviation suggests that this particular great techno-potlatch will continue for a few decades more.

This space-*launch* 'peculiarity' poses an attractive opportunity of huge magnitude to all space-*going* enterprises, including space-originated power-beaming ones, for it indicates that their equipments, consumables, etc. will be transported into space at considerably less than it would cost them in a fully-rational marketplace: basically, suppliers of space-launch services will continue to 'contribute' substantially to their businesses, for nothing in return other than the 'privilege of serving.' In particular, the current 'glut' of space-launch services that has driven prices to historic lows likely will continue into the second decade of this century, for both individual and corporate hopes die hard, pride of both types is hard to swallow, and lots of new romance-captivated competitors will continue to appear to snatch marginal customers and deprive the 'majors' of the business of any real pricing power.

Until-&-unless lunar-derived materials become abundant – i.e., inexpensive – in at least higher Earth orbits – this plenitude of space-launch services will be a great programmatic advantage to expansion of space-originated power-beaming. Leveraging it most effectively can be expected to be one of the key features distinguishing the most successful enterprises in this sector from their competitors.

Initial Deployments And Operations; Importance Of Anchor Tenant(s)And 'Salvage" Buyer(s). The effective cost-of-capital to new enterprises that have yet to attain positive cash-flow is extraordinarily high, for the risk to investment capital is exceptionally large in this phase of any business and thus the risk-discount premium on the demanded rate-of-return is correspondingly huge. It's therefore crucial for any business to minimize the time-interval between putting large amount of capital at risk and that at which customers commence paying for at least the ongoing expenses of the enterprise, i.e., attainment of positive cash flow. [Opponents of civilian nuclear power generation realized this far more effectively than did proponents, and thereby succeeded in annihilating utility-corporate interest in nuclear power plants by creatively employing judicial-regulatory processes to drive up the CWIC – costs while in construction – component of the TUEC of nuclear power to rather uncompetitive levels from initially highly competitive ones. After most of the thereby-burdened capital structure of the American nuclear power industry has been written-down over the past decade, nuclear-generated electricity 'suddenly' has been extremely competitive economically – once again.]

One of the most widely-applicable gambits for attaining relatively early to positive cash-flow – and, equally importantly, to keep the risk-discount to comparatively modest levels prior to that time – is to have contracted with a credible 'anchor tenant' for sale of a major fraction of one's initial stream of goods/services, as soon as they become available. If, as we expect, the Government has already gone into the space-originated power-beaming 'business' for its own, possibly-rather-limited purposes, then it's natural to bid for its custom, either for maintenance of existing supply of beamed-energy or for expansion, either for more-of-the-same or for new applications enabled by lower price-structures.

The recent IRIDIUM experience offers a creative version of inducing the Government to expand its global communications 'buy', albeit in a not-altogether-exemplary manner. Presented with an opportunity to buy a huge block of capacity a unique world-wide cellular telephony business then struggling to stay afloat (after completely writing-off a privately-funded debt structure of historic magnitude, in excess of $3 B), the Government signed up as the anchor tenant, making an annual payment basically sufficient to pay the (remarkably modest) operating expenses of the entire business in exchange for take-or-pay use of several tens of percent of the IRIDIUM system's capacity, leaving the enterprise the freedom to sell the rest of the system's capacity for profit. Whether this will be an enduring example of governmental anchor-tenancy of private enterprise in space is currently an open question – the issue of replacing the IRIDIUM constellation of satellites has yet to be squarely addressed, let alone resolved – but it illustrates the key role that government can play in getting an enterprise "off the ground" in a mutually-beneficial fashion.

Of comparable importance to anchor tenancy for any young enterprise that produces either goods or services at an innately fixed rate – whether it be donuts, cellular telephony services or space-originated power-beams – is that of one or more "salvage use" buyers, ones who are always willing to take excess product at a price that at least equals the production cost of that product-fraction. Generally, if either a good-sized anchor tenant *or* a salvage buyer exists, an enterprise can 'buy down' the risk premium on the capital it needs to get underway. The Government seems a plausible candidate for anchor tenancy, in that it may well have a number of loads already in existence at Time-Zero – on the Earth's surface, in space, or wherever – that require power beamed to each of them "every so often," but perhaps within fairly wide ranges of time, power, etc. Providing power-beaming services to these loads then generates revenues from the anchor tenant from Day One of the service's operation. However, this customer community is likely to be quite price-inelastic: "We need just this much service, and we'll pay-as-contracted for it; however, we don't need any more, however, at any price, thank you."

Private-sector operations seem more plausible 'salvage-use customers,' in that there are many remotely-located work-sites generating electricity at quite high TUECs and at substantial time-averaged power levels, using tediously-imported fuel and machinery, who likely would be willing to 'accept' energy beamed to them, most any time and at most any power-level, and to pay for this electricity-delivery service at a reasonably large fraction of the thereby-avoided costs. This globally-large set of 'salvage-use customers' might generally demand 'turn-key servicing' – i.e., power-beam-driven electricity interfaced into their existing engine-driven generation plant so as to provide seamless, user-transparent energy/power-displacement service. However, as discussed above, the capital cost of Earthside equipment for reception of power-beamed energy can be expected to be a very small fraction of the TUEC of such energy, due to the generally-high intensity of the beamed energy and its corresponding high utilization of receiver-equipment, so that the unit capital cost of 'connecting' such load can be expected to be comparatively modest.

Space-originated power-beaming is likely to be at least as economically-peculiar as telephony and, indeed, nearly mass-market-software-like in its economics: its cost-at-the-margin of providing its product to its customer is asymptotically zero, and most all of its economic costs are those of the capital required to create and deploy its space-based physical plant, with a dab of cost-of-intellectual-capital involved in its system control and revenue-management structures. Thus, the servicing of either anchor tenants or salvage-use customers involves high gross margins, even though neither may involve initial prices greatly in excess of $1/kWe-hr of delivered electrical energy. Real business success, however, will depend on swiftly identifying – and signing up – customers for a sufficiently large fraction of the total product stream to throw off net revenues sufficient to finance rapid expansion, for there a five order-of-magnitude gap between likely initial scales-of-operation of commercial from-space power-beaming and the capacity of the global electricity-producing plant. As already noted, our present estimate is that sales at prices of ≥$10/kWe-hr will be required in initial phases of market penetration, in order to generate ROIs of the ~30% per annum levels noted above as likely-required ones.

<u>Beachhead Expansion Strategies; Importance Of Mobile Customers and 'Salvage' Loads</u>. Once cash-flow resoundingly positive, gross margins are looking like Microsoft's in its heyday, and the space-originated power-beaming enterprise's venture capitalists are beginning to smile – if not yet quite smirk – it's then reasonable to look for the next order-of-magnitude or two in total customer-load: what will it be, and why is it likely to be willing to bear the prices required to sustain a still-high-demanded ROI? From a self-evidently distant vantage-point, we suggest that the mobile user market may well have price elasticity of surprising range and total magnitude. We suspect that people of many different types and habits actually have appetites for side-effects-free electrical-equivalent energy and power while they're "on the move" that may surprise even them, until prospects of satisfying these appetites – likely for presently obscure purposes – immediately present. [The peculiarly unforecasted but quite explosive advent of mass-market cellular telephony again comes to mind in this respect – or mass-market geolocation, for an only slightly less dramatic albeit rather unheralded example.]

Thus, we predict that customers-on-the-move will constitute a huge market-in-the-aggregate for beamed power and that a surprisingly-large fraction of this market will be rather amazingly price-insensitive – willing to buy a megajoule of electrical energy for a dollar or more everyday or two, purely on impulse – provided that they can have it wherewhen they want it, with not much inconvenience that carrying and occasionally unfurling the familiar 10-inch-length umbrella-with-telescoping handle. Servicing an ever-larger – albeit ever-more-price-sensitive – portion of this mobile market may *by itself* provide a path-cum-superhighway into power-beamed electricity markets of all extant sizes.

Intermediating markets, especially large-scale 'salvage' ones, may be of very considerable importance. For instance, generation of hydrogen gas, either electrolytically or by water thermolysis, during non-peak-load intervals, may confer very considerable economic value, the more so if it potentiates the use of 'hybrid' fuel-powerbeam loads, e.g., advanced vehicular and single-residential power-plants using both gas-fed fuel-cells and powerbeam PVAs as 'prime movers'.

In any case, moving from the 10-100 MW scale that we estimate may well be the initial market-scale for space-originated power-beams into the ~10,000,000 MW one that we presume will characterize human electricity time-average demand several decades hence will require unceasing, deep-impact technological innovation in order to reduce prices by the ≥50-fold factor that we estimate actually separates specialty or premium markets for delivered-on-site electrical energy from mass-markets for baseload electrical power. Some of this price reduction will occur naturally, as demanded ROIs descend from those of novel, high-risk technologies and markets to technologically-mature modes of servicing mass-markets, but most all of the gain necessarily will come from technology, not economics. [The advent of the large-scale supply of lunar materials to construction sites for new in-space power-stations exemplifies a major, pertinent technological advance.]

Approach To The 'Natural Limits'. It's of at least passing intellectual interest to inquire as to the natural limits of space-sourced power. If it's superior in some notable respects to ground-sourced power – so that it can potentially grow to supply a substantial fraction of all electrical energy used by humankind, in spite of the entrenched, large-scale character of the competition – why can't it take over completely from all present modes of electricity supply, given the economies of scale and levels of technical (and political, and economic, and psychological, and…) maturity from which it'll presumably benefit, just a half-century hence?

We don't see any single most obvious reason as to why power beamed in the (near-) optical spectrum from space power-stations won't "sweep the board" sometime in the latter part of the 21st century (with a dutiful nod to Marchetti curves of the kinetics of penetrance of new primary energy technologies). We therefore suspect that limitations will be non-technical ones whose nature (and severity, and…) is comparatively obscure to us as technologists. One such prospect is governmental unwillingness to have all of the primary energy-supply eggs positioned in a single relatively-fragile in-space basket – an argument that admittedly resonates with us, and which indeed may find rather widespread sympathy. How beamed-power supply might be best integrated with "back-up" ground-based supplies presumably will depend crucially on the technologies selected, their spatial distribution, etc.

Our basic prediction, in the large-scale-surprise-free scenario, thus is for power-beams from space power-stations to come into exponentially more widespread use during the first half of the 21st century, and moreover for electricity from this source-type to become an ever-larger fraction of the total energy used by humankind for all purposes. We therefore expect that oxidation of fossil hydrocarbons for powering the prime movers of civilization may well recede 'naturally' – particularly as ever-growing challenges in extraction of diminishing supplies continually raise their true prices – without major governmental intervention in large-scale energy markets.

Conclusions. The prospect of space-originated power purposefully beamed to Earthside receivers for civil purposes likely will remain utterly becalmed into the foreseeable future – for the same basic reasons that bring us to the present juncture from Glaser's epochal proposals of a quarter-century ago – unless several fundamental changes-in-approach are made.   Our basic critique of the Glaser proposal is tridentate: [1] its initial scale was innately so huge that only state-sponsorship of historic magnitude could underwrite even its initial implementation; [2] it didn't exploit the many qualitative advantages of power beamed from space, e.g., that set deriving from the enormous agility in spacetime of myriad, commonly-sourced but differently-directed high-radiance beams, and thus didn't offer nearly all the added-value potentially available from large-scale power-beaming from space; [3] it depended critically on technological advances that haven't arrived (e.g., low-cost space launch) and didn't explicitly feature 'hooks' onto which to advantageously 'hang' potentially-pertinent technological advances that have occurred (e.g., thin-film photovoltaic converters, fiber optical technologies, GPS, GSN).

In the foregoing, speaking as professional technologists albeit as amateur economists, we've tried to sketch amendments to the Glaser proposal that appear to be both necessary and sufficient for power beamed from space power-stations to rise to great and lasting significance in human affairs, even during our lifetimes. These amendments call for neither technological nor economic miracles, relative to the present state-of-affairs: e.g., they posit only technologies that already exist at least in labs (generally featuring figures-of-merit within a few-fold of those already demonstrated in space), and <u>no</u> future improvements in costs of key enabling technologies (e.g., GDN-based telecommunications, GPS, space-launch, etc.).

In spite of overt governmental participation in the economic affairs of humankind to the extent of spending 35-70% of the GDP in the advanced economies, public bureaucracies in liberal democracies only very rarely undertake bold initiatives – ones involving major changes in the established order of doing things – including sourcing the energy to power entire civilizations, for fundamental reasons that are well-understood. Thus, if power beamed from space is to become widely available and extensively used, we believe that it'll be via basically private entrepreneurial initiatives, and thus will meet the fundamental criteria and prerequisites of all such initiatives, including comparatively modest initial scales and relatively high risk-discounted rates-of-return on investment during initial phases. However, the notional trajectories that we've sketched for development of large-scale space-originated powerbeaming admittedly are prone to the criticism that they feature large-scale governmental initiatives for initial technology demonstration and hand-off to the private sector; our basic rejoinder is that we rather confidently expect that these may be forthcoming *this* side of the indefinite future from the U.S. national security sector. Likewise, government "anchor tenancy" of initial privately-financed powerbeaming systems for exceptionally high-valued-added loads is also seen as pivotal although possibly not crucial; again, we see the U.S. national security sector as the single most likely such tenant.

Indeed, we suggest that space-based power-beaming involving relatively modest aggregate requirements from customers who are willing to pay handsomely for *electrical power-on-demand, delivered to their loads in a maximally convenient manner* – i.e., anywhere and anytime, at most any rate and for nearly any duration – will comprise the crucial initial market for beamed power, the *sine qua non* base from which expansion will inevitably and inexorably occur, perhaps even at extraordinary speed. □□he history of purposeful U.S. governmental support of the advent of American civil aviation via a well-articulated, reliably-implemented policy of handsome payments to private operators to carry mail-by-air comes effortlessly to mind in this context.] We have sketched some of the technological means by which near-term capabilities to service such quintessential 'spot' markets may be realized, attempting to demonstrate that such systems might be realized for total initial investment well within the private sector's scope and with a risk-return profile potentially appealing to private capital.

We suggest that the extant technological base is sufficiently mature that such efforts could commence servicing small-scale, specialized markets in this century's second decade, if serious, well-focused efforts were to commence today. If intelligently conducted thereafter, with all of the intrinsic advantages of space-originated beamed power leveraged unrelentingly, servicing of mass markets – involving dozens of GW of delivered electrical power – could be underway early in this century's second third, and a large fraction of the total human demand for electrical energy could be space-sourced by early in the second half of this century. Indeed, such inexpensive, conveniently-available electricity could become the principal 'flavor' of civilization's energy, well before this century's end.

The environment consequences of such a fundamental shift in energy sourcing could be large, especially if electricity were to increase its share of total energy supply, e.g., by deeply penetrating the mobile energy-use marketplaces, as we've suggested may well be feasible. Specifically, in the latter part of the 21^{st} century, hydrocarbon oxidation might become an energy source utilized only in small, niche-type applications, e.g., for back-up purposes, and the atmosphere-as-gaseous-sewer for civilization's great engine-sets then may become a quaint (if not altogether archaic) concept.

We therefore consider present U.S. Government interest in power-beaming from in-space power-stations – primarily for national security applications – to be a quite hopeful first-step in developing and performance-demonstrating the key enabling technologies. We anticipate that enlightened private-sector entrepreneurialism will pick up both the technologies and the then-established Government needs for powerbeam-servicing of assorted load-sets, and thereupon retrace the pertinent fractions of the recent histories of space-based telephony and Earth-imagery, perhaps even at a basic pace-of-advance not greatly slower than demonstrated by Global Digital Network – e.g., Internet and digitally-based telephony – developments over the past dozen years.

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[7] See, e.g., http://www.uni-solar.com/government_specialty.html.

[8] Aeschylus, "*Prometheus*".

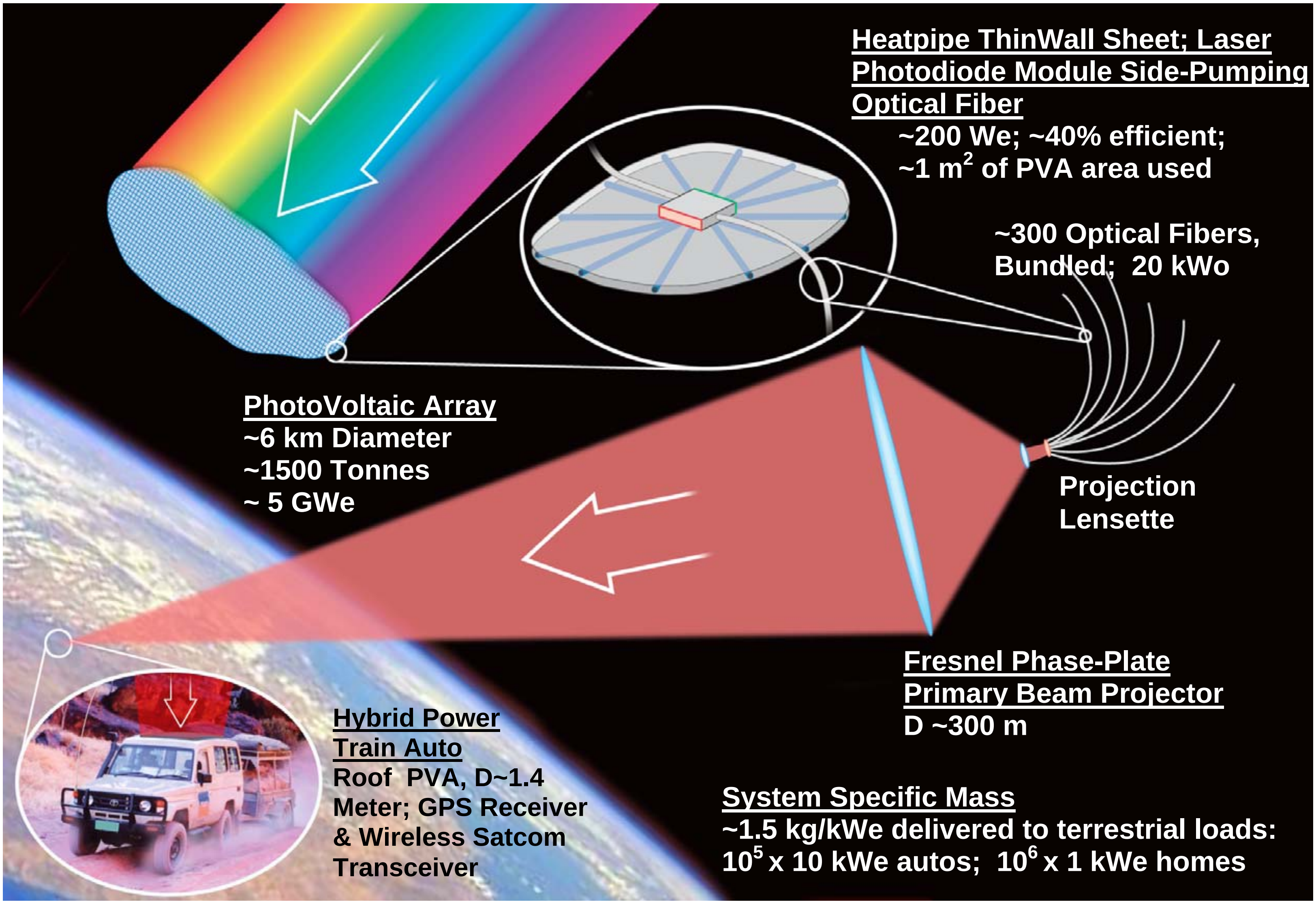
Heatpipe ThinWall Sheet; Laser Photodiode Module Side-Pumping Optical Fiber
~200 We; ~40% efficient;
~1 m2 of PVA area used
~300 Optical Fibers, Bundled; 20 kWo
PhotoVoltaic Array
~6 km Diameter
~1500 Tonnes
~ 5 GWe
Projection Lensette
Fresnel Phase-Plate Primary Beam Projector
D ~300 m
Hybrid Power Train Auto
Roof PVA, D~1.4 Meter; GPS Receiver & Wireless Satcom Transceiver
System Specific Mass
~1.5 kg/kWe delivered to terrestrial loads:
105 x 10 kWe autos; 106 x 1 kWe homes

FIGURE 1. Diagrammatic representation of the major modules of the type of space-based powerbeam-generating station discussed. The ultra-thin film amorphous silicon photovoltaic array (PVA) is covered on its back (contra-Sol) side by a grid of laser photodiodes netted together with fiber optic lines which are side-pumped by the photodiodes, using locally-sourced electrical power from the PVA. The heat dissipated by the photodiodes is sunk back into the PVA's underlying structure, which is water-loaded heatpipe implemented as a thinwalled-sheet structure. The coherent optical power-carrying optical fibers are bundled into sets of size corresponding to various scales of terrestrial loads, and their outputs directed Earthward from the station's focal plane through small (cm-scale) lensettes and thence through the shared main beam projection aperture ~3 km distant and on to the distant receiver-PVAs positioned on the Earth-based loads. These loads signal to the station's control computer as to their geolocation (using GPS receivers and the Global Digital Network) and what their instantaneous power requirements are, as well as providing status and safety-related datastreams (see main text).

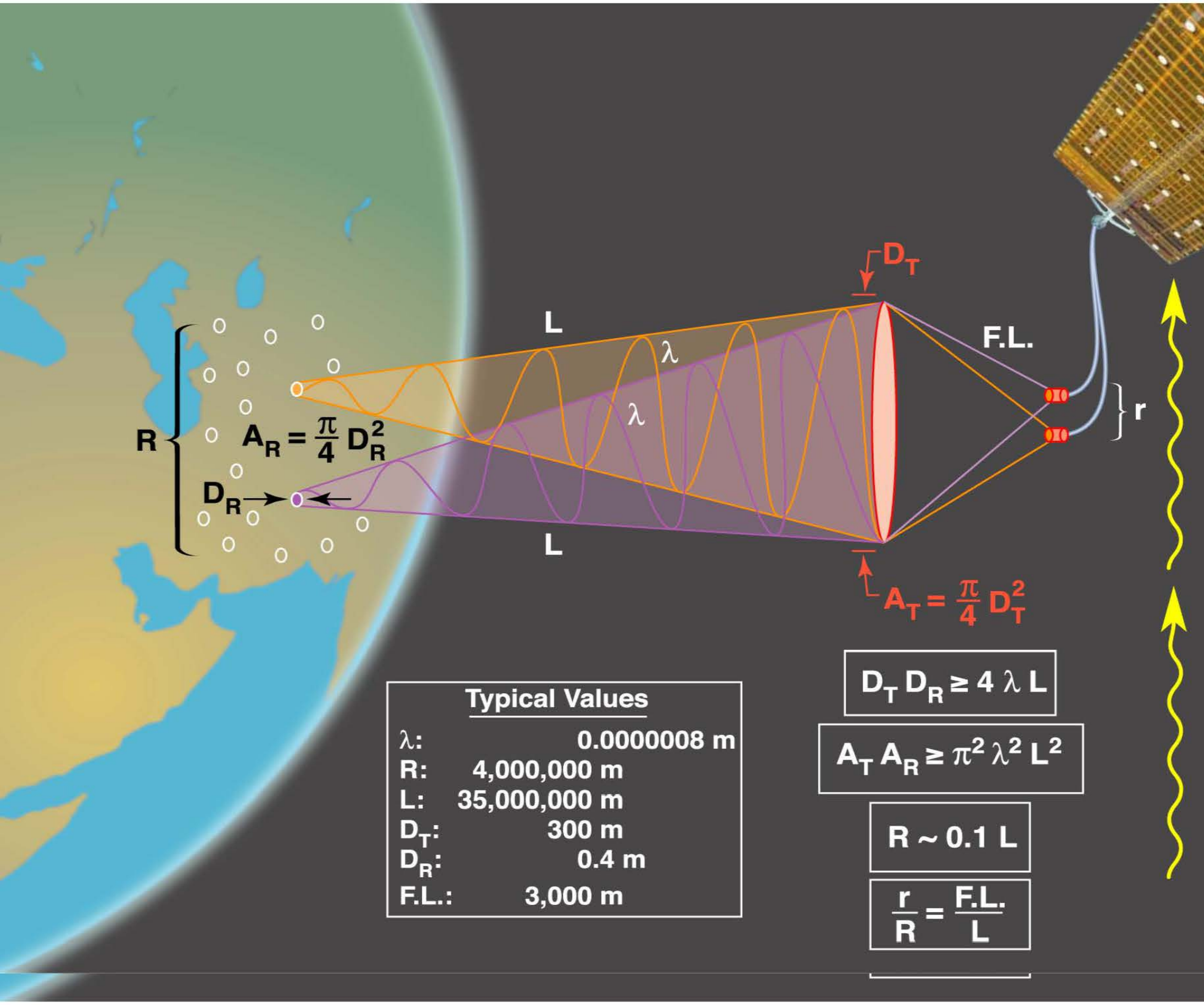
D_T
L
F.L.
λ
λ
r
R
A_R = π/4 D_R^2
D_R
L
A_T = π/4 D_T^2
Typical Values
λ: 0.0000008 m
R: 4,000,000 m
L: 35,000,000 m
D_T: 300 m
D_R: 0.4 m
F.L.: 3,000 m
D_T D_R ≥ 4 λ L
A_T A_R ≥ π^2 λ^2 L^2
R ~ 0.1 L
r/R = F.L./L

FIGURE 2. A diagrammatic sketch of a typical "mature technology" in-space power-beaming station, with key governing equations and an illustrative set of typical parameters indicated. The system is essentially a huge time-reversed telescope: a huge field-area of width R on the Earth's surface is demagnified into the station's focal plane of width r, but the focal-plane objects emit light *toward* the field objects (rather than the reverse, as occurs in astrometric use of telescopes). The use of a large in-space main beam-projection aperture and a short wavelength of the beamed radiation permit very small spot-diameters to be defined even at great distances; this corresponds to high resolving-power of a telescope. The beams of wavelength λ illuminating the receivers of minimum diameter D_R on the Earth's surface are emitted by optical fibers power-loaded by laser diode-pumping on the solar photovoltatic array (PVA) that connect into the station's beam-projecting region, and then pass through associated lensettes that fully illuminate the main projection aperture of diameter D_T located at the focal length distance F.L., which thin lens serves as the common transmitting aperture for all beams emitted by the power-station. The thereby-projected beams then propagate a distance L to respective Earthside receiving apertures.