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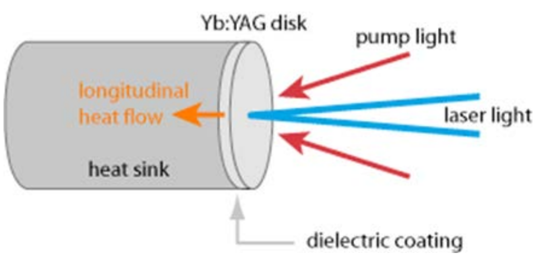
Solar Power Satellites for a Sustainable Industrial Future

By William Mook

The thin-disk laser is a high-power solid state laser developed in the 1990s at the University at Stuttgart, Germany by Adolph Giesen. The gain medium is a thin disk much smaller than the diameter of the laser beam. This geometry allows heat to be extracted through one of the sides while laser energy is efficiently extracted through the other with a minimum of beam distortion. The cooled end reflects both the pump energy and the laser energy. For this reason thin-disk lasers can be thought of as mirrors equipped with a gain medium and are sometimes called active mirrors for that reason.



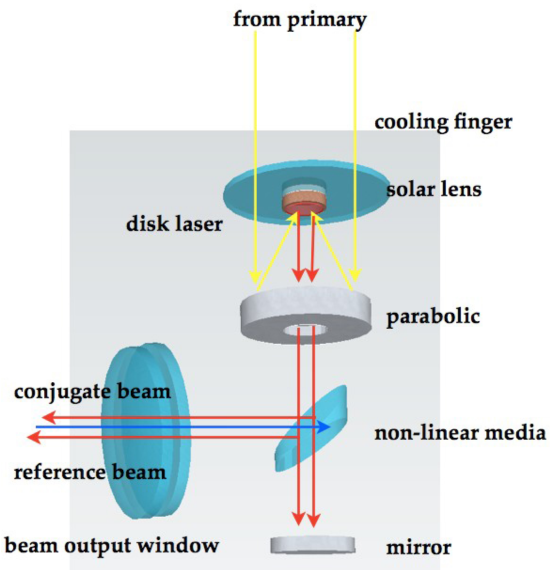
Conjugate optics are set up to recycle reflected pump light 16 times or more in what is known as a multi-pass system. In this way overall efficiency exceeds 80% near the wavelength of the laser's operation.

Multiple gain media layers permit the efficient conversion of solar radiant energy with an overall efficiency in excess of 55%. In this way a new sort of solar energy system may be contemplated, one that uses laser energy made directly from sunlight at high efficiency.

Laser energy created in this way when made to pass through a non-linear optical medium exposed to a reference beam from a power receiver creates a reliable link between generator and receiver. The reference beam interferes with the power beam so that a conjugate beam is produced that travels precisely to the receiver that originates the reference beam regardless of changes in orientation of the two systems. Furthermore, any object that traverses the power beam also intercepts the reference beam, cutting off transmission and thus acting as a safety fuse.

In this way a simple, safe, reliable, and robust space power system can be produced and launched at reasonable cost.

In the late 1950s, inflatable structures in tension were used for a variety of applications. Specific mass was less than 18 grams per square meter with life spans up to three years. Since that time, advances have reduced specific mass of very strong structures to 4 grams per square meter which remain rigid up to 30 years in space while optical quality has been vastly improved.

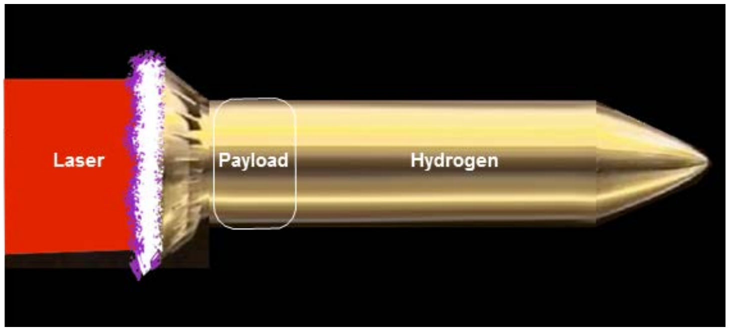


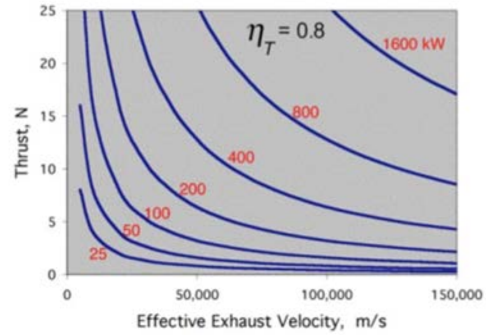
Using these ideas, I have designed a 6,000 meter diameter lenticular parabolic primary concentrator that focuses sunlight 1600x to a solar-pumped thin-disk laser equipped with a 6.6 meter diameter aperture to beam energy to two hundred 6.6 meter diameter receivers on Earth, simultaneously, over a distance of 40,000 km from geosynchronous orbit

This satellite, operating in a geostationary orbit, produces 18.7 billion watts of power delivering an average 90 MW of power continuously to 200 receivers anywhere visible to the satellite on Earth. Three such satellites spaced 120 degrees apart in this orbit are capable of delivering energy anywhere on Earth. At 8 cents per kWh the satellite produces $13.113 billion per year in revenue. Over 26 years at this price, each satellite earns $340.3 billion. At start up, this revenue stream is worth over $170 billion. A four-year program to develop the first satellite easily provides venture capital rates of return for early investors. The cost of a program to develop and orbit the first satellite could be as little as $1.28 billion and take four years. Each additional satellite is orbited at a cost as little as $0.63 billion.

Power Satellite Critical to Human Advance

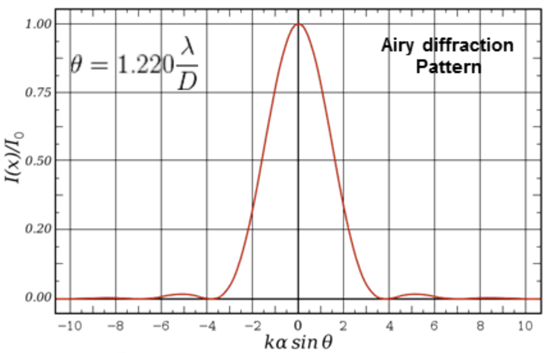
Achieving high living standards using off-world resources would reduce the impact of humanity on Earth's biosphere. Achieving space access for all requires that the present 9.02 TW grow to 45.10 TW. Maintaining a 9.5% economic growth rate to bring about this change quickly gives an 18-year window to achieve the increase described and scales the program. Using the satellites described here requires that we launch 2,400 satellites of this type in this period. This implies a launch rate of one satellite every 65 hours over this period. A fleet of seven vehicles with a 455-hour turn-around provides this capability. With launch center, fleet, supply chain for satellites, and replacement parts for launcher, there would be a $7 billion program cost with an $85 billion per year operating cost at the expected launch costs.

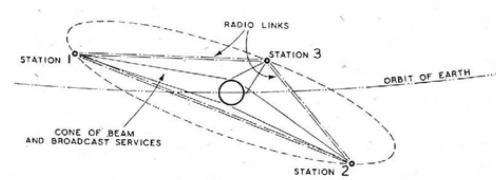




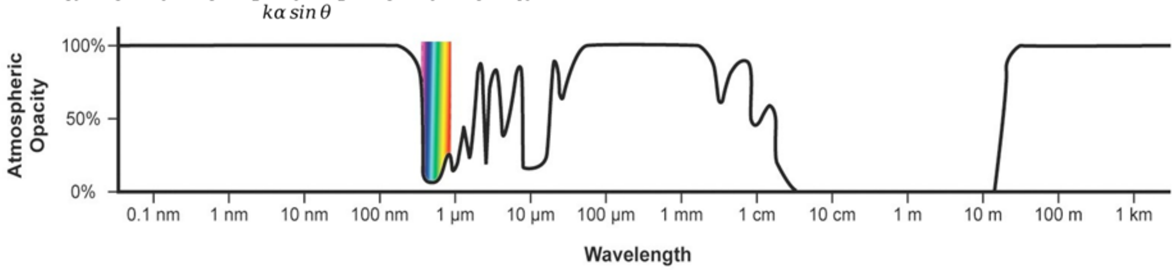
Laser Launch for Laser Power Satellite
Thrust vs. LSP at constant power (total efficiency eta = 0.8). AFRL and NASA researchers have attained 150,000 m/s exhaust speeds using ultra-violet laser beams and mixtures of hydrogen and helium gases. Four-wave mixing and efficient production of UV light on the multi-gigawatt scale are required to produce large, high-performance, laser-powered launchers.

Beaming Energy from Space





Geostationary Orbit

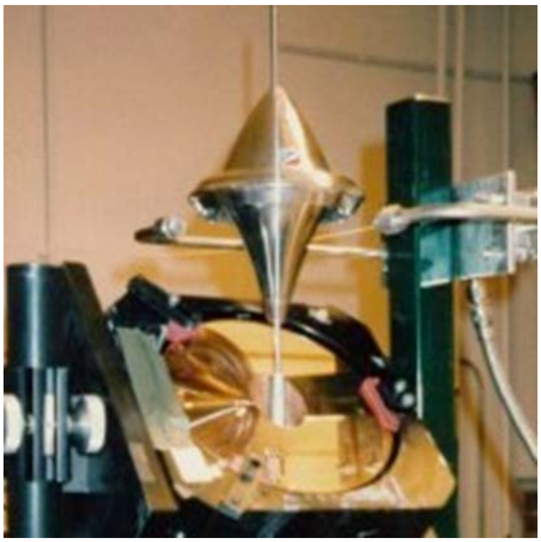


Short wavelength reduces mass on orbit. The Earth's atmosphere has sufficient clarity in the microwave, infrared, and visible portions of the spectrum to beam energy reliably from space. At a distance of 35,786 kilometers, the sizes of the transmitting and receiving apertures are fixed by the wavelength used. Using shorter wavelengths reduces aperture diameter and hence the size and mass of the satellite.

Geostationary Aperture Size and Mass

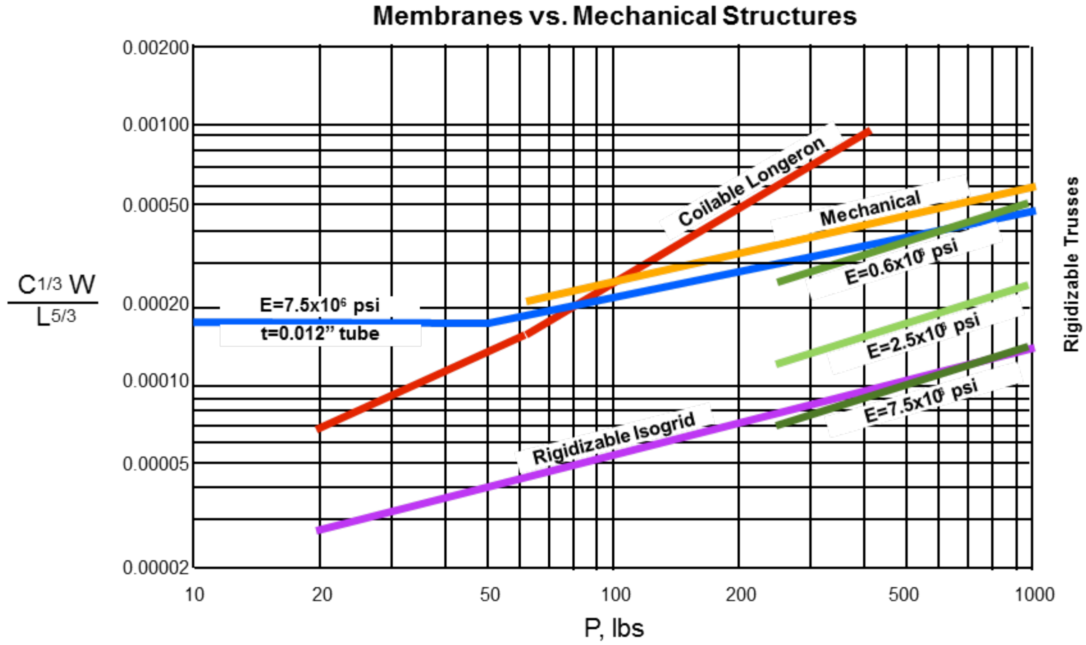
Wavelength	Aperture (meters)	Primary (meters)	Mass (tonnes)	GW	Type
100 cm	2,090 m	2090	27,446	2.8	Direct
10 μm	21 m	4200	887	10.1	Direct Concentrator
1 μm	6.6 m	6000	300	18.7	Indirect Concentrator
500 nm	4.9 m	9000	675	54.9	Indirect Concentrator

Low-Cost Laser Energy Used for Low-Cost Launch



Leik Myrabo and Franklin Mead at the Air Force Research Laboratory Propulsion Directorate proved it was possible to use laser energy to propel a spacecraft. Exhaust velocities in excess of 46 km/sec were achieved using hydrogen. A hydrogen-fueled spacecraft capable of attaining 9.2 km/sec exhaust velocity provides a means to attain orbit with a highly reusable single-stage launcher using minimum energy and power for a given payload mass, with the vehicle delivering 24.7% of its take off mass to low earth orbit, along with 12.0% structure fraction. A vehicle with 2,024.3 tonne take-off weight is capable of delivering 500.0 tonnes to orbit energizing 1,279.8 tonnes of liquid hydrogen with up to 140 GW of laser energy at peak acceleration.

Comparison of Mechanical and Inflatable Booms for Space Applications



Comparison of Mechanical and Inflatable Booms for Space Applications
C is the *column boundary coefficient*, **L** is the *column length*, **W** is the *weight*, **P** is the *load*. Industry standard 12-mil thick composite fabric and 7.5 MPSI modulus of elasticity were used throughout except where noted. Thin film structures have a mass of 1% or less of standard structures.

Lenticular Inflatable Parabolic Reflector

Echo 2 Communications Reflector

Complex membrane structures were flown in space 55 years ago and developed for terrestrial application 60 years ago. These structures massed 17.8 grams per square meter of surface area using 12-micron thick aluminum-coated off-the-shelf material. Today, 3.6-micron thick materials fabricated at a GBO film achieve 4.0 grams per square meter and less with improved optical and mechanical performance.

Cost of Energy vs. Economic Growth

Economics	**$/barrel**	**$/MJ**	**$/kWh**
	$250.00	24.4	$0.301
	$150.00	40.7	$0.181
	$100.00	61.0	$0.120
4% Decline	***$72.00***	***84.7***	***$0.087***
	$50.00	122.0	$0.060
0% Growth	***$36.00***	***169.4***	***$0.043***
	$25.00	244.0	$0.030
4.7% Growth	***$18.00***	***338.9***	***$0.022***
	$15.00	406.7	$0.018
9.5% Growth	***$9.00***	***677.8***	***$0.011***
	$5.00	1,220.0	$0.006
	$2.50	2,440.0	$0.003
	$1.50	4,066.7	$0.002
	$1.00	6,100.0	$0.001

The cost of primary energy determines the growth rate of an industrial economy. At present the world is undergoing a 4% decline each year in real terms because the cost of discovering and bringing to market a barrel of oil is at present $72. The cost of primary energy must be $36 per barrel or less to sustain economic activity. Historically, the inflation-adjusted cost of oil was $18 per barrel and this sustained an average growth rate of 4.8%. Large discoveries resulting in low-cost primary energy are associated throughout history with high rates of economic growth. Energy prices associated with double digit rates of growth were classified as “too cheap to meter” by Leo Strauss, AEC Chairman, in 1953.

Kardashev Scale

$$\left\{K = \frac{1}{10}\left(\frac{\log(P)}{\log(10)} - 6\right), p > 0\right\}$$

How Humanity Stacks Up

2012 AD	9.02 TW	K = 0.696
2089 AD	10.00 QW	K = 1.000 (at 9.5% growth)
2164 AD	10.00 QW	K = 1.000 (at 4.7% growth)
2342 AD	10^{26} Watts	K = 2.000 (at 9.5% growth)
2665 AD	10^{26} Watts	K = 2.000 (at 4.7% growth)

Rapid Growth Reduces Environmental Impact

2012	7.057 billion	$ 11,506/year	1,278 Watts
2089	18.892 billion	$4,763,921/year	529,324 Watts
2164	58.396 billion	$1,541,201/year	171,244 Watts

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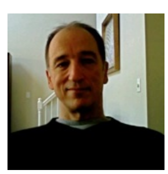
About William Mook, PE: Bill Mook has innovative science and technology ideas for more subjects than anyone you have met. Those subjects range from the rocket history to sustained industrial futures in Space. He approaches his subjects from a mix of engineering knowledge through financial analysis and imbeds them in philosophical rationale as a foundation to support his statement *"The heavens will open to humanity."* He has had management and fiscal responsibility on Fortune 500 R&D teams and provided analytic work for the White House during both the Clinton and Bush Administrations. He holds patents for ground-breaking product developments. He is a member of the Board of Editors for *The Journal of Space Philosophy*.



Editors' Postscript: We encourage readers to find the published work of Bill Mook on the Internet. His analyses of Earth and Space energy and Space resources are solid evidence within *the Law of Space Abundance* that the Kepler Space Institute formulated in 2009. ***Bob Krone and Gordon Arthur*.**