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EFFICIENT SPACE PROPULSION ENGINES BASED ON LASER ABLATION

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## **Efficient Space Propulsion Engines Based on Laser Ablation**

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### **ABSTRACT**

Recent results<sup>1</sup> have shown laser momentum transfer coefficients  $C_m$  as large as 700 dyne-s/J from visible and near-infrared laser pulses with heterogeneous targets. Using inexpensive target materials, it is now possible to deliver a 1-tonne satellite from LEO to GEO in 21 days using a 10-kW onboard laser ablation engine, or to maintain several 1-tonne GEO satellites on station from Earth indefinitely using a laser with 100-W average power.

### **Introduction**

In Laser Impulse Space Propulsion (LISP), a repetitively pulsed laser transmits a high-quality beam to an ablation disk mounted on a space vehicle. This disk causes the vehicle to propel itself by reaction forces arising from the ablation jet produced when the laser beam strikes its surface. The space vehicle's ablation disk is the "fuel" for the mission, and is completely and efficiently expended. The correct laser parameters to heat the ablation surface to the temperature needed to form an efficient jet are achieved by appropriately choosing laser wavelength, pulse energy, pulse duration and target illumination area. For very large range between source and disk, gas lenses<sup>2</sup> will play a role in achieving the required diameter. The laser may be mounted on the space vehicle rather than being remote, in which case fiber optics suffice for beam delivery.

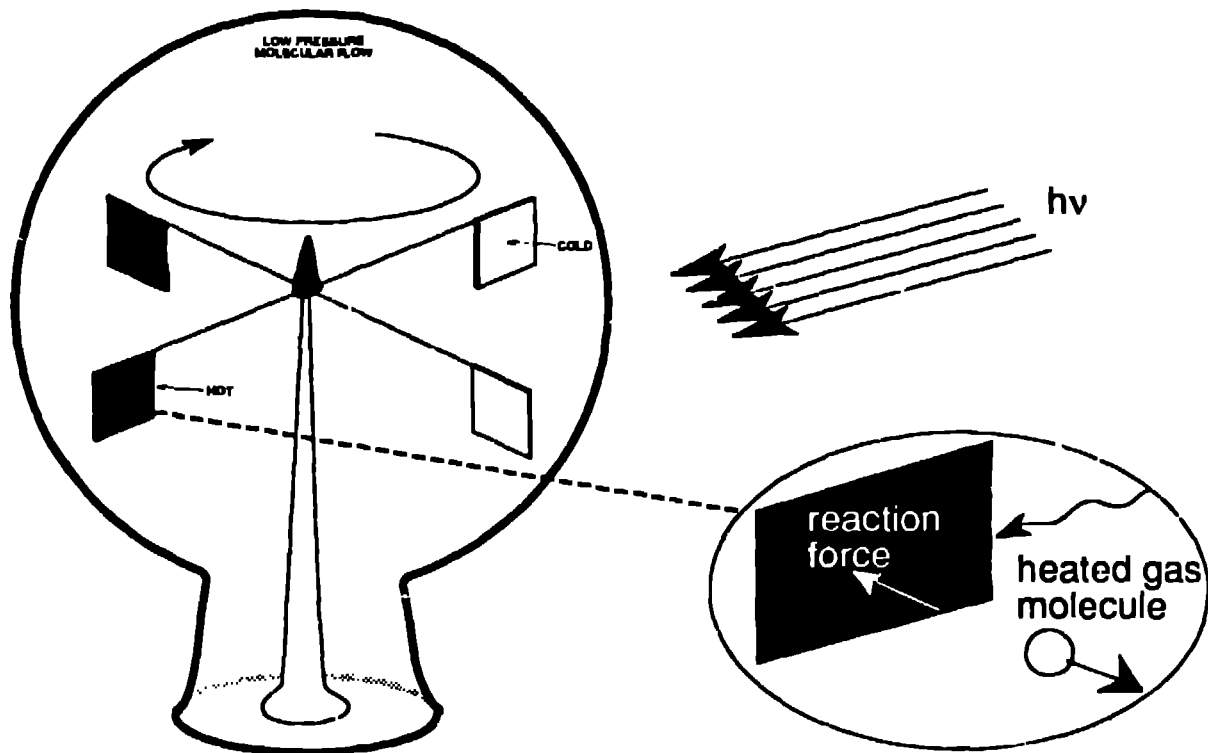
LISP is an old idea which has experienced a renaissance recently, due to advances in gas laser technology, high speed segmented mirrors and improved coefficients for momentum coupling to targets. Specifically, these advances include the advent of low cost, high electrical efficiency DP gas lasers capable of 40 J/litre as well as 800-nm laser diode arrays capable of 100W/cm<sup>2</sup> average power output at system costs around \$10/W, dramatic advances in laser momentum coupling coefficients to the neighborhood of 700 dyne s/J, and 2kHz system bandwidth for phase error correction in moving segment, phased array mirrors, permitting real time compensation of atmospheric turbulence. This capability also gives added safety margin against thermal blooming instability effects in a high power beam path.

LISP applications include LEO LISP (launch of massive objects into low Earth orbit at dramatically improved cost per kg relative to present practice); LEO LISP (LEO to

geosynchronous transfers); LO-LISP (periodic re-boost of decaying LEO orbits); and LISK (geosynchronous satellite stationkeeping). We do not expect one type of laser is best for all scenarios (Table I).

**Table I: No one type of laser is best for all scenarios**

<b>LISP variant</b>	<b>Definition</b>	<b>Energy Cost</b>	<b>Optimum <math>\lambda</math></b>	<b>Governs <math>\lambda</math></b>	<b>Laser Location</b>
<b>LISK</b>	<b>GEO Station-keeping</b>	<b>Mod</b>	<b>530 nm</b>	<b>Range &amp; atmospheric transmission</b>	<b>Planet surface</b>
<b>LEGO-LISP</b>	<b>LEO to GEO orbit transfers</b>	<b>Mod</b>	<b>800 nm</b>	<b>Laser diode parameters and fiber transmission</b>	<b>On board</b>
<b>LO-LISP</b>	<b>LEO re-boost</b>	<b>High</b>	<b>4 <math>\mu</math>m</b>	<b>Energy cost &amp; atmospheric transmission</b>	<b>Planet surface</b>
<b>LEO-LISP</b>	<b>Direct launch, to LEO</b>	<b>Very High</b>	<b>4 <math>\mu</math>m</b>	<b>Energy cost &amp; atmospheric transmission</b>	<b>Planet surface</b>
<b>NEO-LISP</b>	<b>Near-Earth-Object deflection</b>	<b>Very High</b>	<b>248 nm</b>	<b>Range</b>	<b>Planet surface</b>
<b>LISK-BROOM</b>	<b>Clearing Space Junk</b>	<b>Low</b>	<b>530 nm</b>	<b>Range, object size</b>	<b>Planet surface</b>



**Figure 1: Radiometer illustrates how molecular reaction force exceeds photon pressure**

In fact, propulsion by light has been around - in one form or another - for centuries! (See Figure 1). It is important to realize that we are not talking about propulsion by photon pressure here. The Figure illustrates this point. The reaction force of gas molecules heated by the black surface is many times larger than the reaction of photon pressure alone, which is why the radiometer vanes spin in the direction shown. When the incident light beam is sufficiently intense to cause *ablation* of the surface, this reaction force is usually several thousand times larger than the force due to photon pressure.

### Why Do This?

Conventional launch costs can be as large as \$10k/kg.

LISP offers dramatically improved payload delivery mass ratio over chemical rockets, lower cost per unit mass delivered to a new orbit, and more efficient use of scarce energy resources.

This is because it is easy to achieve plasma temperatures of 5 eV, giving 10 - 20 times larger exhaust velocity than that available from chemical reactions and, therefore, 3 - 4 times greater impulse per unit exhaust mass expended. Every mission has an optimum coupling coefficient (defined below), and the numerical range of these optimum values exceeds that available from chemical reactions. Also, LISP shares the traditional advantage of solid over

liquid-fueled rockets, in that exhaust mass is carried in solid form so that the dead weight of tanks and pumps need not be carried by the spacecraft. In LISP, nozzles may be desirable, but are not necessary. Thrust vector direction is controlled by turning the spacecraft, since (except in unusual situations) thrust will always be perpendicular to the illuminated surface.

Finally, for very high energy missions, LISP permits deriving energy on the ground, where it is cheap.

In the present paper, we do not have room to discuss all these concepts, so we will focus on three of the near-term, practical applications which involve modest expense and high utility.

### Laser Coupling to Surfaces in Vacuum

The laser momentum coupling coefficient  $C_m$  is defined as the momentum flux  $s$  (dyne-s/cm<sup>2</sup> or taps) imparted to the target per unit incident laser fluence  $\Phi$  (J/cm<sup>2</sup>):

$$C_m \equiv s/\Phi \quad \text{dyne-s/J} \quad (1)$$

Recently, momentum coupling coefficients as large as 100 dyne-s/J have been demonstrated in vacuum<sup>3</sup>, and  $C_m$  values as large as 700 dyne-s/J have been obtained in air, with passive targets.<sup>4</sup> Both results benefited from "trapped ablation", which occurs when laser light is absorbed beneath the surface of a homogeneous absorber, or within deliberately designed inhomogeneous targets.

Figure 2 illustrates the way in which we divide laser ablators for the present discussion.

Separate descriptions have been developed for the mechanisms obtaining for homogeneous volume absorbers in vacuum, and for "designer absorbers" based on trapped ablation. Fabbro, *et al* (reference 3) have calculated pressure generated in a stratified target with buried absorber and transparent overlay, which leads to trapped ablation. Recently, Skourdoulis, has obtained similarly large  $C_m$  values with visible light and coumarin doped nylon.<sup>5</sup>

The other important laser ablation parameter is  $Q^*$ , the ratio of incident laser fluence to the ablated mass flux:

$$Q^* = \Phi/\mu \quad \text{J/g} \quad (2)$$

Since the momentum  $\sigma = \mu v_E$  may be considered as having arisen from removal of the ablated mass  $\mu$  (g/cm<sup>2</sup>) at an effective exhaust velocity  $v_E$  (cm/s), it is seen that  $v_E$  is given by the product  $C_m Q^*$ , independently of the efficiency of absorption:

$$C_m Q^* = \sigma/\mu = v_E \quad \text{cm/s} \quad (3)$$

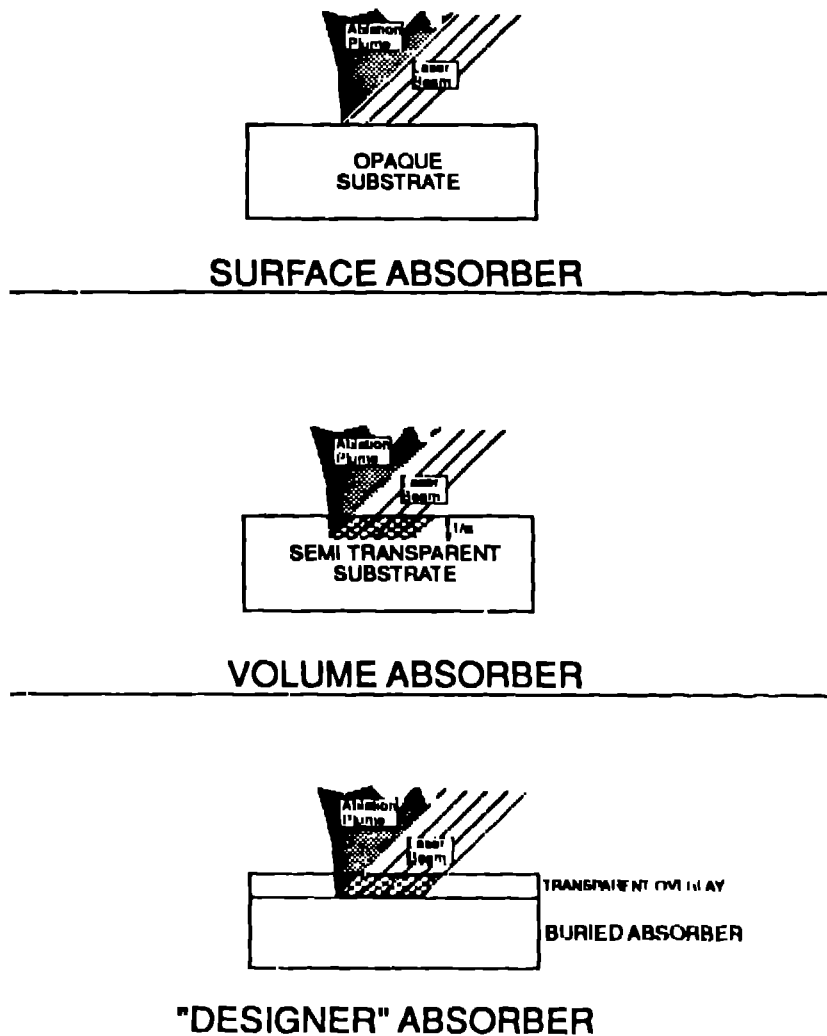


Figure 2 Laser absorption mechanisms

Note that Eq. (3) gives an effective velocity independent of assumptions about laser absorption efficiency.

The connection with the so-called "specific impulse" of conventional propulsion theory is made by noting

$$I_{sp} = v_E/g = C_m Q^*/g \quad (4)$$

where  $g$  is the acceleration of gravity ( $cm/s^2$ ). Conservation of energy requires

$$10^7 \eta_{AB} \Phi = \mu v_E^2/2 \text{ J/cm}^2 \quad (5)$$

where  $\eta_{AB}$  is the energetic efficiency of the ablation. Thus,  $C_m$  is not independent of  $Q^*$  or  $I_{sp}$ , since two constant products control their interrelationship:

$$C_m I_{sp} = (2 \times 10^7/g) \eta_{AB} = 20,394 \eta_{AB} \quad (6)$$

and  $C_m^2 Q^* = 2 \times 10^7 \eta_{AB} \quad (7)$

Eqs. (6) and (7) show that it is not necessarily desirable to seek the largest possible value for  $C_m$ , since large  $C_m$  values come at the cost of low  $I_{sp}$  and, therefore, inefficient use of the vehicle's ablation mass, giving low delivered mass ratio. It is also apparent that low  $C_m$  values are disadvantageous, since a larger and more costly laser is required to move the same mass.

For the LEO-LISP mission (which we have discussed elsewhere), we have shown<sup>6</sup> that the optimum value for  $C_m$  is 30 – 40 dyne-s/J. For LEGO, we will show that the optimum  $C_m$  is about 70 dyne-s/J.

### Range

Laser wavelength  $\lambda$  is an important parameter determining range, since cost limits the diameter  $D_1$  of the laser beam director. For propagation of a laser beam which is "N-times diffraction limited," propagation theory gives for the range to the so-called beam waist:

$$z_R = \pi D_1^2 / 8N\lambda \quad \text{cm.} \quad (8)$$

In the case of LISK, it is sensible to place a large receiving mirror of diameter  $D_2$  on the satellite which focuses the received beam onto the ablation disk. The mirror can be low quality aluminized mylar, since it will receive low fluence and its focusing requirements are not stringent. Then, the range  $Z$  is dramatically increased:

$$Z/z_R = 1 + [2(D_2/D_1)^2 - 1]^{1/2}. \quad (9)$$

### LISK: Geosynchronous stationkeeping

LISK)<sup>7</sup> is one of the most attractive LISP variants. Since the range  $Z = 36,000$  km for LISK, assuming a beam quality factor  $N = 2.8$ , even after installing a large receiving mirror  $D_2 = 30$  m on the satellite, we are forced to use short wavelengths  $\lambda \leq 530$  nm. In contrast, infrared gas lasers are most desirable for LEO-LISP because the shorter range permits them and they have low cost per joule. We assume a geosynchronous satellite mass of 2 tonnes, and a required positional drift correction of  $0.2^\circ$  per 3 months. The resulting velocity increment  $\Delta v = 1.87$  cm/s can be provided with a coupling coefficient of  $C_m = 100$  dyne-s/J with a total laser energy of 37 kJ. The upper limit of target intensity required to generate this coupling coefficient is  $I = 1$  GW/cm<sup>2</sup>, and we take the focal spot area of the satellite's 30-m-diameter receiving mirror to be  $A = 10$  cm<sup>2</sup>, so a 10-GW laser pulse is required. With  $D_1 = 3$  m, intensity in the atmosphere is 140 kW/cm<sup>2</sup>. Because the beam will be generated by frequency-doubling a 1.06  $\mu$ m Nd:glass laser, we pick  $\tau = 10$  ns pulse duration to simplify the doubling process, and the laser energy is  $W = 100$  J per pulse. Then, the 37 kJ to reposition the satellite will require a total of  $m = 370$  pulses which, at 1 Hz, can be applied over 6.2 minutes. The average laser output power is just 100 W. The mass ablated per three month correction is just  $18.7/\eta_{AB}$  grams, giving a lifetime of 130 years for a 10 kg ablation disk under ideal conditions. Considering the cost of geosynchronous satellites, and the fact that one laser can obviously keep a number of satellites properly positioned, this is a very attractive case for immediate

application. Such a laser could be built easily and cheaply [probably < \$100k] using standard components developed for inertial-confinement fusion (ICF). The most expensive components of the system would be the beam director and tracking system, but these would certainly not be dedicated to LISK, and could be used most of the time for more conventional purposes. The satellite would require extra design features to receive and utilize the laser pulse.

These consist of a large receiving optic, an ablator, and a rudimentary pointing mechanism to direct ablator thrust. The optic would be a self-deploying aluminized mylar sheet supported by a lightweight structure, and can be a low-quality optic (mrad surface accuracy), since its focus is only 30 m or so distant. It might be easiest to make the sheet in planar form with embossed grooves to form a reflective analog to a Fresnel lens.

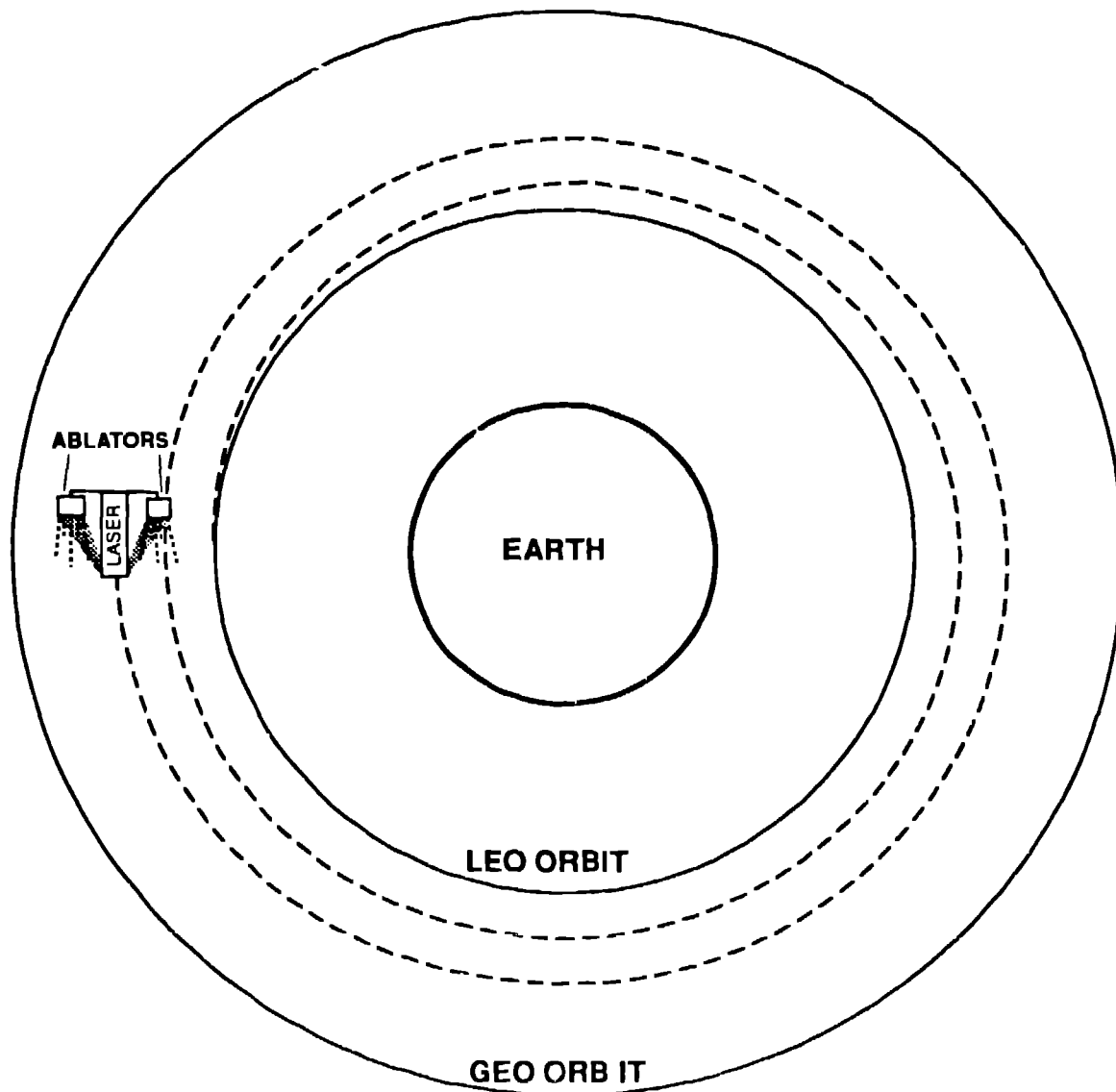
**Table II: Parameters for Geosynchronous Stationkeeping**

Range	36,000 km
Satellite angular correction	0.2 degrees
Interval	3 months
Satellite mass	2 tonnes
$\Delta v$	1.87 cm/s
$\Delta p$	$3.74 \times 10^6$ dyne-s
$C_m$	100 dyne-s/J
Total Laser Energy $NW = N\Phi A$	37.4 kJ
Target Intensity $I$	1 GW/cm <sup>2</sup>
Target Coupling Area $A$	10 cm <sup>2</sup>
Peak Laser Power $P_{pk}$	10 GW
Pulse Duration $\tau$	10 ns
Pulse Energy $W$	100 J
Pulse Repetition Rate $r$	1 Hz
Total Number of Pulses $N$	374
Time to Deliver Correction	0.2 minutes
Average Laser Power $P_{avg}$	100 W
Laser Wavelength	530 nm
Launch Mirror Diameter	3 m
Receiving Mirror Diameter	30 m
Range $z_y$	35,880 km
Beam Quality $\mu$	2.8
Mass Ablated per 3 month Correction	$(18.7/h_{ABR}) E$



We estimate the total cost of the laser system and modifications for one geosynchronous satellite to be \$1M. The cost of a single geosynchronous satellite is on the order of \$250M, but its lifetime is limited to about 10 years by dissipation of stationkeeping fuel. Since we can extend this lifetime, using LISK, by a factor of 5 indicates the benefit-to-cost ratio of a LISK setup is 1000:1.

**LEGO: LEO to GEO transfer**



**Figure 3: Illustrating LEGO**

For LEGO, our concept features an onboard laser, which provides a low level of continuous thrust for a period of weeks. The practical advantage of this technology, compared with plasma thrusters, is that the necessary mass ablation does not degrade the propulsion engine. Electrical

efficiencies are about the same: laser diode arrays can now claim 50% electrical efficiency. In this case, optical fibers deliver the laser beam the short distance to the ablation target, and the most effective laser wavelength is the near IR, about 800 nm, taking advantage of highly electrically efficient laser diode arrays which have been developed in that region. We consider a nearly-circular spacecraft orbit, and find that the cost of orbit transfer  $W/m$  (J/g) is given by

$$C = Q^* \left\{ \frac{1 - \exp \left[ \frac{(v_f - v_o)}{v_E} \right]}{\exp \left[ \frac{(v_f - v_o)}{v_E} \right]} \right\} \quad \text{J/g.} \quad (10)$$

Through  $v_E = C_m Q^* = \sqrt{(2 \times 10^7 h_{AB} Q^*)}$ , this expression depends on  $Q^*$  in a complicated way. We will show that the energy cost  $C$  has a minimum when the following transcendental relationship is satisfied:

$$\sqrt{Q^*} = \left\{ \frac{a}{\ln \left( 1 + \frac{a}{2\sqrt{Q^*}} \right)} \right\} \quad (11)$$

where 
$$a = \frac{v_f - v_o}{\sqrt{2 \times 10^7} \eta_{AB}} \quad (11a)$$

For the case we consider here, with  $\eta_{AB} = 1$ , the solution of Eqn. (11) is  $Q^* = 4384$ ,  $C_m = 67.5$  and  $C_m Q^* = 2.96 \times 10^5$  cm/s. Here,  $v_o$  is the velocity  $\sqrt{(GM/R_o)}$  of the object in a LFO orbit, in this case  $7.8 \times 10^5$  cm/s,  $v_f$  is the GEO velocity,  $3.08 \times 10^5$  cm/s,  $v_E = C_m Q^*$ , and  $P = dW/dt$  is the incident laser power (watts). The change of total energy  $H = V + E$  for such a transfer from a 200-km initial altitude is 25.7 kJ/g. With  $C_m = 67.5$  dyne-s/J,  $Q^* = 4384$  J/g and  $C_m Q^* = 2.96 \times 10^5$  cm/s, a 10-kW average-power laser diode array will be capable of delivering a 1-tonne satellite to a geosynchronous orbit in about 20 days, for a total laser energy of 17.2 GJ. Mass of the object in LEO is 4.92 tonnes, so 20% of the initial mass survives. Total energy change is 25.7 GJ for the delivered satellite. As an example of the cost of deviation from this optimum coupling, consider the case  $C_m = 447$  dyne-s/J,  $Q^* = 100$  J/g, and  $C_m Q^* = 447$  m/s, typical, e.g., of laser-vaporized ice at very modest laser intensity. Starting with a 10.6-tonne object in LEO, we find the total required laser energy is less: just 1.05 GJ, but only 276 g is delivered to orbit, and the energy cost of delivery is 3.8MJ/g.

Results for the whole range of LISP scenarios discussed are shown in Table III.

**Table III: Summary**

<u>LISP VARIANT</u>	<u>LASER</u>			<u>DELIVERY OPTICS</u>
	<u>Wavelength</u>	<u>Pulse Format</u>	<u>Avg. Power</u>	
LISK: geosynchronous stationkeeping	530 nm	10 ns, 100J 1 Hz	100W	3-m observatory telescope
LEGO-LISP: LEO to GEO transfer	800 nm	500 $\mu$ s, 40J, 250 Hz	10 kW	optical fibers
LO-LISP: LEO reboost	3 - 4 $\mu$ m	50 $\mu$ s, 20 kJ, 5 Hz	100 kW	3-m observatory telescope
LISK-BROOM	0.5 $\mu$ m	200 ns & 5 $\mu$ s, 60 kJ, 1 Hz	60 kW	5-m observatory telescope

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