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Title: 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[1] 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[2] 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 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 DF gas lasers capable of 40 J/litre as well as 800-nm laser diode arrays capable of $100 W/cm^2$ 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); LEGO 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

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

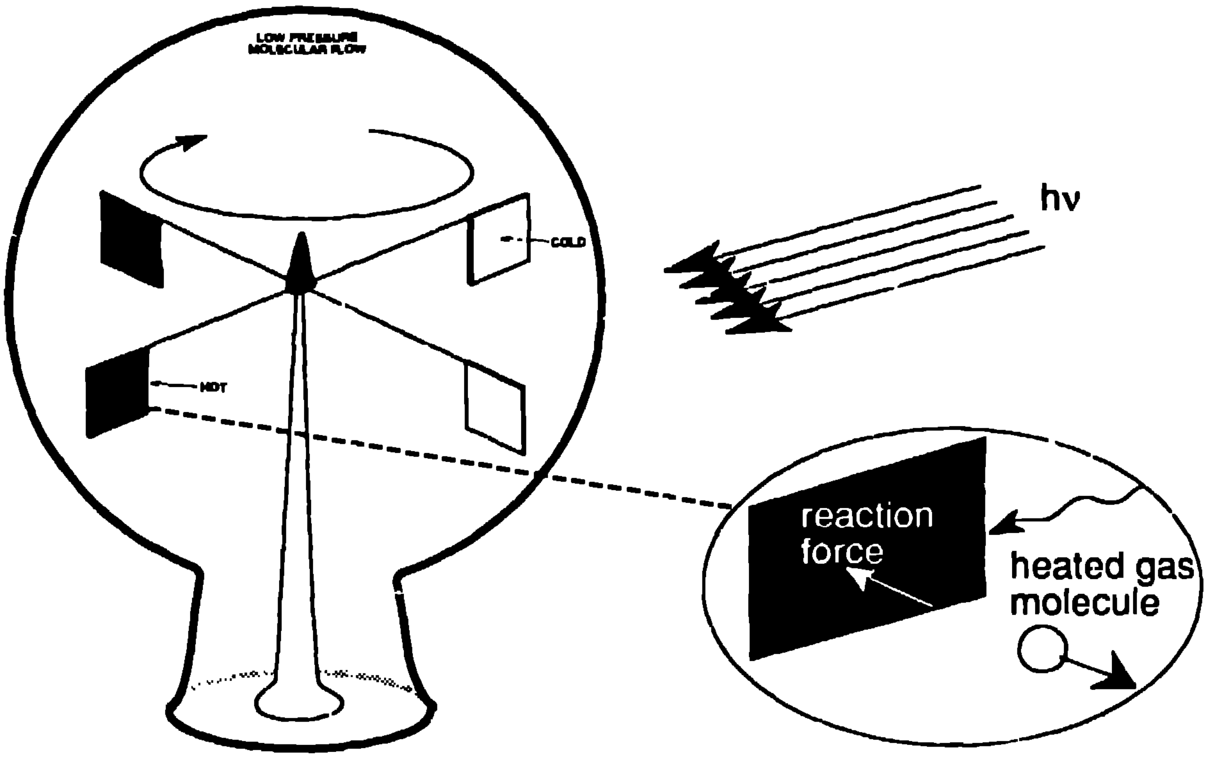

Figure 1: Radiometer illustrates how molecular reaction force exceeds photon pressure

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^2 or taps) imparted to the target per unit incident laser fluence Φ (J/cm^2):

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

Recently, momentum coupling coefficients as large as 100 dyne-s/J have been demonstrated in vacuum[3], and C_m values as large as 700 dyne-s/J have been obtained in air, with passive targets.[4] Both results benefited from "trapped ablation", which occurs when laser light is absorbed beneath the surface of a homogeneous absorber, or within deliberately designed inhomo-geneous 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 vol-ume 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.[5]

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

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

Since the momentum $\sigma = \mu v_E$ may be considered as having arisen from removal of the ablated mass μ (g/cm^2) 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:

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

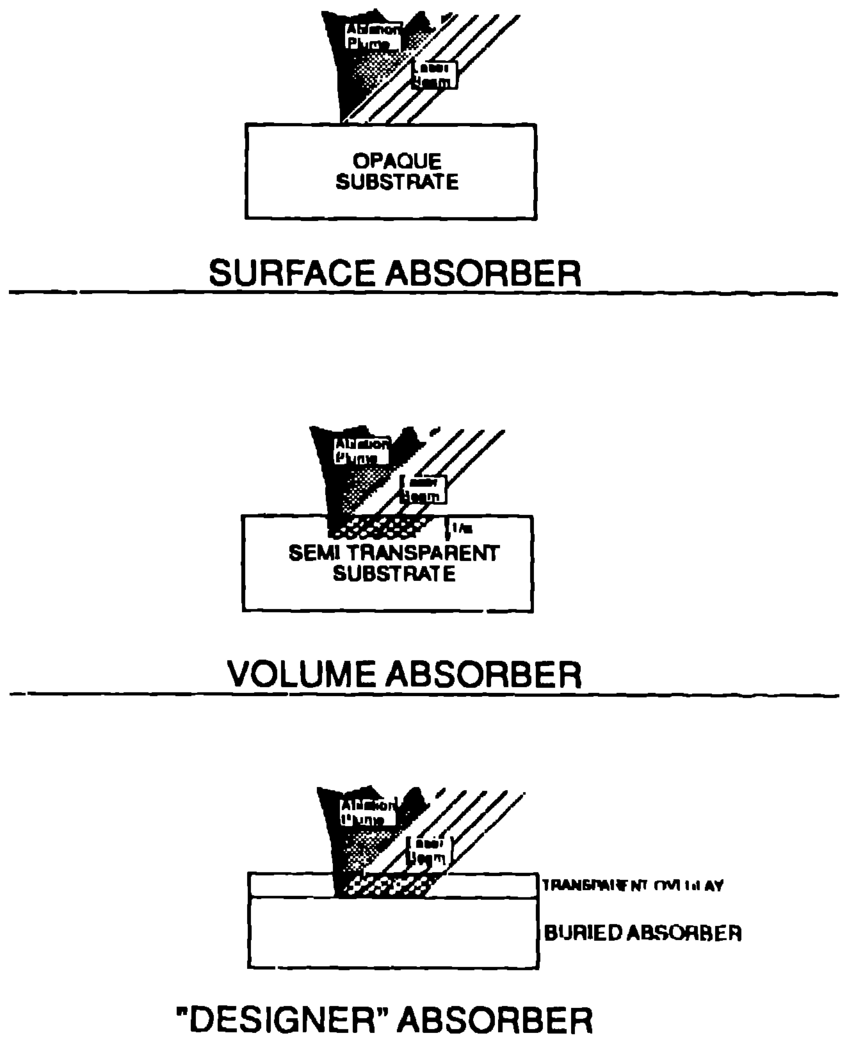

Figure 2 Laser absorption mechanisms

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

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

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

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

where η_{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:

$$C_m I_{sp} = (2\times10^7/g)\eta_{AB} = 20{,}394\ \eta_{AB} \qquad (6)$$

and

$$C_m^2 Q^* = 2\times10^7 \eta_{AB} \qquad (7)$$

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[6] 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 λ 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:

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

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:

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

LISK: Geosynchronous stationkeeping

LISK)[7] 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 = 30m 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° per 3 months. The resulting velocity increment Dv = 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 = 1GW/cm^2, and we take the focal spot area of the satellite's 30-m-diameter receiving mirror to be A = 10 cm^2, so a 10-GW laser pulse is required. With D_1 = 3m, intensity in the atmosphere is 140 kW/cm^2. Because the beam will be generated by frequency-doubling a 1.06 μm Nd:glass laser, we pick τ = 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/η_{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-confine-ment 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
Δv	1.87 cm/s
Δp	3.74×10^6 dyne-s
C_m	100 dyne-s/J
Total Laser Energy $NW = N\Phi A$	37.4 kJ
Target Intensity I	1 GW/cm^2
Target Coupling Area A	10 cm^2
Peak Laser Power P_{pk}	10 GW
Pulse Duration τ	10 ns
Pulse Energy W	100 J
Pulse Repetition Rate r	1 Hz
Total Number of Pulses N	374
Time to Deliver Correction	6.2 minutes
Average Laser Power P_{avg}	100 W
Laser Wavelength	530 nm
Launch Mirror Diameter	3 m
Receiving Mirror Diameter	30 m
Range z_S	35,880 km
Beam Quality μ	2.8
Mass Ablated per 3 month Correction	$(18.7/\eta_{AB})$ g

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

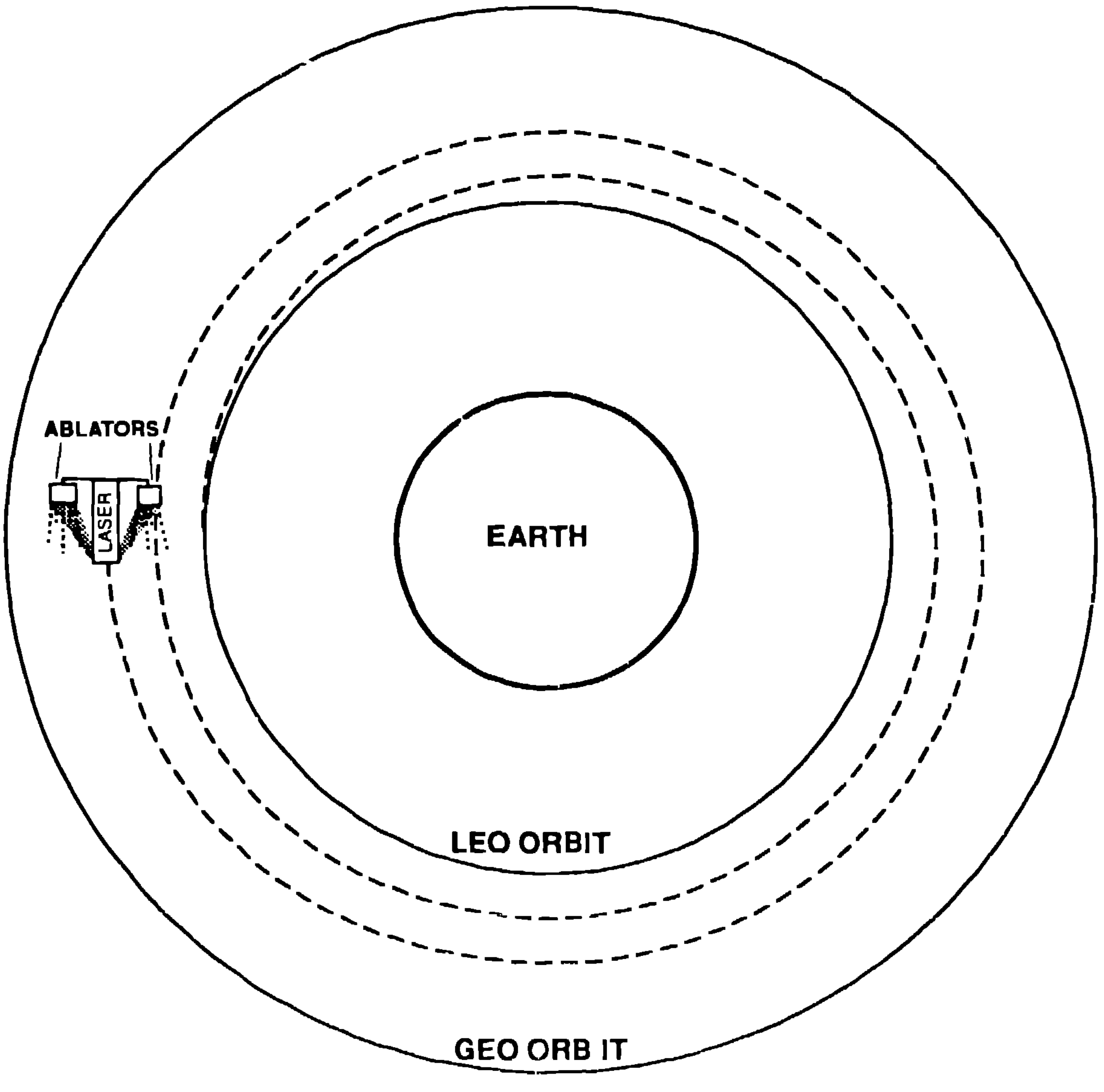

Figure 3: Illustrating LEGO

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

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

Through $v_E = C_m Q^* = \sqrt{(2x10^7 h_{AB} Q^*)}$, 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:

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

where

$$a = \frac{v_f - v_o}{\sqrt{2x10^7\, \eta_{AB}}} \tag{11a}$$

For the case we consider here, with $\eta_{AB} = 1$, the solution of Eqn. (11) is Q* = 4384, C_m = 67.5 and $C_m Q^*$ = 2.96x10^5 cm/s. Here, v_o is the velocity $\sqrt{(GM/R_o)}$ of the object in a LEO orbit, in this case 7.8 x 10^5 cm/s, v_f is the GEO velocity, 3.08 x 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 $C_m Q^*$ = 2.96x10^5 cm/s, a 10-kW average-power laser diode array will be capable of deliver-ing 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

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

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