Mysteries of Lasers in Space

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Presented at the "Applications of High Power Lasers in Space"
Workshop, CERN, October 15-16, 2015

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Laser space propulsion

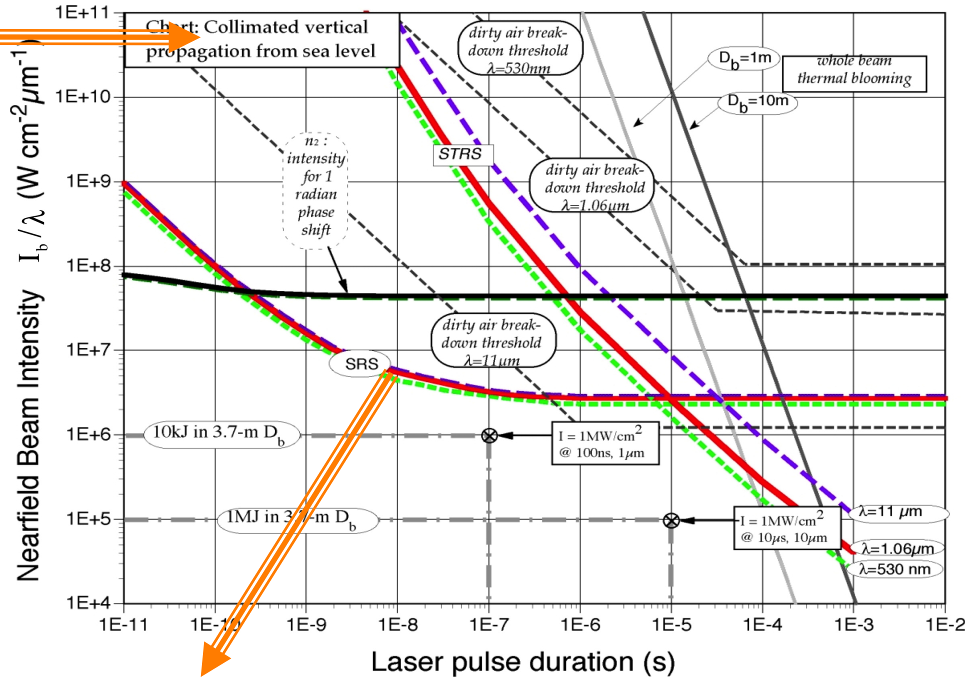
Outline

- Introduction: Advantages of space for beam transmission
- Very high electric fields from short intense pulses
- Momentum transfer to targets by pulsed laser ablation
- Successful estimation scheme for peak coupling
- State of the art in pulsed lasers
- Common errors in calculating laser intensity at long range
- Laser applications in space
- Summary and conclusions

Introduction: space is great!

- I’m very happy to return to Europe! Sincere thanks to IZEST and Prof. Mourou for inviting me to this interesting workshop!
- Beam transmission from Earth to space in air is limited by(1):
  - Self-focusing
  - SRS, SBS conversion
  - Optical breakdown
  - Thermal instabilities
- In space:
  - None of these limitations, so:
    - Transmit almost any wavelength
    - Transmit almost any intensity

Where we would like to operate



Must operate BELOW all these curves in air!

(1) C. Phipps, et al. “Optimum parameters for laser-launching objects into low Earth orbit,” *Laser and Particle Beams* vol. 18, no. 4, pp. 661-695 (2000)

Short pulse lasers give high E fields

Relativistic electrons if $\lambda = 1\mu m$

I (TW/cm^2)	E (V/cm)	E (V/µm)	E (V/Å)	Examples	
1E6	2.8E10	2.8E6	280	5kJ/cm^2	5fs
				3.9mJ in 10µm spot	5fs
1330	1E9	1E5	10	6.6J/cm^2	5fs
				133kJ/cm^2	100ps
0.012	3E6	300	0.03	60µJ/cm^2	5fs
				1.19J/cm^2	100ps

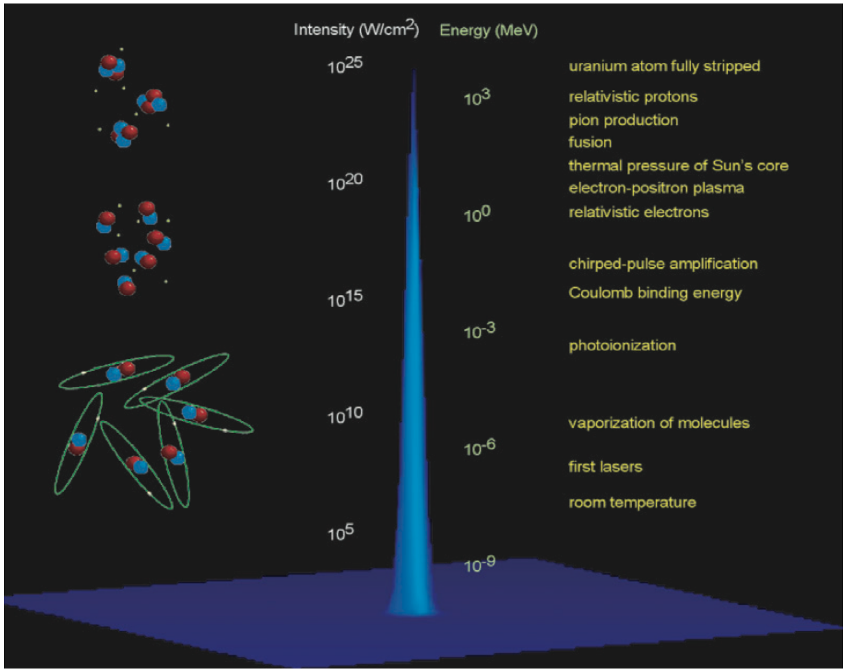


Figure: D. Umstadter, “Relativistic laser-plasma interactions,” *J. Phys. D. Appl.Phys.* vol. 36, p. R153 (2003)

Modeling is great…

Starting with vapor regime coupling coefficient C_{mv} developed from “SESAME” tables of p vs. T:

$$p=[(1-\eta_i)p_v+\eta_i p_p]=[(1-\eta_i)C_{mv}+\eta_i C_{mp}]I$$

$$C_{mp}=1.84E-4\frac{\Psi^{9/16}}{A^{1/8}(I\lambda\sqrt{\tau})^{1/4}}$$

$$\Psi=\frac{A}{2[Z^2(Z+1)]^{1/3}}$$

$$Z=\frac{n_e}{n_i} \qquad \sum_{j=1}^{j\,\max}(n_j)=n_i$$

$$kT_e=0.256\frac{A^{1/8}Z^{3/4}}{(Z+1)^{5/8}}(I\lambda\sqrt{\tau})^{1/2}eV$$

$$\frac{n_e n_j}{n_{j-1}}=\frac{2u_j}{u_{j-1}}\left(\frac{2\pi\, Am_p kT_e}{h^2}\right)^{3/2}\exp\left(-W_{j,j-1}/kT_e\right)$$

$$S_j=\frac{n_{i\,j}}{n_{i,j-1}}=\frac{8.64E26}{n_e}\frac{2\,u_j}{\theta^{1.5}u_{j-1}}\exp[-W_{j,j-1}/kT_e]$$

$$P_j=\prod_{k=1}^{j}S_k=\left[\frac{n_1}{n_o},\frac{n_2}{n_o},\frac{n_3}{n_o},\dots.\right]$$

$$R_1=\frac{n_i}{n_o}=\sum_{j=1}^{j_{\max}}P_j$$

$$R_2=\frac{n_e}{n_o}=\sum_{j=1}^{j\,\max}j\,P_j$$

$$Z=\frac{R_2}{R_1}$$

$$\eta_i=\frac{n_i}{(n_o+n_i)}=(1+1/R_1)^{-1}$$

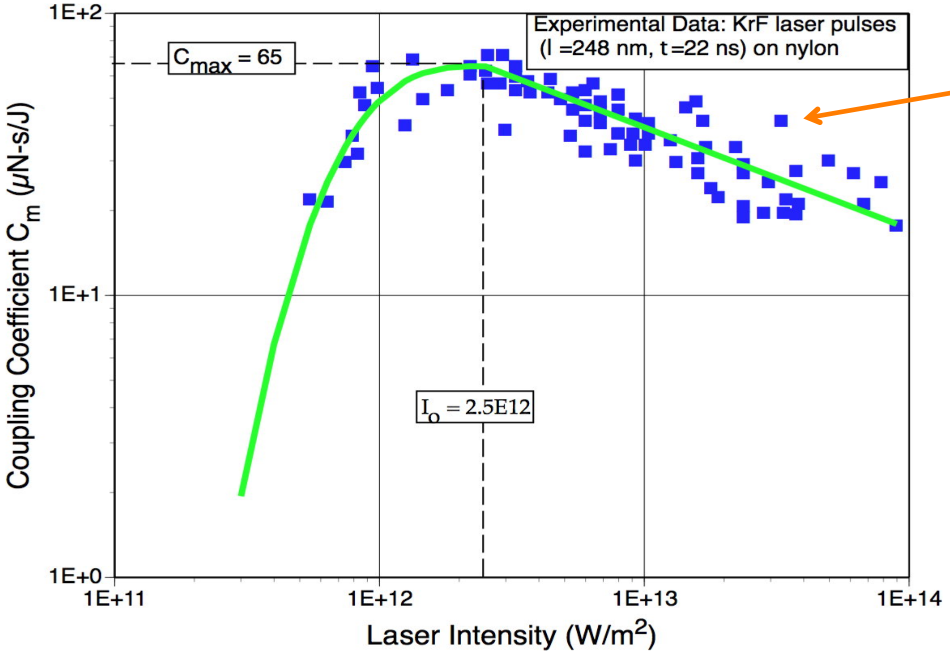
$$n_e=\frac{R_2}{(kT_e/p)(1+R_1+R_2)}$$

….But there are times when we would like to quickly estimate coupling parameters for system design! →

Ref: C. Phipps et al. “Removing Orbital Debris with Lasers,” *Adv. Space Resch.* 49, 1283-1300 (2012)

Typical plot of C_m vs. I

- We've spent a couple of decades on the problem of how to estimate optimum parameters for system design
- In the following, we'll show how this is done



Problem: predict this peak value & where it occurs

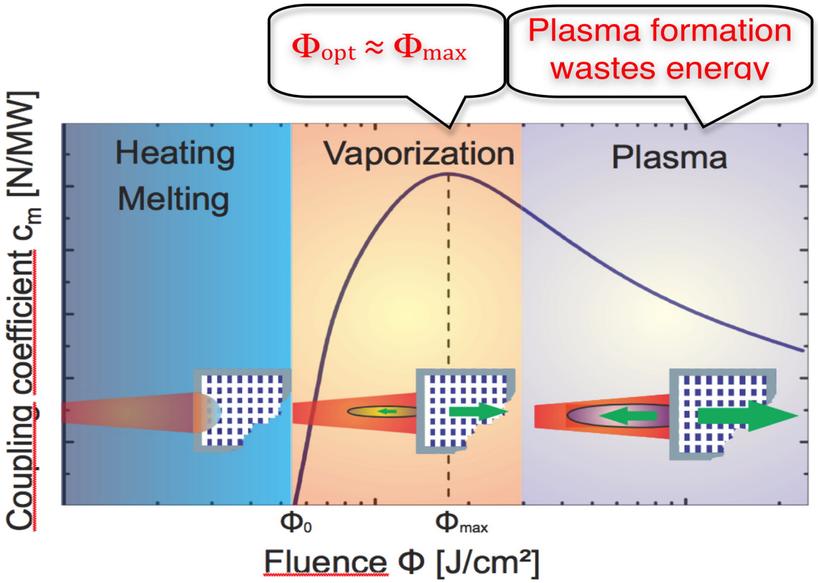


Figure above: C. Phipps et al., "Impulse coupling to targets in vacuum by KrF, HF, and CO_2 single-pulse lasers," *J. Appl. Phys.* 64(3): 1083-96 (1988)

Figure above: Courtesy of H.-A. Eckel, DLR Stuttgart

Impulse coupling coefficient C_m

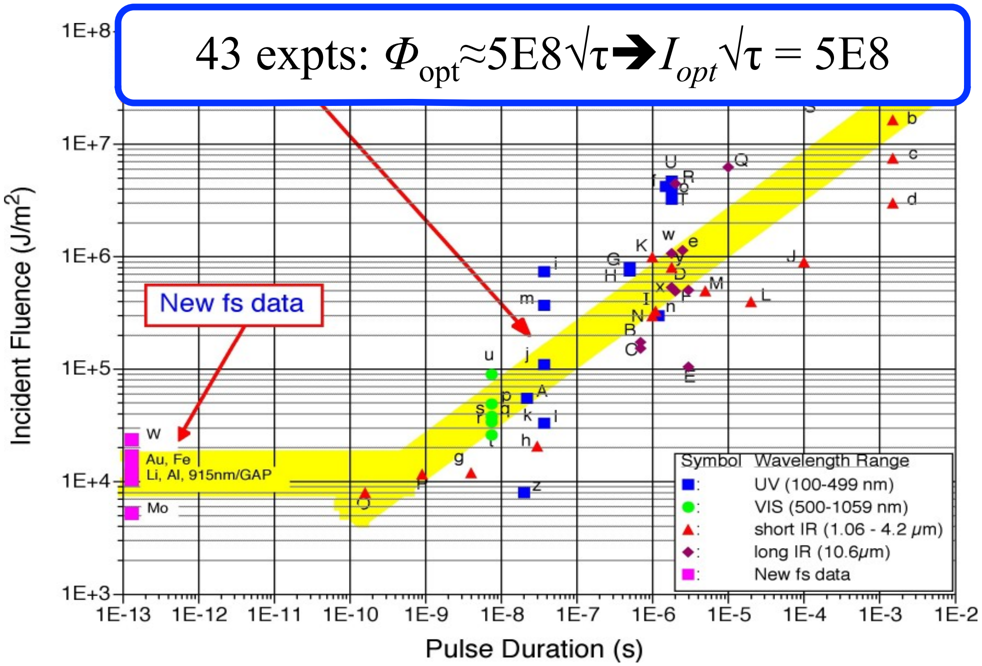
- First principles theory for $\tau > 100$ps in plasma regime gives$^{(1,2)}$

$$C_m \approx C_{mo}/(I\lambda\sqrt{\tau})^{1/4}, \quad C_{mo} = \mathrm{fn}(A,Z)$$

- Peak is at $I_{opt}\sqrt{\tau} = 5E8$ W/m^2-√s

- *Combining these expressions gives*

$$C_{mopt} \approx 0.21\, C_{mo}/\lambda_{\mu m}^{1/4} \quad \frac{N-s}{J}$$



43 expts: $\Phi_{opt} \approx 5E8\sqrt{\tau} \rightarrow I_{opt}\sqrt{\tau} = 5E8$

↑ No benefit for $\tau < 100$ps

- UV short pulses give us: better C_{mopt}, smaller spot <u>and</u> lower fluence
  - Predict: $C_{mopt} \approx$ 100N/MW at 355nm, 100ps on Al, $\Phi_{opt} = 8.5$ kJ/m^2

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(1): C. Phipps et al. *App. Surf.Sci.*, **252** (2006) 4838-4844

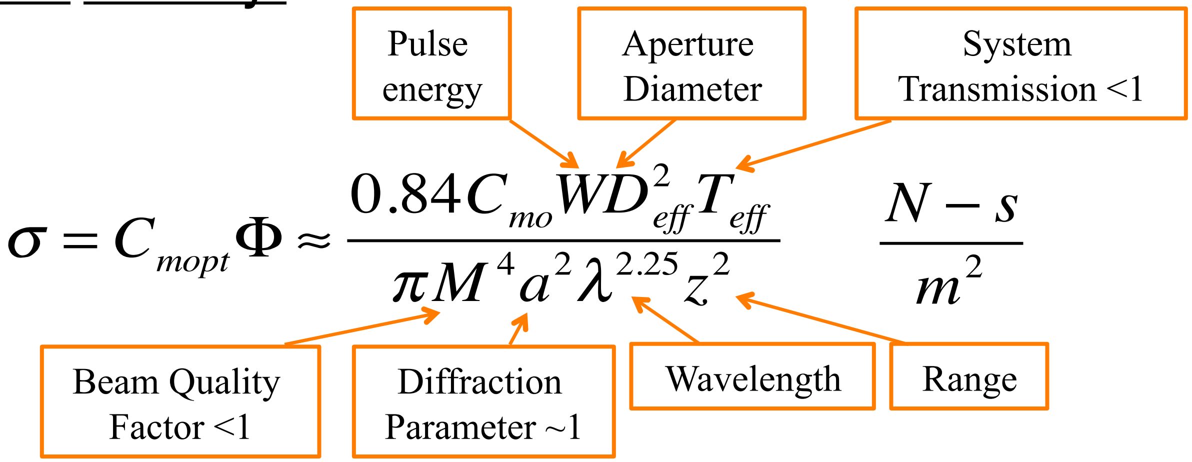
(2) C. Phipps "L'ADROIT," *Acta Astronautica* vol. 104, pp. 243-255(2014)

System considerations

- Because diffraction limits fluence delivered to target,

$$\Phi = \frac{4WD_{eff}^2 T_{eff}}{\pi M^4 a^2 \lambda^2 z^2} \qquad J/m^2$$

- Maximum impulse density delivered:



Pulse energy

Aperture Diameter

System Transmission <1

$$\sigma = C_{mopt}\Phi \approx \frac{0.84 C_{mo} W D_{eff}^2 T_{eff}}{\pi M^4 a^2 \lambda^{2.25} z^2} \qquad \frac{N-s}{m^2}$$

Beam Quality Factor <1

Diffraction Parameter ~1

Wavelength

Range

- It's easy to see we want short wavelength!
  - ➢ We gain a factor of ~12 in σ going from 1060 to 355nm

Consequences

- Shortest possible wavelength λ
- Largest possible beam aperture D_{eff}
- Best: 100ps, 355 nm UV lasers
  - Damage thresholds are poor at 266nm
  - We propose using monolithic DPSSL technology, typically 300J, 20Hz, 6kW avg power [3TW peak]
  - Phased fiber arrays [ICAN] are a very attractive alternative when mature
- Optical damage limits of components which generate or transmit the beam still apply!

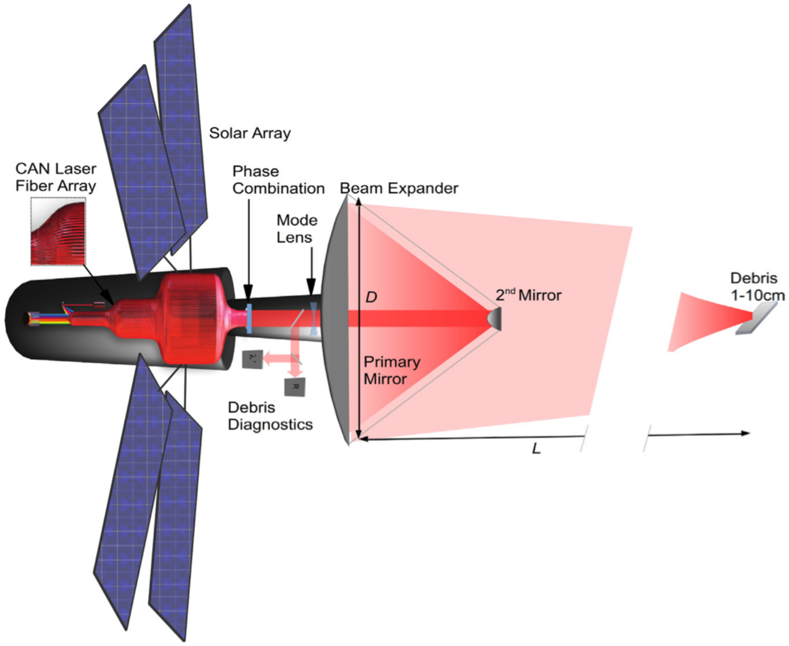


Figure: R. Soulard et al, “ICAN: a novel laser architecture for space debris removal,” *Acta Astronautica* **105**, 192-200 (2014)

Data fitting example: Nylon 248nm

- Pretty good!

In this case, value of $I\lambda\sqrt{\tau}$ at peak, and C_m peak value are predicted to within a few percent

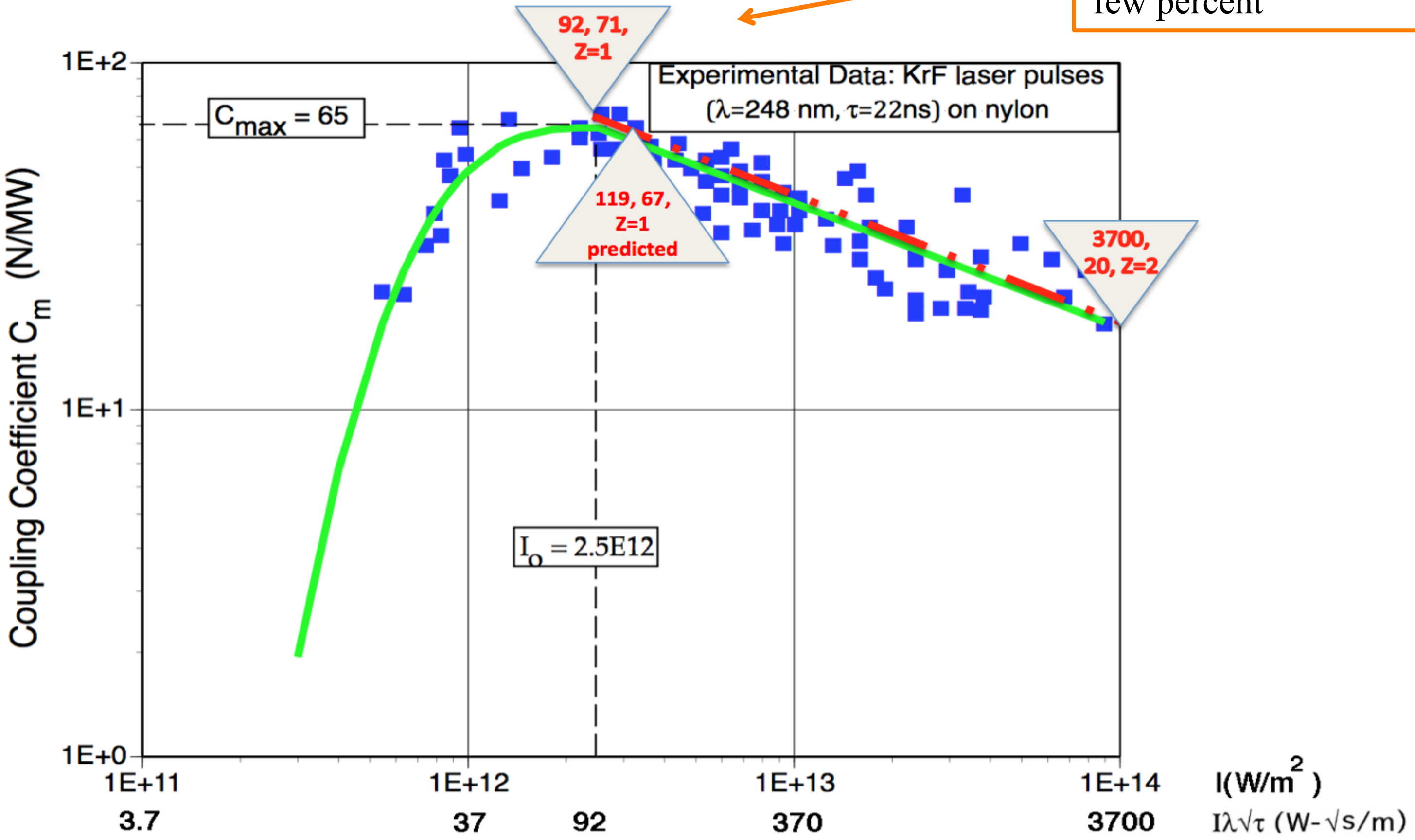


Figure modified from C. Phipps et al., “Impulse coupling to targets in vacuum by KrF, HF, and CO_2 single-pulse lasers,” *J. Appl. Phys.* 64(3): 1083-96 (1988)

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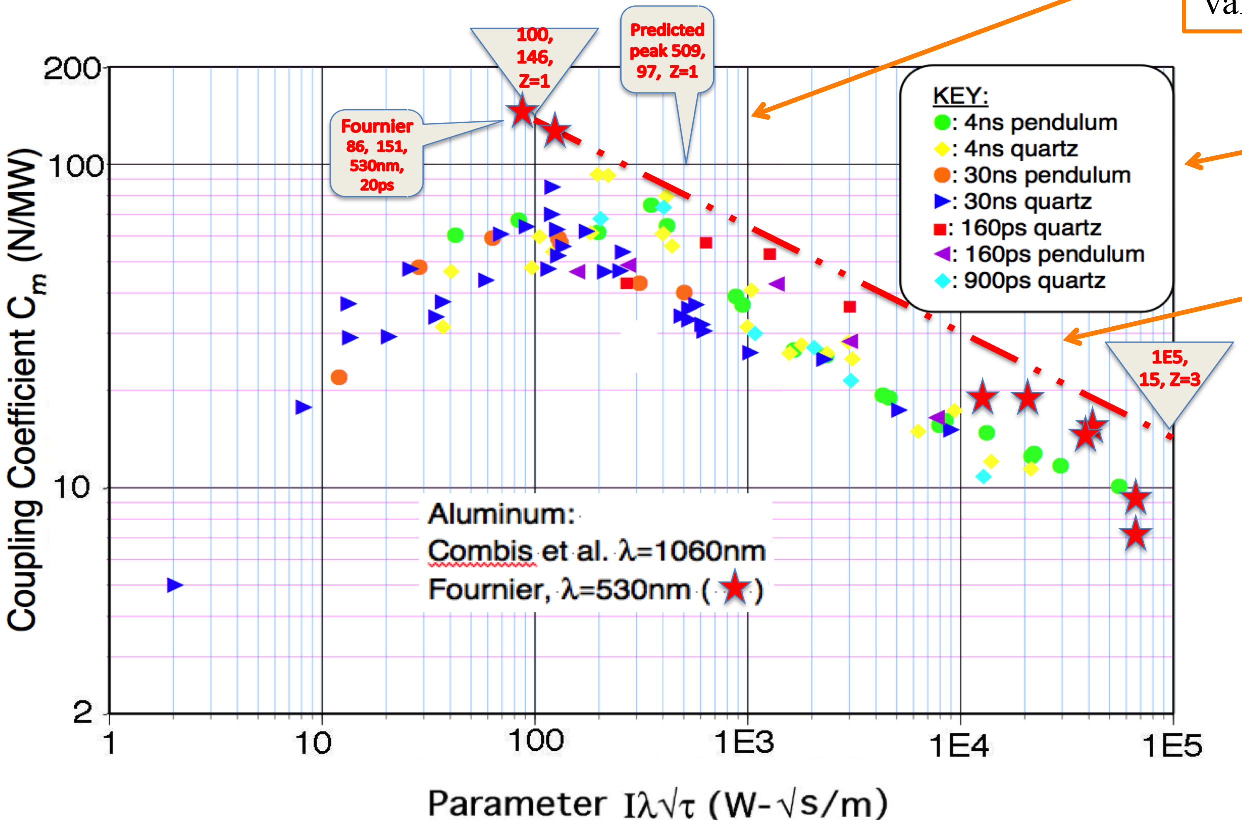
Data fitting example: Al 530, 1060nm



In this case, predicted value of $I\lambda\sqrt{\tau}$ at peak is off by factor of 3, but predicted value accurate to ±40%

Key refers to measurement techniques used in Combis et al$^{(3)}$

Fournier data$^{(4)}$ (dashed line) at 530nm agrees well

(3) Figure adapted from: P. Combis, et al, *Revue Scientifique et Technique de la Defense, CEL-Valenton no.4*(1992)

(4) K. Fournier, et al, “LASNEX calculations of laser-coupling coefficients for Al targets,” Lawrence Livermore Laboratory presentation UCRL-Pres 226849 p. 29 (2006) *[paper in preparation]*

State of the art in “portable” DPSSL’s

System	**Wavelength**	**Pulse energy**	**Pulse duration**	**Rep rate**	**Location**
DIPOLE	1030 nm	10J	10ns	10Hz	SERC, UK
Gigashot	532nm	2J	10ns	10Hz	LLNL, USA
Klenke CPA	1030nm	1.3mJ	670fs	400kHz	FSU, Jena

Laser System TRL’s and references

System	TRL	Ref.
Monolithic Diode Pumped Solid State single pulse	8	[5]
Monolithic Diode Pumped Solid State repetitive pulse	6	[6]
Modelocked, phased low intensity CW fiber, N=64	5	[7]
Modelocked, phased femtosecond pulse fiber array, N=2-4	4	[8]
Modelocked, phased femtosecond pulse fiber array, N=10k	2	---

5. A. Bayramian, et al. LLNL-PRES-581113 (2012)

6. S. Banerjee et al. *Optics Letters* Volume 37, p2175 (2012)

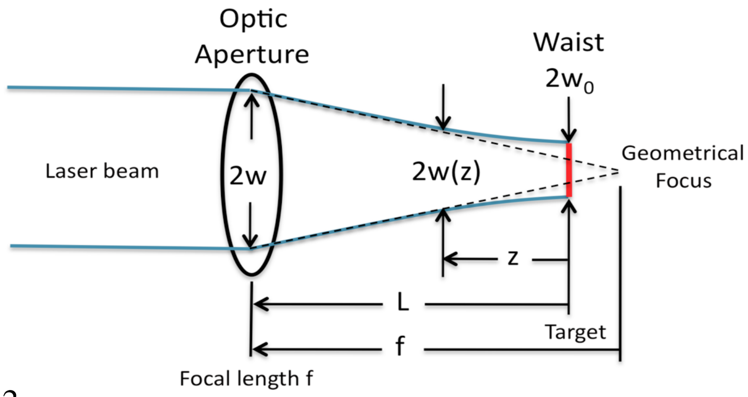
7. J. Bourderionnet, et al. *Optics Express*, Volume 19, 17053-17058 (2011)

8. A. Klenke, *Opt. Lett.*, Volume 38, 2283-2285 (2013)

Spot sizes for small Fresnel no.

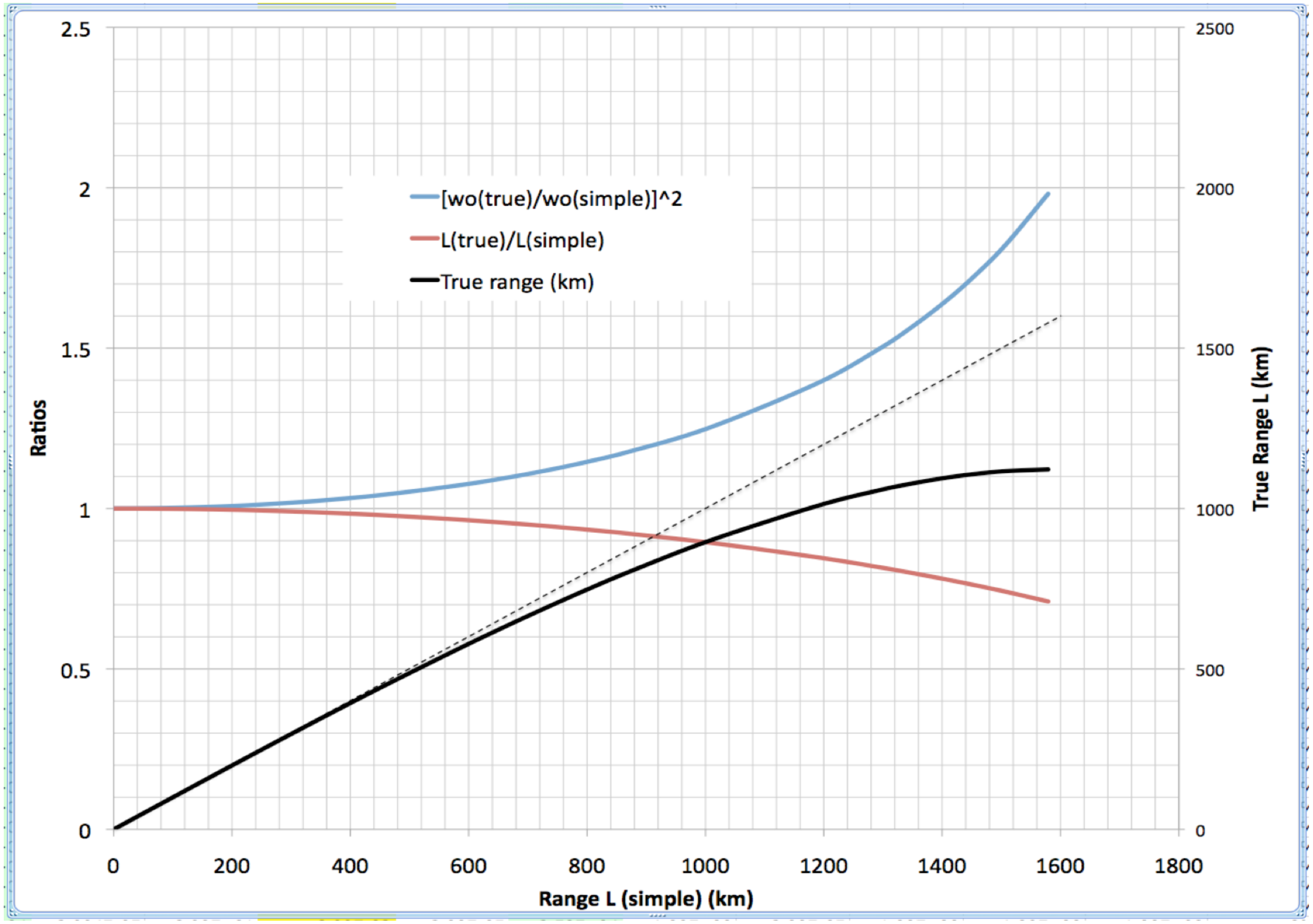
- Fresnel number $F = w^2 / (L\lambda)$
- Classic expression $w_{oc} = \dfrac{L\lambda}{\pi w} = \dfrac{w}{\pi F}$

  for perfect gaussian is incorrect for small F
- True result $$\left[1 - \frac{2w_o^2}{w^2}\right]^2 = 1 - \left(\frac{2w_{oc}^2}{w^2}\right)^2$$
- For imperfect beam: $\lambda \rightarrow M^2\lambda$



Example: Focal Spot Error	
Wavelength λ(μm)	0.35
Range L(km) = z_R (km)	8,980
Aperture radius w(m)	1
Fresnel number F	0.32
Classic w_o^2	1.00
True w_o^2	0.50
Error in focus area	100%

Consequence



$$\lambda = 0.35\mu m, w = 1m$$

As much as 100% error in estimated fluence on target

Using classical spot size to predict range gives 40% error

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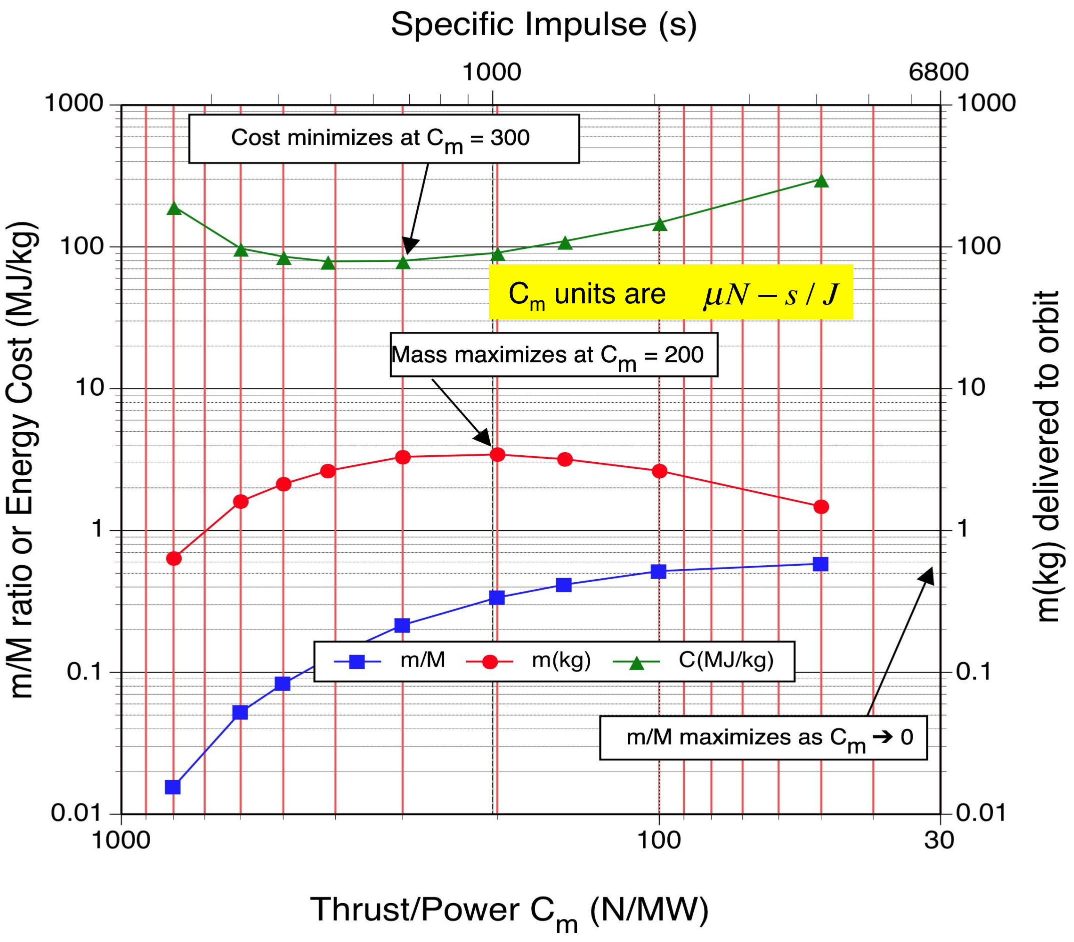
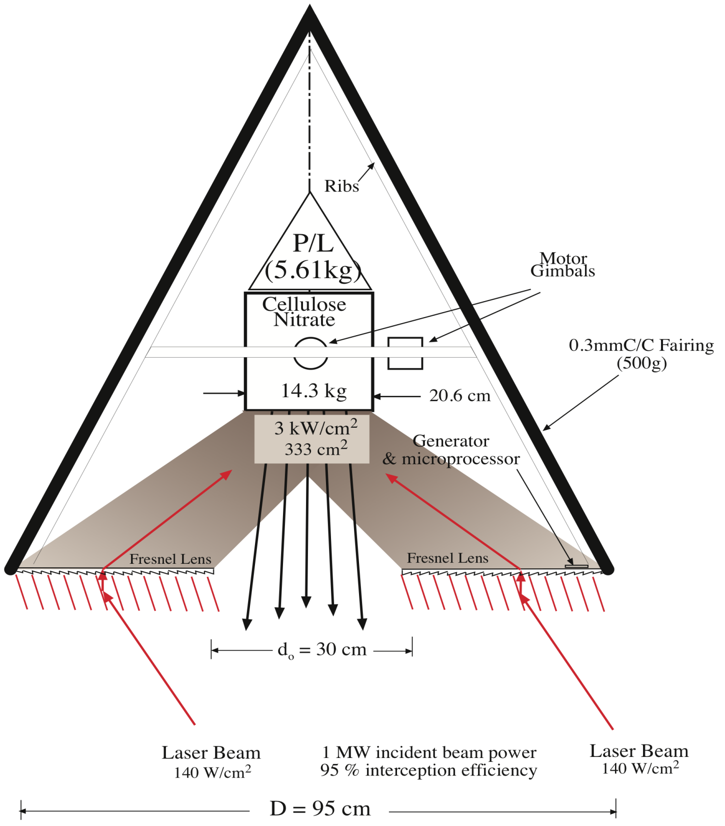
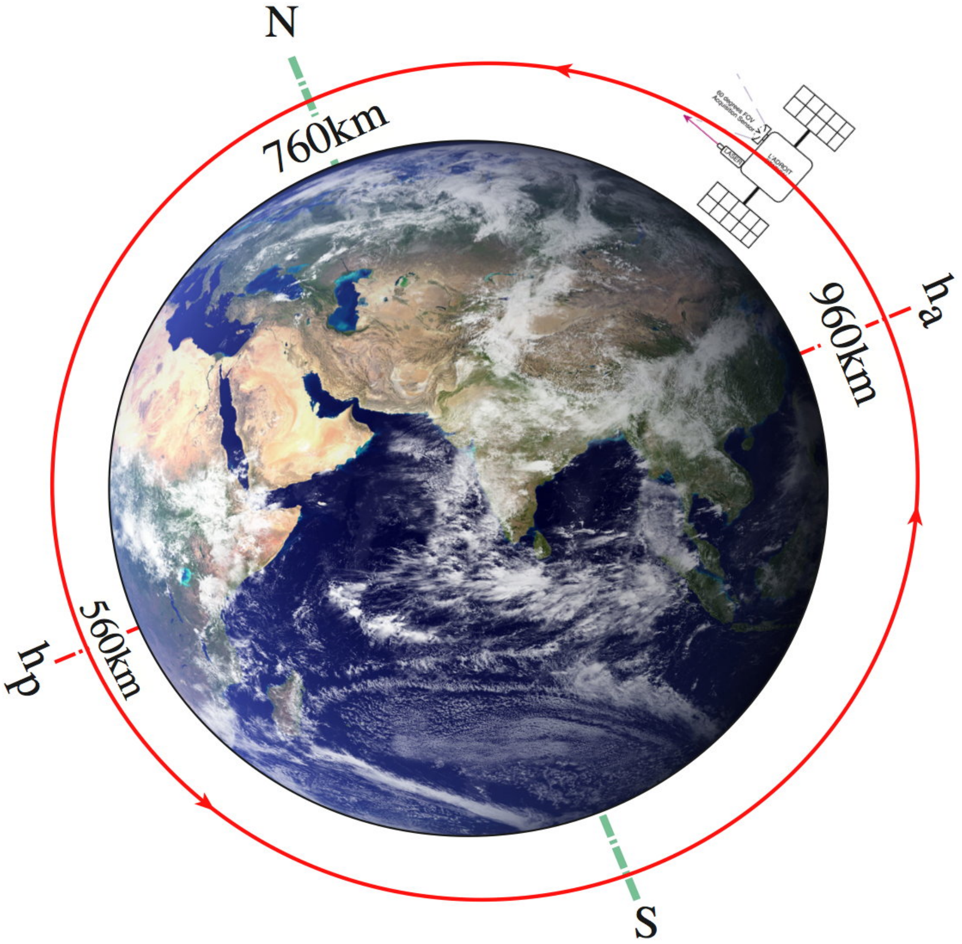
App. #1: Direct launch to LEO





C. Phipps et al. *J. Laser and Particle Beams*, ibid. Dozens of simulated flights for laser-driven object with 0.95m diameter starting from 35km altitude

App. #2: Small debris re-entry



10-ton station generates 355nm, 100ps pulses with 380J/pulse, 56 Hz (21kW burst power) operating at 250km range for 10s and producing 100N/MW.

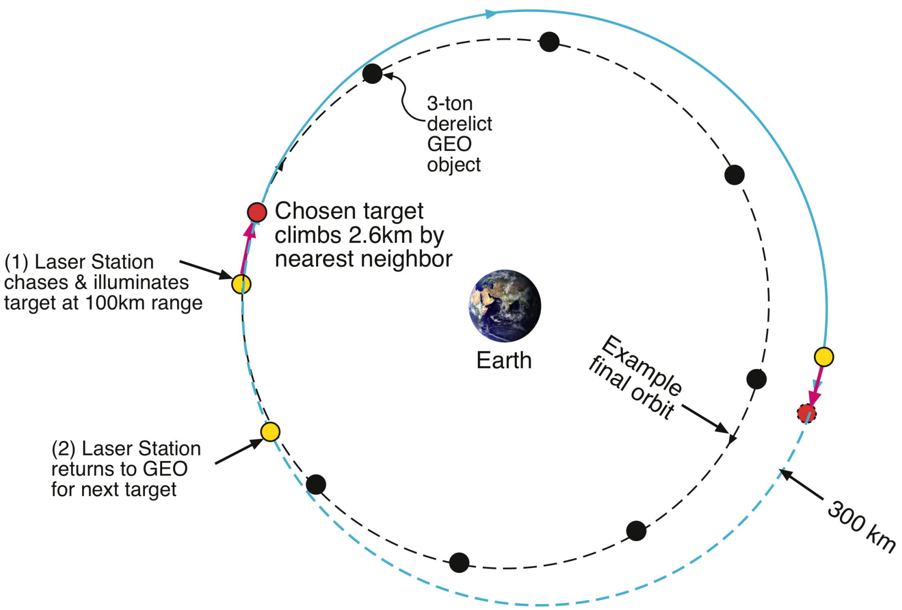
Result: 30 targets removed per hour at \$310 per object, 100k targets in LEO < 38 grams removed in 5 months.

C. Phipps “L’ADROIT,” *ibid.*

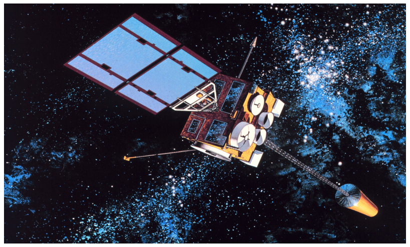
App. #3 GEO "Chaser" variant

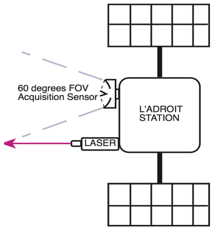
- Pluses:
  - 10km laser range, easy pointing
  - No misses!
  - Ready for new target in 16hrs [simple case] or 50hrs [targets inclined ≤15°]
  - Raises targets indefinitely
  - Simpler, 30-cm dia. mirror
- Minuses:
  - 5.2kg fuel *to chase an in-plane target* or 150kg for 15° inclination to +300km
  - Mission duration limited by fuel mass

Scales exagerrated



Station repositioning interval is variable



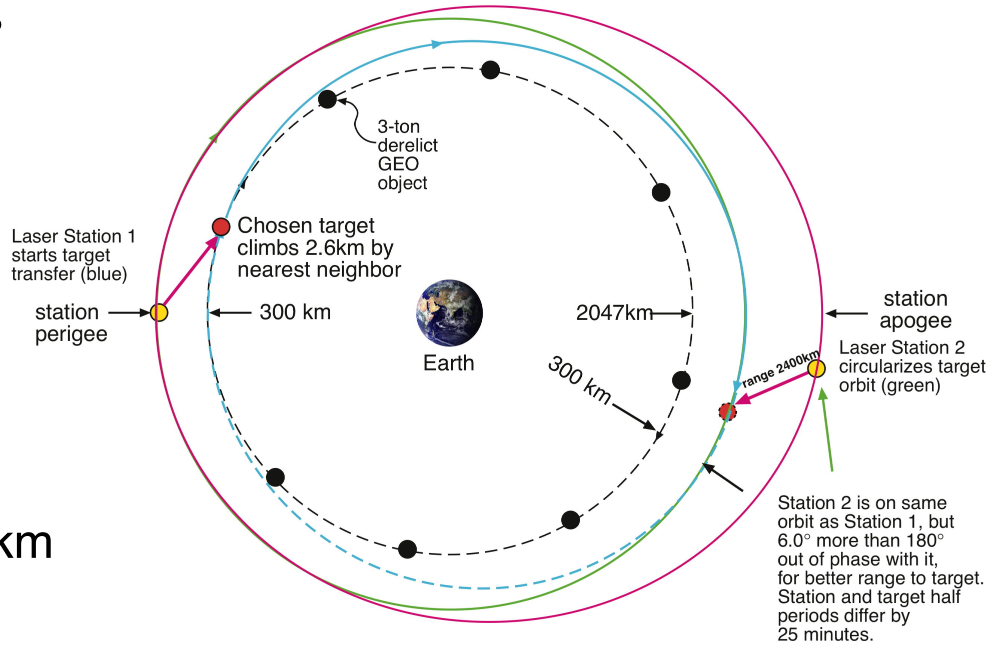


C. Phipps and C. Bonnal, *Acta Astronautica*, to appear

App. #3: GEO "Volleyball" variant

- Pluses:
  - Use Xe/Kr fuel only for orbit and attitude maintenance, zero kg Xe for chasing
  - Automatically revisits accessible targets each 25 days
  - Raises targets indefinitely
  - Station can work on *multiple* targets
  - Can handle anything within range (3.4° inclination)
- Minuses:
  - Expense: 2 stations to circularize
  - Max laser range 2400km
  - 3-m dia. mirror
  - 100km target altitude increments
  - Needs 75 days to raise one target 300km

Scales exagerrated



Station 2 is on same orbit as Station 1, but 6.0° more than 180° out of phase with it, for better range to target. Station and target half periods differ by 25 minutes.

Station orbit retrogrades 60 minutes per day, 25 day repeat interval

C. Phipps and C. Bonnal, *Acta Astronautica*, to appear

Conclusions

- Still a long distance between requirements and actualities in “portable” high peak and high average power lasers
- Laser ablation propulsion is an efficient and dexterous method of propelling objects remotely
- Applications range from low Earth orbit to GEO and beyond
- Thank you for your attention!