Launching of Micro-Satellites Using Ground-Based High Power Pulsed Lasers

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20031017 123
DRAFT

LAUNCHING OF MICRO-SATELLITES USING GROUND-BASED HIGH POWER PULSED LASERS

DEPS 6TH Annual Directed Energy Symposium

20-24 October 2003

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Agenda

- Laser Propulsion Concept
- Candidate High-Power Lasers
- Pulsed Carbon Dioxide Laser Technology Overview
- Relevant Legacy Programs
- Candidate Concepts/Architectures
- Propagation Enhancement Concepts
- Program Plan/Schedule
- Conclusions
Why Laser Propulsion?

• Benefits
  ➢ Avoids carrying heavy propulsion system components through the atmosphere and into space; the laser is not on board
  ➢ Higher performance potential than chemical rockets
  ➢ Higher thrust than electric propulsion concepts
  ➢ None of the polluting or radioactive exhaust associated with chemical or nuclear rockets
  ➢ Can be accomplished by extensions and integrations of existing rocket propulsion technologies; no physics breakthroughs required
  ➢ Repeatedly shown to be economically viable; AF, NASA, and DARPA have all done independent studies

• Draw Backs
  ➢ Requires expensive, high power laser which is typically not mobile
  ➢ Lacks complete demonstration after 33 years from conception

The benefits outweigh the negative aspects!
The Lightcraft Concept

- A Lightcraft is a small spacecraft; diameter is about 1 m, weight is about 2 kg (1 kg payload)

**Forebody**
- Aerodynamically contoured surface
- Analogous to rocket payload bay; opens in space to release payload and expose solar cells

**Shroud**
- Centrally located "belt"
- Analogous to rocket combustion chamber; ejected plasma provides thrust

**Afterbody**
- Analogous to rocket nozzle; parabolic mirror and plug nozzle (resolution: 7 to 15 cm)

**Large tank** holds liquid propellant (N₂, NH₃, or H₂) for use in space

**Small tank** holds gas (He) for attitude control
Low Cost Access To Space: The Primary Lightcraft Application

- Laser-propelled beam rider
  - Rides ground-based laser beam into space
  - Single stage to orbit
  - Very high performance
  - Airbreathing in atmosphere, uses propellants in space
  - Launch on demand to anywhere in low Earth orbit

- Simple, reliable, safe, environmentally clean
- High launch rate – anywhere, anytime with electric laser
- Less than $500 of electrical power (~$150/lb) needed to reach low Earth orbit
- Vehicle production cost estimated at $3,000 per vehicle (1 kg payload)
- Interest in this concept expressed by AF, NASA, DARPA, NRO
Ground-Based Laser Launch: Launch From A Single Site ("89" SDIO Study)

30° Initial Launch Angle

Flight Path

19.5° Final Angle

Laser-propelled launch vehicle; $V_{\text{final}} = 8 \text{ km/s}$ @ 500 km

Launch Stand

Ground-based laser launch facility

Earth surface
Ground-Based Laser Launch:
With Use Of Space Assets ("89" SDIO Study)
Program Summary

- Feasibility demonstrated through a series of historic flights and experiments at White Sands

- Composite materials and a 100-kW laser will enable vertical flights to the edge of space within a few years

- No technology breakthroughs are needed, although construction of a MW class laser and large beam director will be required

- Laser propelled vehicles could be useful in a wide range of applications

Laser Propulsion technology has the potential to make low-cost access to space a reality in the near future.
Additional Laser Propulsion Applications

• "Nanosatellites" : 1 to 10 kg – for a wide range of applications
  ➢ Potential use by AF, NASA, BMDO, NRO, communication companies, private industry, individuals
  ➢ Launch on demand to anywhere in low Earth orbit

• A vehicle can be configured as one-meter diameter telescope, making it useful for:
  ➢ High-resolution imaging, surveillance, and mapping
  ➢ Global positioning and tracking
  ➢ Threat detection and tracking
  ➢ Communications and relay
  ➢ Astronomy
## CANDIDATE HIGH-POWER LASERS

<table>
<thead>
<tr>
<th>LASER</th>
<th>ISSUES</th>
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</thead>
<tbody>
<tr>
<td>CO₂*</td>
<td>LARGE λ, ATM. ABSORPTION</td>
</tr>
<tr>
<td>CO*</td>
<td>LARGE λ, ABSORPTION, TOXICITY</td>
</tr>
<tr>
<td>HF/DF*</td>
<td>ABSORPTION, CORROSIVE CHEMICALS,</td>
</tr>
<tr>
<td></td>
<td>PULSE ENERGY (?) RUNNING COST,</td>
</tr>
<tr>
<td></td>
<td>BEAM QUALITY</td>
</tr>
<tr>
<td>OXYGEN IODINE*</td>
<td>CHEMICALS, PULSE ENERGY (?)</td>
</tr>
<tr>
<td></td>
<td>RUNNING COSTS</td>
</tr>
<tr>
<td>NEODYMIUM</td>
<td>COST, AVERAGE POWER, RUN DURATION</td>
</tr>
</tbody>
</table>

*MW-CLASS AVERAGE POWER LEVELS DEMONSTRATED*
PULSED CARBON DIOXIDE LASER TECHNOLOGY OVERVIEW
Energy Levels for the Three Vibrational Modes in the CO$_2$ Molecule with those of N$_2$ and CO

[Diagram of energy levels and transitions involving vibrational modes of CO$_2$, N$_2$, and CO, with labels for transition energies and modes.]
Basic Rate Equation and Discharge Categories

\[ \dot{n}_e = S + (a - \beta)n_e - \gamma n_e^2 \]  \hspace{1cm} (1)

- \( S \): E-BEAM SECONDARY ELECTRON GENERATION RATE
- \( a \): IONIZATION RATE
- \( \beta \): ATTACHMENT RATE
- \( \gamma \): RECOMBINATION RATE

- **E BEAM SUSTAINED**
  \[ N_E = \sqrt{\frac{S}{\gamma}} \]

- **S:SUSTAINED LONG-PULSE**
  \[ a = \beta \alpha (E / N)_G \]

- **S:SUSTAINED SHORT-PULSE**
  \[ \gamma N_E >> \beta \]
  \[ a = \gamma N_E \]
Fraction of Discharged Energy Deposited in Various Modes of a He: N₂: CO₂ 3:2:1 Mixture
Discharge Preionization or Ionization Options

PREIONIZATION OR IONIZATION

UV
- FLUSH FACTOR
- ENERGY LOADING
- APERTURE SCALING

E-BEAM

X-RAY
- FLUSH FACTOR
- ENERGY LOADING
Experimental Data Verifying Conductivity Dependence of E-beam Stabilized Discharge

\[ n_{eo} = \sqrt{S/\gamma} \quad (2) \]
Specific Output Energy (Room Temp-gas)
Specific Output Energy (Cold-gas - 220°K)
RELEVANT LEGACY PROGRAMS
Thumper Laser
25 X 200 CM ABEL E-Gun
Candidate Concepts/Architectures

- 100 kW CO$_2$ Pulsed Laser

- Multi-Megawatt Class Pulsed CO$_2$ Laser
Closed-Cycle 100 kW Transmitter

ADVANTAGES
- Design based on previously developed power amplifier (government funded LICD contract) system
- Avoids difficulties of significant scaling + retrofit
- Runs any gas mixture/isotopes
- Relatively small footprint
- Could use some existing hardware (e.g., E-gun, bushings, etc)

DISADVANTAGES
- Represents state-of-the-art which entails some risks
  - DVT’s will be required to support PDR
- In-line catalysis will be required for long-duration isotope runs
- Longer development time compared with other options
Representative Schematic of Flow Loop Components
Projected MOPA Outputs

Oscillator:
- Dim: 10x10x250 cm$^3$ x 2
- Pump: 150 J/l; $P_{out} = 168.75$ kW
- Pump = 250 J/l; $P_{out} = 281.25$ kW
- Rep Rate = 125 Hz
- $T_p = 20 \ \mu s$
- Extraction Eff. = 20%

Amplifier:
- Aperture = 30x30 cm$^2$
- Pump = 250 J/l @ $g_0 = 0.03$ cm
- Isat = 25 kW/cm$^2$ @ 1 atm.
- Mixture: 3:1:0.08 (N2:CO2:H2)
Schematics of Flow system

Gas Pressure:
P1 = 150 Atm
P2 = 2 - 2.5 Atm
P0 = 1 Atm (ambient)
Flow speed: 50 m/s

Gas Physical Parameters:
Mixture: N2:CO2:H2 (3:1:0.08)
a = 271 m/s (acoustics)
M = 0.18 (Mach No)
m = 31.5 (Effective Molecular Weight)
Density = 1.3 kg/m³
Laser Operation Requirements

Flow System: Blow down
- Gain section
  Cross Section: A=0.3 x 3.0 = 0.9 m²
  Volume: V = 0.3 x 0.3 x 3.0 = 0.27 m³
  Flow speed: u=50 m/s (@ 125 Hz & flash factor=1.3)
  Dynamic pressure: ΔP=2000 Pa (0.02 Atm)
  Mass flow rate: q=60 kg/s / module (45 m³/s std)
  Run time: t = 300 sec
    Total: Q=240 kg/s (72 m tons)

- Plenum chamber:
  Volume: V2=0.5 x 3.0 x 1.5=2.25 m³
  Static pressure: P2 = 2.02 x 10⁵ Pa (2 atm)
  Sonic orifice plate: perforation = 17.5 %
  Flow screen: loss > 0.2 - 0.3
  Skin friction: loss ~ 0.08

- Gas Storage Tank: Run time=300 Sec & 4 - 5 Runs
  Pressure: P1 = 2.066e+7 Pa (200 atm)
  Volume: V1 = 68 m³ x 4
Laser Operation Requirements:

Flow Acoustics:

- Physical parameters:
  \( \gamma = 1.39, \ M = 31.25 g, \ C_p = 730.4 \text{ J/kg-K}, \ & c = 286.3 \text{ m/s} \)
  \( \beta = 4.063 \times 10^{-4} \) (Gladstone-Dale Coeff.)

- Medium homogeneity requirements:

<table>
<thead>
<tr>
<th>( \Delta \rho / \rho )</th>
<th>BQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.38 \times 10^{-3}</td>
<td>2.0</td>
</tr>
<tr>
<td>4.10 \times 10^{-4}</td>
<td>1.1</td>
</tr>
<tr>
<td>2.72 \times 10^{-4}</td>
<td>1.05</td>
</tr>
</tbody>
</table>

@ \( \lambda = 10 \mu \text{m} \) & l = 3 m
Acoustics Suppression

Pumping induced medium in homogeneity:
- \( \Delta P/P = 0.94 \) @ \( P = 300 \) J/l

Acoustic Suppression:
- Flow direction
  Expansion horn provides impedance match eliminating reflection of pressure waves
- Normal to flow direction
  Using acoustics muffler to dump out transverse pressure waves
  Muffler requirements:
  Attenuation factor < 0.55
  Number of bounces between pulses: \( n = 8 \) (\( \Delta \rho/\rho \sim 1.0 \times 10^{-5} \))
Conceptual Design of Four-Unit Multi-Megawatt CO2 Laser

- Beam Combining Concept
- Power Oscillator or Master Oscillator-Power Amplifier
  Unstable Resonator Cavity
  Grating & Rotating mirrors Beam-Combine Techniques
- Flow and Gas Handling System
  Blow down - Exhaust to Atmosphere
- Acoustics Suppression
  Expansion Horn Down Stream
  Anode Muffler
Transmitter Schematic Block Diagram For Single-Module Megawatt-Class Laser
Beam Combining with Synchronized Rotating Mirrors

M1 M2 M3 M4

T = t1

G1 G2 G3 G4

Time

Output Pulse format
Conceptual Beam Combining with Hot Cell
Intra-cavity
Conceptual External Beam Combining Design

M1 & M2: Cavity mirrors
BS: Beam splitter
G: Intracavity Grating
Hc: Hot cell
GC: Laser Gain Medium
Oscillator Parameters for Each Transmitter

- Energy Loading: $E_p = 300 \text{ J/l}$ *
  Gain Vol = 0.27 m$^3$ (x4)
  $A - K = 0.3 \text{ m}$
  Gain Length = 3 m

- Specific Laser Output = 65 J/l

- Estimated Extraction Efficiency: $\eta = 20\%$

- Rep Rate: $R = 125 \text{ Hz } @ \ 20\mu$s

- Output Wavelengths **: 10.6, 10.2, 9.6, & 9.3 $\mu$m (Mixed)

- Gas Mixture : 3:1:0.08 (N2:CO2:H2)

- Pressure : $1.013 \times 10^5 \text{ Pa (1 Atm)}$

- Flash Factor : 1.3

** Select P & R Branch Lines in Both Bands
* Higher loadings at reduced gas temperature
Optical Resonator Cavity: Optical Components

- Resonator Type: Confocal Unstable with Rotating Mirrors Beam Combining
  Magnification: M=4
  Cavity length: L=36.5m
  Equivalent Fresnel Number = 3.4
  Cavity Mirrors: M1 = 97.3m (concave)  M2 = 24.3m (convex)

- Gain Cell: 0.3 x 0.3 x 3.0 m³
  Gain Length: l = 3 m

- Beam Combine Mirrors: 75 x 75 cm² Flat (30 x 30 cm² apertures)
  @ \( \lambda = 10.591 \, \mu \) [I - P(20)]
  M1 (0 hole)  M2 (1 hole)
  M3 (2 holes)  M4 (3 holes)

- Low Pressure Hot Cell (Hc): 0.3 - 0.5 Ghz suppression near line center

- Output Scraper Mirror: D = 0.075 m (tapered)
Power Oscillator: Optics

End Mirrors: M1 Concave (R1 = 97m)  
M2 Convex (R2 = 24m)
Magnification: M = 4
Output Scraper: SP 36x36 cm (outer)  
7.5x7.5 cm (inner)

Acoustic Muffler: AM
Electrodes: E

Cavity Length: 36.5m
Gain Length: 3m
Aperture: 0.3x0.3 m
Oscillator With Line Selection By Intracavity Hot Cell And Grating

M1 & M2 : End Mirrors
Hc : Hot Cell
AM : Acoustic Muffler
PS : Output Coupler
GT : Grating
Master Oscillator & Power Amplifier: MOPA

IST: Optical Isolator
M3: Turning Flat
OE: Beam Expansion Optics & Interface
PROPAGATION ENHANCEMENT

CONCEPTS
Peak Line Frequency Suppression Using Hot Absorption Cell

$\Delta v : 4 \text{ GHz. @ 1 atm.}$
$Dv : \text{Longitudinal mode separation (c/2L)}$
\( C^{12}O^{16} \) Band II P22 Transmission From Specified Alt to Space

Fascode Tropical, Vis = 23 km, Background Strat - Mod Vol

\[
f_0 = 3.132896150046396 \times 10^{13} \text{ Hz}
\]
\[
\lambda_0 = 9.56917955916159 \mu
\]
\[
\kappa_0 = 1045.02166964 \text{ cm}^{-1}
\]
CONCLUSIONS

- A PULSED CO₂ REPETITIVELY PULSED TRANSMITTER WHICH USES A 300-SECOND BLOWDOWN AND BEAM COMBINING CAN PROVIDE THE POWER LEVELS AND ENERGIES OF INTEREST

- SPECTRAL TAILORING AND MOUNTAIN TOP OPERATION SHOULD PROVIDE REASONABLE ATMOSPHERIC TRANSMISSION

- LOW COST OPERATION ACHIEVABLE WITH HELIUM-FREE GAS MIXTURES, WHICH USE NITROGEN, CARBON DIOXIDE AND SMALL QUANTITIES OF HYDROGEN

- SUBSCALE TEST WILL BE USED TO ANCHOR DESIGN AND THUS REDUCE RISK

- LEGACY PROGRAMS SUPPORT MANY ASPECTS OF THIS APPROACH

- GROWTH POTENTIAL WITH COLD-FLOW AND AERO WINDOWS SHOULD DOUBLE POWER OUTPUT