Laser Microengineering and the Advances that can be Gained by Using the Jefferson Laboratory Free Electron Laser

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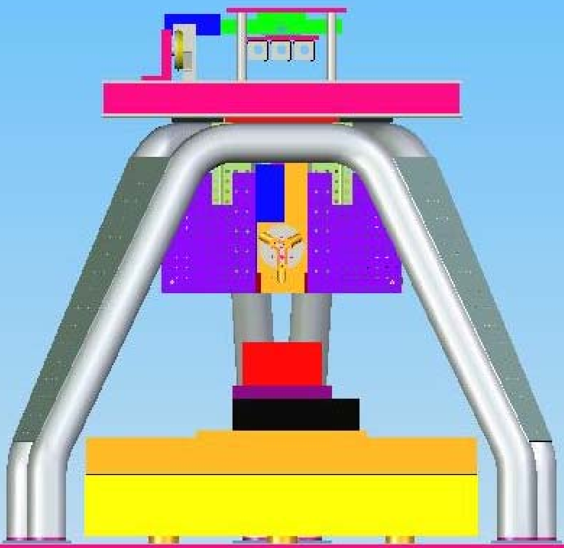
The Laser Microengineering Experimental Station”

at the

Jefferson Laboratory Free Electron Laser Facility



Enable Development of Laser Materials Processing Technology in the USA

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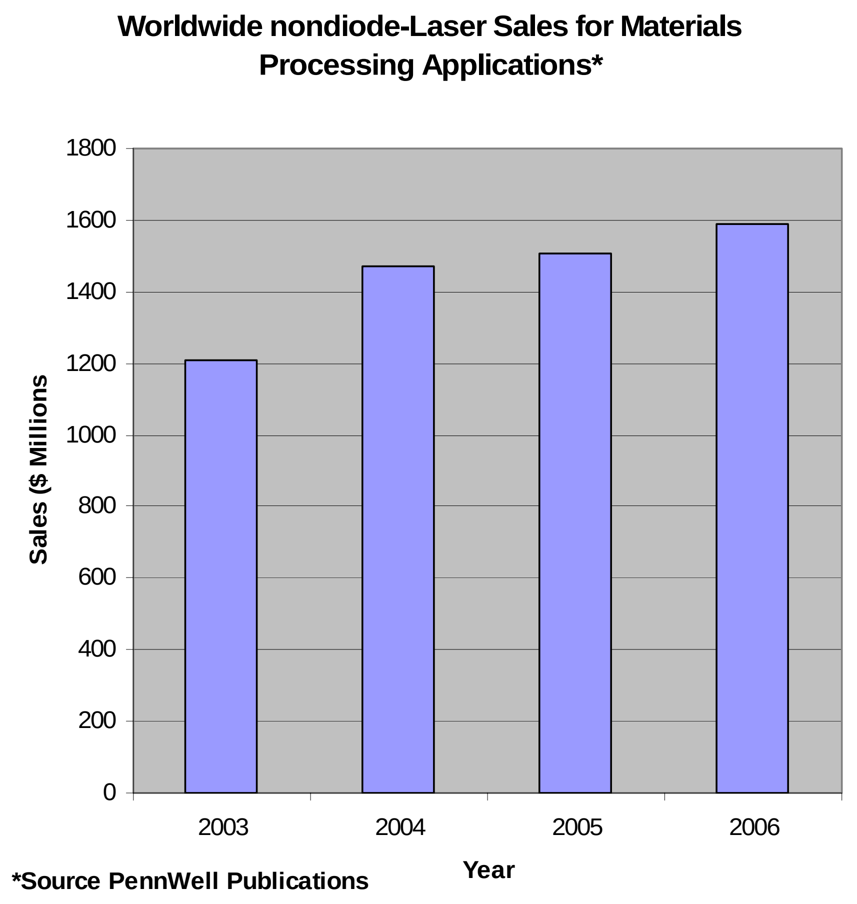
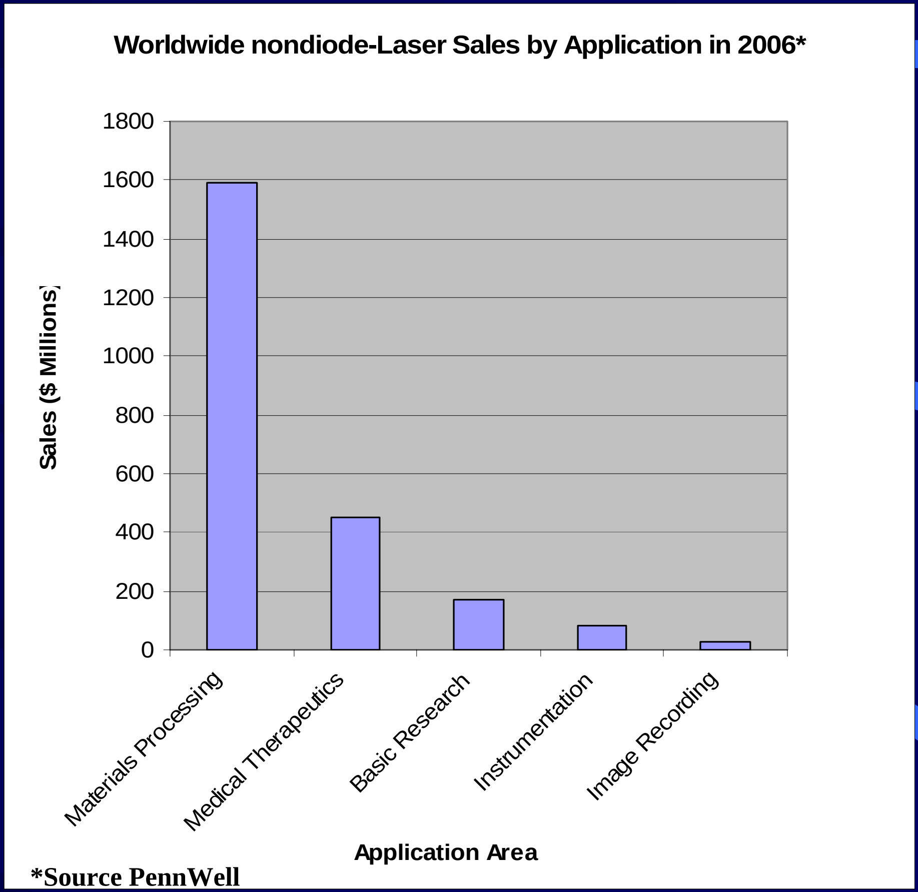
Materials Processing Applications Lead World Wide Sales


Worldwide nondiode-Laser Sales for Materials Processing Applications*

*Source PennWell Publications

~ 1.6 $B in Laser Sales
Alone Expected in 2006


Worldwide nondiode-Laser Sales by Application in 2006*

*Source PennWell Publications

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Laser Microengineering

Controlled Alteration of a Material Property in the Surface or Volume that with Patterning Leads to the Development of a Structure/Device/Component

Examples of Processes

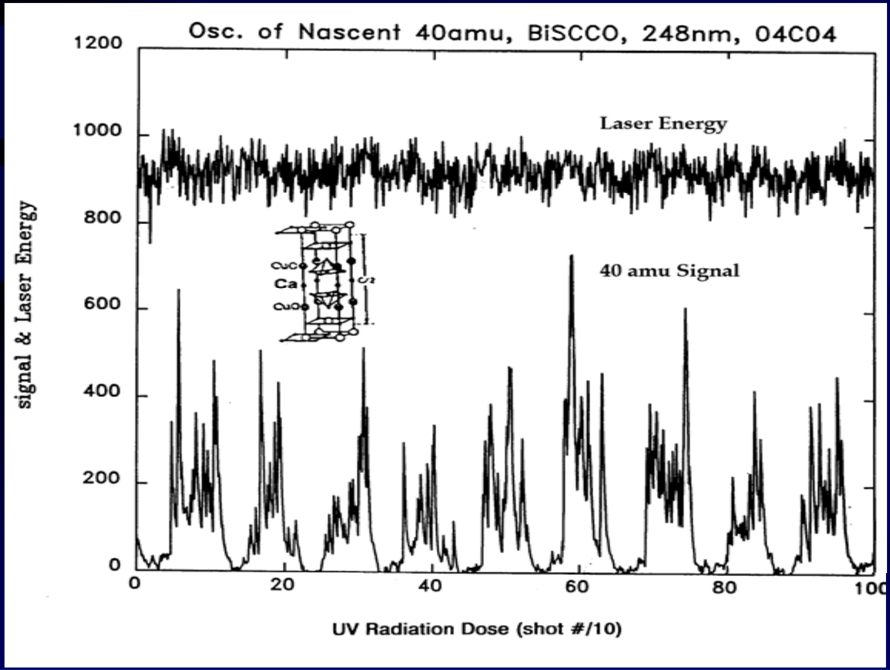
- Single laser volumetric exposure in photoactive materials (e.g. holography).
- Multi laser volumetric exposure in active materials (e.g. photonic crystals).
- Percussion and ablative machining
- Polishing (e.g. mirrors coatings)
- Laser chemical vapor deposition (LCVD)
- Laser induced plasma deposition
- Laser induced forward transfer (LIFT)
- Laser induced phase transformation (i.e. crystallization, amorphous)
- Fusing (i.e. welding on the micron scale)
- Bending (i.e. curvature control on the nanometer scale)
- Texturing (i.e. control of surface topology)
- Pulsed laser desorption (atoms/molecules) and ablation (monolayers or greater).

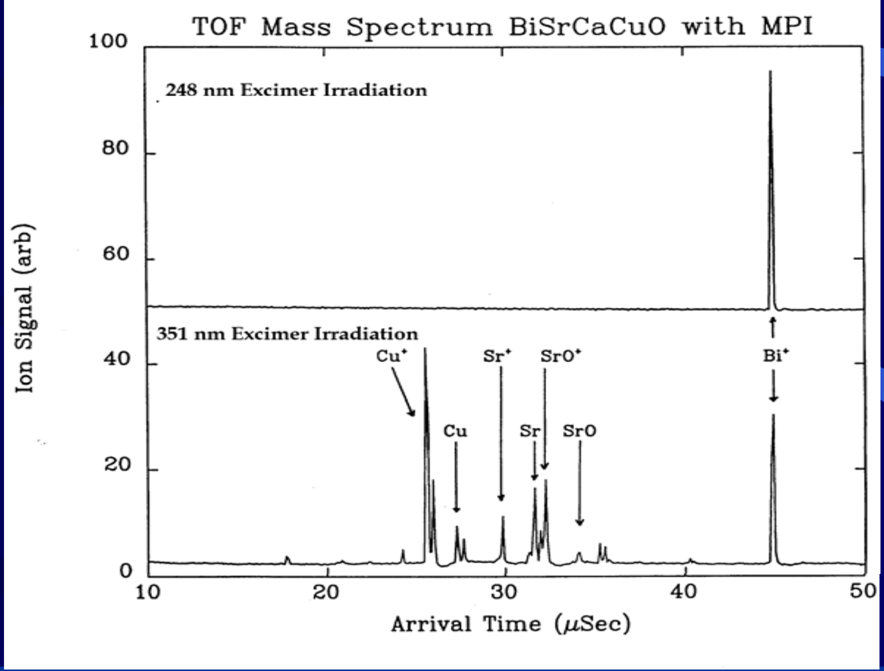
“Rules of thumb” for Laser Microengineering

- In inducing a physical process by laser irradiation, there is more control with multiple small-energy laser pulses rather than a single large-energy pulse.
- Laser material interaction processes that are mostly driven by non-thermal events are likely to be more precise than processes governed by thermal induced phenomena.
- Tuning to a laser material interaction resonance helps.

Examples From Prior Experiments
“atomic layer-by-layer pealing & species specific desorption”*

- Low-KE Pulsed Atomic Beam Source for Controlling Epitaxial Deposition.
  - Practical applications
    - Atomic beam of specific species “layer-by-layer” atomic pealing of surfaces.
  - Impracticality
    - Measured removal rates 10^{-7} – 10^{-2} monolayers/shot (10^{11} species/cm^2 per shot).
  - Scaling
    - At MHz laser repetition rate deposition rates can be made to compete with MBE (deposition rates 0.1ML/s^{-1}).





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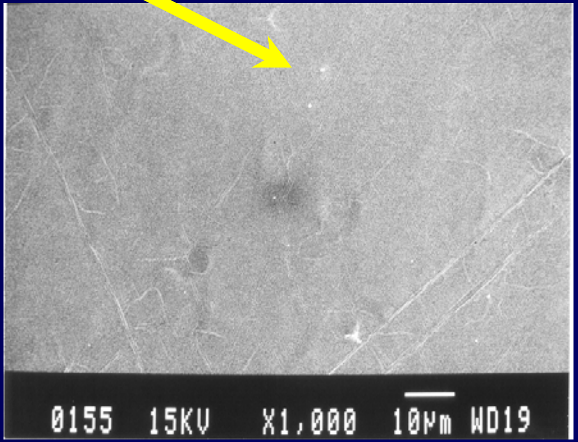
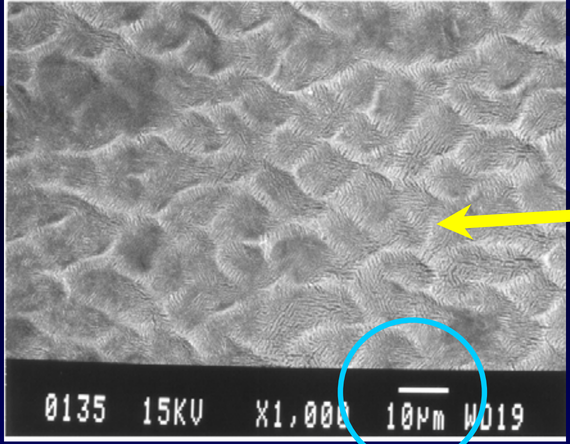
* H. Helvajian, L. Wiedeman and H. –S. Kim “Photophysical Processes in Low-fluence UV Laser-Material Interaction and the Relevance to Atomic Layer Processing”, Adv. Mat. For Opt. And Elect. Vol. 2 (1993) 31-42.

Examples From Prior Experiments
“surface texturing in the non-thermal domain”*

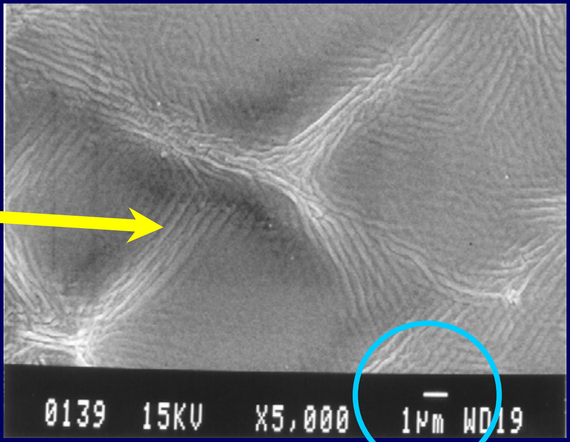
- Laser induced surface texturing in the “non thermal domain”.
  - Practical Applications
    - Fabrication of a catalytically active surface on metals.
    - Nanometers scale control surface topological features
  - Scaling
    - 1 KHz laser can prepare surface at speeds ~ 0.005 mm/sec
    - 1 MHz laser can prepare surface at speeds ~ 5mm/sec.

15K Laser Shots (355nm)
Low Fluence (<30mJ/cm²)





200K Laser Shots (355nm) Low Fluence (<30mJ/cm²)



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*D. P. Taylor and H. Helvajian “ Pulsed UV laser induced desorption of ions from Aluminum”, Surface Science 451 (2000) 68-75.

- Practicalities of Industry
  - Utilizing large number of laser pulses per unit area means increased processing time and therefore increased cost.
    - Advantages of processing material in the “non-thermal regime” are nullified because of the large number of required laser pulses. These processes become relegated as scientific observation and deemed not practical.

- Possible “game” or paradigm changers
  - A laser with high repetition rate (>MHz) and high average power that is wavelength tunable.
  - A means for controllably delivering, with high fidelity, laser pulses with prescribed amplitudes (energy) to a material that is moving under pattern control.
  - A laser material process in which the laser light only “activates” the material but the desired physical transformation occurs in a follow-on batch process (e.g. chemical etch step)

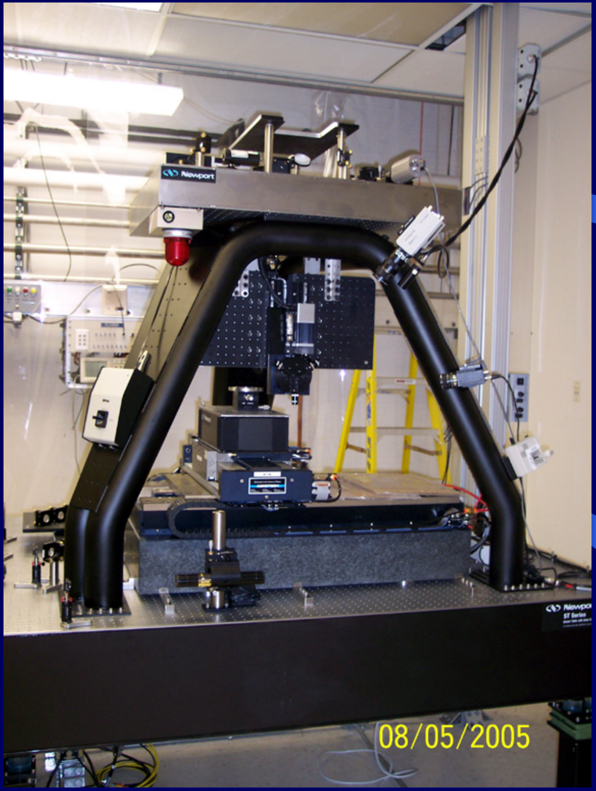
The JLAB IRFEL & UVFEL

Unique Light Sources for Laser Material Processing

High Repetition Rate - Tunability

The Laser Microengineering Experimental Station (LMES) at JLAB

A Three Axes Motion Tool Designed For the Controlled Delivery of the FEL Light
to a Moving Surface (speeds > 400mm/sec)
with
Positioning Accuracy on the Nanometer Scale
and
Illumination Spot Size that can be Dialed Down to Micrometer Scale



08/05/2005

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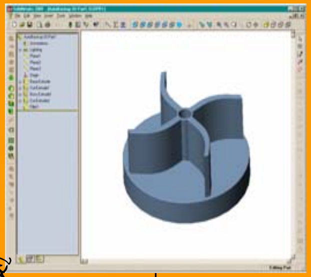
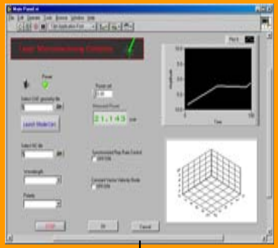
Useful Attributes of the LMES

User Capabilities Microengineering & Rapid Prototyping
Software Module Sequences

SolidWorks

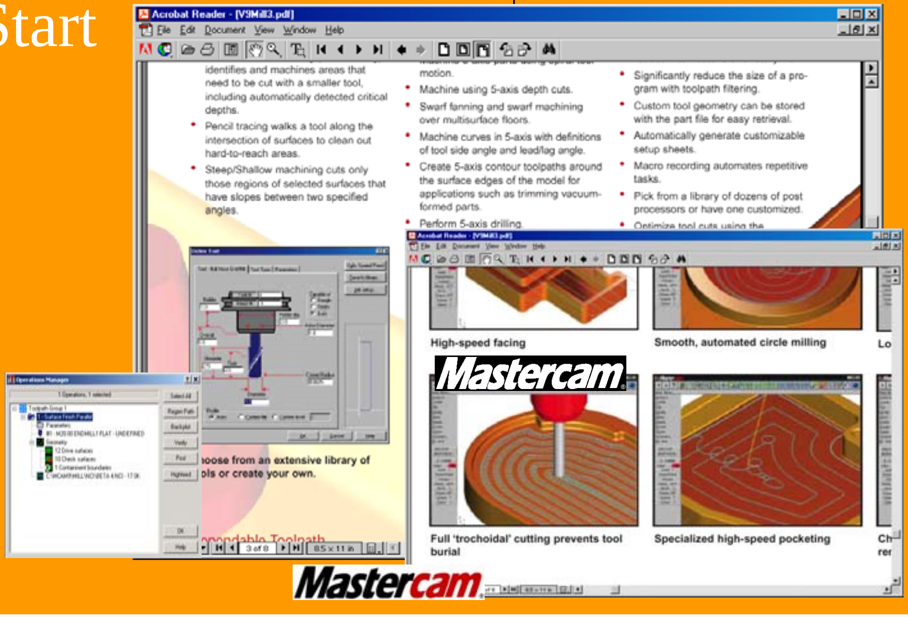


NATIONAL INSTRUMENTS LabVIEW



Automated
RUN JOB

Start



identifies and machines areas that need to be cut with a smaller tool, including automatically detected critical depths.

- Pencil tracing walks a tool along the intersection of surfaces to clean out hard-to-reach areas.
- Steep/Shallow machining cuts only those regions of selected surfaces that have slopes between two specified angles.

motion.

- Machine using 5-axis depth cuts.
- Swarf fanning and swarf machining over multisurface floors.
- Machine curves in 5-axis with definitions of tool side angle and lead/lag angle.
- Create 5-axis contour toolpaths around the surface edges of the model for applications such as trimming vacuum-formed parts.
- Perform 5-axis drilling.

- Significantly reduce the size of a program with toolpath filtering.
- Custom tool geometry can be stored with the part file for easy retrieval.
- Automatically generate customizable setup sheets.
- Macro recording automates repetitive tasks.
- Pick from a library of dozens of post processors or have one customized.
- Optimize tool cuts using the

High-speed facing

Smooth, automated circle milling

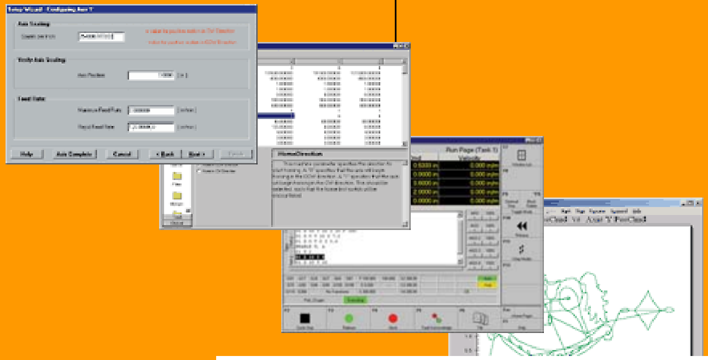
Full 'trochoidal' cutting prevents tool burial

Specialized high-speed pocketing

hoose from an extensive library of
ols or create your own.

Mastercam

Mastercam



AUTOMATION 3200 THE INTELLIGENT 32 AXIS MOTION, VISION & I/O SYSTEM

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Dynamic Control of Laser Power to Compensate for the Expected Changes in Motion Velocity that Occurs During Patterning

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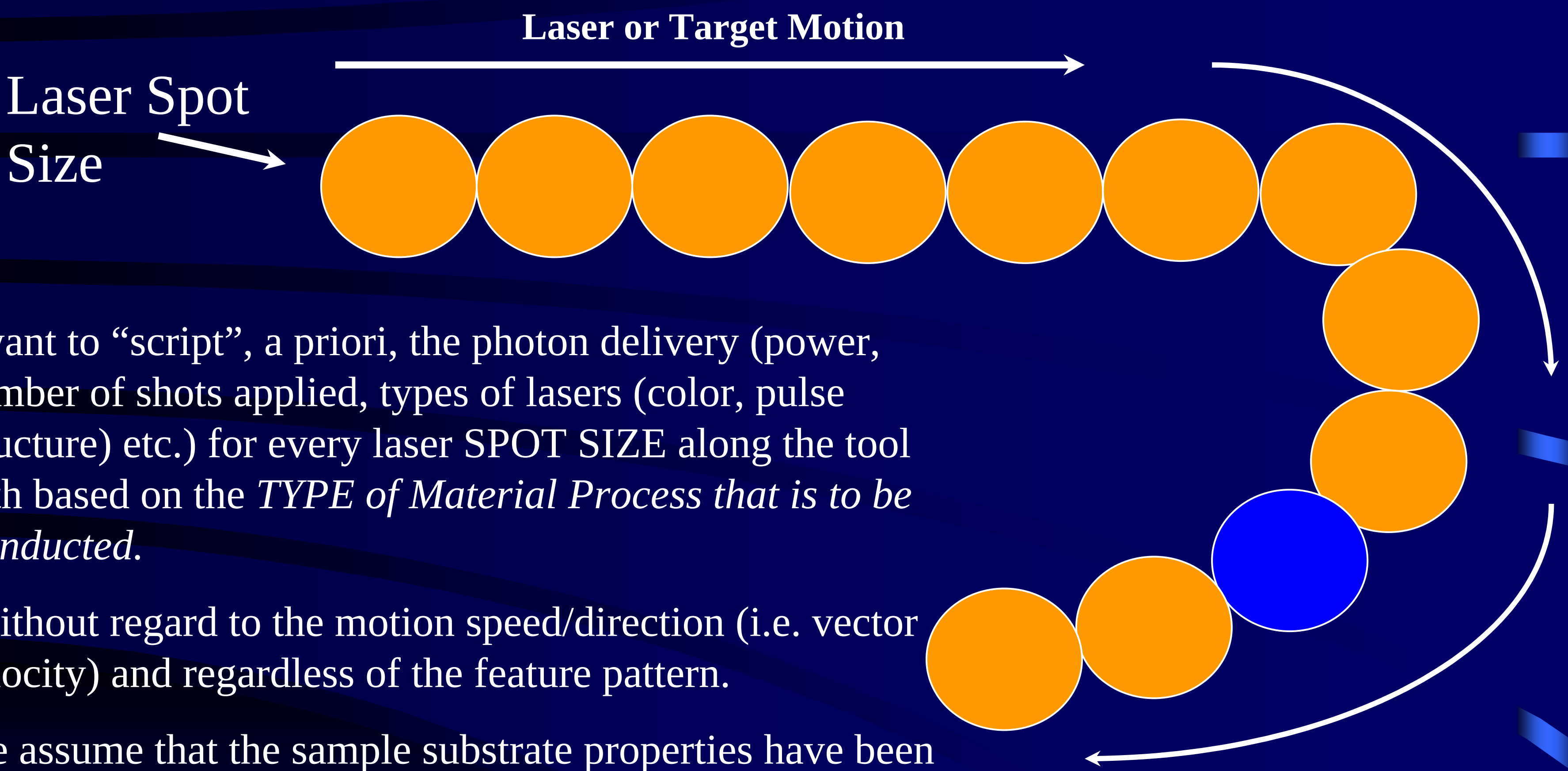
High Fidelity Control of Laser Pulse Energy to “target”



Laser or Target Motion

Laser Spot Size

- I want to “script”, a priori, the photon delivery (power, number of shots applied, types of lasers (color, pulse structure) etc.) for every laser SPOT SIZE along the tool path based on the *TYPE of Material Process that is to be Conducted.*
- Without regard to the motion speed/direction (i.e. vector velocity) and regardless of the feature pattern.
- We assume that the sample substrate properties have been mapped in 3D, a priori.
- We assume that the material has “properties” that can be expressed via controlled deposition of light.

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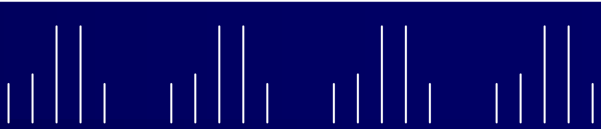
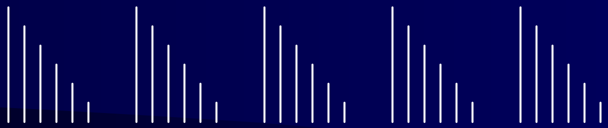
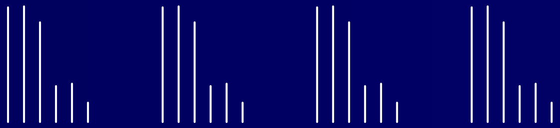
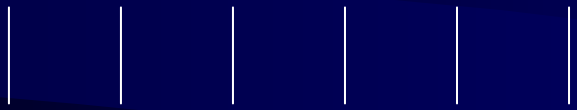
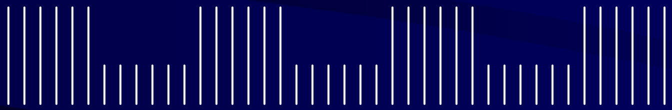
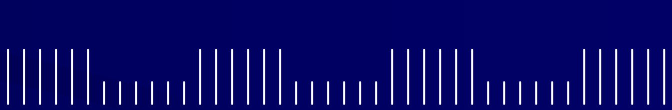
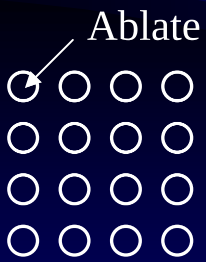
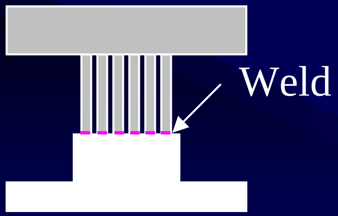
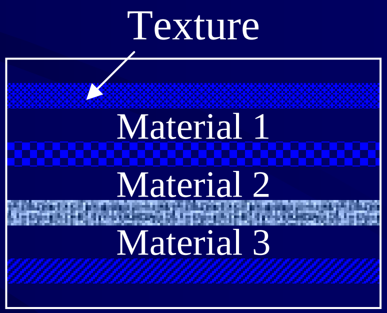
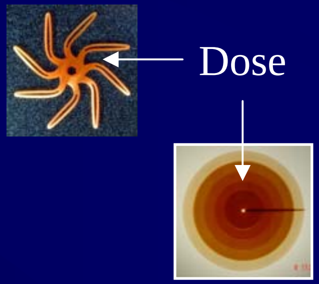
Laser Material Processing Using Modulated Pulse Sequences

Process	Laser Pulse Structure Mat1	Laser Pulse Structure Mat2
a] Ablation		
b] Welding		
c] Texturing		
d] Dosing		









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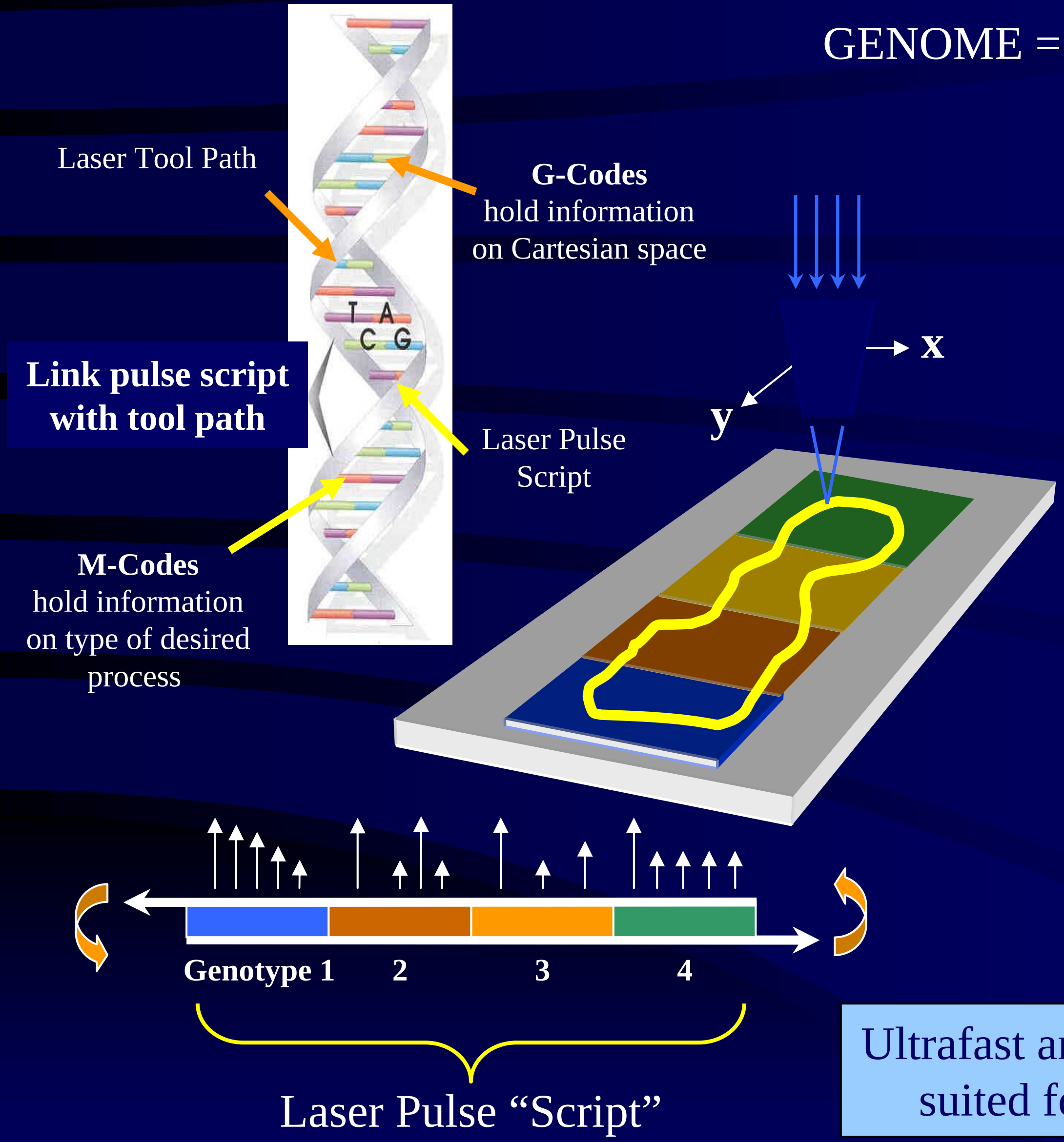
Use of Digitally-Scripted Genotype Pulse Patterns



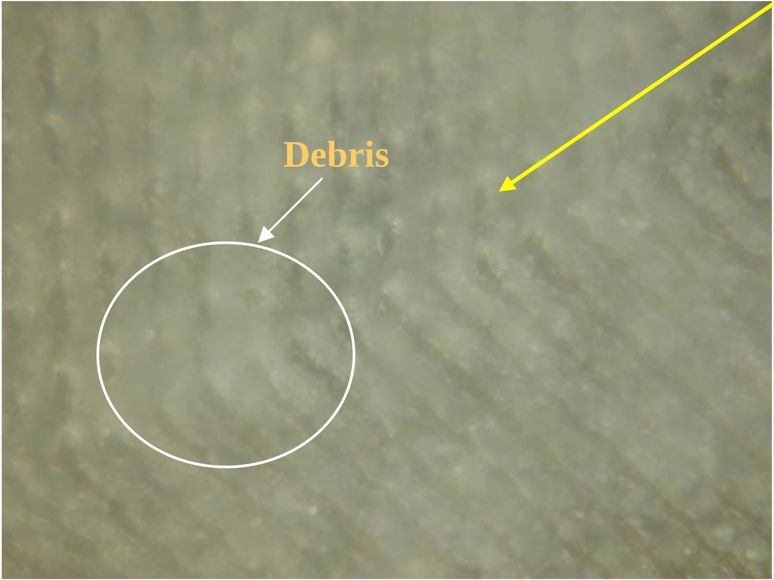
GENOME = Sequence of concatenated genotypes that define a “script”.
“Script” contains attributes that are to be expressed according to the specific sequencing.

- Laser-processing programmer develops a pulse “script”
- “Script” is synchronously matched with the laser tool path
- “Script” can be altered on a per laser spot basis
- Feed rate can be “throttled” to control speed, exposure and resolution

Ultrafast and high repetition rate lasers are ideally suited for digitally-scripted laser processing

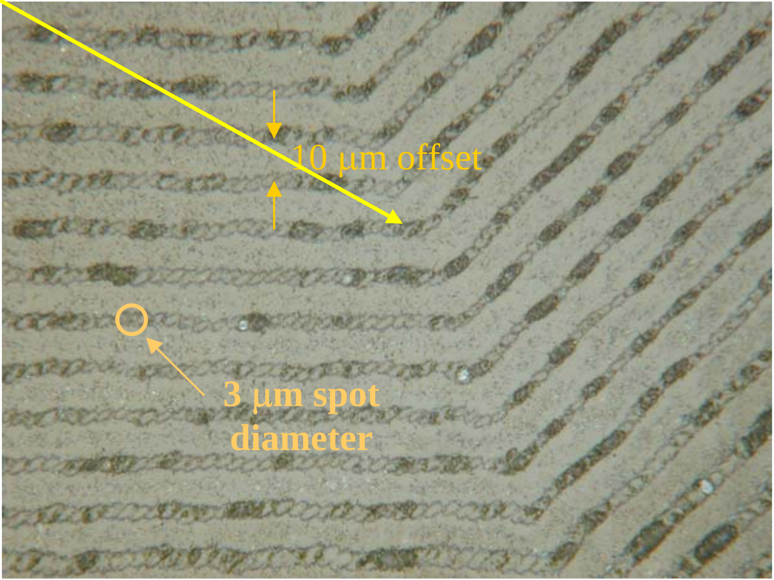
Ablation of Glass Using Modulated fs Laser Pulses at 400 nm

Velocity Compensation OFF



- Spallation and debris formation
- Fractures and thermal-induced stress

Velocity Compensation ON



- Localized material removal
- Patterns are clean and well defined

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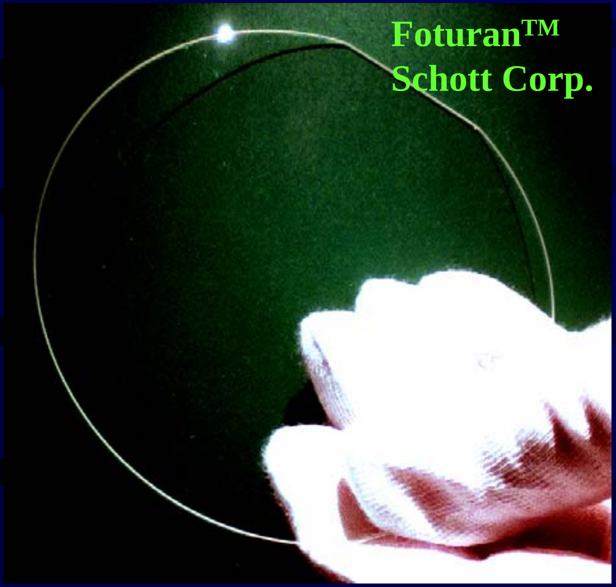


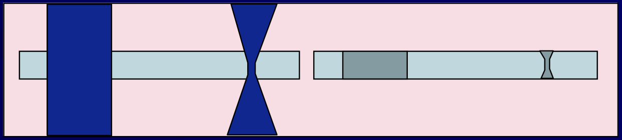
Processing Photoceramic Glasses

Typical Process Flow

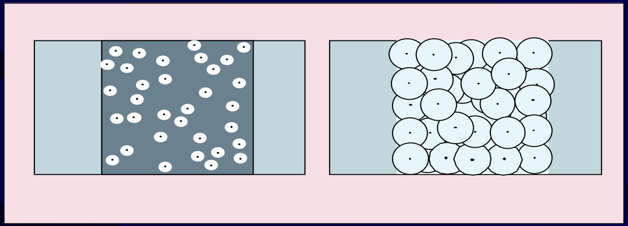
Step 1: UV Illumination/Latent Image

$$Ce^{3+} + h\nu \text{ (312nm, 2 J/cm}^2\text{)} \rightarrow Ce^{4+} + e^-$$

$$e^- + Ag^+ \rightarrow Ag^0$$

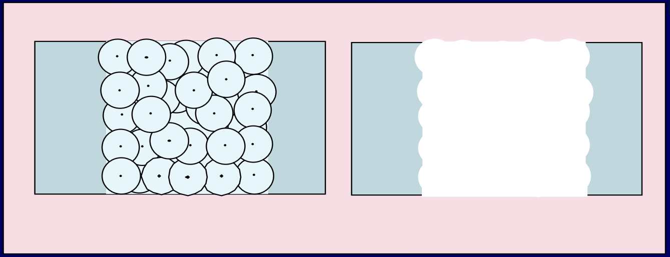


Step 2: Ceramization to a Meta-Silicate



Step 3: Preferential Isotropic Etching

- Crystalline Li_2SiO_3 dissolves 20x faster than the amorphous glass in 5% hydrofluoric acid.
- $Li_2SiO_3 + 3HF \rightarrow 2LiF + H_2SiF_6 + 3\,H_2O$



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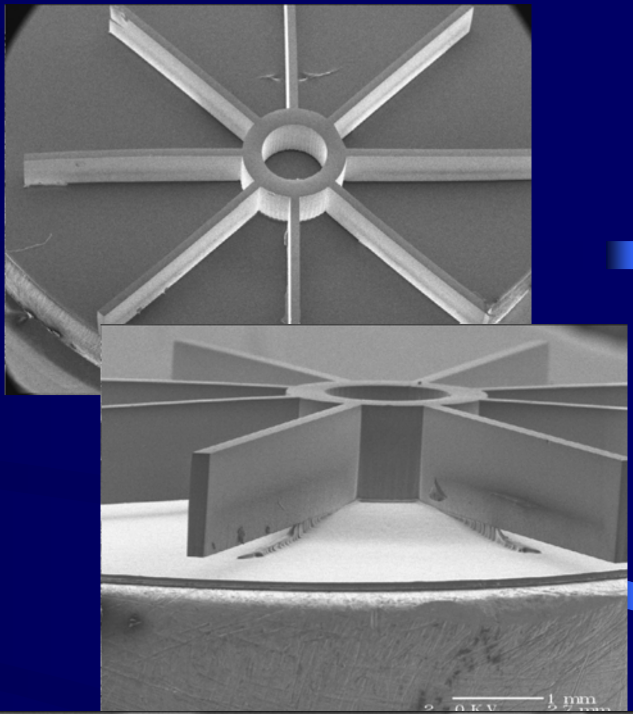
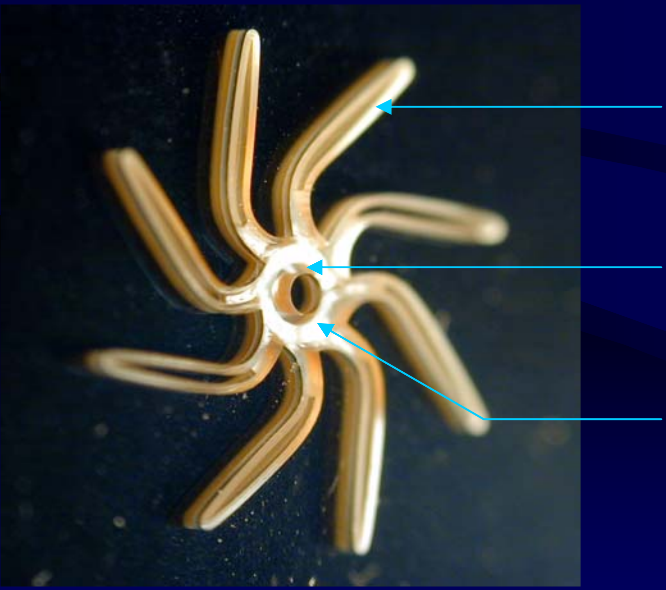
Arrays of Meso-scopic Scale Microturbines

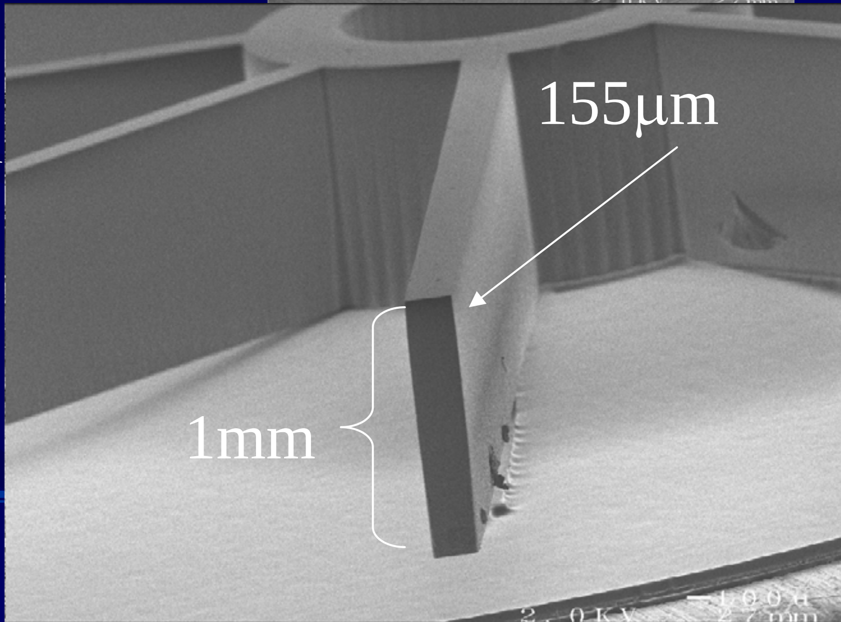




Rotors: 200 µm thick

Spindle depth: 500 µm

Trough: 300 µm



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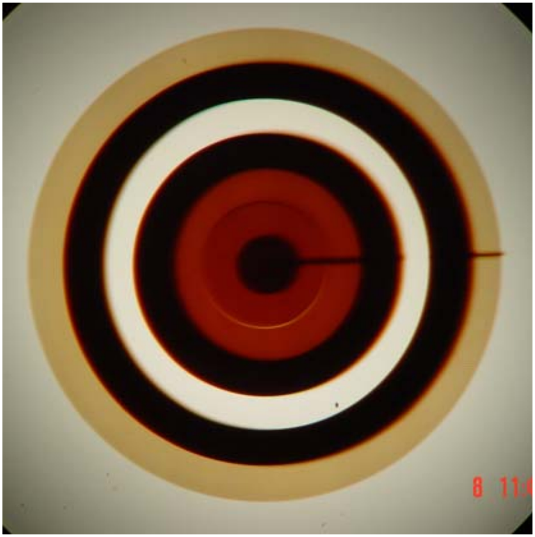
Exposed and baked



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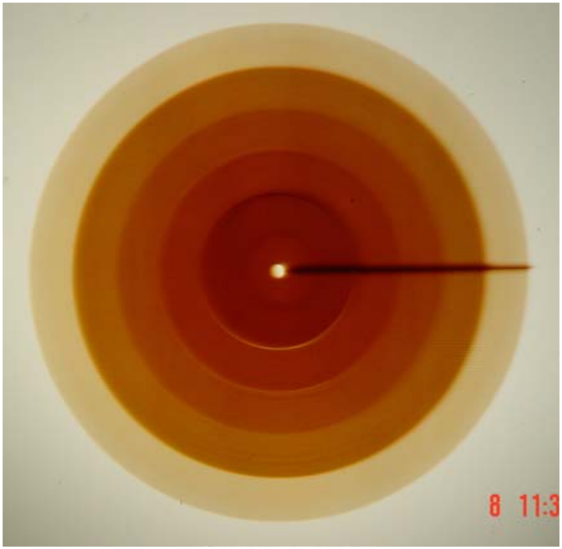
Control of Optical Transmission (IR)



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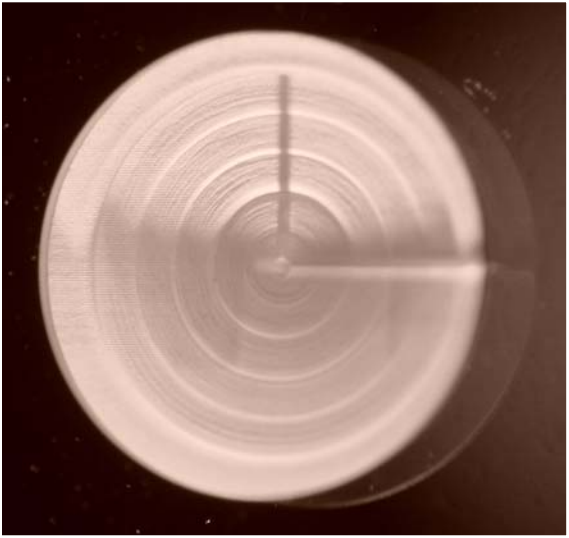
What time is it?
THz Fresnel Lens



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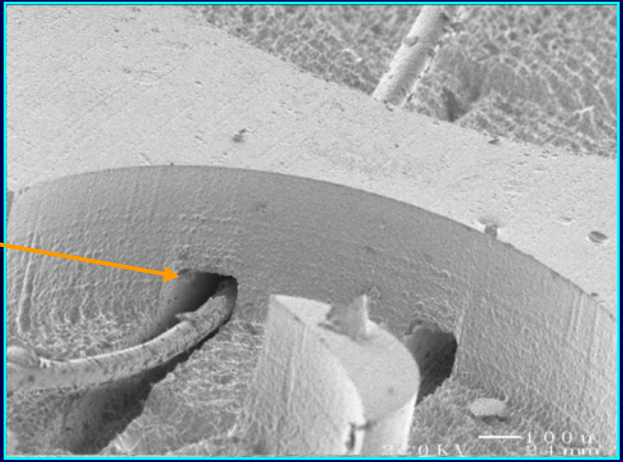
Undercut Structures



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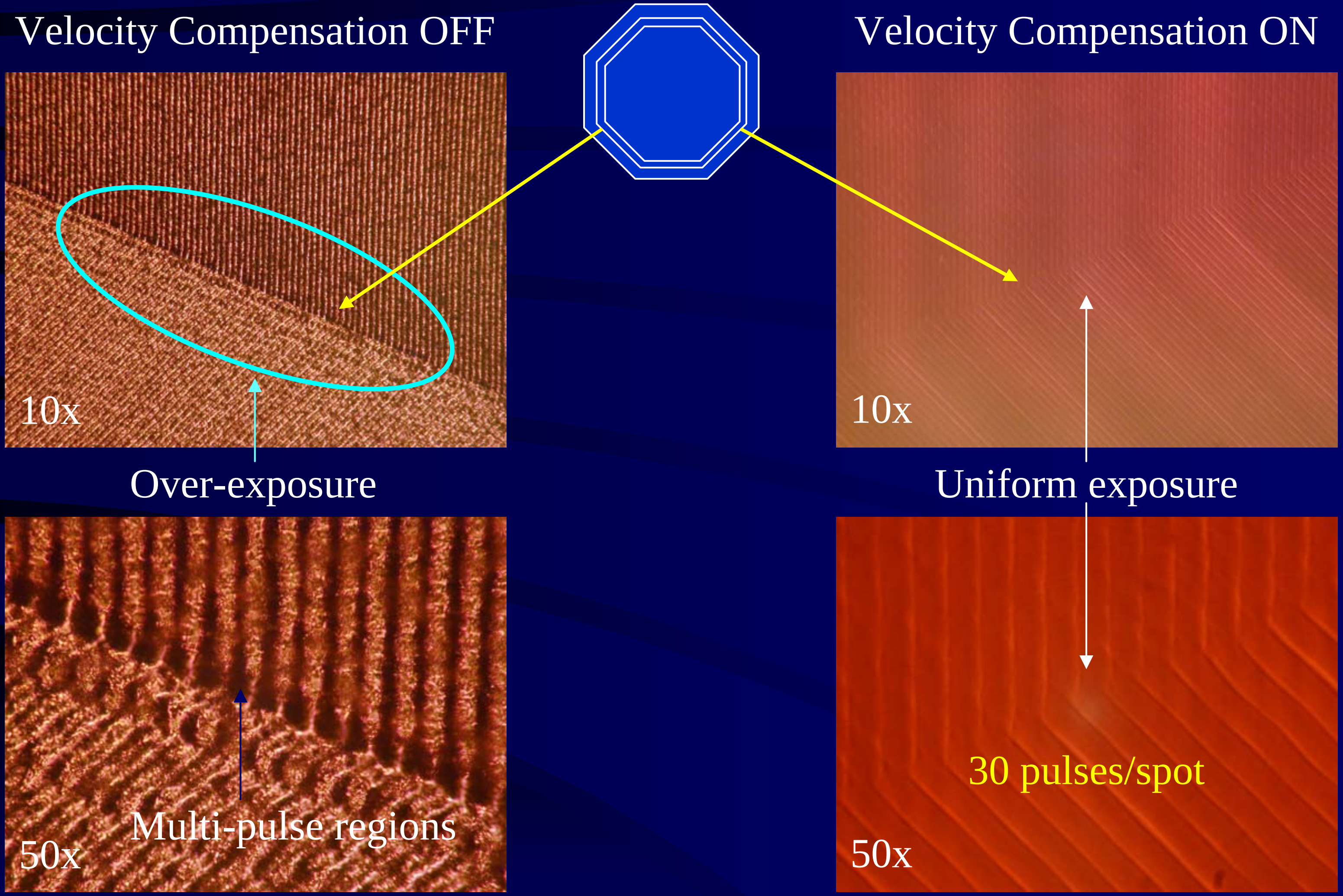
Exposure of Photosensitive Glass Using Modulated fs Laser Pulses at 400 nm



Velocity Compensation OFF

Velocity Compensation ON

10x

10x

Over-exposure

Uniform exposure

Multi-pulse regions

50x

30 pulses/spot

50x

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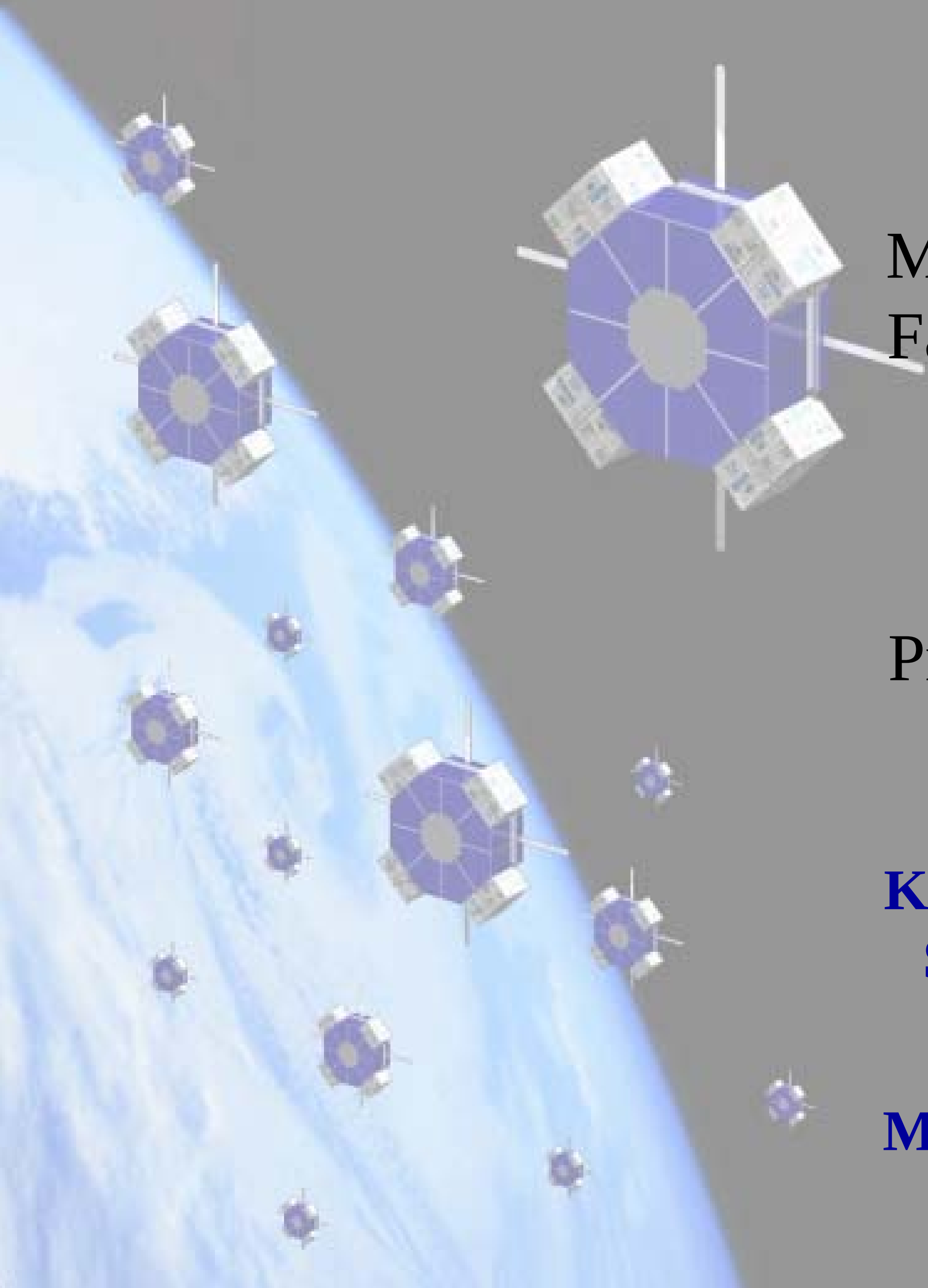
Why is the The Aerospace Corporation, a Federally Funded Research & Development Center of Department of Defense Interested in the Development of a LMES?



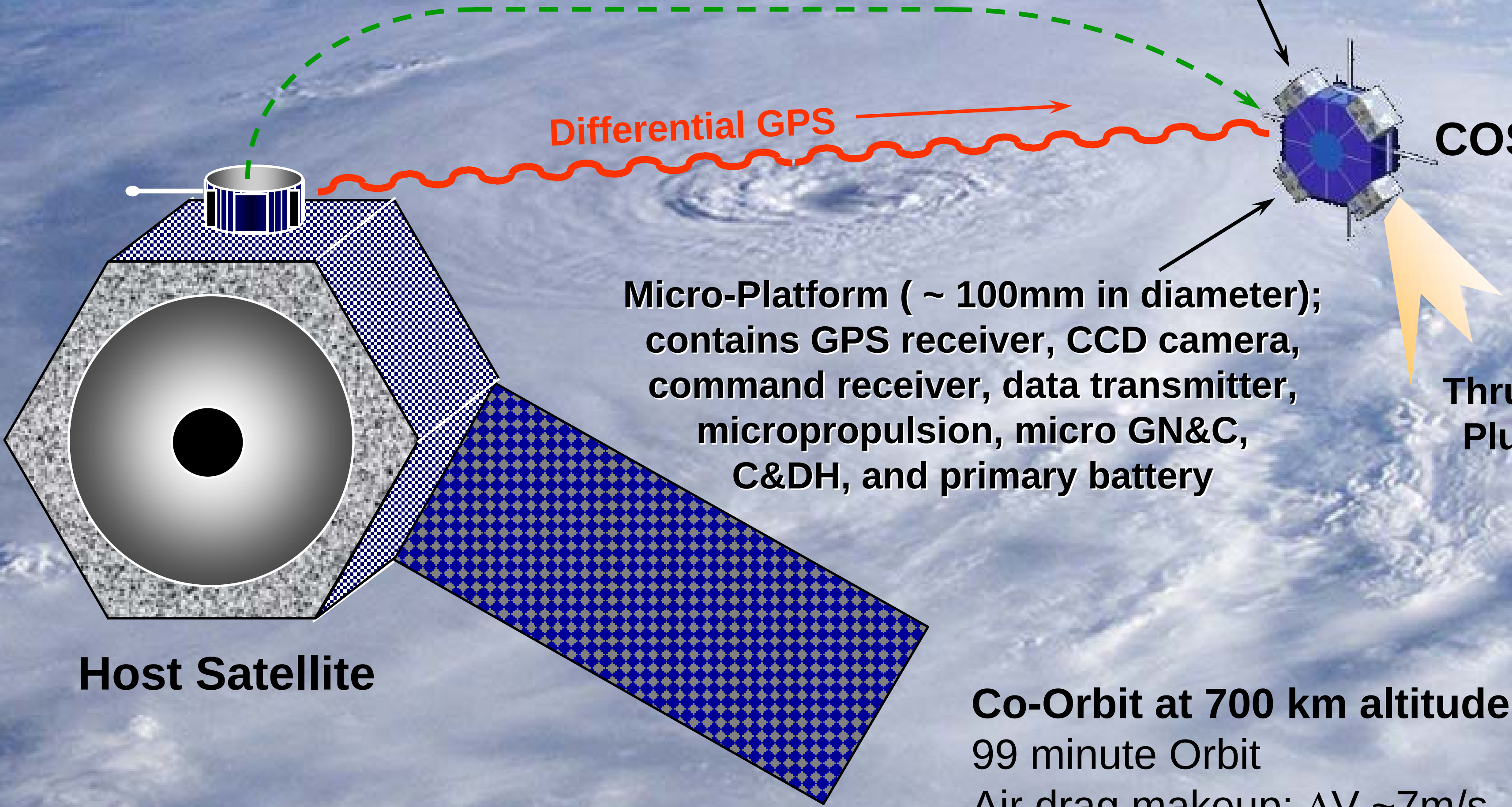
Development of a Direct-Digital Manufacturing Methodology for the Design, Fabrication and Assembly of Small Satellites

Satellites that are Mass Producible and can be Mass-Customized

Key: Materials in Satellite Must Serve a Multifunctional Role

Consider Glass-Ceramic Materials as Structural Support For Small Satellites

The Co-Orbiting Satellite Assistant (COSA) Mission



Antenna for Comm-link to Host
Vehicle and Earth

Differential GPS

COSA

Micro-Platform (~ 100mm in diameter);
contains GPS receiver, CCD camera,
command receiver, data transmitter,
micropropulsion, micro GN&C,
C&DH, and primary battery

Thruster
Plume

Host Satellite

Co-Orbit at 700 km altitude:
99 minute Orbit
Air drag makeup: ΔV ~7m/s
Observation Orbit: ΔV ~.180 m/s
Total Mission: ΔV ~ 8m/s

COSA Observation Trajectories

Co-orbital with Inclination:

Phasing orbit:

- 1st impulse: 3 mm/s
- 2nd impulse: 3 mm/s
- 99 minutes @ 700 km
- mN thrust levels

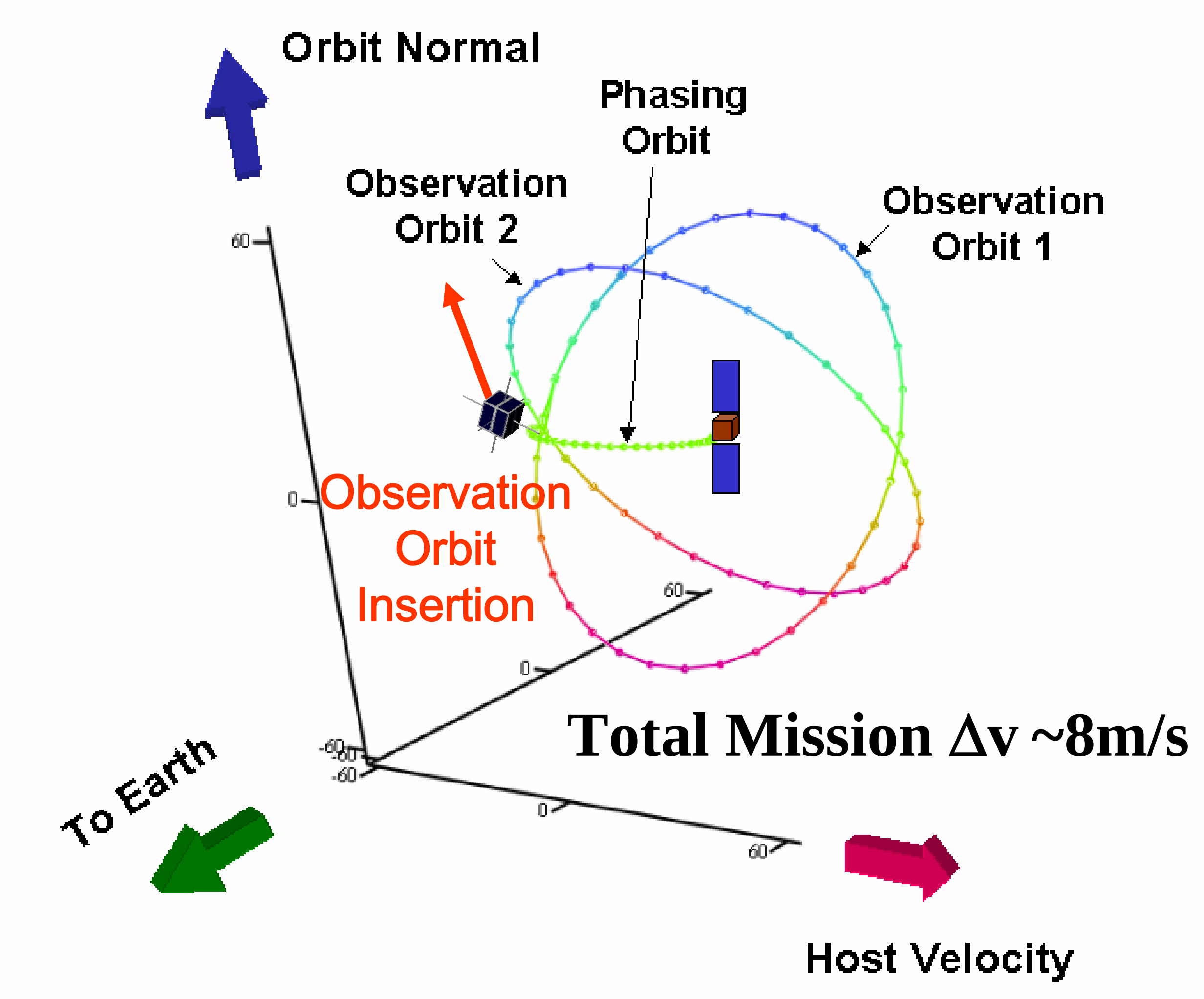
Observation orbits:

- Total: ~.180 m/s
- mN thrust levels

$F\delta t = m\,\Delta v$

$\Delta v = 1\mathrm{mN}(1\mathrm{s})/0.1\mathrm{Kg}$

$\Delta v = 0.01\mathrm{m/sec}$



Total Mission Δv ~8m/s

Air Drag Δv ~7m/s De-Orbit Δv ~0.2m/s

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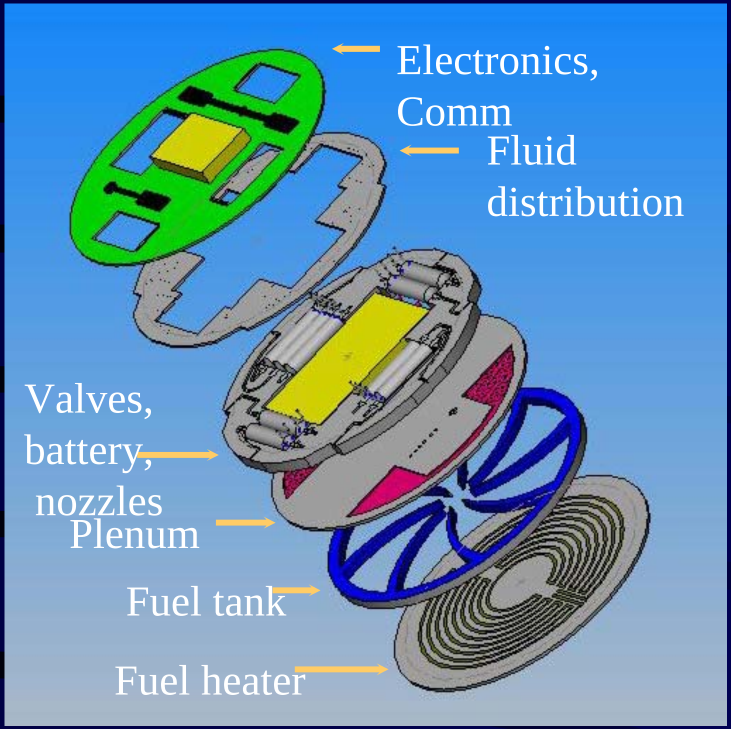
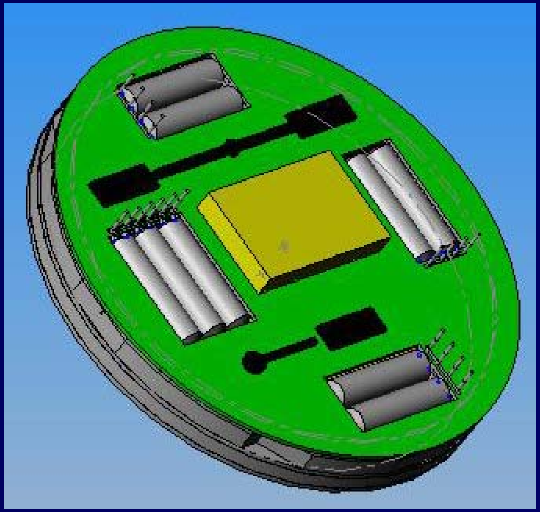
COSA: All Direct-Digital-Manufacturing



Manufacturing Approach:

- Generate solid models of all patterned PSGC wafers and components.
  - Conduct tests for form fit,
  - Conduct mission analysis tests.
- Generate tool-path files for all laser direct-write operations.
  - Material to be removed, deposited, altered.
- Translate tool-path code to patterning motion.
- Pattern via laser direct-write variable exposure processing

A Propulsion System with Guidance, Navigation and Control (GNC) in PSGC Material



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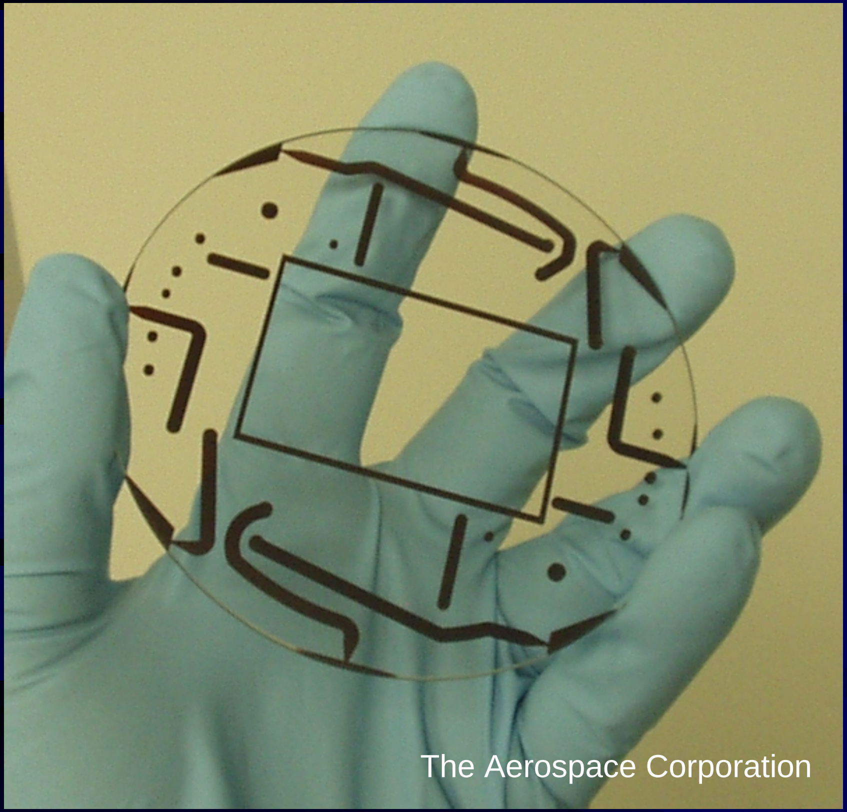
COSA Wafers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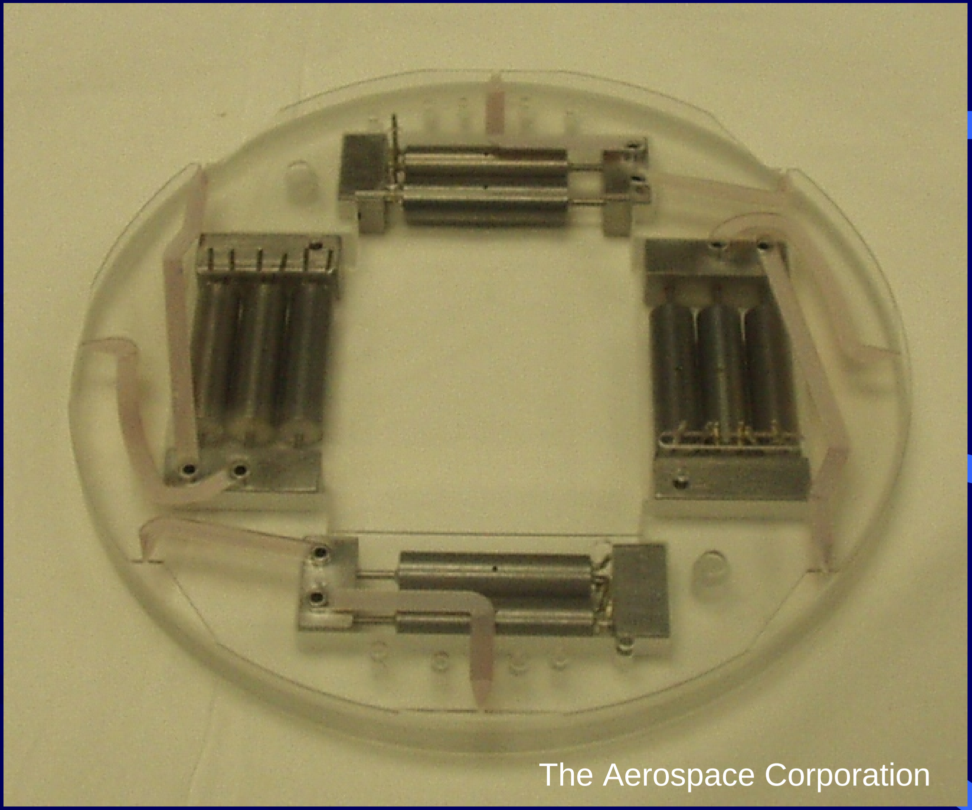
Exposed and baked nozzle layer


The Aerospace Corporation

Etched nozzle and valve layers with valves

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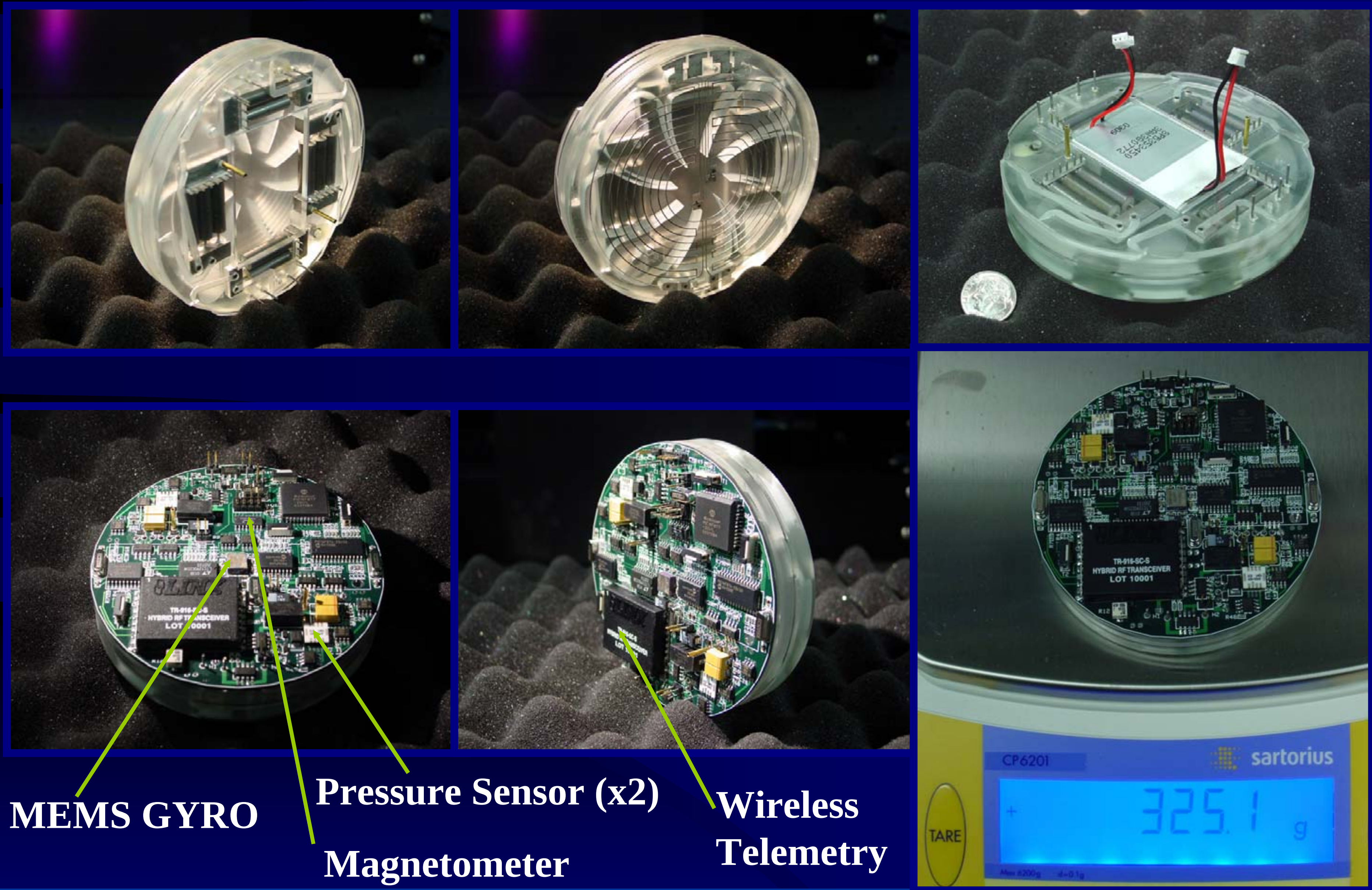
"COSA: The Prototype Propulsion Module[*]



MEMS GYRO

Magnetometer

Pressure Sensor (x2)

Wireless Telemetry

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[*] S. Janson, A. Huang, W. Hansen and H. Helvajian, J. AIAA 2004-6701

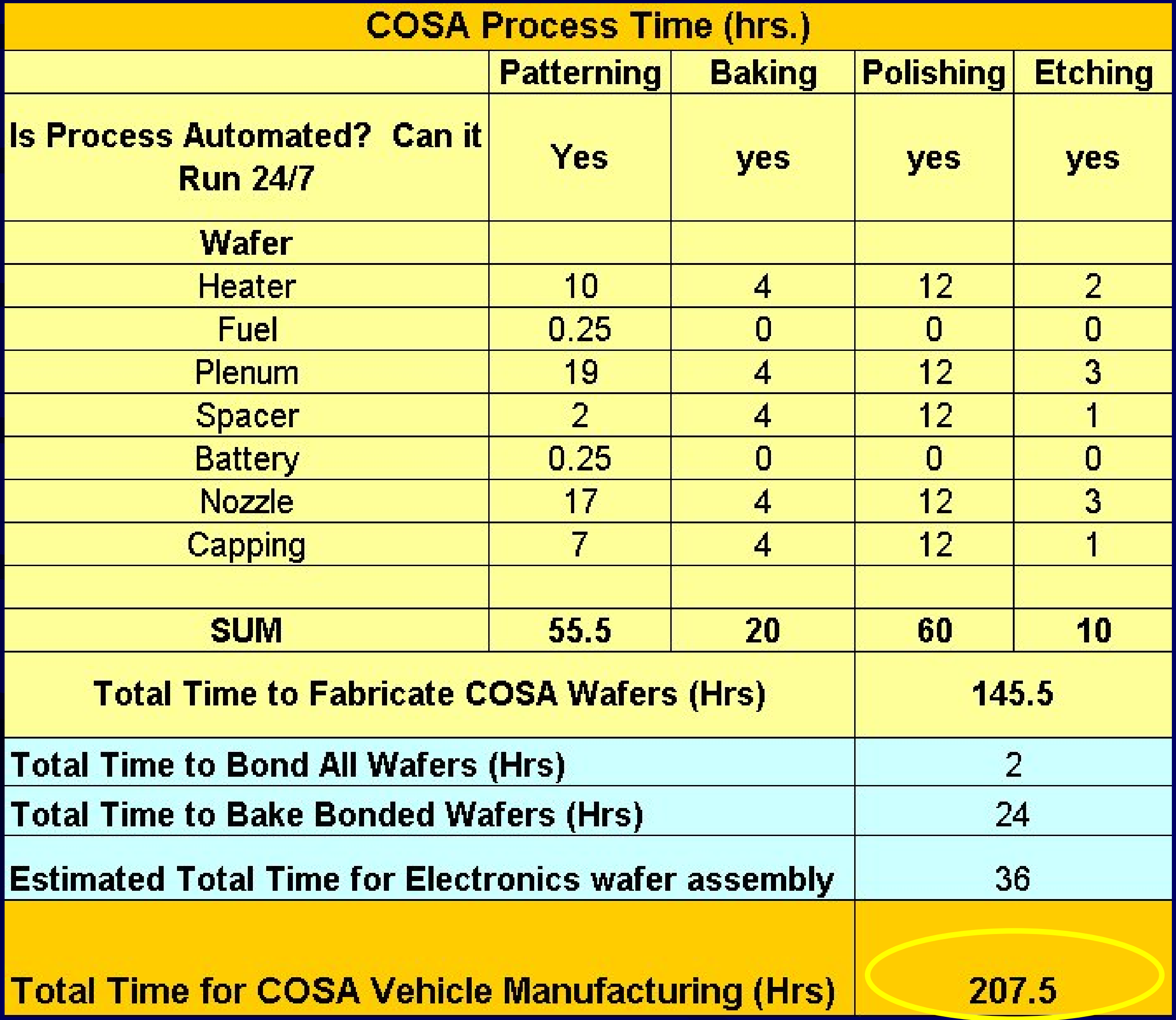
THE AEROSPACE CORPORATION

Orientation Control Tests for the COSA Vehicle “Hope”

Rotation on Air Table <u>Without</u> Thrust or Orientation Control

IMU guided Rotational Control <u>with</u> pulsed thrusting

COSA Manufacturing Process: Prototype Vehicle



COSA Process Time (hrs.)				
	Patterning	Baking	Polishing	Etching
Is Process Automated? Can it Run 24/7	Yes	yes	yes	yes
Wafer				
Heater	10	4	12	2
Fuel	0.25	0	0	0
Plenum	19	4	12	3
Spacer	2	4	12	1
Battery	0.25	0	0	0
Nozzle	17	4	12	3
Capping	7	4	12	1
SUM	**55.5**	**20**	**60**	**10**
Total Time to Fabricate COSA Wafers (Hrs)			**145.5**	
Total Time to Bond All Wafers (Hrs)			2	
Total Time to Bake Bonded Wafers (Hrs)			24	
Estimated Total Time for Electronics wafer assembly			36	
Total Time for COSA Vehicle Manufacturing (Hrs)			**207.5**	

The LMES and the JLAB FEL can Serve as a Manufacturing Testbed for a High Throughput Patterning of Glass Ceramic Nanosatellite/COSA Parts

- A complete set of COSA vehicle wafers can be patterned in less than 30 minutes (instead of 55 hours).
- <u>Multiple</u> COSA vehicles can be assembled in batch mode in less than 30 hours (instead of 1 per 210 hrs).
- All digital direct manufacturing allows for design alterations to be done on the digital model of the vehicle which is directly realized in the processed part.

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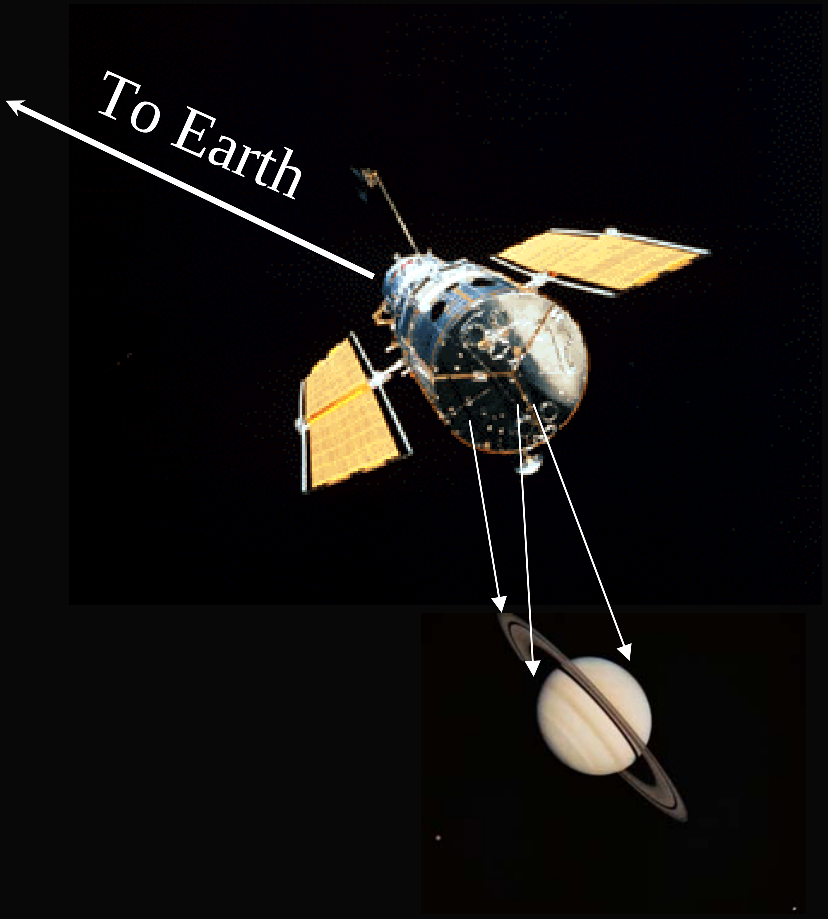
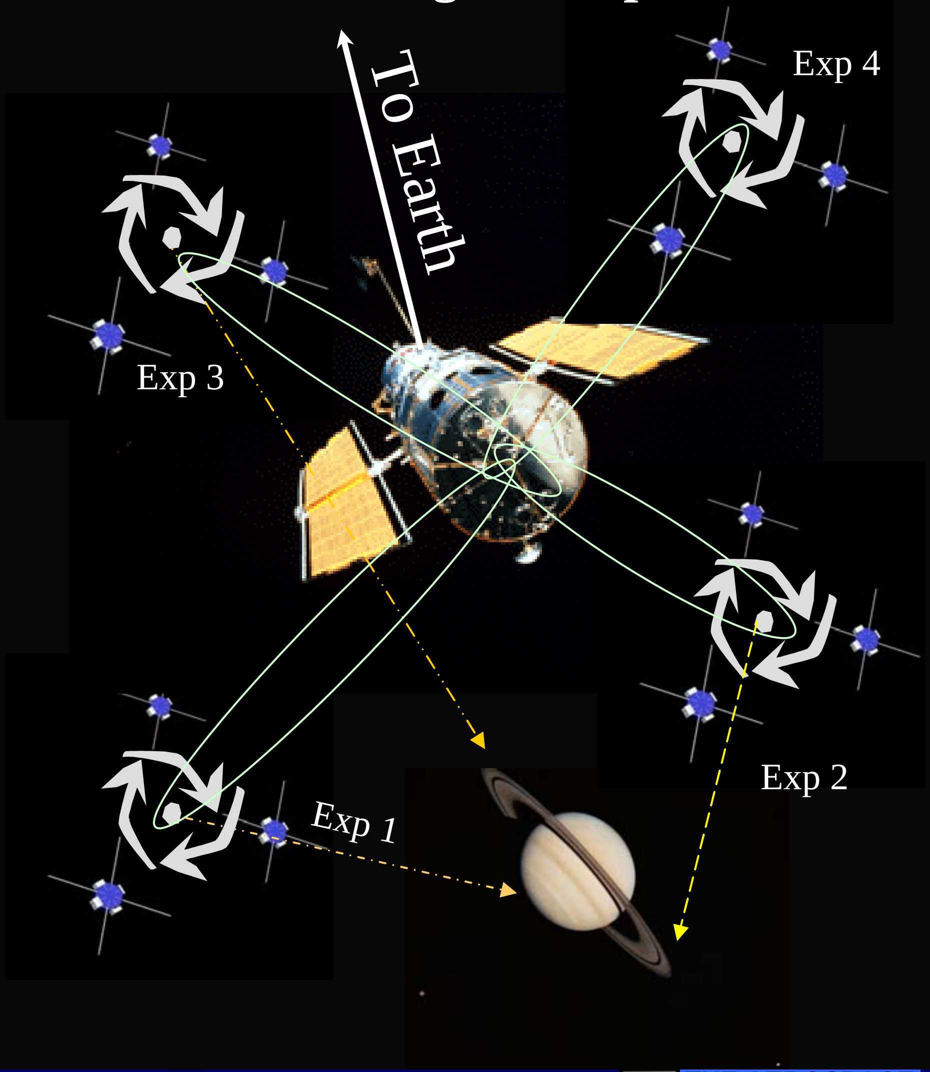
Changing the Approach on Future Space Missions

Adaptable Data Acquisition: Inspired by 3rd Generation (3G) Cell Phone Technology

Current Architecture Design
One Spacecraft



Future Architecture Design
“Mother & Daughter” Spacecraft



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VPN: Virtual Private Network

Conclusions

- Laser material processing is a growing industry world wide.
- Laser microengineering with the JLAB FEL can make high fidelity precision processes (e.g non thermally governed processes) commercially feasible for industrial use.
- A unique laser direct-write patterning tool (LMES) has been developed and installed at JLAB that permits the high fidelity controlled delivery of laser pulses based on a preprogrammed “script”.
- Laser microenginering becomes <u>most</u> cost effective when the laser is used only to “activate” the material not to induce the desired physical transformation process.
- The JLAB FEL with LMES patterning tool is a test bed for the manufacturing of miniature glass/ceramic space systems by a Direct-Digital Development methodology. “radically alter small satellite design and manufacture paradigms” – producing a nanosatellite space vehicle a day.

Thank You