Freeform Machining with Precitech Servo Tool Options

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A growing number of optics manufactures are investigating servo tool machining technologies. The goal of this document is to provide:

- A practical understanding of the operating characteristics of the various Precitech servo tool options.
- Information to determine which servo tool best fits an application.
- A method to calculate servo tool machining cycle times.

Benefits of servo tool machining

Using Precitech servo tool options, non-rotationally-symmetric surfaces (including freeform surfaces) can be produced economically on Precitech's two-axis diamond turning lathes, the Precitech Nanoform 200, 350, and 700 systems.

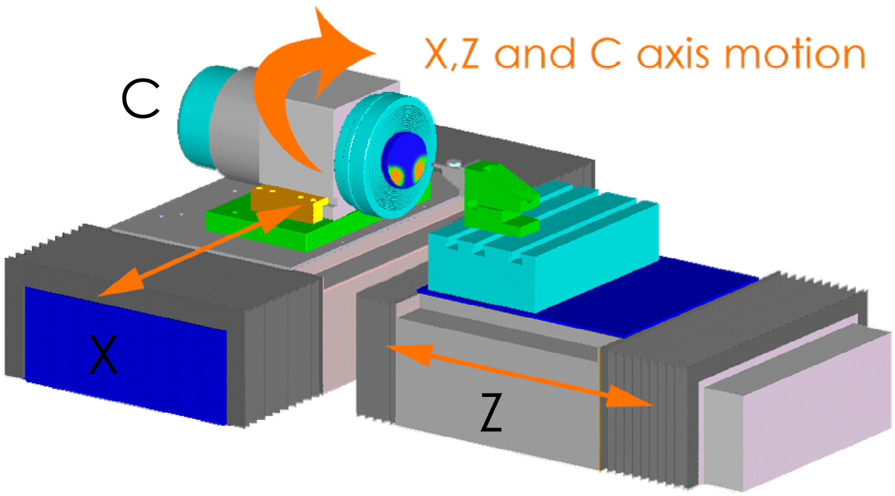
With servo tool machining customers can produce non-rotationally-symmetric surfaces via a turning operation at significantly lower costs over traditional manufacturing methods (e.g. raster fly cutting).

Components that can be turned off-axis (i.e. off-axis-rotationally-symmetric parts: high order aspheres, parabolas, torics etc.) can now be turned on-axis with servo tool machining. Advantages of this approach include:

- Increasing the range of components that can be made on your existing Nanoform lathes. Off-axis parts that can't be produced because the off-axis setup exceeds the swing capacity of the diamond turning machine can now be produced on-axis with servo tool machining.
- Reducing cost and lead times for work piece holding fixtures. On-axis fixtures are typically less expensive and less technically challenging than off-axis fixtures (aka "surrounds"). This is particularly useful when producing a low quantity part or when a short lead time to a first-piece prototype is critical.

Servo Tool Machining – typical system configuration

A typical machine configuration for servo tool machining is shown below.
The work piece is mounted on the C axis (a work holding air bearing spindle with precision velocity and position encoders). The C axis is mounted to the X axis carriage. The servo tool option is mounted on the Z axis carriage. Machining with this machine configuration is also known by the shorthand term "**XZC machining**".



Three servo tool options
Precitech offers three servo tool options to cover the widest range of application requirements. Table 1 shows the general characteristics of the **Slow Tool Servo (STS)** and two fast tool servo (FTS) options: the **FTS500** and **FTS70**.

Table 1 General Characteristics Precitech STS, FTS500 and FTS70 servo tools

	STS	FTS 500	FTS 70
Drive & "bearing" technology	Linear motor / Hydrostatic Oil bearing	Voice coil / Air bearing and counter mass	Piezoelectric stack / Flexure element
Characteristic Travel*	10 mm (@ 2 Hz)	500 um	70 um
Characteristic Bandwidth**	70 Hz	1000 Hz	700 Hz
Characteristic Surface finish^	5 nm Ra	8 nm Ra	5 nm Ra
Characteristic form accuracy^	250 nm PV	300 nm PV	600 nm PV
Position sensor	Scale	Analog	Analog
Programming Software	Diffsys	SOP	SOP

* See Figure 1 for a more complete description
** Related to servo control design and performance
^ Typical performance for test specimens (also typical real world results for many applications)

The **STS** option (lower acceleration, long excursion) is typically used to produce high amplitude non-rotationally-symmetric continuous surfaces. A continuous surface does not feature any inflection points (instantaneous changes) in the surface slope or step changes in surface height that require radical changes in tool velocity.

The **FTS70 and FTS500** options (high acceleration, short excursion) are typically used to produce higher frequency (higher spatial density), lower amplitude, surface structures that may also have discontinuities in the surface.

Discontinuous surfaces can be found on optical components like micro-mirror arrays, lenslet arrays and components where two or more optical elements are integrated into one surface (e.g. bifocals). The FTS servo tools feature very fast reaction times so that the tool can accurately follow the surface of a component across surface discontinuities.

Which servo tool option best fits an application?

In many cases an application can be produced by more than one of the servo tool options. Choosing the correct servo tool is a function of:

- Surface finish requirements
- Form accuracy requirements
- Transition area specifications (i.e. the area between clear apertures on discontinuous surfaces)
- Cycle time (productivity) goals

Each of the servo tool options also has unique operating characteristics related to their physical design, drive technology and servo control algorithms. These subtle differences can be exploited to provide ultra-high performance in relation to a specific application.

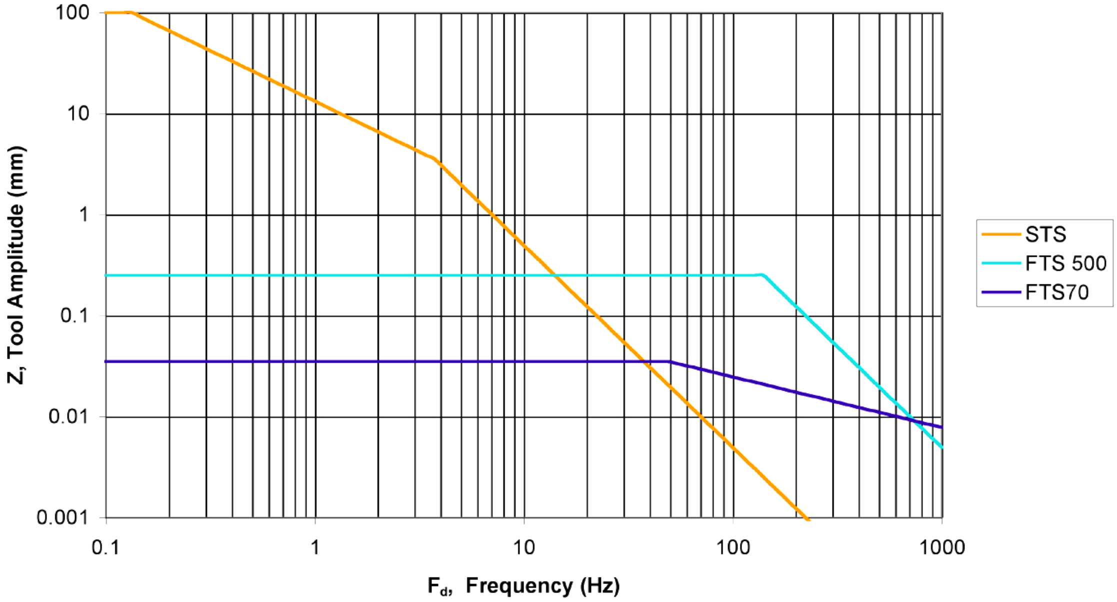
The **STS** and **FTS500** (linear motor and voice coil drives) both excel in the area of form accuracy. Both of these drive systems feature very linear response curves which contribute to their achieving high form accuracy.

The **FTS70** (piezo stack) excels in the area of surface finish. The low mass, high characteristic bandwidth and extremely high positioning resolution of **FTS70** is an ideal combination for generating high quality surface finishes.

The first step in choosing the most suitable servo tool option is to determine if the tool path amplitude and the drive frequency required by the application falls within the operational limits of the servo tool.

Figure 1 (below) shows the maximum amplitude of tool motion vs. drive frequency curves for each Precitech servo tool. The tool path amplitude and tool excitation frequency required to generate a surface can be plotted as an operation point (Hz, mm) in relation to these curves. In general, as the operation point approaches the amplitude/frequency limits of the servo tool, form accuracy and/or surface finish degrade. This may be acceptable depending on the cost / performance requirements of the application.

Figure 1. Operational Limits for STS and FTS (XZC) Machining



Drive amplitude

Amplitude represents one half of the total Z axis motion (worst case) for a given revolution of the work piece. This motion is the non-rotationally symmetric component of the desired surface. Example: A 2mm tilted flat requires a 1mm excursion in +Z and a 1mm excursion in the –Z direction, so the drive amplitude is 1 mm.

Tool drive (excitation) frequency

Drive frequency is the number of tool motion cycles per second. It is directly related to the rotational speed of the work piece. Continuous surfaces typically feature simple arithmetic relationships between excitation frequency and rotational velocity (RPM). A tilted flat surface completes one cycle of the tool motion per revolution of the part. A tilted flat being cut at 400 RPM will require a tool excitation frequency F_d of 400/60 or 6.66 Hz. A toric surface features two tool motion cycles per revolution. A toric surface being cut at 400 RPM will require a tool driving frequency of 2*400/60 or 13.33 Hz.

In general, any off-axis-rotationally-symmetric continuous surface can be reduced to predominantly two tool motion cycles per revolution. While higher order motions (4 cycle/rev, 8 cycle/rev) may be generated by the surface path, the amplitude of these higher order motions are typically < $1/10^{th}$ that of the fundamental 2 cycle/rev path. At such small amplitudes, the higher harmonic components have little effect on the operational limits.

Determining the drive frequency for discontinuous surfaces like lenslet arrays needs to be treated in a different fashion.

For discontinuous surfaces, maximum tool excitation frequency can be approximated by the following formula:

$\mathbf{F_d}$ (Hz) = $(2\pi R_{max})N(rpm)/60P$

Where:

- P = the pitch (spacing in mm) of the optical elements' center lines (or chord distance across an element).
- R_{max} = the maximum turning radius in mm from the center of rotation to the most outlying optical element.
- N = spindle speed

A lenslet array with 1 mm lenses on a 10 mm diameter mold insert being cut at 200 RPM (assumed for the moment) would require a tool drive frequency of: $(2x\pi x5x200)/(60x1)$ or 105 Hz.

As noted, tool drive frequency is a function of spindle speed. In theory, if you slow down the spindle enough the STS option, even with its lower bandwidth, could cut any size feature. The down side to this is obviously productivity. Secondly, very long cycle times (e.g. many hours) allow the machine to respond to thermal disturbances from the environment. Finally, some materials are not easily machined at very low speeds.

For discontinuous surfaces, maximum spindle speed is often limited by the following error created when the tool bit is instructed to make a radical change in its path as it crosses a discontinuity in the surface. The recovery time of the servo tool should be considered whenever there are abrupt changes in the slope of the surface or steps in the height of the surface.

Transition areas in discontinuous surfaces

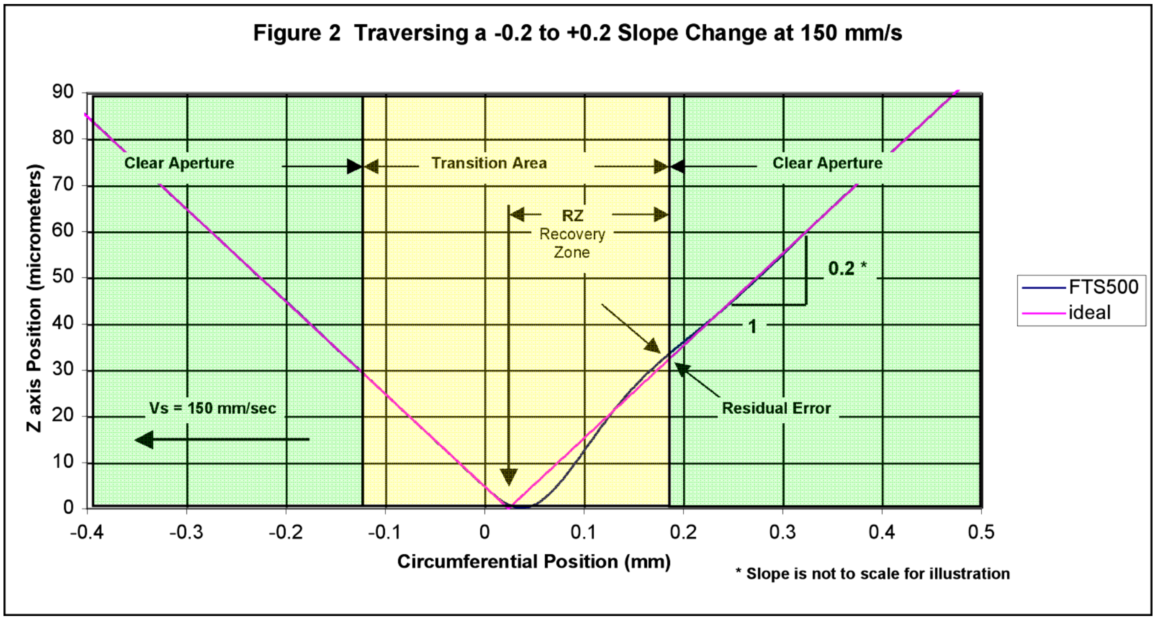
Components that feature discontinuities in their surfaces or repetitive shapes nested together across the surface (lenslet arrays for example) typically specify the clear aperture area of each optical element. Between the clear apertures is a transition area or edge zone. Form errors in the edge zone are allowed to exceed those in the clear aperture. A reasonably sized edge zone enables the part to be manufactured at reasonable cost.

The following items are typically known from the component specifications and the characteristics of the servo tool:

- The allowable form error in the clear aperture area,
- The physical dimensions of the clear aperture and transition areas,
- The characteristic bandwidth of the servo tool

With this information and using Figure 3, the maximum surface velocity of the part relative to the tool bit can be calculated. From this the spindle speed and the part cutting cycle time can then be determined. This will be demonstrated later.

Background
Figure 2 shows a classic control loop response to a tool path command that changes the direction of motion. In this example, the circumferential speed (V_s) of the work piece as it passes by the tool is 150 mm/sec.



The difference between the ideal motion and the actual motion results in form error in the surface of the part. How "quickly" the tool path can correct for radical changes in slope or surface height is related to the characteristic bandwidth of servo tool's control loop. The period of the sinusoidal error motion shown in Figure 2 is the inverse of the natural frequency of the servo tool control loop. The characteristic bandwidth of the servo tools shown in Table 1 is the drive frequency where resulting (output) tool motion amplitude is 3 dB (30%) down from the commanded (input) amplitude. The natural frequency of the servo tool control loop is typically 30% lower in frequency than the characteristic bandwidth.

Within a small number of cycles the error motion (form error) decays to a very low value. The term "Residual Error" (RE) is equal to the allowable form error in the clear aperture region. Typically the cutting speed is tuned so that the residual error on exiting the transition area (at the end of the recovery zone) is less than (just under) the allowable form error.

Bringing it all together

Figure 3 is a dimensionless presentation of the relationships between:

- Error motion amplitude and tool path slope (S) , error = f(S)
- Recovery zone width (RZ) and Servo tool bandwidth (BW), RZ = f(1/BW)
- Tool surface velocity (Vs) and Recovery Zone width RZ, $Vs = RZ \times BW / RZ_{bar}$

Figure 3 Dimensionless Surface Error When Machining a Corner with Equal +/- Slopes at a Surface Velocity Vs

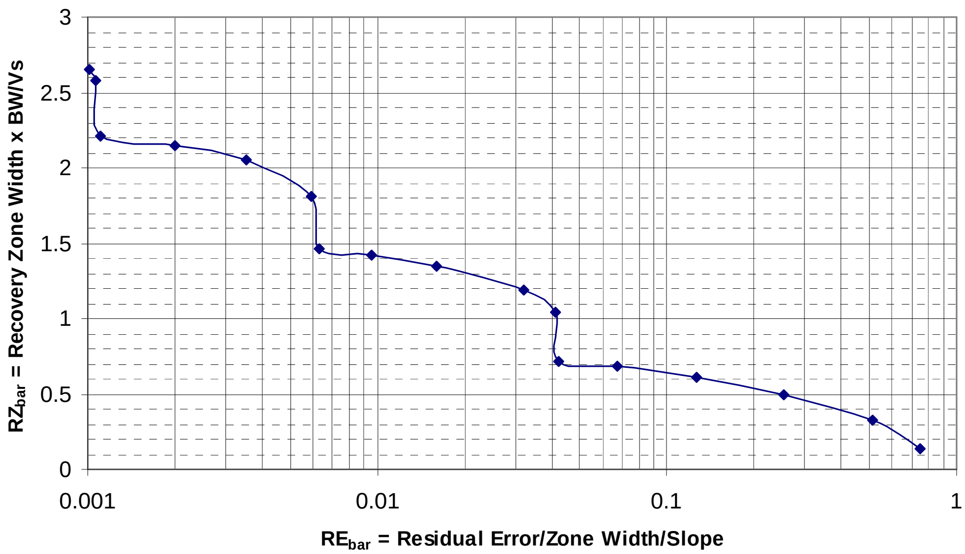


Figure 3 is used to determine the maximum surface velocity at which the servo tool's cutting path can meet the clear aperture form error specifications of the component.

Here is an example showing how to apply this information to determine the correct servo tool to use for an application and then estimate the cycle time for a finish cut.

Application: Lenslet Array

- Component size: 50mm diameter
- Lens diameter (pitch) (P) 5 mm
- Lens form spherical R = 12.5mm (PV sag = 0.25 mm)
- Allowable form error within the clear aperture (also equal to the residual error(RE)) RE = 0.00031 mm = 0.31 µm
- Clear aperture diameter 4.61mm (clear aperture area is 85% of the overall lens area)
- Recovery Zone width (Transition area span / 2 ^^): RZ = 0.195 mm
- Tool path slope (rise/run) within transition area (S) S = 0.2

^^ Note: In this example the part is designed with the transition area placed symmetrically about the boundary between the lens features. Tool path error is not symmetric in relation to these boundaries. Following error predominates. This can be exploited to further reduce part manufacturing costs if the optical design allows for non-symmetric transition areas.

Servo Tool Amplitude

Based on the tool amplitude needed (125µm = 0.25mm / 2) and referring to Figure 1 this component could be cut using either the **FTS 500** or the **STS** servo tool but cannot be cut with **FTS 70** servo tool.

Maximum Spindle Speed:
The maximum spindle speed is calculated next using Figure 3.

RE_{bar} = RE(µm) / RZ(µm) / S = 0.31 / 195 / 0.2 = 0.00795

Using the RE_{bar} value and the curve in Figure 3 the RZ_{bar} value can be found: **~ 1.3**

Assuming for the moment the **FTS 500** servo tool option (BW= 1000 Hz) the maximum surface velocity Vs is:

Vs = BW (Hz) * RZ(mm) / RZ_{bar} = 1000 * 0.195 mm / 1.3 = **150 mm/sec = 9,000 mm/min**

Spindle speed, RPM = Vs / (circumference $_{max}$) = 9000 / (Π * 50) **= 57 RPM**

Servo Tool Drive Frequency
The tool drive frequency can be calculated next:

$\mathbf{F_d}$ **=** (2 * Π * N(RPM) / (60 * P)) = (2 * Π * 57 / (60 * 5) = **30Hz**

Referring back to Figure 1 this drive frequency and amplitude combination exceeds the capabilities of the **STS** servo tool. More to the point, because of the lower bandwidth of the **STS** option the spindle speed would have to be lowered to 4 RPM in order to meet the clear aperture form error requirements of the part.

Finish Cut Cycle Time
Assuming a constant spindle speed (not required, see below) and 3 µm feed / rev, the cycle time for the finish cut is:

Cycle time (min) = Part dia. / (2 * feed/rev * RPM) = 50/(2*0.003*57) **= 146 min.**

(For comparison, using the STS servo tool to cut this part, the spindle speed would need to be reduced to 4 RPM. The finish cut cycle time would be 2080 min or 34 hours.)

If spindle speed is kept constant, the part surface velocity will fall as the tool approaches the center of rotation. Within practical limits, spindle RPM over the course of a part cut can be increased to shorten part cutting cycle time.

Other application examples:
Table 2 (attached) lists relevant operational parameters for a variety of applications. All of these examples are based on actual cutting experiments performed at Precitech. The results in Table 2 are consistent with practical production results reported by our customers.

Summary:
Precitech offers the widest range of servo tool options in the ultra-precise machining industry. Selecting the best servo tool for your applications requires consideration of many factors. The Precitech application engineering team frequently works with new and existing customers to help find the best solutions to demanding applications. Precitech's XZC machining solutions are also robust and production ready.

Beyond the scope of this paper, but key to the successful use of XZC machining, is the Precitech UPX controller. The UPX features the fastest code execution rate in the ultra-precision industry: The UPX controller can execute 1800 blocks of tool path instructions per sec. A block or line of instructions can control up to six axes of motion. This computational power allows users to produce excellent surface finishes at much higher cutting rates (lower part cutting cycle times) than could be realized with older technologies. The UPX does not use motion control cards. Customers do not have to down-grade surface definitions (increase point to point spacing) to accommodate motion control card rotary buffer limitations. A simple example of the robustness and stability of UPX is the use of manual panel controls (like spindle override and cycle hold) while XZC programs are running without affecting overall system stability. Finally part cutting programs can be set up to cut multiple roughing and/or finish passes without operator intervention between each pass.

The Precitech SOP programming environment for fast tool servo XZC machining greatly simplifies the task of programming tool paths for complex freeform surfaces. For example, the entire cutting path for the lenslet array application above is defined within SOP with only ten lines of C-code.

Research and development is ongoing to both improve form/finish results of the current STS and FTS servo tools and develop new servo tool configurations.

In March 2005 Precitech was awarded a sizeable Phase II STTR contract from NASA to develop a new "Fast Linear Axis" (aka "Live-Axis") servo tool configuration. This work will build on the Phase I contract received in 2003. A description of the goals of the NASA project can be found at:

http://sbir.gsfc.nasa.gov/SBIR/abstracts/03/sttr/phase2/STTR-03-2-T4.01-9768.html

Table 2 Cutting results using various servo tool options

Application Description	Servo Tool	Part Dia. (mm)	Spindle (rpm)	Feed/ Rev (µm)	Cycle Time (min.)	Z amplitude (mm)	Drive Freq. (Hz)	Tool Radius (mm)	Measured Form Error PV (µm)	Ideal Surface Finish Ra (nm)	Measured Surface Finish Ra (nm)
2mm Tilted flat -- Cu	STS	50	50	10	50.0	1	0.83	1.5	0.35	2.1	2.7- 4.7
2mm Tilted flat -- Cu	STS	50	150	5	33.3	1	2.50	1.5	<0.25	0.53	2.9 - 4.5
2mm Tilted flat -- Cu	STS	50	150	8	21	1	2.50	2.5	0.2	0.82	3.0-4.0
2mm Tilted flat -- Cu	STS	50	225	10	11.1	1	3.75	1.5	<0.25	2.1	5.0 - 8.1
A12TF 200um Tilted flat - Cu	FTS500	12	500	2	6.0	0.1	8.30	0.77	0.25	0.16	3.1 - 4.5
A13TF 200um Tilted Flat - Cu	FTS500	12	1000	2	3.0	0.1	16.70	0.77	0.25	0.16	3.2 - 5.4
500um Tilted Flat - Cu	FTS500	12	500	2	6.0	0.24	8.3	0.5	0.3	0.26	3.2 – 6.4
500um Tilted Flat - Cu	FTS500	12	1000	2	3.0	0.24	16.7	0.5	0.3	0.26	3.2 –11.0
Toric surface in 303 SST (Aps Note 0303) (CBN tool)	FTS70	9	2000	2.5	0.9	0.031	66.67	0.5	<.35, .42	0.40	N/A
Toric -- Cu (Aps Note 0301)	FTS70	9	2000	2.5	0.9	0.032	66.67	0.5	< .25, .37	0.40	3.5 – 8.5
70um Tilted flat - Cu	FTS70	12	500	4	3.0	0.035	8.30	2.16	0.35	0.24	2.8 - 3.7
2mm Lenslet Array -- Nickel (Aps Note 03.11-1DT)	FTS70	12	250	4	6.0	0.031	75.00	0.5	1.5	1.02	3.7 - 10
35um Tilted flat-- Cu (Aps note 0306)	FTS70	20	1000	1	10.0	0.017	16.67	0.5	0.206	0.70	1.3
35um Tilted Flat -- OFHC Cu (Aps Note A-0316)	FTS70	50	1000	2.5	10.0	0.017	16.67	0.5	0.017	0.70	1.54
Corner Cube Lens Array -- OFHC Cu (Aps Note A-0214)	FTS35	50	150	5.3	31.4	0.015	87.27	1.0	0.097	0.92	3.4