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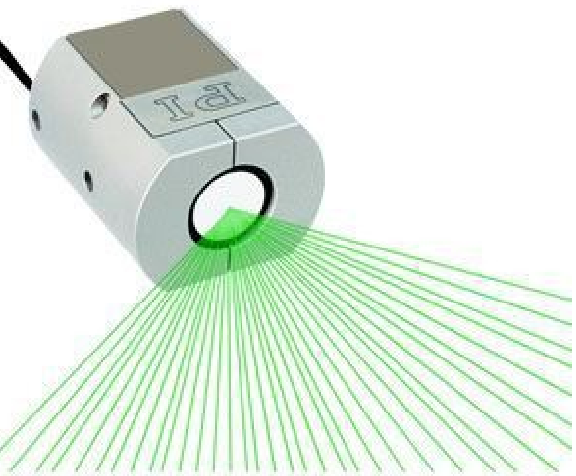
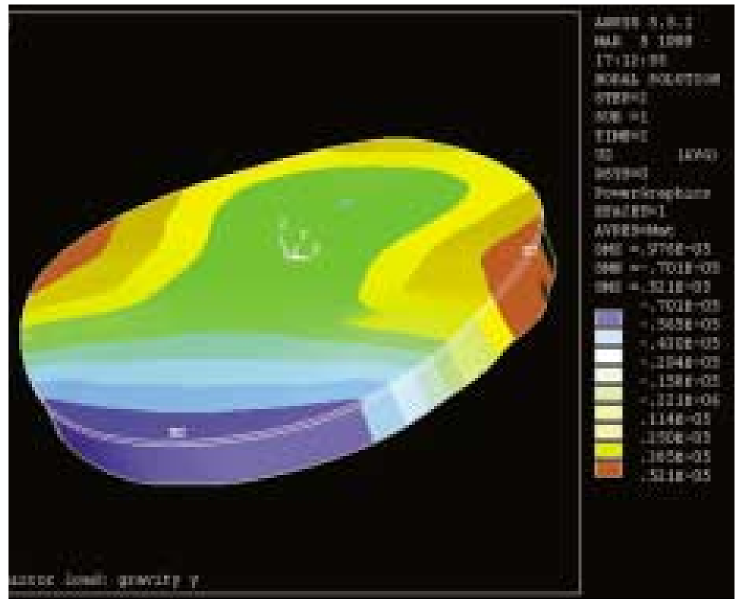
Tip-Tilt Mirrors for Free Space Optical Communication

and Astronomical Telescopes / Active Optics





FEA analysis of a mirror platform can help detect smallest aberrations, such as nanometer level deformation caused by gravity

Piezo Tip/Tilt Solutions

- Tripod and Differential Designs
- Custom designs for optics up 12"
- Fast Rise Time to Sub-Millisecond
- Standard, OEM and custom designs
- Resolution sub-arc-second/
- Closed-loop operation for highest accuracy,
- Frictionless wire-EDM-cut flexures, no backlash
- FEA optimized designes for precision trajectory control
- Invar, titanium, steel, aluminum:optimize thermal match
- Standard, custom and OEM control electronics (digital and analog controllers, with advanced high-speed servos)

PI offers a variety of high-speed Piezo Tip-Tilt mirrors designed for image correction & active optics applications. Providing a tilt range of several milliradians, fast response (sub-millisecond and sub-microradian resolution, the systems are ideal for dynamic operation.

Applications of Piezo Tip-Tilt Systems

- Free Space Optical Communication
- Bore-sight systems (defense industry, law enforcement)
- Laser beam steering and tracking (telecom satellites, etc.)
- Beam switching, alignment, steering
- Interferometry (Fabry-Perot filters)
- Dynamic error correction in refraction systems
- Optical path length stabilization
- Vibration cancellation (laser systems, imaging)
- Image stabilization (astronomical telescopes, imaging)
- Image resolution enhancement (dithering)
- Laser beam stabilization (resonators, optical setups)
- Laser beam scanning (lithography, optical setups)
- Mass storage (optical disk) mastering

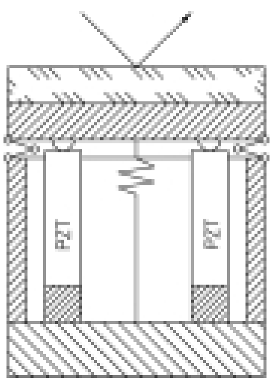
For the latest specs visit www.tip-tilt-stage.com

Designs of Multi-Axis Piezo Tip-Tilt Platforms

I. Differential-Design No Piston Motion

The platform is supported by four piezo actuators (two pairs) spaced at 90° intervals. Each actuator pair is operated as a unit in push/pull mode.

The differential design exhibits excellent angular stability over a wide temperature range. Here too, temperature changes only affect the vertical position of the platform (piston motion) and have no influence on the angular position. After the operating voltage is removed, the platform returns to the center position.

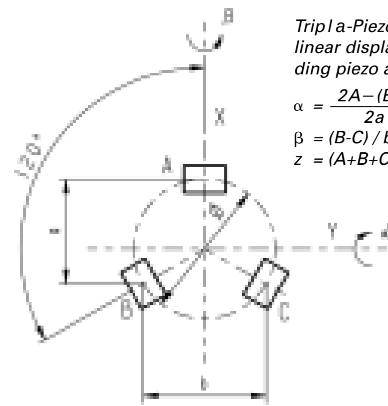


II. Tripod Design Z-Tip-Tilt (for Path-(Length Correction)

The platform is supported by three piezo actuators spaced at 120° intervals. Because expansion of an individual PZT actuator affects both θ_X and θ_Y rotation, external coordinate transformation (software or hardware) is required to allow platform position commands in θ_X and θ_Y coordinates. See the equations.

The tripod allows active vertical control (piston motion) of the platform—an important feature for interferometric applications and correction of path length errors. Also, the design allows for a central clear aperture, ideal for transmitted-light applications.

Like the differential drives, the triple-piezo-actuator design exhibits excellent angular stability over a wide temperature range. With this arrangement temperature changes only affect the vertical position of the platform (piston motion) and have no influence on the angular position.



Trip l a-Piezo-Drive: A, B, C is the linear displacement of the corresponding piezo actuator.

$$\alpha = \frac{2A-(B+C)}{2a}$$

$$\beta = (B-C)/b$$

$$z = (A+B+C)/3$$

Dynamics

In addition to the amplifier, controller and sensor bandwidths, the maximum operating frequency of a tilt platform depends on its mechanical resonant frequency. To estimate the effective resonant frequency of the tilt mirror system (platform + mirror), the moment of inertia of the mirror substrate must first be calculated.

Moment of inertia of a rotationally symmetric mirror:

$$I_M = m\left[\frac{3R^2+H^2}{12}+\left(\frac{H}{2}+T\right)^2\right]$$

Moment of inertia of a rectangular mirror:

$$I_M = m\left[\frac{L^2+H^2}{12}+\left(\frac{H}{2}+T\right)^2\right]$$

where:

m = Mirror mass [g]

I_M = Moment of inertia of the mirror [g·mm²]

L = Mirror length perpendicular to the tilt axis [mm]

H = Mirror thickness [mm]

T= Dist ance, pivot point to platform surface (see technical data table for individual model) [mm]

R = Mirror radius [mm]

Using the resonant frequency of the unloaded platform and the moment of inertia of the mirror substrate, the system resonant frequency is calculated according to the following equation:

Resonant frequency of a tilt platform/mirror system

$$f' = \frac{f_0}{\sqrt{1+I_M/I_0}}$$

where,

f' = Resonant frequency of platform with mirror [Hz]

f_0 = Resonant frequency of unloaded platform [Hz]

I_0 = Moment of inertia of the platform (see technical data table for the individual model) [g·mm²]

I_M = Moment of inertia of the mirror [g·mm²]

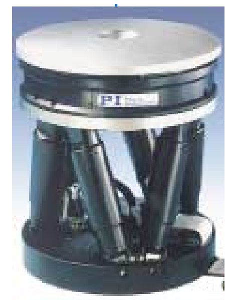
Custom Tip-Tilt Steering Mirror Examples

Custom tip/tilt steering mirror with controller, for astronomical telescope

Active tip/tilt mirror for Subaru Telescope (Mauna Kea, Hawaii). Mirror diameter: 150 mm Tip/Tilt range: ±600 µrad Resonant frequency: 610 H

Custom tip/tilt steering mirror

Tip/tilt steering mirror units for the Keck Outrigger telescope in Hawaii. The units are controlled by a high-performance digital controller with a fiber optic interface



Active secondary tip/tilt mirror for the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii, with Hexapod 6-degree-of-freedom alignment system

Tip/tilt steering mirror with manual coarse adjustment unit

Custom tip/tilt steering mirror (250 mm diameter) with digital motion controller and capacitive sensor controller, for astronomical telescope

Custom tip/tilt steering mirror (100 mm diameter)

Custom tip/tilt steering mirror with controller, for astronomical telescope

Custom open-loop steering mirror

Custom steering mirror, closed-loop with capacitance sensors

Custom steering mirror with capacitance sensors

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Differential Tip-Tilt Mirror for Optical Beam Pointing

Applications

- Free Space Communication
- Image stabilization
- Laser beam stabilization
- Beam switching
- Adaptive optics systems
- Laser beam steering & scanning
- Correction of polygon scanner errors.

- **±1 mrad θ_X and θ_Y Tilt Range**
- **For Mirrors to 100 mm Ø**
- **Sub-µrad Resolution**
- **Closed-Loop Versions**
- **Differential Design for Excellent Temperature Stability**

S-340.AL Tip/Tilt Platform

S-340 piezo tip/tilt platforms are fast and compact tilt units, providing precise angular movements of the top platform in two orthogonal axes. The tilt range is ±1 mrad (each axis) with sub-µrad resolution. Closed-loop versions are available for highest accuracy and repeatability. S-340 systems are designed for mirrors up to 100 mm diameter and have outstanding angular stability over a wide temperature range.

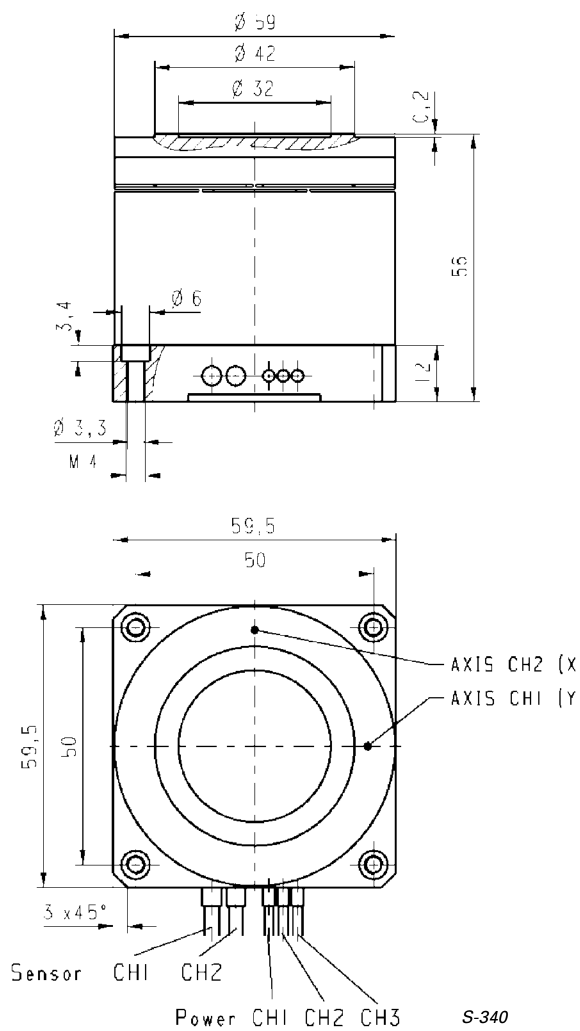
To match the CTEs (coefficients of thermal expansion) of various mirror materials, platforms made from different materials are available (see ordering information)

Materials Match

Platform	Recommended Mirror	Models
Aluminum	Aluminum	S-340.Ax
Invar	Zerodur glass	S-340.ix
Titanium	BK7 glass	S-340.Tx
Steel		S-340.Sx

Working principle

S-340 tip/tilt platforms are equipped with two pairs of low-voltage piezoelectric linear drives (0 to 100 V) operating as a unit in push/pull mode (see p. 3-15 for schematic diagram). The aluminum case is equipped with an integrated, FEA-modeled (finite element analysis) circular flexure featuring zero stiction, zero friction and exceptional guiding precision.



S-340 dimensions (in mm)

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In open-loop operation, the platform angle roughly corresponds to the drive voltage (see p.4-1 1 in the "Tutorial" section for behavior of open-loop piezos). The open-loop models are ideal for applications where the position is controlled by an external loop, based on data provided by a sensor (e.g. PSD quad cell, CCD chip, ...).

The closed-loop versions are equipped with two pairs (one per axis) of LVDT (linear variable differential transformer) sensors operated in a bridge circuit for ultra-high resolution and angular stability. They provide sub-µrad resolution and repeatability (with PI control electronics).

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Technical Data

Models	S-340.A0	S-340.AL	Units	Notes see p. 3-16
Active axes	θ_X, θ_Y	θ_X, θ_Y		
Open-loop tilt angle @ 0 to 100 V	±1	±1	mrad ±20%	A2
Closed-loop tilt angle ≥	-	±1	mrad	A3
Integrated feedback sensor	-	4 x LVDT		B
Closed-loop / open-loop ***resolution ≤	- / 0.1	0.5 / 0.1	µrad	C1
Closed-loop linearity (typ.)	-	±0.1	%	
Full-range repeatability (typ.)	-	±1	µrad	C3
Electrical capacitance	7.2 / axis	7.2 / axis	µF ±20%	F1
* Dynamic operating current coefficient (DOCC)	0.45 / axis	0.45 / axis	µA/(Hz x µrad)	F2
** Unloaded resonant frequency (f_0)	1.4	1.4	kHz ±20%	G2
** Resonant frequency w/ ∅ 50 x 15 mm glass mirror	0.9	0.9	kHz ±20%	G3
** Resonant frequency w/ ∅ 75 x 22 mm glass mirror	0.4	0.4	kHz ±20%	G3
Distance, pivot point to platform surface (T)	7.5	7.5	mm	
** Platform moment of inertia	18000	18000	$g \cdot mm^2$	
Operating temperature range	- 20 to 80	- 20 to 80	°C	H2
Voltage connection	3 x VL	3 x VL		J1
Sensor connection	-	2 x L		J2
Weight (w/o cables)	335	335	g ±5%	
Material (case / platform)	Al / depends on version	Al / depends on version		L

** Dynamic Operating Current Coefficient in µA per hertz and µrad.*
Example: Sinusoidal scan of 100 µrad at 10 Hz requires approximately 0.45 mA drive current.

*** Value for aluminum top plate. Lower resonant frequency for other platforms due to higher moment of inertia: titanium: +60%; invar: +200%; steel: +190%.*

**** Resolution of PZT tip/tilt platforms is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier.*

Tripod Tip-Tilt-Z for Optical Communication

Applications

- Free Space Communication
- Image stabilization
- Laser beam stabilization
- Beam switching
- Adaptive optics systems
- Laser beam steering & scanning
- Correction of polygon scanner errors.

S-325.3SD
High-Dynamics Piezo Z/Tip/Tilt Platform, 5 mrad, 30 µm, SGS, Sub-D Connector

S-325.3SL
High-Dynamics Piezo Z/Tip/Tilt Platform, 5 mrad, 30 µm, SGS, LEMO Connector

S-325.30L
High-Dynamics Piezo Z/Tip/Tilt Platform, 5 mrad, 30 µm, Open-Loop, LEMO Connector

High Resolution, Stability and Dynamics

The S-325 offers piston movement of up to 30 µm (ideal for path length adjustment) and mechanical tilt up to 5 mrad (equivalent to 10 mrad optical beam deflection). The zero-friction piezo drives and flexure guidance allow sub-nanometer linear resolution and sub-microradian angular resolution.

It is designed for industrial applications where 1.000.000.000 motion cycles have to be performed without failure or performance degradation. The systems are designed for mirrors and optics up to 25 mm in diameter and can be mounted in any orientation.

The tripod drive offers optimum angular stability over a wide temperature range. Compared to stacked, (two-stage), piezo or galvo scanners, the single platform design provides several advantages: smaller package size, identical size, identical dynamic performance in all axes, faster response and better linearity. It also prevents polarization rotation.

High Reliability and Long Lifetime

The compact S-325 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and provide better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free, not subject to wear and offer extraordinary reliability.

- **Optical Beam Deflection to 10 mrad, Resolution to 50 nrad**
- **Piston Movement up to 30 µm (for Path Length Adjustment)**
- **Compact Tripod Design with Coplanar Axes Eliminates Polarization Rotation**
- **Sub-Millisecond Responsiveness**
- **Closed-Loop Versions for Higher Precision**
- **For Mirrors up to 25 mm (1") Diameter**
- **Frictionless, High-Precision Flexure Guiding System**
- **Parallel Kinematics for Enhanced Dynamics and Better Multi-Axis Accuracy**

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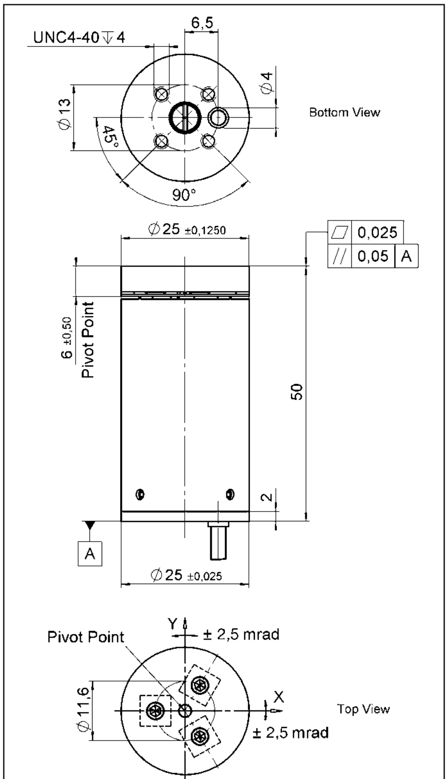

S-325 dimensions in mm

Technical Data

Model	S-325.30L	S-325.3SL	S-325.3SD	Units	Tolerance
Active axes	Z, Θ_X, Θ_Y	Z, Θ_X, Θ_Y	Z, Θ_X, Θ_Y		
Motion and positioning					
Integrated sensor	–	SGS	SGS		
Open-loop travel, 0 to +100 V	30	30	30	µm	min. (+20 %/-0 %)
Open-loop tip/tilt angle, 0 to +100 V	5	5	5	mrad	min. (+20 %/-0 %)
Closed-loop travel	–	30	30	µm	
Closed-loop tip/tilt angle	–	4	4	mrad	
Open-loop resolution	0.5	0.5	0.5	nm	typ.
Open-loop tip/tilt angle resolution	0.05	0.05	0.05	µrad	typ.
Closed-loop linear resolution	–	0,6	0,6	nm	typ.
Closed-loop tip/tilt resolution	–	0.1	0.1	µrad	typ.
Mechanical properties					
Unloaded resonant frequency	2	2	2	kHz	±20 %
Resonant frequency (with 25 x 8 mm glass mirror)	1	1	1	kHz	±20 %
Distance of pivot point to platform surface	6	6	6	mm	±0.5 mm
Platform moment of inertia	515	515	515	g • mm²	±20 %
Drive properties					
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	9.3	9.3	9.3	µF	±20 %
Dynamic operating current coefficient	39	39	39	µA / (Hz • mrad)	±20 %
Miscellaneous					
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	°C	
Material casing	Aluminum	Aluminum	Aluminum		
Mass	0.065	0.065	0.065	kg	±5 %
Cable length	2	2	1.5	m	±10 mm
Sensor / voltage connection	LEMO	LEMO	Sub-D		

For maximum tilt range, all three piezo actuators must be biased at 50 V. Due to the parallel-kinematics design linear travel and tilt angle are interdependent. The values quoted here refer to pure linear / pure angular motion. See equations (p. 2-84).

Recommended controller / amplifier

Versions with LEMO connector: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503.00S (three channels) (p. 2-146) or 1 x E-505.00S and 2 x E-505 (high speed applications) (p. 2-147) and E-509 controller (p. 2-152) (optional)

Single-channel (1 per axis): E-610 OEM servo controller / amplifier (p. 2-110), E-625 servo controller bench-top (p. 2-114)

Versions with Sub-D connectors: E-616 servo controller for tip/tilt mirror systems (p. 2-132)

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Large Angle PZT Tip/Tilt-Mirror for Free Space Communication

Applications

- Free Space Communication
- Image stabilization
- Laser beam stabilization
- Beam switching
- Adaptive optics systems
- Laser beam steering & scanning
- Correction of polygon scanner errors.

S-334.1SD
High-Dynamics Piezo Tip/Tilt Platform, 25 mrad, SGS, Sub-D Connector, incl. Mirror

S-334.1SL
High-Dynamics Piezo Tip/Tilt Platform, 25 mrad, SGS, LEMO Connector, incl. Mirror

S-334.2SD
High-Dynamics Piezo Tip/Tilt Platform, 50 mrad, SGS, Sub-D Connector, incl. Mirror

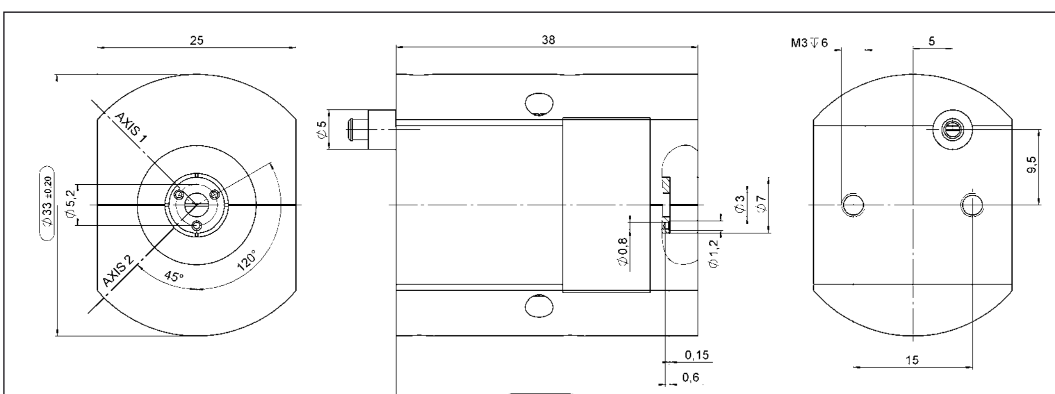
S-334.2SL
High-Dynamics Piezo Tip/Tilt Platform, 50 mrad, SGS, LEMO Connector, incl. Mirror

S-334 piezo tip/tilt mirrors / scanners provide extremely large deflection angles in a miniaturized package. These fast steering mirror systems are based on a sophisticated parallel-kinematics design with two coplanar, orthogonal axes and a fixed pivot point.

Large Tip/Tilt Ranges with Excellent Motion Characteristics

The novel flexure/lever design with minimized inertia allows for the exceptionally large tip/tilt range of 60 mrad (50 mrad in closed-loop operation, which is equivalent to 100 mrad optical beam deflection) and very fast response in the millisecond range. These parameters make the system unique in the market of piezo driven tip/tilt mirror systems.

- **Miniature Design**
- **Optical Beam Deflection to 120 mrad (~ 6.8°)**
- **Coplanar Axes & Fixed Pivot Point; Eliminate Polarization Rotation**
- **Factory Installed Mirror**
- **Millisecond Response, Resolution to 0.2 µrad**
- **Closed-loop Position Servo-Control for High Accuracy**
- **For Mirrors up to 12.5 mm (0.5") Diameter**
- **Frictionless, High-Precision Flexure Guiding System**
- **Parallel Kinematics for Enhanced Dynamics and Bette Multi-Axis Accuracy**



S-334 dimensions in mm

For the latest specs visit www.tip-tilt-stage.com

Sub-Microradian Resolution

In addition to the large angles and the high dynamics the S-334 provides sub-microradian resolution. The integrated high-resolution, full-bridge strain gauge sensors (SGS) provide absolute position control, excellent repeatability and high linearity, typically better than 0.05 % over the entire travel range.

High Reliability and Long Lifetime

The compact S-334 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and provide better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free, not subject to wear and offer extraordinary reliability.

Differential Drive for Improved Stability and Dynamics

The S-334 is based on a parallel-kinematics design with coplanar axes and a single moving platform. Two pairs of differentially-driven piezo actuators are employed to provide the highest dynamics and position stability over a wide temperature range.

Compared to stacked, (two-stage), piezo or galvo scanners, the single-platform design provides several advantages: smaller package size, identical dynamic performance in both axes, faster response and better linearity. It also prevents polarization rotation.

Factory Installed Mirror

The S-334 is equipped with a factory-installed mirror 10 mm in diameter and 2 mm thick (flatness λ/5, reflectivity >98 % from 500 nm to 2 µm).

Model	S-334.1SL S-334.1SD	S-334.2SL S-334.2SD	Units	Tolerance
Active Axes	θ_X, θ_Y	θ_X, θ_Y		
Motion and positioning				
Integrated sensor	SGS	SGS		
*Open-loop tilt angle at -20 to +120 V	30	60	mrad	min. (+20 %/-0 %)
*Closed-loop tilt angle	25	50	mrad	
Open-loop resolution	0.2	0.5	µrad	typ.
Closed-loop resolution	1	5	µrad	typ.
Linearity	0.05	0.05	%	typ.
Repeatability	2	5	µrad	typ.
Mechanical properties				
Resonant frequency underload (with standard mirrors)	3.0	1.0	kHz	±20 %
Load capacity	0.2	0.2	N	Max.
Distance of pivot point to platform surface	6	6	mm	±1 mm
Platform moment of inertia	1530	1530	g • mm²	±20 %
Standard mirror (mounted)	diameter: 10 mm, thickness: 2 mm; BK7, λ/5, R > 98 % (λ = 500 nm to 2 µm)	diameter: 10 mm, thickness: 2 mm; BK7, λ/5, R > 98 % (λ = 500 nm to 2 µm)		
Drive properties				
Ceramic type	PICMA® P-885	PICMA® P-885		
Electrical capacitance per axis	3	3	µF	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material casing	Titanium	Titanium		
Mass	0.065	0.065	kg	±5 %
Cable length	2	2	m	±10 mm
Sensor / voltage connection	LEMO connector / 25-pin sub-D connector	LEMO connector / 25-pin sub-D connector		

Recommended controller / amplifier
Closed-loop versions with D-sub connector: E-616 controller for tip/tilt mirror systems (p. 2-132);
Open-loop versions with LEMO connector: Modular piezo controller system E-500 (p. 2-142) with amplifier module E-503.00S (three channels) (p. 2-146) or 1 x E-505.00S and 2 x E-505 (high speed applications) (p. 2-147) and E-509 servo controller (p. 2-152 / 3-16)
Open-loop: E-663 three channel amplifier (p. 2-136)

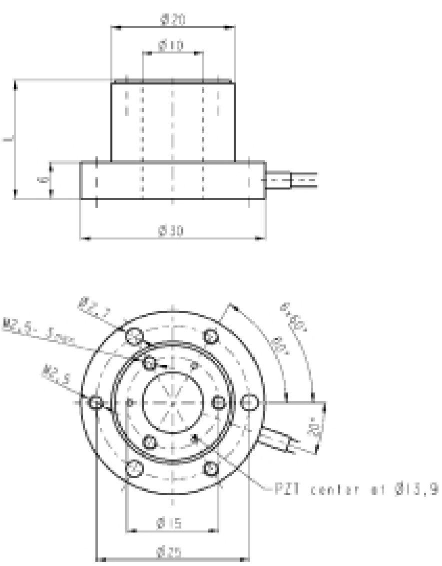
Resolution of PI piezo tip/tilt platforms is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier, (p. 2-146).

*Mechanical tilt, optical beam deflection is 120 mrad (open loop) and 100 mrad (closed-loop), respectively.

Tripod Tip-Tilt-Z w/ Aperture for Optical Communication

Applications

- Optical filters
- Laser cavity tuning
- Free Space Communication
- Image stabilization
- Laser beam stabilization
- Beam switching
- Adaptive optics systems
- Laser beam steering & scanning
- Correction of polygon scanner errors.



S-310 - S-316 dimensions (in mm)

- **10 mm Clear Aperture**
- **Triple-PZT-Actuator-Supported Platform**
- **Tilt Range up to ±600 µrad**
- **Piston Movement up to 12 µm**
- **Closed-Loop Versions**
- **For Optics, Mirrors or Other Components**

S-310 to S-316 multi-axis tip/tilt platforms and Z-positioners are fast and compact units based on the triple-piezo-drive-supported platform design (see page 3-7 for details and equations). They offer piston movement up to 12 µm and tilt movement up to ±600 µrad with sub-msec response and settling. The S-310 to S-316 systems are designed for mirrors and optics up to 25 mm diameter; the clear aperture is ideal for transmitted-light applications. The units can be mounted in any orientation.

In open-loop operation, the vertical position/platform angle roughly corresponds to the drive voltage (see page 4-11 in the "Tutorial" section for behavior of open-loop piezos). The S-310 to S-315 open-loop models are ideal for applications where the position is controlled by an external loop based on data provided by a sensor (e.g. PSD quad cell, CCD chip, ...). The S-316.10 closed-loop version allows absolute position control, high linearity and repeatability based on the internal ultra-high-resolution feedback sensor.

S-310.10
Vertical Piezo Positioner with Clear Aperture, 6 µm

S-311.10
Multi-Axis Piezo Tip/Tilt Platform with Clear Aperture, ±300 µrad, 6 µm

S-314.10
Vertical Piezo Positioner with Clear Aperture, 12 µm

S-315.10
Multi-Axis Piezo Tip/Tilt Platform with Clear Aperture, ±600 µrad, 12 µm

S-316.10
Multi-Axis Piezo Tip/Tilt Platform with Clear Aperture, ±600 µrad, 12 µm, Closed-Loop

Custom Designs

Five different versions are available:

- **S-310.10**
- **S-314.10**

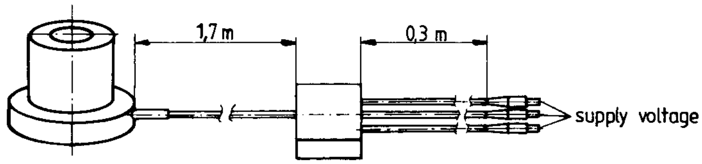
Open-loop Z-platforms; all three piezo linear actuators are electrically connected in parallel, providing vertical positioning (piston movement) of the top ring. Only one drive channel is required. The three piezo actuators are individually matched for equal displacement, providing straight motion with tilt errors of less than 70 µrad over the complete range.

- **S-311.10**
- **S-315.10**

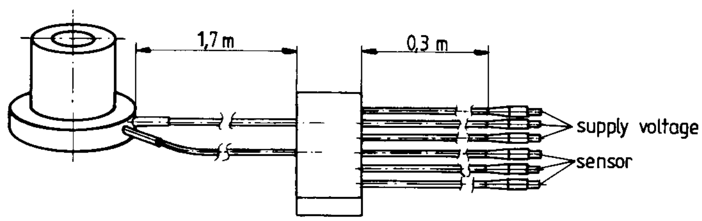
Open-loop Z, tip/tilt positioners; all three piezo linear actuators can be driven individually (or in parallel) by a three-channel amplifier. Vertical (piston movement) positioning and tip/tilt positioning is possible.

- **S-316.10**

Closed-loop Z, tip/tilt positioner. All three piezo linear actuators are equipped with strain gauge position feedback sensors and can be driven individually (or in parallel) by a three-channel amplifier/position servo-controller. Vertical positioning (piston movement) and tip/tilt positioning is possible. The integrated position feedback sensors provide sub-µrad resolution and repeatability (with PI control electronics).



S-315 cable configuration



S-316 cable configuration

Technical Data

Models	S-310.10	S-314.10	S-311.10	S-315.10	S-316.10	Units	Notes see p. 3-16
Active axes	Z	Z	Z, θ_X, θ_Y	Z, θ_X, θ_Y	Z, θ_X, θ_Y		
* Open-loop tilt angle @ 0 to 100 V	-	-	±300	±600	±600	µrad ±20%	
* Closed-loop tilt angle ≥	-	-	-	-	±600	µrad	A3
Open-loop linear travel @ 0 to 100 V	6	12	6	12	12	µm ±20%	A5
Closed-loop linear travel ≥	-	-	-	-	12	µm	A6
Integrated feedback sensor	-	-	-	-	3 x strain gauge		B
Closed-loop *** angular resolution ≤	-	-	-	-	±0.05	µrad	C1
Closed-loop / open-loop *** linear resolution ≤	- / 0.1	- / 0.2	- / 0.1	- / 0.2	0.2 / 0.4	nm	C1
Stiffness (Z)	20	10	20	10	10	N/µm ±20%	D1
Electrical capacitance	0.7	1.4	3 x 0.23	3 x 0.45	3 x 0.45	µF ±20%	F1
** Dynamic operating current coefficient (DOCC)	15	15	3 x 5	3 x 5	3 x 5	µA/ (Hz x µm)	F2
Unloaded resonant frequency (f_0)	9.5	5.5	9.5	5.5	5.5	kHz ±20%	G2
Resonant frequency w/ ∅ 15 x 4 mm glass mirror	6.5	4.4	5.5	4.1	4.1	kHz ±20%	G3
Resonant frequency w/ ∅ 20 x 4 mm glass mirror	6.1	4.2	4.4	3.4	3.4	kHz ±20%	G3
Distance, pivot point to platform surface (T)	-	-	5	5	5	mm	
Platform moment of inertia	-	-	150	150	150	gmm^2	
Operating temperature range	- 20 to 80	- 20 to 80	- 20 to 80	- 20 to 80	- 20 to 80	°C	H2
Voltage connection	1 x VL, 2 m cable	1 x VL, 2 m cable	3 x VL, 2 m cable	3 x VL, 2 m cable	3 x VL, 2 m cable		J1
Sensor connection	-	-	-	-	3 x L, 2 m cable		J2
Weight (w/o cables)	45	55	45	55	55	g ±5%	
Material (case / platform)	N-S / N-S	N-S / N-S	N-S / N-S	N-S / N-S	N-S / N-S		L
Recommended amplifier/controller (codes explained p. 6-46)	G, C	G, C	G, C	G, C	H, D		

** For maximum tilt range, all three piezo actuators must be biased at 50 V. Linear travel and tilt angle are interdependent. The values quoted here refer to pure linear / pure angular motion. See triple-piezo-drive tilt platform equation on page 3-7 for more information.*

*** Dynamic Operating Current Coefficient in µA per hertz and µm (per actuator). Example S-314.10: Sinusoidal scan of 10 µm at 10 Hz requires approximately 1.5 mA drive current. For tilt calculation, calculate power requirement for the individual actuators and use triple-piezo-drive tilt platform equation on page 3-7.*

**** Resolution of PZT tip/tilt platforms is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier.*

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Differential Tip-Tilt Mirror for High-Speed Optical Beam Control

S-330.10
$\theta_X\theta_Y$ Piezo Tip/Tilt Platform ±1 mrad, Closed-Loop

S-330.30
$\theta_X\theta_Y$ Piezo Tip/Tilt Platform ±1 mrad

Custom Designs

- **Sub-µrad Resolution**
- **For Mirrors to 50 mm Ø**
- **Closed-Loop Versions**
- **Differential Design for Excellent Temperature Stability**

S-330 piezo tip/tilt platforms are fast and compact tilt units, providing precise angular movements of the top platform in two orthogonal axes. The tip/tilt range is ±1 mrad (special version with ± 2.5 mrad available on request) with sub-µrad resolution. Closed-loop versions are available for highest accuracy and repeatability. S-330 systems are designed for mirrors up to 50 mm diameter and have outstanding angular stability over a wide temperature range. To match the CTE (coefficient of thermal expansion) of Zerodur glass, the S-330 is equipped with an invar top platform.

Applications

- **Free Space Communication**
- **Image stabilization**
- **Laser beam stabilization**
- **Beam switching**
- **Adaptive optics systems**
- **Laser beam steering & scanning**
- **Correction of polygon scanner errors.**

Technical Data

Models	S-330.30	S-330.10	Units	Notes see p. 3-16
Active axes	θ_X,θ_Y	θ_X,θ_Y		
Open-loop tilt angle @ 0 to 100 V	±1*	±1	mrad ±20%	A2
Closed-loop tilt angle ≥	-	±1	mrad	A3
Integrated feedback sensor	-	4 x strain gauge		B
Closed-loop / open-loop ** resolution ≤	- / 0.05	0.1 / 0.05	µrad	C1
Closed-loop linearity (typ.)	-	±0.2	%	
Full-range repeatability (typ.)	-	±2	µrad	C3
Electrical capacitance	3.6 / axis	3.6 / axis	µF ±20%	F1
*** Dynamic operating current coefficient (DOCC)	0.22 / axis	0.22 / axis	µA/(Hz x µrad)	F2
Resonant frequency (f_0) without mirror	3.3	3.3	kHz ±20%	G2
Resonant frequency w/ ∅ 25 x 8 mm glass mirror	2.4	2.4	kHz ±20%	G3
Distance, pivot point to platform surface (T)	6	6	mm	
Platform moment of inertia	1530	1530	g·mm²	
Operating temperature range	- 20 to 80	- 20 to 80	°C	H2
Voltage connection	3 x VL, 2 m cable	3 x VL, 2 m cable		J1
Sensor connection	-	1 x L, 2 m cable		J2
Weight (w/o cables)	200	200	g ±5%	
Material (case/platform)	N-S / I	N-S / I		L

** Special version with ± 2.5 mrad a vaillable on request.*

*** Resolution of PZT tip/tilt platforms is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier.*

**** Dynamic Operating Current Coefficient in µA per hertz and µrad.
Example: Sinusoidal scan of 100 µrad at 10 Hz requires approximately 0.22 mA drive current.*

For the latest specs visit www.tip-tilt-stage.com

Working Principle

S-330 tilt Platforms are equipped with two pairs of low-voltage piezoelectric linear drives (0 to 100 V) operating as a unit in push/pull mode (see figure p.3-13 for schematic diagram). The stainless steel case is equipped with an integrated, FEA-modeled (finite element analysis) circular flexure featuring zero stiction, zero friction and exceptional guiding precision. In open-loop operation, the platform angle roughly corresponds to the drive voltage (see p.4-11 in the "Tutorial" section for behavior of open-loop piezos). The open-loop model is ideal for applications where the position is controlled by an external loop, based on data provided by a sensor (e.g. PSD quad cell, CCD chip, ...).

The closed-loop version is equipped with two pairs (one per axis) of strain gauge sensors operated in a bridge circuit for ultra-high resolution and angular stability. They provide sub-µrad resolution and repeatability (with PI control electronics).

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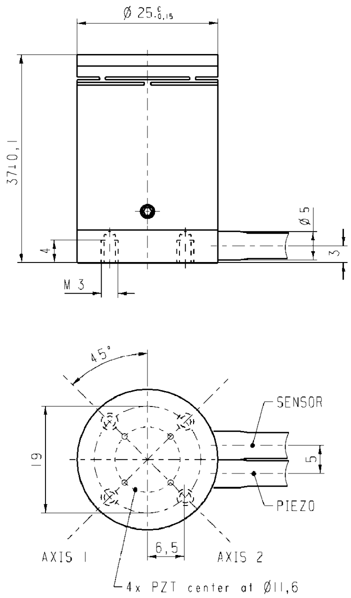
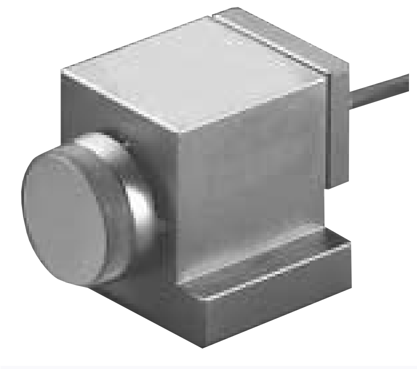


S-330 dimensions (in mm)

Single Axis Piezo Tilt Mirror for Optical Beam Steering



S-224.00
Piezo Tilt Platform 2.2 mrad with Mirror

S-226.00
Piezo Tilt Platform 2.2 mrad with Mirror, Closed-Loop

Custom Designs

- **Sub-µrad Resolution**
- **Sub-Millisecond Response**
- **2.2 mrad Tilt Range**
- **Optional Position Feedback Sensor**
- **Includes BK7 Mirror**

S-224/S-226 miniature tilt platforms are extremely fast and compact tilt units, providing a tilt range of 2.2 mrad and sub-millisecond response. The units can be clamped at the flanges. The S-224 is specifically designed for open-loop operation. The S-226 closed-loop version is available for highest accuracy.

Working Principle

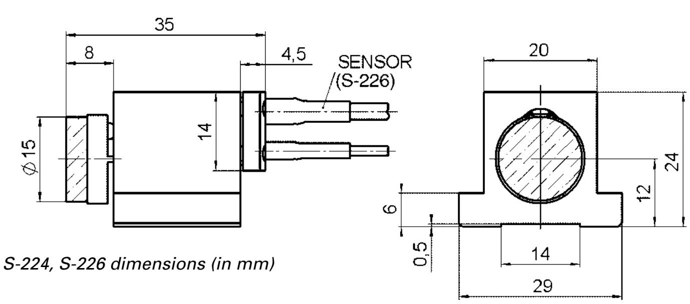
S-224/S-226 miniature tilt platforms are equipped with low-voltage piezoelectric linear drives (0 to 100 V) pushing a frictionless, flexure-mounted platform. The flexure is FEA (finite element analysis) modeled for zero stiction, zero friction and exceptional guiding precision; it also serves as the pivot point and preload for the PZT.

Open- and Closed-Loop Operation

In open-loop operation, the platform's angular position is roughly proportional to the drive voltage (see p. 4-11 in the "Tutorial" section for behavior of open-loop piezos). The open-loop models are ideal for applications where the position is controlled by data provided by an external optical sensor, a CCD camera, etc. The closed-loop version (S-226) allows absolute position control, high linearity, and repeatability based on the internal ultra-high-resolution feedback sensor.

Applications

- **Laser beam steering & scanning**
- **Beam switching**
- **Correction of polygon scanner errors**
- **Laser beam stabilization.**



S-224, S-226 dimensions (in mm)

Technical Data

Models	S-224.00	S-226.00	Units	Notes see p. 3-16
Active axes	θ_x	θ_x		
Open-loop tilt angle @ 0 to 100 V	2.2	2.2	mrad ±20%	A2
Closed-loop tilt angle ≥	-	2.2	mrad	A3
Integrated feedback sensor	-	strain gauge		B
Closed-loop / open-loop ** resolution ≤	- / 0.05	0.1 / 0.05	µrad	C1
Closed-loop linearity (typ.)	-	0.2	%	
Full-range repeatability (typ.)	-	±3	µrad	C3
Electrical capacitance	1.8	1.8	µF ±20%	F1
* Dynamic operating current coefficient (DOCC)	0.1	0.1	µA/ (Hz x µrad)	F2
Unloaded resonant frequency (f_0)	9.0	9.0	kHz ±20%	G2
Resonant frequency w/ ∅ 15 x 4 mm glass mirror (included)	7.5	7.5	kHz ±20%	G3
Resonant frequency w/ ∅ 15 x 4 mm copper mirror	5.7	5.7	kHz ±20%	G3
Distance, pivot point to platform surface (T)	4	4	mm	
Platform moment of inertia	215	215	g·mm²	
Operating temperature range	- 20 to 80	- 20 to 80	°C	H2
Voltage connection	VL	VL		J1
Sensor connection	-	L		J2
Weight (w/o cables)	98	98	g ±5%	
Material (case / platform)	N-S / N-S	N-S / N-S		L
Recommended amplifier/controller (codes explained p. 6-46)	G, C	H, D		

** Dynamic Operating Current Coefficient in µA per hertz and µrad. Example: Sinusoidal scan of 100 µrad at 10 Hz requires approximately 0.1 mA drive current.*

*** Resolution of PZT tip/tilt platforms is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier.*

Large Tip-Tilt Mirrors for Astronomical Telescopes

During the last decades, PI has designed several large-aperture tip/tilt systems for image stabilization. Resolution in large earthbound telescopes is limited by atmospheric turbulence and vibrations which cause image shifting. Piezoelectrically driven active secondary mirrors significantly improve telescope resolution, up to 1000% during long integrations, by correcting for these image shifts in real time.

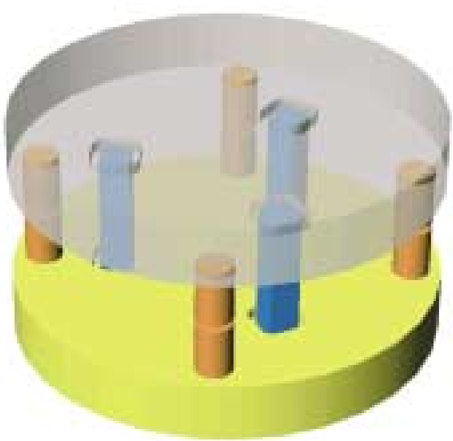
Momentum Compensation

Due to the inertia of the large mirrors and the high accelerations required to correct for image fluctuations, significant forces can be induced in the telescope structure, causing unwanted vibrations.

To cancel these forces before they excite vibrations in the structure, PI has developed momentum compensation systems integrated into the tip/tilt platforms. Any vibration caused by the motion of the mirror is canceled with an efficiency of up to 95% by the internal, piezoelectrically driven momentum-compensation mechanism.

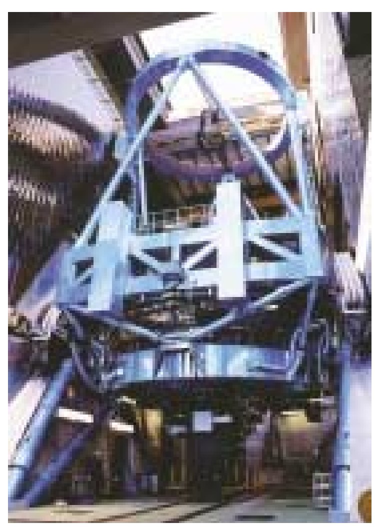
The Horsehead Nebula. Photo: Brian Lula.

Active secondary tip/tilt mirror for the United Kingdom Infra-Red Telescope (UKIRT) on Mauna Kea, Hawaii, with Hexapod 6-degree-of-freedom alignment system (for information on Hexapod systems see the "MicroPositioners" section, p. 7-1 ff.).
Mirror diameter: 314 mm
Tip/Tilt range: ±500 µrad
Resonant frequency: 280 Hz



Basic design of an active optics platform featuring three actuators and four sensors

Active secondary tip/tilt mirror for ESO's (European Southern Observatory) 2.2 m telescope in La Silla, Chile.
Mirror diameter: 100 mm
Tip/Tilt range: ±400 µrad
Resonant frequency: 900 Hz



View inside the 8.2 meter optical infrared Subaru Telescope on Hawaii. From http://SubaruTelescope.org/index.html, courtesy of NAOJ.