STATUS REPORT

Cobra Fiber Positioner in Full-Scale Production

for Subaru Telescope Prime Focus Spectrograph

Manufacturing results exceed projections for yield and efficiency, demonstrating New Scale's unique competencies in technology development combined with large-scale micro mechatronic manufacturing

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NEW SCALE TECHNOLOGIES
small, precise, smart... in motion

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Summary

In May 2016 New Scale demonstrated full production capacity — 200 per month — of **Cobra fiber positioners** for the Subaru Telescope Prime Focus Spectrograph (PFS).

Our production results are exceeding our projections for yield and efficiency. New Scale plans to deliver a total of 2,550 Cobra positioners to the California Institute of Technology by June 2017.

This important production milestone was reached after eight years of research and development, resulting in:

- Unique and patented piezoelectric motor technology with reduced operating voltage (10 volts) and longer-life (> 400K cycles) that is uniquely suited for the Cobra application.
- Patented drive electronics that are sufficiently small and low power to be integrated in the close-packed Cobra arrays.
- A validated Cobra system design that meets the science requirement of the PFS including:

  8 mm actuator array spacing with 9.5 mm diameter fiber patrol area.

  5 µm fiber positioning with < 0.3 degree fiber tilt and < 25 µm fiber defocus.

  Robustly hold position without power and zero backlash.

  Efficiently converge to target positions.
- A global supply chain for the 32 unique Cobra components.
- Assembly tools, fixtures and processes sufficient for producing 200 Cobra positioners per month.
- Quality assurance and 100% in-line testing methods that verify all critical Cobra specifications.
- A highly trained and experienced Cobra positioner production staff.

__The PFS is a fiber-fed multi-object spectrometer__ that will conduct a variety of automated studies of dark energy, galaxy evolution, and galactic archaeology.

New Scale is proud to be part of the PFS team and contribute to this program's goals to better understand the nature of the universe.

Cobra production demonstrates New Scale's unique competencies in technology development combined with large-scale micro mechatronic manufacturing. We expect to contribute these skills to other fiber spectrometer programs in the near future.

Cobra Positioner Design and Performance

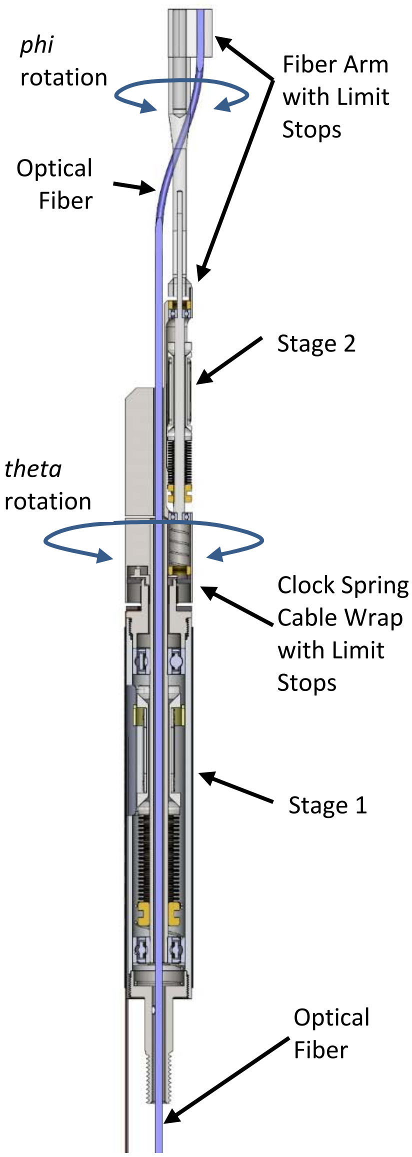

Figure 1: Cobra 2-Axis Fiber Positioner.

The Cobra Positioner is a two-degree-of-freedom positioner that moves individual optical fibers in the prime focus plane with a precision of 5 µm. It is a theta-phi style mechanism where two rotary piezoelectric motors are stacked together with their centerlines offset in "SCARA robot" configuration. The optical fiber is routed through the center of stage 1 (theta) and connected to a stage 2 rotating arm (phi).

This design enables the tip of the optic fiber to be placed anywhere in a 9.5 mm diameter patrol region. This patrol region is larger than the 7.7 mm diameter of the actuator, enabling a close packed hex array pattern of positioners that have overlapping patrol areas and deliver 100% sky coverage.

The PFS will have 2,394 Cobra positioners in a close-packed hex array pattern on 8-mm centers. The demonstrated Cobra performance parameters include:

Parameter	Stage 1	Stage 2
Range (deg.)	370	180
Step Size (deg.)	< 0.06	< 0.12
Torque	> 300 µNm	
Fiber Tilt Error	< 0.3 deg.	
Fiber Focus Error	< 25 µm	
Operating Voltage	10V	
Lifetime	> 400,000 cycles	
Temperature	- 5 ˚C	
Length	< 80 mm	
Outside Diameter (stage 1)	< 7.7 mm	
Thru Hole for Fiber	1 mm	
Offset (stage 1 to stage 2)	2.375 mm	

In 2014 New Scale delivered Cobra positioners to Caltech for Engineering Model validation testing for the Subaru-PFS[1]. These results confirmed that Cobra positioners meet the PFS science requirements and are ready for production.

The Cobra positioners were tested in a lab environment that simulates the orientation, temperature and fiber manipulation in the PFS. Each Cobra was moved with open-loop commands, by adjusting burst duration, without an in-situ angle sensor. A CCD camera imaged the tip of the backlit fiber to determine its location. Over 100 simulated cosmological targets were tested using the Cobra positioner and showed that the Cobra positioner can converge on over 95% of its targets within 5µm in less than six open loop move iterations.

[1] Charles Fisher, Chaz Morantz, David Braun, et al., "Developing engineering model Cobra fiber positioners for the Subaru Telescope's prime focus spectrometer", Proceedings of SPIE Vol. 9151, 91511Y (2014).

Cobra Positioner Development History

New Scale's development of the Cobra fiber positioner started in 2008 with the California Institute of Technology and NASA-JPL team[2]. The objective was to create a two-axis rotary fiber positioner (theta-phi style) that:

- Achieved an array spacing of 8 mm for 2400 optical fibers
- Positioned each optical fiber within a 9.5 mm diameter patrol area using a "SCARA robot" design.
- Achieved 5 micrometer step precision while holding position without power or backlash and minimizing fiber tilt and defocus.

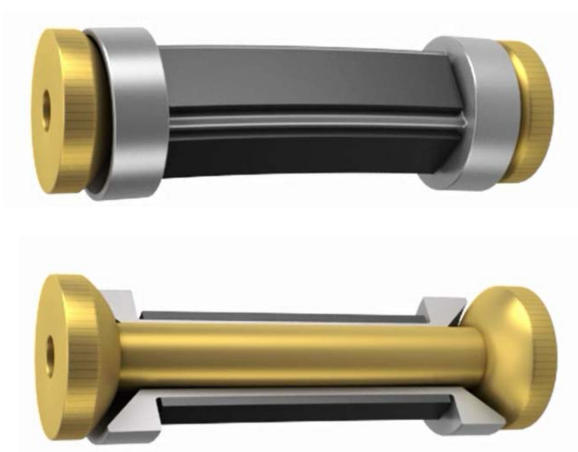

Figure 2: *Cobra motor design principle showing "wobbling" square tube with conical ends that is frictionally coupled to a rotating shaft with spherical ends. For animation see http://www.newscaletech.com/technology/squiggle-motors.php*

The Cobra positioner is a novel implementation of previously demonstrated piezoelectric rotary motors that use the first bending resonant vibrations of a tube. The orthogonal vibrations of the tube create a "wobbling motion" that is frictionally coupled to a rotating shaft to create high torque in very small angular steps without gear reduction. The operating principle of the Cobra motors is shown in figure 2.

One early example of a wobbling rotary motor was conceived by Williams and Brown (1948)[3]. This motor uses an orbiting stator to engage a round shaft or gear where tangential contact produces rotation. In 1995, a similar rotary motor was demonstrated by Morita[4] which uses a thin walled piezoelectric cylinder.

A miniaturized rotary motor, using two piezo plates and a hollow metal tube, was demonstrated by Koc, Catagay and Uchino[5] in 2002.

In 2003 New Scale invented[6] the Squiggle ultrasonic motor that combines the piezo rotary motor with a lead screw to create a novel linear actuator.

The first Cobra positioner prototypes were delivered to Caltech in 2009 and demonstrated the feasibility of this new approach for fiber positioning. Several improvements were implemented in subsequent design iterations to better match the needs of the PFS.

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[2] Fisher, C., Braun D., Kaluzny, J., Haran, T., "Cobra – a Two-Degree of Freedom Fiber Optic Positioning Mechanism," IEEE Aerospace Conference paper #1185, Version 5 (2009).

[3] W. Williams and W.J. Brown, "Piezoelectric Motor", US Patent, 2439499, April 1948.

[4] T. Morita et al: "An Ultrasonic Micro Motor using a bending transducer based on PZT thin film", Sensors and Actuators A, Vol. 50, pp. 75-80, 1995.

[5] Koc, B., Cagatay, S., Uchino, K., "A piezoelectric motor using two orthogonal bending modes of a hollow cylinder", IEEE Trans. Ultrasonic Ferroelectric Freq. Cont. 49, 495 -500, 2002.

[6] Squiggle motor patents from New Scale Technologies include: US Patents 6,940,209, 7,170,214, 7,309,943 and 7,339,306.

These improvements include:

a) Integration of precision ball bearings to more precisely locate the theta and phi axes of the rotation and maintain the fiber focus within 25 µm and tilt less than 0.3 degrees.

b) Integrating a “clock spring” cable wrap with limit stops inside the Cobra assembly to connect the moving stage 2 (phi) motor to the drive electronics.

c) Increasing Cobra lifetime from 100,000 cycles to greater than 400,000 cycles by identifying and testing a new and longer-life friction contact materials (sapphire on steel).

d) Reducing the motor operating voltage from 100’s of volts to 10 volts.

e) Reducing the size of the drive electronics to a width less than the diameter of the Cobra assembly.

These improvements —especially d) and e) — were derived from parallel research at New Scale Technologies that incorporates advanced co-fired multi-layer piezoelectric materials in piezo motors and eliminates the need for voltage boost circuits[7].

To further miniaturize the drive electronics, “smart” full-bridge switching circuits are used that: (1) track the optimum drive frequency; (2) control velocity, duty cycle and power; and (3) reduce operating power using novel full-bridge switch timing[8].

[7] Reduced voltage piezo motors from New Scale Technologies include US Patent 8,217,553.

[8] Novel piezo motor drive electronics from New Scale Technologies include US Patents 8,698,374, 8,450,905, 8,299,733, and 8,304,960.

Cobra Positioner Manufacturing

In 2016 the unique Cobra positioners became a mature product that is routinely manufactured at New Scale Technologies. This important milestone was reached after two years of investment in supply chain, quality assurance, process design, tooling validation, testing methods and staff training.

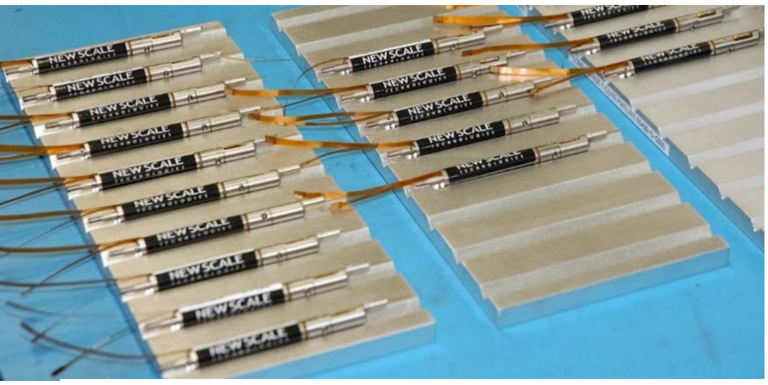

Figure 3: *Cobra positioners after final test, ready to be packaged for shipment.*

Cobra positioner production began in February 2016. The target capacity of 200 per month was achieved in May 2016. New Scale is exceeding projections for yield and efficiency, and plans to deliver a total of 2,550 Cobra positioners to Caltech by June 2017 (Figure 3).

Cobra positioners use 32 distinct parts that are purchased from our global supply chain. Key components include piezoelectric ceramic plates, sapphire rotors, hardened steel motor cores, flexible printed circuits, micro ball bearings and precision machined stainless steel housings and shafts.

We work continuously with our vendors to insure all requirements are mutually understood and 100% verified. Quality assurance (QA) includes rigorous in-house checks prior to using parts in the Cobra assembly line. For example, in-house dimensional verification is completed using our coordinate measuring machine (CMM) (Figure 4) or optical Smart Scope inspection tool.

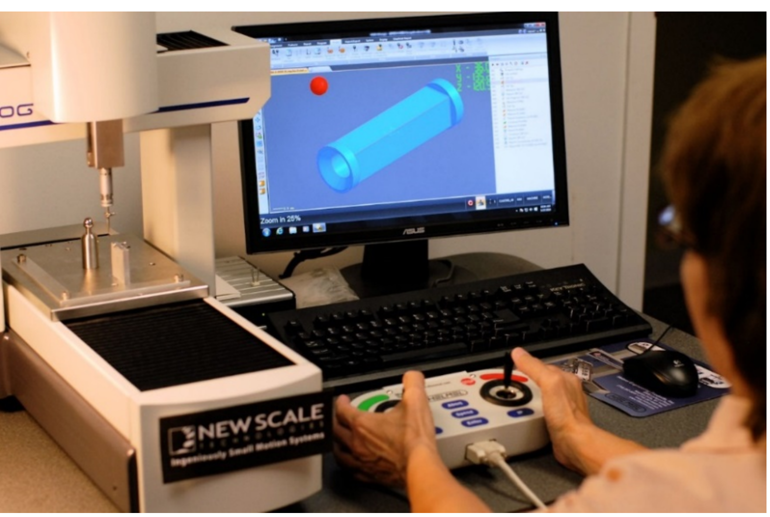

Figure 4: *Coordinate Measuring Machine (CMM) checking dimensions of a Cobra motor body.*

After parts pass QA they are placed in inventory, ready for assembly. Assembly jobs are planned and parts kitted using our Enterprise Resource Planning (ERP) to track quality and yield and provide traceability.

Cobra positioner assembly is completed by our highly trained staff using proven tools and processes. Our staff has an average of 20 years of experience with precision micro mechatronic assembly.

Detailed cleaning protocols are followed at every step and many operations must be completed under a microscope to achieve and verify assembled dimensions.

Final assembly and testing is completed using benchtop clean hoods. See Figure 5.

Figure 5: Part of the New Scale manufacturing facility production area for Cobra positioners.

Cobra Positioner Testing

After each major operation, subassemblies and final assemblies are tested at 11 stations. Figure 6 is an example test report, with specific pass/fail criteria noted.

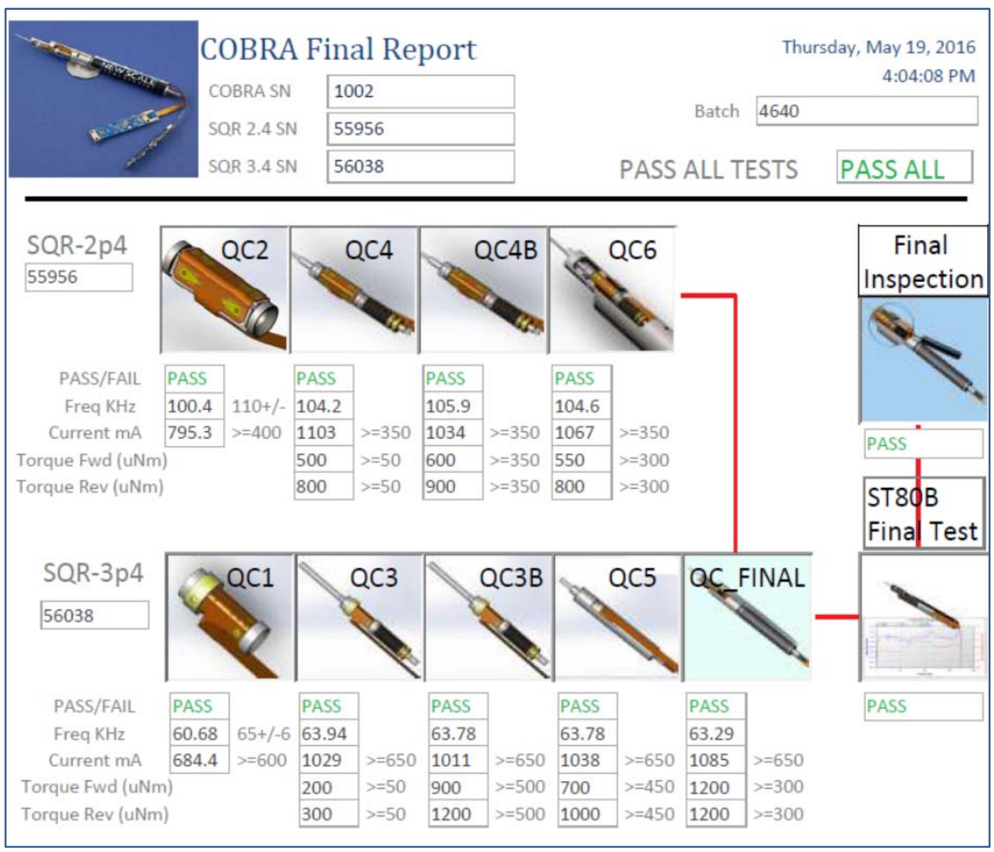

Figure 6: Cobra Final Test Report by date, batch and serial number including results from subassemblies and final assembly

The 100% in-line Cobra tests include stall torque, electrical parameter verification, and motion and stepping performance. Offline testing is also performed at several stages in the production process.

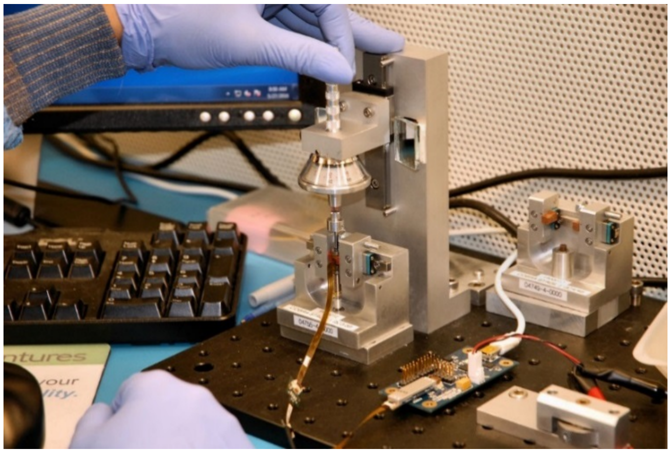

Figure 7: *Motor torque measurements using torque watch.*

The stall torque of each Cobra motor is verified using a jewel bearing torque watch for each motor subassembly and at final assembly (Figure 7).

The resonant frequencies, capacitances and operating currents of each motor are verified by measuring operating current versus drive frequency.

After final assembly, motion and stepping performance of each Cobra positioner is verified using a unique automated machine vision test station (ST80B) with angular precision better than 0.01 degrees (Figure 8).

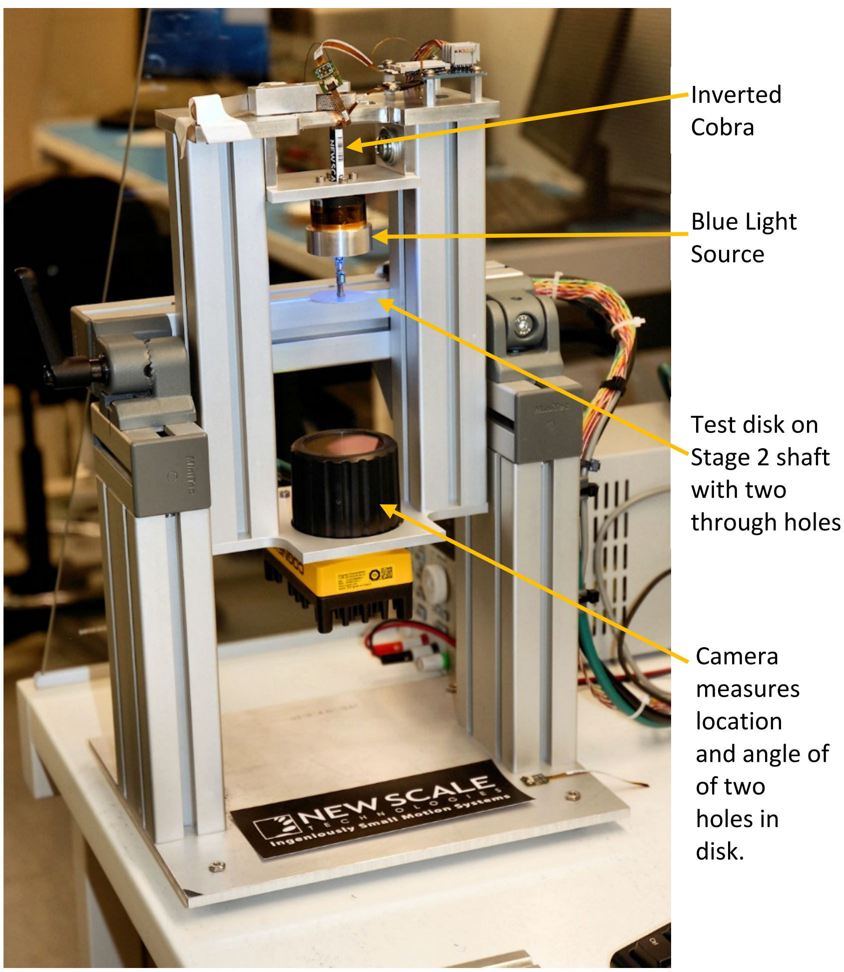

Figure 8: *ST80B Automated Cobra Test Station*

The ST80B test station emulates the operating conditions of the PFS as follows:

a) The Cobra positioner is mounted with Stage 2 down.

b) A test disk is installed on the Stage 2 shaft with two thru holes.

c) A test fiber is installed to emulate the torque produced through the range of motion.

d) The test disk is backlit with a blue light source and the machine vision cameras measure the locations and angle formed by the two thru holes.

e) Stage 1 and stage 2 are operated by sending each motor a burst of motor drive pulses at the operating frequency. The operating software adjusts the burst duration periodically to maintain an approximate step size of 0.06 degrees. The actual burst duration versus angular step size is recorded over the range of travel as show in in Figure 9.

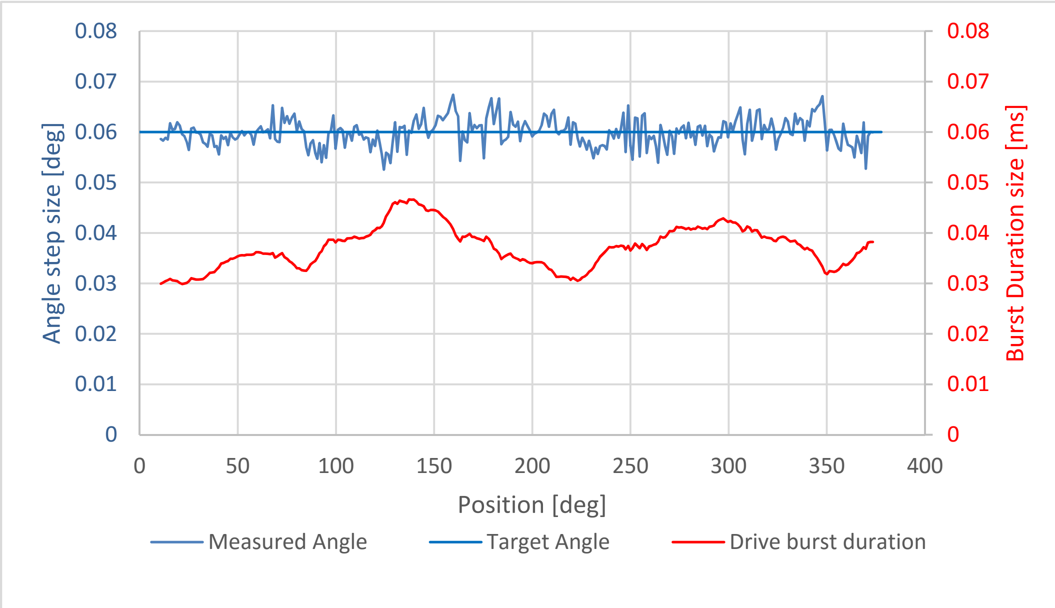

Figure 9: *Typical test result for Cobra angular step size versus burst duration using ST80B.*

Figure 10: *Two Cobra positioners in 400,000 cycle life test using ST80B in temperature chamber.*

Off-line testing is also completed throughout the Cobra production process. One example is monthly life testing of two randomly selected production Cobra units.

The life test is completed up to 400,000 cycles at -5 ˚C with a test fiber installed. ST80B performance (Figure 9) is verified every 100,000 cycles. After the life test is completed, the Cobra positioners are disassembled and inspected for any problems and the results reported.

Conclusion

The maturity of New Scale's processes for Cobra positioner production and testing demonstrates the companies' unique ability to support fiber spectrometer programs with the volume, consistency and quality required for these important endeavors.

References and further reading

New Scale Technologies application note
http://www.newscaletech.com/app-notes/cobra-jpl

VIDEO: Manufacturing the Cobra Fiber Positioner
http://www.newscaletech.com/videos/cobra-manufacturing.php

VIDEO: The Cobra Fiber Positioner in action, including a demonstration of performance and illustration of the operating principle (2:52)
http://www.newscaletech.com/videos/cobra-fiber-positioner.php

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