FOCUS

(Focal Optical Control Using Steppers)

"Stepping" into the future of autonomous focal plane control

The allignment of optical components in infrared telescopes is an involved process. The FOCUS design is presented to ensure that optics stay in the proper orientation at cryognic temperatures. FOCUS is based on converting the infinite rotary motion supplied by a stepper motor into linear motion. This motion is used to create a three point actuation system to control the focus and tilt of a focal plane. This system can be modified to actuate any element of the satellite needing three axis positioning. Emphasis has been placed on the mechanical aspects of the design with the knowledge that the controls can later be designed to yield a completely autonomous system. Testing of a prototype shows that linear travel of 0.26 mm with resolution of 0.01 ηm may be accomplished. Tilt tests of the same system indicate that angular travel of 192 arcsec with 15 arcsec resolution is possible.

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1.0 Introduction and Background

One of the most crucial parts of infrared telescopes is the mounting of the detector, the "eye" of the telescope. It is very important to provide a thermally isolated mount that is rigid enough to withstand the tremendous forces experienced during launch while keeping the detector in alignment with the rest of the telescope. Utah State University has developed FiST (Fiber Support Technology) as an answer to this design problem. FiST has several advantages, including extremely low conductive parasitic heat load (less then 1 mW), and very high first resonant frequency (~ 700 Hz).

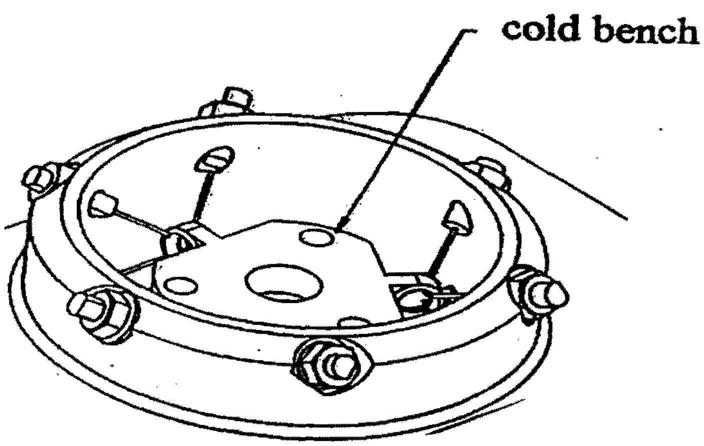


Figure 1 FiST (Fiber Support Technology)

However FiST is subject to the same problem inherent in all support systems that are assembled at room temperature and then brought to cryogenic temperatures. It is very difficult to properly orient the focal plane array on the first attempt. Once the telescope is assembled, under vacuum, and at its operating temperatures, it can be tested for alignment. The process of correcting an alignment problem is very long and tedious. First, the whole system must be brought up from cryogenic temperatures to room temperature. The vacuum is then destroyed, and small shims are placed under certain bolts. The system is again pumped out for several days, cooled to cryogenic operating temperature, and re-tested for alignment. The process is repeated until alignment is achieved. As one can imagine, this process takes many weeks.

Once such a system has been aligned, it is desirable for the system to remain in alignment for the duration of its mission. Relatively massive support structures are still required to withstand the harsh environment of launch and cool down.

2.0 Objectives

FOCUS (**F**ocal **O**ptical **C**ontrol **U**sing **S**teppers) has been developed to show that the lengthy alignment process can be eliminated and that it is possible to provide in-flight autonomous focus and tilt correction that will facilitate smaller, lighter and more reliable satellites.

3.0 Requirements

The requirements for the FOCUS system are dependent on the wavelengths observed by the specific telescope in which it functions. The amount of motion required is equal to the depth of focus (δ) of the instrument, given by:

$$\delta = \pm 2\lambda \left(\frac{f}{D}\right)^2$$

where λ is the wavelength of light to be measured, f is the focal length of the telescope, and D is the exit pupil diameter. Our prototype was designed around the SABER infrared telescope currently being designed and built by Space Dynamics Laboratory. The depth of focus for SABER ranges from 0.01 to 0.13 millimeters (see Appendix A), so to meet these requirements FOCUS must provide ±0.13 mm of motion with .01mm of resolution (Esplin 1996).

The tilt requirements for SABER are based on the depth of focus requirements for the instrument. Assuming one side of the focal plane remains fixed, the other may move up or down within the depth of focus for the given wavelength. This means that FOCUS must be capable of raising or lowering one side of FiST up to 0.13 mm with a resolution of 0.01 mm. This corresponds to a tilt requirement of ±192 arcseconds with a resolution of ±15 arcseconds (Esplin 1996).

For the future, FOCUS must also be able to withstand the forces generated during launch. This was kept in mind when designing FOCUS, but it will not be subjected to any shake testing. The main purpose of this first generation prototype is to show that the necessary motion can be achieved. Keeping the system small enough to be applicable in today's smaller, faster, and cheaper designs was also a priority. This was quantified by the requirement that the system fit within the same diameter of FiST (152 mm), and be capable of being made even smaller.

4.0 Alternative Designs Considered

In the search for the optimal design that would meet both the requirements and objectives of FOCUS, several alternative concepts were evaluated.

4.1 Piezo-based Concepts

Piezoelectric actuators were initially looked at because of the high resolution in positioning required. The original concept of orientation at the beginning of the project was to actuate the fasteners (bolts) that held the focal plane's Kevlar support fibers. In this manner, the focal plane could be oriented directly, similar to how a puppet-master animates his puppets. A stack of piezoelectric crystals was to be positioned between every Kevlar supporting fastener and FiST. A controllable voltage source would then make the crystal stacks expand and contract as it controlled the voltage difference across the stacks.

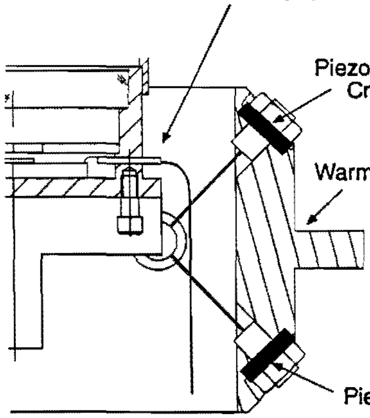


Figure 2 Original Concept

This design appeared to be simple, reliable, and easy to implement. In calculating the height of the piezoelectric stack needed for direct actuation, this concept turned out to be not feasible. A 36.8 cm stack of crystals (Physik Instrumente, 1995) under each fastener would have been required to provide the focal plane with the necessary travel! This was obviously unacceptable.

In an attempt to decrease the height of the stacks to a reasonable level, a hydraulic-piezo design was considered. A thinner, but wider piezo stack would be in direct contact with a small reservoir of hydraulic fluid. The Kevlar supporting fastener would have a significantly smaller diameter than that of the stack. As the stack displaced the hydraulic fluid, the fastener would be displaced a much larger amount, thus moving the focal plane a greater distance. Calculations determined that the stack diameter and height would need to be 4.3 cm and 1.3 cm, respectively. While these are more reasonable dimensions, an obvious disadvantage to this design is that hydraulic fluid would be located near the focal plane. Because of the vacuum, this would introduce contamination problems into the system. In addition to this, the additional mass, volume, and cost of the entire system would be increased significantly if these actuators were positioned on all twelve Kevlar support fasteners.

Another conflict with integrating this design would have to do with the Kevlar support fibers. In order for FiST to have such a high first resonance frequency, the strands need to be pretensioned to 50 lbf (222 N). Providing the high pressure in the hydraulic system required to keep the 50 lbf of tension in support fibers would be very difficult.

In order to eliminate the challenges introduced in trying to actuate the pretensioned support fibers, an attempt was made to control the orientation of the entire FiST assembly. The first concept involved a stack of piezoelectic crystals connected to the short end of a lever. The opposite end would be attached to the flange of FiST. As the stack moves a small distance, the lever would amplify the motion of FiST's outer flange. If three of these actuators were attached and evenly distributed around the outer circumference of the flange, then focusing and tilting would be possible. Removing all backlash and play from the lever system would be challenging, but is conceptually possible.

A similar idea was conceived using a high travel, piezoelectric based actuator called an inchworm motor. An inchworm motor uses three piezo crystals to "inch" its way along a shaft (Burleigh, 1996). One crystal contracts to grip the shaft while another expands, separating the first and the third crystal. The third then grips the shaft, after which the first crystal releases and the second crystal contracts, thus minimizing the distance between the crystals. The process is then repeated, allowing the high travel actuator to proceed down the shaft.

This actuator could be used by attaching the inchworm to the long end of the lever while attaching the opposite end to FiST. Since the inchworm can only provide a weak axial load, the levering would increase it's effectiveness. The accuracy and precision that the motor is capable of supplying is two orders of magnitude greater than required. This, of course, would increase as the inchworm's motion is scaled down by the lever.

A problem with this system is that inchworm motors cannot support a significant axial load. Eliminating all axial loads in any system would be challenging. Another restriction was the cost of the system. Because of the precision of the inchworms, the combination of three motors and a three axis controller would be over $3000 (Burleigh, 1996).

In addition to the characteristics listed above, all of the piezoelectric based actuation systems have one main drawback. Once the system focusses and orients the focal plane into the proper position, the controller must continue to be active. If voltages are not kept constant across the stacks, then the actuation system will respond accordingly, slipping, creeping or returning to its equilibrium position (out of focus). This indicates that piezobased actuation systems could have problems with reliability, especially if something went wrong with the controller during the mission.

4.2 Motor Based Systems

In order to find a system that would become passive after the focal plane had been properly positioned, motor based systems were investigated. The attempt to directly control the pretensioned support fibers as proposed in the first piezoelectric alternatives was quickly abandoned when it was discovered that small motors could not provide the torque necessary to actuate the fiber supports. Another large drawback was the complexity of the gearing system.

An alternative system was suggested by Dr. Rees Fullmer to minimize the torque requirements. This system is the Linear Actuation Device, or LAD (Fullmer, 1996). It is consists of two small disks connected with Kevlar strands coming from the edges, forming the "walls" of a cylindrical system. As the disks are rotated in opposite directions, they are forced closer together due to the fact that the Kevlar is no longer parallel with the axis of the "cylinder". These systems, which could be geared to motors, would ideally take the place of the current Kevlar strands. They would act as both the actuator and the thermal isolator.

A disadvantage of LAD is that the motors would have to be numerous, or the gearing would need to be complex. Another problem is that very little is known about this type of actuation. Questions about additional heat leakage to the focal plane arise as well as concerns about losing the stability of the highly tensioned support fibers. It was apparent that much research would need to be conducted in order to successfully use LAD.

5.0 Final Design Decisions

The design ideas that operated on moving, or altering the tensioned support fibers had all failed. Therefore, it was decided that a workable system would have to operate by orienting FiST in its entirety. Just as in the final piezo based systems, a three actuator motor system was proposed. In theory, a worm, driven by a micro motor, would turn a worm gear mounted to a shaft. The top of the shaft would be connected to a lead screw threaded into FiST. As the motor drove the system, the lead screw would raise or lower FiST, depending on the motors direction. To accomplish the tilt requirements, one actuator may be raised while another is lowered. This would deliver the small required tilt angles before serious problems with binding could arise (Figure 3).

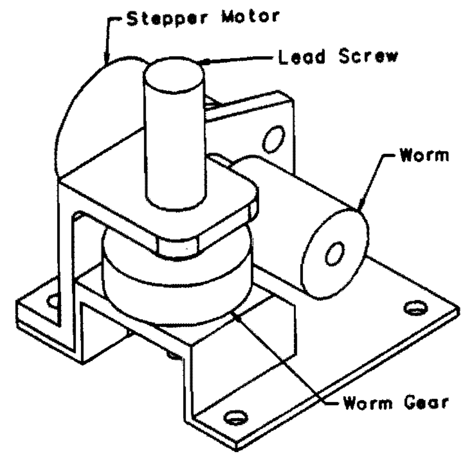


Figure 3 Final Design

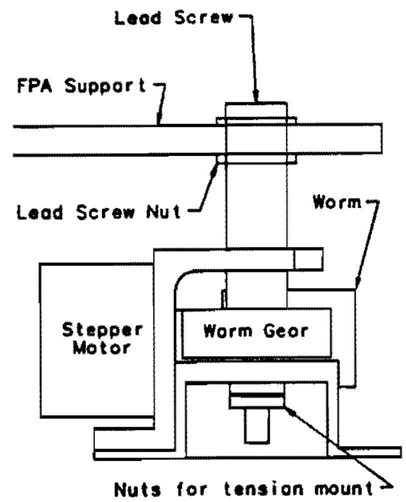


Figure 4 Final Design

A small stepper motor was suggested because of its ability to repeatably rotate through a known angle. This would allow the system to be easily converted to provide fully autonomous control.

The stepper motor/lead screw design seemed to solve many of the problems that were introduced in the previous alternatives as well as offer many of its own advantages. First, since the stepper motor system operates from rotary motion, travel would be limited only by the length of the lead screws. Next, since any reasonable gear ratio and lead screw lead could be chosen, the resolution of the system per step of the motor could be much smaller than the requirements. This could correct for any slight precision errors in the fabrication while still offering the precision and resolution called for by the requirements.

An additional attractive feature of the stepper motor system was its apparent simplicity and reliability. Stepper motors are a well known and trusted component in actuation systems. They would not have to be constructed, tested, or further developed as the LAD or a crystal stack, but could be bought off the shelf. The technology readiness of stepper motors is very high because they have already flown in many spacecraft applications. This increases the overall reliability of the system.

Another major advantage that set the stepper motor system apart from the other workable systems was the availability of miniature motors with low mass and volume. Since each of the three actuators could be made very compact, it was apparent that volume could be minimized. Rough preliminary calculations also projected it to have a reasonably small mass.

The stepper motor also dominated in another area of concern--cost. Stepper motors are available at a cost approximately twenty times less than that of an off the shelf piezo actuator (Bingham and Felt, 1997). The cost of a stepper controller is much lower than other actuator controllers. They are also small and simple enough to be wired onto a small, single circuit board of a satellite.

The paramount advantage of the stepper motor/lead screw system over piezobased designs was its capability of being a passive system after focus and orientation. After alignment, the motor may be completely turned off. The worm gear to worm interface would lock the unit into a stationary, fixed position. Slight vibrations from the spacecraft would have no effect on it. However, if something happened to the focal plane's orientation during the mission, the motor could step it back into position quickly and effectively. The combination of these advantages was the basis for choosing to design and develop the stepper motor/lead screw version of FOCUS.

5.1 Calculations

Many calculations were made in order to completely design the FOCUS prototype. Most non-trivial calculations can be found in appendices A-F of FOCUS Final Report (Bingham and Felt, 1997). The first major calculation was finding the torque needed to drive the entire system. By graphing the required torque versus the load on the lead screw for various gear combinations, the optimal gear combination was determined. This also identified that the maximum torque required by a perfectly built system was 0.25 oz-in.

Once the gear train was established, the vertical displacement of FiST per angle of rotation of the stepper motor was determined to be 22.3 microns per degree. For FiST to translate through the required resolution of 0.0127 mm, the motor shaft must turn 570 degrees or 1.58 revolutions. This type of resolution was desired so that a large safety factor could assure the required performance.

Another area of concern was the backlash at the worm and the worm gear interface. It was desired to document how the backlash between these gears affect the vertical position of FiST. Calculations show that for FiST's vertical position to change 0.01 mm, the worm gear would have to rotate 14.4 degrees. Since the worm gear cannot rotate more than 5 degrees without engaging the worm, the concern over backlash was eliminated.

Determining the required torque and FiST's vertical displacement per degree rotation made stepper motor selection possible. The objective of motor selection was to find the smallest, lightest, most inexpensive stepper available that could carry out the torque requirements with a considerable safety factor. This turned out to be the Z-20540, 20.1 mm diameter, 0.8 oz stepper motor from Hayden Switch and Instrument Company. The specification data are located in Appendix F (Bingham and Felt, 1997). This motor provided a safety factor against binding of 3.76 when operating at one-fourth duty cycle.

Aluminum brackets were designed for mounting and aligning the worm gear train. Since the flight version of FOCUS is required to withstand the forces due to launch, a detailed stress and fatigue analysis was performed on the main areas of concern of FOCUS. In order to verify the calculations, a finite element analysis was also performed on both the top and bottom bracket. Calculations dealing with solid mechanics can be found in Appendix B (Bingham and Felt, 1997).

The combination of the results of these calculations indicate that FOCUS will be able to withstand the forces due to launch. It is important to note, however, that these calculations include the assumption that the resonance frequencies of FOCUS would not match the forcing frequencies experienced during launch. Such an occurrence would result in a large transmission ratio that would magnify the forces that FOCUS would experience. Therefore, a flight version of FOCUS must be built as stiff as possible to avoid such resonant frequencies.

6.0 Fabrication

Top and Bottom Brackets

The fabrication of FOCUS was carried out in a very precise manner to obtain the desired resolution of 0.01mm. Because the top and bottom brackets were one of the biggest areas of concern, they were manufactured by the machine shop at Space Dynamics Laboratory. The bracket drawings were converted into .dxf format and sent to the machine shop where a computer controlled mill used the drawings to machine these parts. A single hole on the top bracket, however, had to be drilled manually. This resulted in a loss of precision due to human error. This hole, and its corresponding hole on the bottom bracket through which the lead screw shaft fits, should have been drilled at the same time with the brackets assembled. This would have ensured a perfectly vertical alignment of the lead screw shaft.

Lead Screw and Bearing Supports

The fabrication of the lead screw that positions FiST was somewhat difficult. The small pitch of 80 threads per inch on the precision lead screw had to be handled carefully so as not to damage the threads, but also had to be held firmly enough to allow a hole to be drilled along the center of its axis. This was accomplished by placing the lead screw into its mating nut and by clamping down on the nut in a mill. The nut was placed on parallels to ensure that the hole would be parallel to the axis of the screw. Using a dial indicator, the mill was centered on the lead screw, and the hole was drilled.

Steel shafting was cut on a lathe to the specified length and threaded on one end to connect the lead screw to the FOCUS unit. This shaft was also polished until it just fit into the bearings used to support it. The smooth ends of the three shafts were then epoxied into the holes drilled into the lead screws with Epibond epoxy.

It was initially planned to use a light press fit to support the bearings. This damaged the bearings. A washer with an inside diameter slightly smaller than the diameter of the hole was epoxied to each bracket to hold the bearing into place. This could be avoided by the use of a shouldered bearing and the appropriate holes.

Test Fixtures

The fixtures used for testing were also manufactured on the computer controlled mill. These included the FiST simulator, a round plate with three holes for the precision lead screws, and a baseplate to which FOCUS was mounted.

Mounting

Mounting FOCUS to the baseplate to be used in testing proved to be extremely difficult. First, the FiST simulator was firmly attached to the actuators by bolting it to the lead screw nuts. The actuators were then bolted to the baseplate. Because the shafts were not perfectly aligned, the lead screws and brass bolts tended to bind. After attempting to shim each actuator into its proper position and bolting them to the baseplate, it was determined that a new method of attaching the actuators to the baseplate was needed. Only perfectly flat surfaces and perfectly straight parts would allow them to be bolted together without serious binding occurring in the lead screws.

To solve this problem, the actuators were detached from the baseplate and left firmly attached to the FiST simulator. The actuators were allowed to sit in their respective equilibrium positions and then epoxied to the baseplate with Epibond epoxy. This resulted in freely turning shafts that could easily be turned by the stepper motors.

The control card for the stepper motors was wired into a three channel switch which was used to control each motor individually. The motors simply bolted to the assembly; but, due to a tolerance error, a washer had to be placed under one end of the motor to allow the worm to mesh with the worm gear.

Motor to Worm Adaptor

A part was needed to mate the 0.079 inch diameter rod of the motor to the 0.125 inch diameter hole in the worm. A sleeve was made on a lathe by drilling a hole in 0.125 inch shafting and polishing until it fit into the worm. A small hole was then drilled through the wall of the sleeve. This allowed the set screw to clamp directly to the motor shaft, providing a good connection that was not permanent.

7.0 Testing

In order to quantify the performance of FOCUS, various tests were performed. In general, three series of tests were conducted. The first tests were to simply document that the stepper motors were able to actuate FiST without bogging down. This "operational" test was performed before any displacements were measured in order to confirm that the system was in working condition.

The next test series were carried out on the Coordinate Measuring Machine (CMM) at the Space Dynamics Laboratory. The CMM is a computer based measuring system accurate within 0.0002 in (0.00508 mm)(Bingham and Felt, 1997). FOCUS was placed on the large granite, floating table of the CMM and bolted into place. The CMM was zeroed and oriented on a plane made up of three points on the FiST simulator surface, directly next to the lead screws. The motors were driven with an input voltage of 12 Volts. For the focus test, after each motor was stepped 38 times (one resolution increment), a measurement was made by the CMM at each of the three points. This procedure was followed until the motor could no longer turn the geared assembly. At this point the direction was reversed, still stopping to make the three measurements every 38 steps. Passing through equilibrium, the system continued until a stepper motor failed. Changing directions, the stepper motors were stopped after FOCUS reached equilibrium.

The CMM tilt test was then performed. Only Motor 1 was stepped and measured in an attempt to quantify the maximum angle to which the focal plane could be tilted.

The final series of tests were to ensure that the focal plane of FiST would truly experience the required motion. The setup consisted of a spring loaded linear-variable differential transformer (LVDT) and a digital volt meter (DVM) capable of displaying five significant figures. The LVDT was mounted firmly on a stand directly in the middle of the FiST simulator, exactly where the focal plane would be located. At the equilibrium position of FiST, the LVDT was displaced by a few millimeters to assure that a good contact would be kept throughout testing.

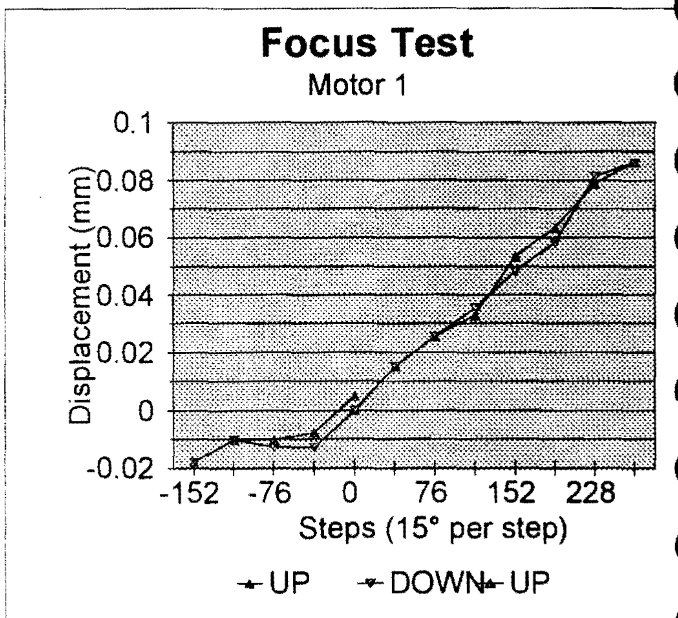
Each motor was driven at the voltage required to ensure a complete range of motion. They were each stepped two complete revolutions. After this, the voltage from the DVM was recorded. This process was repeated until each motor had gone through 22 rotations. The direction of rotation of the motors was then reversed, and the procedure was repeated on the way back to equilibrium. This process was then repeated in the opposite direction starting from the equilibrium position. This run simulated a complete focussing cycle.

In order to test the tilt, the LVDT was positioned right next to Motor 3. Motor 3 was then stepped throughout its required range in increments of two motor rotations. Data were recorded for a complete cycle.

8.0 Performance

The initial "operational" tests showed that FOCUS had a hard time reaching its full range of motion when driven by a 12 volt power supply. This was expected because of the fabrication flaws in the straightness of the shafts. However, when increasing the driving voltage to 25-30 Volts for short periods of time when the motors were in a tough spot, an entire range of motion for focussing and tilting the FiST simulator was accomplished.

The CMM test runs documented the performance of each of the three individual stepper actuators. Figures 5, 6, and 7 show the vertical displacement of the individual systems versus the number of 15 degree steps.



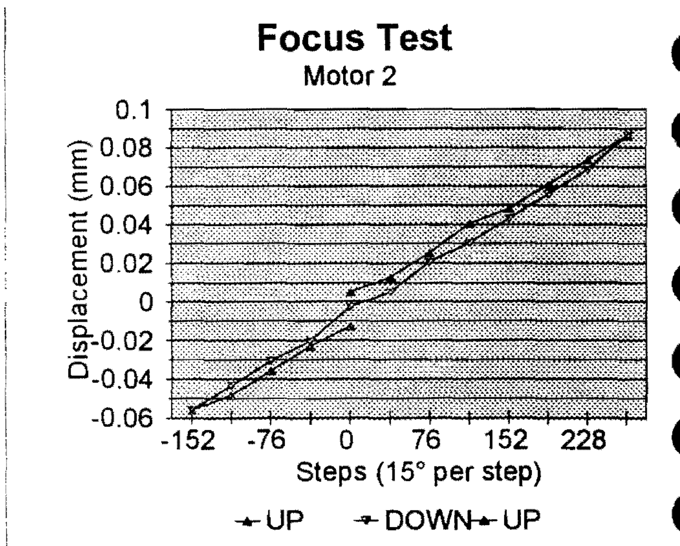


Figure 5&6 Test results from CMM Motor 1&2

It can be readily seen that Motor 2 displays the closest displacement versus step relationship to the theoretical value. Motors 1 and 3 deviate slightly more from the predicted linear relationship.

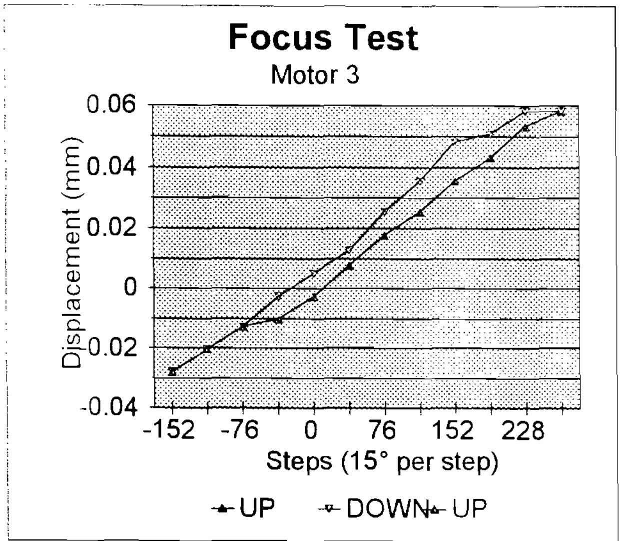


Figure 7 Test Result of CMM of Motor 3

The average experimental slope of Motor 1 is lower than the theoretical value. This is indicative of some type of fabrication error. This would also explain the lower response of Motor 3. These displacement characteristics when averaged should, in theory, predict how the focal plane in the middle of FiST would respond. Since the CMM was accurate to ±0.004mm, it provided important individual motor performance numbers. It also documented that the amount of backlash between the lead screw and threaded portion of FiST was within the requirements of the system. This ensures that small spacecraft vibrations will not rattle the focal plane out of position.

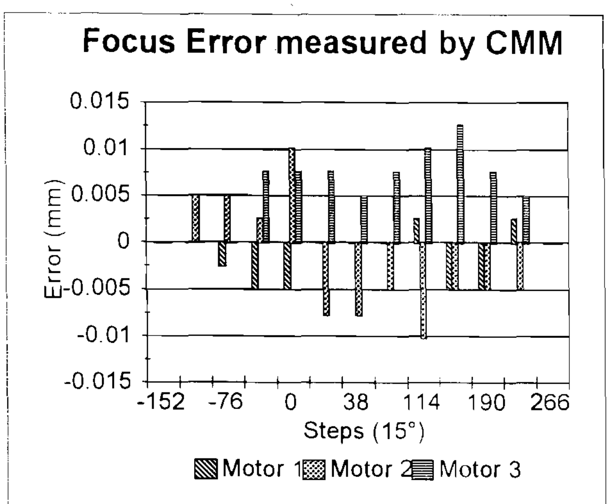


Figure 8 Total difference between measurements

The difference between FiST's vertical displacement when going up and when lowering quantifies the maximum amount of backlash that the actuators could possibly allow. This is not to say that this value is the actual backlash, but its maximum possible value. Hysteresis, and other system characteristics must be included in this value as well. Figure 8 plots this difference and labels it the focus error.

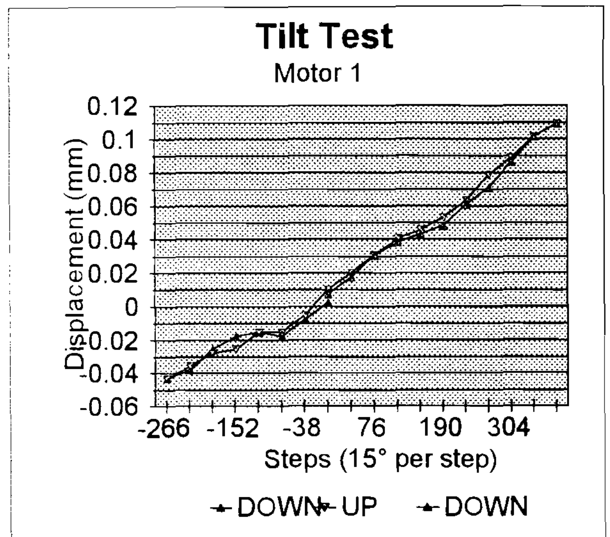


Figure 9 Tilt test results of Motor 1 by the CMM

It can be seen that this error does not, except for one point, exceed FOCUS's resolution. This point can be explained by the accuracy level of the CMM (±4μm). This shows that the backlash in the precision lead screw/FiST interface would be small enough to not hinder its ability to maintain its proper position over time.

The CMM tilt test performed by Motor 1 was also very successful. As shown in Figure 9, the test displayed similar Motor 1 characteristics.

The maximum possible backlash for this tilt test, as shown in Figure 10, is well under the value of the resolution. These CMM tests showed that the performance of FOCUS could match and even surpass the required performance.

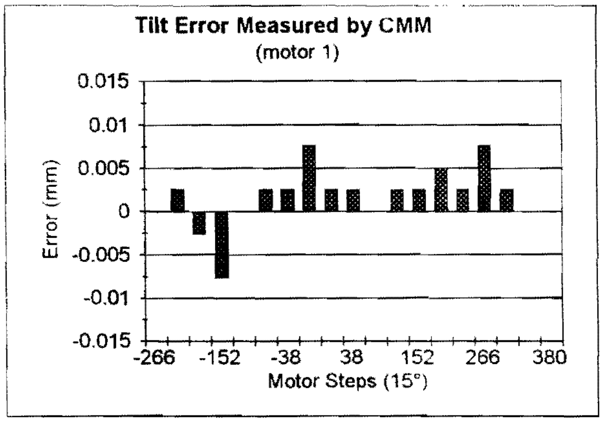


Figure 10 CMM measured difference in Motor 1

The LVDT focussing and tilt tests better quantify the performance of FOCUS. Figure 11 shows the results of the LVDT focus test. This vertical displacement represents the actual movement of the focal plane of FiST.

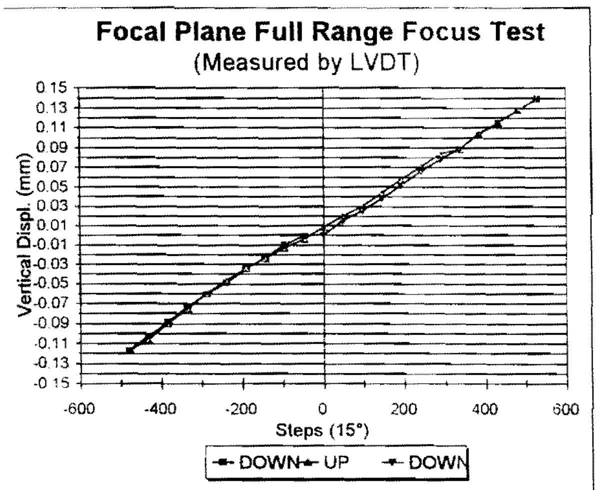


Figure 11 Simulated focal plane focussing results by the LVDT

By using a higher voltage input, the required range of focussing was accomplished and documented. The average vertical displacement per step for this test was found to be 2.65e-04 mm/step. This response is identical to the combined average of the individual response of the stepper motors. Because such repeatability should be expected for a precision system, this verifies the testing results and procedures.

The maximum possible backlash for the LVDT test is shown in Figure 12. As discussed before, the displacement error is well below that of the resolution, ensuring that the system would not fail due to backlash problems. This has also been documented for the tilt test that was conducted on Motor 3 (see Figure 13).

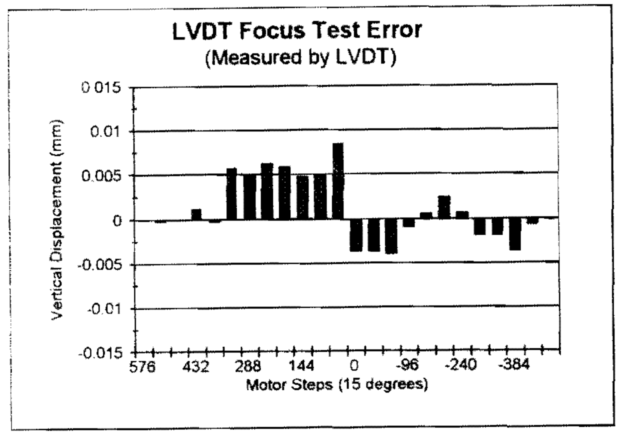


Figure 12 Focal plane focus error by LVDT

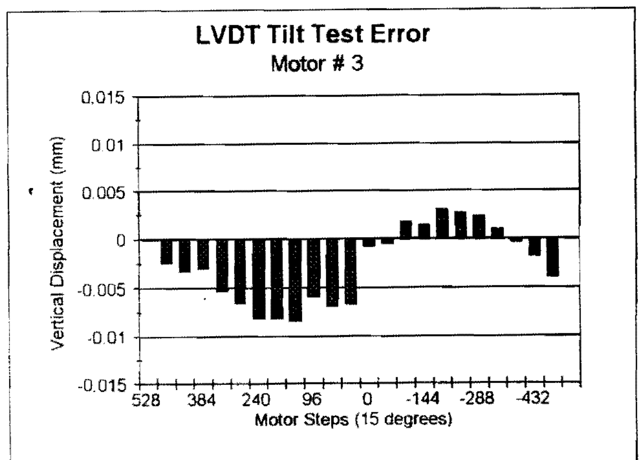


Figure 13 LVDT measured difference of motor 3 tilt

The LVDT tilt test, shown in Figure 14 further verifies the proposed concept of achieving tilt by raising the actuators to different levels. This test proves that the tilt requirements can be met without binding.

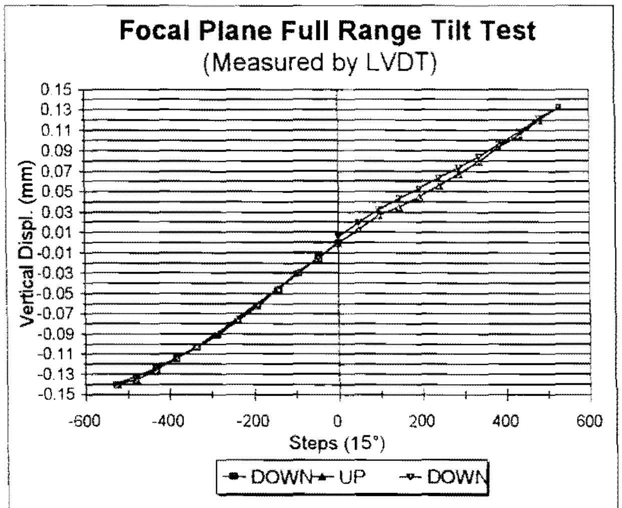


Figure 14 Motor 3 tilt performance as measured by the LVDT

The combined results of the tests were very encouraging. They indicate and document the performance of FOCUS. The test results verify that the focussing and tilting capabilities of the FOCUS prototype surpass that of the requirements.

9.0 Recommendations

Changes to Current Design

There are several improvements that can be made to the FOCUS system for a second generation design. The first and foremost improvement would be to make the top and bottom brackets one single part. This would eliminate the possibility of misalignment for the holes through which the lead screw shaft passes. This would also make the assembly much stronger against forces generated during launch.

Another area of concern is the fabrication of the lead screw shaft. Epoxying a rod into the hole drilled in the lead screw results in a joint that is not straight and that binds up the threads in the lead screw assembly. The effects of this can be seen on the graphs of the focus testing (Figures 1-3) performed on the Coordinate Measuring Machine. The epoxy joint is also a weak point in the design and will likely fail if shaken to simulate launch. Turning down one end of a long lead screw will solve many of the problems associated with the epoxy joint. Machining the shaft out of one piece of material will result in a much stronger and straighter part, enhancing the performance of the whole system.

Testing

Presently, only limited testing has been performed on FOCUS. Eventually, the focus and tilt tests will be repeated several times using the LVDT to measure displacement. The focus and tilt tests will be performed and repeated for each motor so they can be statistically analyzed. This will allow the motion provided by FOCUS to be more accurately quantified. Testing should also be performed to determine the lateral motion of the FiST simulator as it changes focus and tilt.

FOCUS should also be tested in a vacuum and thermally cycled to show that FOCUS performs well for cryogenic applications in space. When a more sturdy version of FOCUS is built, it will also be shaken to determine its first natural frequency.

10.0 Conclusions

Fiber Support Technology is a novel and effective way of increasing the rigidity of a focal plane assembly while decreasing its parasitic heat loads. In order to receive these benefits, however, the focal plane must be aligned precisely with the rest of the telescope's optics. This alignment process is a tedious, iterative task, consuming large amounts of money and time. Furthermore, if this precision is lost due to the harsh launch environment, nothing can be done to bring the system into realignment.

Team Serendipity has successfully taken the first few steps toward developing an autonomous orientation and control unit to complement FiST. Three stepper motor based actuators make up a system that can focus and align a focal plane assembly both on the earth and while in orbit.

The test results of a first generation FOCUS prototype surpassed the linear and angular motion required in order to precisely align a focal plane. Continued development and testing will result in a flight worthy autonomously controlled FOCUS system that can be implemented in various small satellite applications.

11.0 References

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