A Near IR Fabry-Perot Interferometer for Wide Field, Low Resolution Hyperspectral Imaging on the Next Generation Space Telescope

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ABSTRACT

We discuss work in progress on a near-infrared tunable bandpass filter for the Goddard baseline wide field camera concept of the Next Generation Space Telescope (NGST) Integrated Science Instrument Module (ISIM). This filter, the Demonstration Unit for Low Order Cryogenic Etalon (DULCE), is designed to demonstrate a high efficiency scanning Fabry-Perot etalon operating in interference orders 1 - 4 at 30K with a high stability DSP based servo control system. DULCE is currently the only available tunable filter for lower order cryogenic operation in the near infrared. In this application, scanning etalons will illuminate the focal plane arrays with a single order of interference to enable wide field lower resolution hyperspectral imaging over a wide range of redshifts. We discuss why tunable filters are an important instrument component in future space-based observatories.

Keywords: Fabry-Perot NGST infrared cryogenic interferometer etalon

1. INTRODUCTION

In this paper we will discuss work in progress to design, build and test a near-infrared tunable filter for the Goddard baseline wide field camera on the Next Generation Space Telescope (NGST) Integrated Science Instrument Module (ISIM). This camera is one of the core recommended science instruments that will carry out most of the highest-ranking NGST science programs. This interferometer/filter, the Demonstration Unit for Low Order Cryogenic Etalon (DULCE), was designed to demonstrate a high efficiency scanning Fabry-Perot etalon operating in interference orders 1 – 4 over the 3 - 5μm wavelength range at 30 K with a high stability DSP-based servo control system. Our design emphasizes low risk and cost, low power dissipation, operations simplicity, and low mass, all advantageous characteristics for NGST instrumentation.

2. ADVANTAGES OF TUNABLE FILTERS ON NGST

There are several possible instrument concepts for carrying out imaging spectroscopy with NGST over a large field of view. These include imaging Fourier Transform Spectrometers (IFTS; Graham et al., 1999), dispersive-based multi-object spectrometers (Mackenty et al., this conference), image slicers (LeFevre et al., this conference), and tunable filters or Fabry-Perots. For the specific application of carrying out imaging spectroscopy for a narrow range of redshifts over the entire NGST field of view, or for scientific applications requiring the observation of only several spectral lines in extended sources, Fabry-Perots provide overall sensitivities comparable to that of a grating. However, unlike a grating, imaging spectroscopy of every pixel in the field of view is obtained. In conventional cameras, Fabry-Perots provide much greater flexibility in wavelength and bandwidth choice than a fixed inventory of filters. For example, **in order to provide complete coverage of the 0.6-5 μm wavelength range at a spectral resolution of R=200, 440 narrow band filters would be required.** Tunable filters can be designed to provide complete 1-5.3 μm spectral coverage with only two separate etalons.

Without a narrow band imaging capability over the near-IR wavelength regime, the scientific potential of the near-infrared camera in achieving the core mission goals can be seriously compromised. For example, important emission line galaxies can be completely undetected by broad band deep surveys designed to identify the first stars and galaxies . These emission line galaxies can be efficiently studied by follow up narrow band imaging of broad band deep fields. These techniques have been used on the ground to reveal a growing population of otherwise undetected Lyman alpha sources (e.g., Jones 1999, Baker et al. 1999, Cowie & Hu 1998). *A narrow band imaging capability on NGST will open up a new discovery space by enabling the identification of sources that would otherwise be undetected by broad band surveys.*

Fabry-Perots greatly enhance a camera's science potential, are extremely compact, are based on relatively mature technology, and can easily be accommodated at a large pupil location or, in some cases, at a field position. They are therefore a powerful and versatile potential instrument component in future observatories such as NGST.

3. PROJECT DESCRIPTION

3.3 Work in Progress and Achievements to Date

3.3.1 Background

A Fabry-Perot (FP) interferometer or etalon consists of two flat, parallel, semi-transparent plates coated with films of high reflectivity and low absorption. The pass band of the etalon is determined by the separation between the plates which is generally varied using piezoelectric translators (PZT). Fabry-Perots have been used extensively for the last several decades over a wide range of wavelengths. Queensgate Instruments, for example, has provided a number of scientifically fruitful state-of-the-art Fabry-Perots (see e.g., Pietraszewski 2000). However, these etalons have been traditionally operated at room temperature and at moderate to high resolving powers ($R > 500$). Options for low-resolution variable interference filters have typically been restricted to circular variable filters or linear variable filters. These options require an optical design that includes a small (1-2 mm diameter) pupil. With the advent of large aperture wide field telescopes, incorporating a small pupil in the optics design while retaining good image quality and spectral purity over the desired field of view (FOV) is extremely difficult. Such a situation will exist in any camera design for NGST. In such situations, low resolution FPs are an ideal option for narrow-band imaging. They ease size requirements on filter wheels and offer flexibility in choice of spectral resolution.

Tunable filters on NGST will require operation at cryogenic temperatures. At these temperatures, PZTs alone do not provide sufficient translation to tune the etalon over the desired orders of interference without becoming large and cumbersome. In addition, low-resolution infrared etalons require cavity spacings on the order of a micron. A PZT-driven low resolution etalon assembled at room temperature and then operated cryogenically requires a mechanical design that achieves a high degree of thermal expansion compensation to achieve the desired sub micron gap within the limited cryogenic scan range of the actuator. As a result of these technical challenges, no commercial near-infrared cryogenic low order etalon existed prior to the development of at NASA/GSFC.

3.3.2 Achievements to Date

We have developed and tested a 3-5 μm prototype near-infrared tunable bandpass filter that can be developed for use in a camera design similar to the baseline wide field camera of the NGST ISIM. DULCE is designed to demonstrate a high efficiency scanning Fabry-Perot etalon operating in interference orders 1-4 at 30 K with a high stability DSP-based servo control system (see Satyapal et al. 2000). The detailed requirements of this etalon are summarized in section 4. In Figures 1 and 2, we display the first iteration of DULCE currently assembled and tested. The details of the design are specified in section 5. DULCE utilizes mechanically amplified PZT actuators, capacitive micrometry for plate separation sensing and control, and a 16 bit DSP-based controller. To minimize cost, our first iteration employed previously purchased non-optimal optical plates. The clear aperture of this etalon is 25 mm and the overall outer envelope is approximately 85 mm. We have conducted extensive room temperature testing of this etalon and have achieved a performance limited solely by the optical quality of the plates. In section 7.2, the details of our test procedure are summarized along with a description of our performance data. Cryogenic testing of this etalon is currently underway.

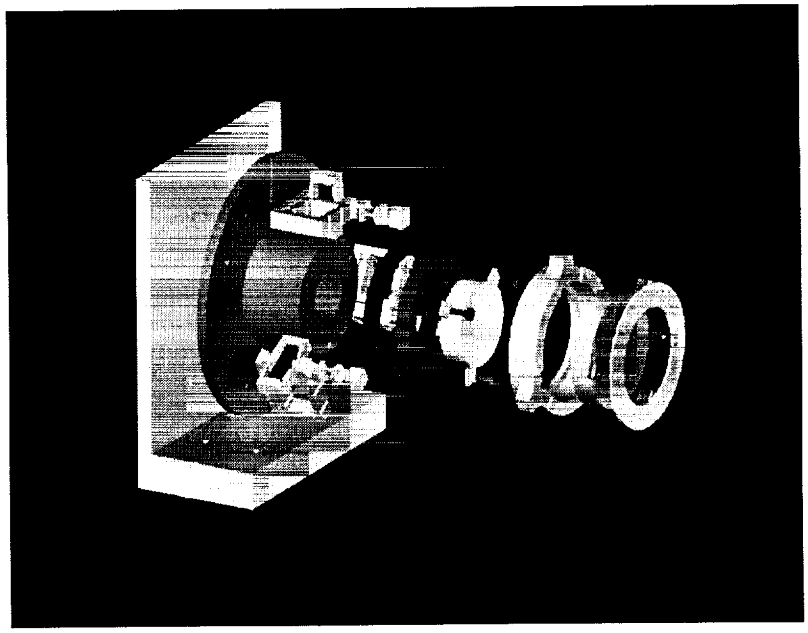


Figure 1: DULCE exploded assembly shows details of design.

Our compact design will enable the proposed etalon to be placed at the pupil location in a near-infrared camera similar to the GSFC Yardstick ISIM. The near-infrared camera in the Yardstick ISIM (Greenhouse et al. 1999) has a 4′× 4′ field of view that is divided by a pyramid mirror into four identical camera modules that each cover a 2′× 2′ field of view. Each module contains an Offner relay that produces a 40 mm pupil at the location of the etalon. The filter wheel contains broad band filters for photometric imaging or order sorting the proposed R=50-200 tunable filters when they are rotated into the beam. The range of angles passing through the 40 mm aperture etalon is small enough that the shift in wavelength across the array will be less than one resolution element. Monochromatic full field imaging will therefore be possible.

4. KEY TECHNOLOGY CHALLENGES

4.1 Mechanical Challenges

The extreme change in temperature from ambient to the cryogenic operating range demands careful mechanical design. One of the key challenges is developing a design that achieves and maintains, to nanometer accuracy, the required sub-micron gap at cryogenic temperatures. In addition, the optical plates in the etalon are required to be flat and parallel to a high degree of precision for the FP to achieve the required performance. Developing a secure mounting scheme that does not deform the optical plate when cooled is needed. Since the optical plate material will in general be different from the material of the mounting structure, CTE mismatches between mechanism components create a particular difficulty. In order to accommodate such differential contractions, parts are usually manufactured to provide room-temperature gaps. However, given the nanometer precision to which the plate separation must be known and maintained, continuous mechanical loading is required. Another mechanical challenge arises from the requirement that the plate spacing following cool down be within the capture range of the actuators so that the full range of required plate separations can be achieved. These key mechanical challenge areas are summarized below.

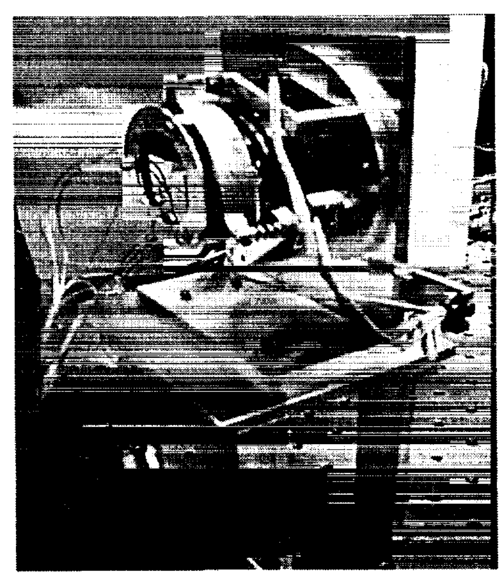


Figure 2: Currently assembled DULCE

4.2 Actuators

The central challenge for all NGST actuator technology is to provide sufficient stroke with high precision at cryogenic temperatures. In addition, a compact and robust design that enables efficient packaging is critical to our design. Another feature that is essential for NGST is low power dissipation. Finally, survivability at cryogenic temperatures over the 5yr+ mission is necessary for any actuator concept chosen.

4.3 Optical Coatings

The optical coatings for the etalon should provide high reflectivity over a broad wavelength range, low absorptivity to maximize transmission, and extremely flat surfaces. An additional challenge is faced by low order etalons, where the thickness of the coating is comparable to the separation of the plates. Since there is a phase shift upon reflection that is dependent on wavelength, the tuning characteristics of the etalon will not generally be constant with wavelength. Without control of this phase shift, the free spectral range will be too small, resulting in a greater number of required order sorting filters. It is necessary for the free spectral range of the etalons to be less than the bandwidth of the fixed broad band filters required by the camera.

5. INSTRUMENT REQUIREMENTS AND OPERATION

In the table below we summarize the detailed design and operational requirements for our tunable filter effort.

Fabry-Perot Requirements	
Performance Requirements	
Wavelength Range (μm)	3-5
Spectral Resolution ($\lambda/\Delta\lambda$)	50-200
Etalon efficiency	0.8
Free Spectral Range (μm)	5
Derived Engineering Requirements	
Total Finesse	25[1]
Order	1-4
Minimum optical gap (μm)	1.5
Actuator stroke (μm)	30
Position resolution (nm)	3
Sensing resolution (nm)	0.6
Plate parallelism (nm)	15
Plate flatness at 632 nm	$\lambda/40$
Coating reflectivity	0.85
Clear aperture (mm)	25
Outer diameter (mm)	80

Thickness (mm)	80
Position settling time (min)	2
Power dissipation (mW)	<5
Operating Temp (K)	77
Vibration	N/A[2]

[1] limited by poor reflectivity of DULCE optical elements
[2] the first iteration of the DULCE design was not intended to be vibrated

6. DESIGN CONCEPT

6.1 Mechanical Design

6.1.1 General Features

The DULCE effort addresses many of the design challenges outlined in section 4. In this design, two 1-cm thick silicon plates are coated with multilayers of dielectric in a 25 mm diameter central aperture. Three gold deposition pads outboard of the aperture, on the same surface are used for capacitive sensing of the plate parallelism and separation. These capacitive pads will be mismatched in size to limit the effect of fringing fields and changes in capacitive area during translation and will be of high-purity gold to enhance conductivity and electric field reflectivity. The plates are in aluminum mounts and are held apart by three mechanically amplified PZT stack actuators. A detailed description of the current mechanism is given below. In Figure 1, we show the first iteration of DULCE currently assembled. Here a previously purchased ZnSe plate is mounted via three phenolic tabs, which are bonded to the plate and clamped to the aluminum structure with a belvil washer. (Hereafter this plate will be referred to as the "fixed plate". The optic that is moved by the actuators will be referred to as the "movable plate".) This epoxy scheme was used simply to enable use of these previously purchased optical plates. Relative radial motion between the plate and aluminum is allowed due to a light preload from the washer. The movable plate rests on three diamond turned pads which are machined into the mount. The back of the plate is clamped to the mount via a circular spring which is manufactured to apply pressure only to three points directly opposite the diamond-turned pads, to prevent warping of the optics surface. Using a ball bearing between the spring and the aluminum pad that contacts the plate minimizes local stresses. This mechanism ensures that clamping stresses are always distributed over the whole pad area. Finite element analysis shows that this design allows for secure mounting with negligible optical surface deformation. As can be seen from the figure, the movable plate is chosen to have a larger diameter than the fixed plate, allowing the optical surfaces to achieve the desired sub micron separation without interference from the mounts.

The current design allows for manual adjustment of the cavity spacing and parallelism. The fixed plate is mounted in an aluminum ring that is threaded on the outer edge to provide coarse adjustment of the plate separation with a 10-20 micron resolution. Parallelism adjustment is accomplished through differential screw assemblies located beneath each actuator (not shown in Figure 1). DULCE utilizes state-of-the-art mechanically amplified PZT actuators. These actuators, manufactured by Dynamic Structures and Materials, LLC (formerly Garman Industries) are small - less than one-inch length - PZT stacks in an aluminum frame. This frame provides approximately a factor of 6 in amplification as well as preloading of the stack. Therefore, although there is a 75 percent reduction in PZT stroke at cryogenic temperatures, the mechanically amplified stroke at 40 K is 30 μm, approximately 15 orders of interference, with a maximum drive voltage on the PZT of 150 volts. The cryogenic strain and contraction upon cooling of each actuator was measured using eddy current sensors. The contraction from room temperature to 77 K was measured to be approximately 500 μm. This testing procedure is described in more detail in section 7.1.

6.1.2 Optical Mounts

A unique development of the DULCE design is the optic mount. The movable plate in the design shown in figure 1 is held in a flexure clamp. The front of the optic rests on three diamond-turned pads that are machined into the mount. Diamond turning of these pads was done to assure their coplanarity. The back of the optic is preloaded via a radial flexure that is designed to apply pressure only to the three places directly across from the diamond-turned pads. This is done so as not to induce moments through the optic that could warp the active surface. The spring is an annulus with radial slotting to create three leaf springs. Since the aluminum mount will shrink more than the optic, local stresses were a concern. To alleviate this concern, holes were drilled into the end of the leaf springs and steel balls were placed between them and rectangular aluminum pads that contact the optic. The aluminum pads are lapped on one side and have a divot in the other to secure the ball. This arrangement allows for a rotation about the ball as the outer end of the spring moves closer to the optic surface during cooling. This also reduces tangential forces on the optic as these were shown, using finite element analysis, to be deleterious to optical performance. Our study has shown that this design allows for secure mounting at room temperature while creating only a 5 nm surface deformation. This clamp mount was very successful in the lab, however, the design needs closer examination for future development of this mechanism. The clamping force should be strong enough at ambient temperature to securely hold the optic during launch vibrations. Due to the thermal expansion mismatch between the optic and the housing, the force increases as the system gets colder. The spring must be sized so as to provide security for launch, yet not deform the optic on cool down.

The method used to secure the fixed plate of the first design iteration shown in figure 1 (phenolic tabs affixed with adhesive) is clearly suboptimal. The current design, which is in development, involves machining a flange directly into the optic. This flange is then used to secure the fixed plate to the fixed plate housing using an optical mount similar to that used for the movable optic but with the annular spring compressing the machined flange instead of the active surface.

6.1.3 Manual Adjustment

The mechanical design allows for the plate parallelization and spacing to be manually adjusted. The fixed plate is mounted to an aluminum ring that is threaded on the outer edge. The threads engage a steel ring that is threaded on the inside. This 'coarse adjustment' ring is captured by loose ball bearings so that it spins without translation while the aluminum ring with the optic attached translates to change the plate spacing. Three guide pins prevent the aluminum ring from rotating. Parallelization is accomplished through differential screw assemblies located beneath each actuator. Each actuator is held in a flexure that provides stiffness in all directions but 'Z' (boresight). The stiffening flexures consist of 2 sets of double-vane flexures anchored to a rigid structure on one end and to the actuator on the other. One pair of vanes attaches to the top of the actuator while the other attaches to the bottom. Since the other ends are secured to the base-plate, the flexures preload the actuator against these differential screws. Since each screw assembly independently adjusts only one actuator, parallelization can be done manually. For a flight mechanism, these adjustment provisions must be analyzed for vibration. Insufficiently loaded screws will loosen under launch vibration conditions. A future design will either have to incorporate an adjustment-disabling device such as pinning or potting after adjustments have been made.

6.1.4 Electrical Interface

The mechanism team went through three distinct development efforts to find a suitable method of interfacing the sensor electronics to the capacitive sensors. The primary difficulty in achieving this interface is the proximity of the sensors to the active surface of the optics. Any method used will be required to not obtrude into the overlap between the movable and fixed optics which are mismatched in diameter to facilitate a method or retention that allows the active surfaces to be brought to within 3 microns of one another as noted in section 6.1.1 above.

The first design iteration involved devising a method of interfacing the sensors which had been deposited onto ZnSe. These optics were in the form of very simple upright cylinders with no accommodation for electrical or mechanical interface. The design response was to add gold pads along the beveled edges of the fixed optic. Fine wire was then soldered to this using indium-gold alloy. The movable optic capacitive sensor electrodes were connected to alumina pads affixed to the mechanical bus using the ultrasonic bonding process used to bond wires to the dies inside of microchips. It became evident that these bonds were too fragile to support typical laboratory handling let alone vibration testing. Another method was sought.

The second iteration involved soldering directly to the capacitive sensor surfaces of the movable plate using the indium-gold alloy. This bond was quite stable but the soldering process threatened the optical surfaces of the fixed plate and may have had a deleterious effect on optical finesse. The final solution was to redesign the fixed optic from the ground up with special lands machined in to accommodate direct indium-gold soldering without threat to the optical surface. The movable plate remained in the form of an upright cylinder to preserve the mechanical design of the housing. Special care will be used in soldering this optic to assure that no flux spatters onto the active surface. A layer of photo-resist may be used prior to soldering.

6.1.5 Actuators

The actuators being used on DULCE are mechanically amplified PZT stacks designed and built by Dynamic Structures and Materials – formerly, Garman Systems. These off-the-shelf actuators use commercial grade 5-mm x 5 mm x 20-mm PZT stacks that are preloaded in a diamond-shaped aluminum flexure. (See figure 3.) The slight angles of the diamond-shaped flexure magnify the displacement of the stack. Therefore, even though at cryogenic temperatures the stroke is decreased to one fourth that of ambient, a final 30 μm of stroke at cryogenic temperatures is achieved with a maximum 120 V applied to the actuator. Without this mechanical amplifier approach, we would require PZT lengths of 60-70 mm which would likely have to be thicker to be structurally sound and likely require greater voltages, not to mention larger structure for preloading. The actuator, as designed and implemented, isolates the PZT stack from side and shear loads which are often the downfall of piezo ceramic stacks. Aluminum was chosen as the flexure material in order to maximize the stroke. The current configuration exceeds the requirements for stroke and positioning resolution. A proposed future development will address two concerns regarding the actuators: lateral stiffness and flexure material.

6.1.5.1 Lateral Stiffness

As shown by FEA analysis, the actuators, as purchased, were not sufficiently stiff in the two axes normal to the intended gap change motion of the optic. Therefore an additional flexure was added to stiffen these modes. One of the challenges of our continuing development is to reduce the outer envelope of the mechanism. In light of this it would be desirable in a future design iteration to integrate the stiffening flexure into the actuator flexure for increased compactness.

6.1.5.2 Flexure material

Aluminum has a fatigue limit, therefore it is not generally recommended as a flexure material. While it may be possible to analyze the loads and number of cycles and determine that the flexures in our case can be made of aluminum, the design will be more robust if a more suitable material is chosen. Other materials such as steel have the property that for loads under a certain amount, infinite cycles are possible with no fatigue. The flexure redesign sited above will have to address any increase in stiffness that could limit the stroke. There are two obvious solutions. Beryllium-copper and steel have no fatigue limit and are stronger so the flexures can be machined thinner to be more flexible yet have the same strength as the current aluminum actuator. Also, two PZT stacks could be incorporated into the actuator to provide more force and achieve the same stroke with a stiffer flexure.

6.1.6 PZT Stability and Life Testing

Two of the most important issues that must be addressed regarding PZT-based actuators are cryogenic dimensional stability and life-test survival. Conventional PZT actuators use ceramic wafers that are glued together, mechanically in series, electrically in parallel, after the individual wafers have been fired. These polymeric adhesives are relatively weak in shear and tension and may yield plastically under stress. Also, mechanical and dimensional properties may vary with temperature as a result of moisture trapped in the bonded joints.

There is a development in progress directed towards answering the survivability and dimensional stability question of these actuators, which is the co-firing of piezo-ceramic materials. Co-firing is a process in which polymeric bonding is accomplished prior to firing. During firing most of the polymer and moisture is driven out of the joint leaving a clean, stable bond. Actuators using these materials are under active development and testing at several manufacturers. Morgan Matroc, Inc., Electro Ceramics Division, for example, has produced co-fired actuators which, using a sinusoidal wave at 1000-Hz with a 20-lb load, has operated in excess of three billion cycles at full voltage without failure.

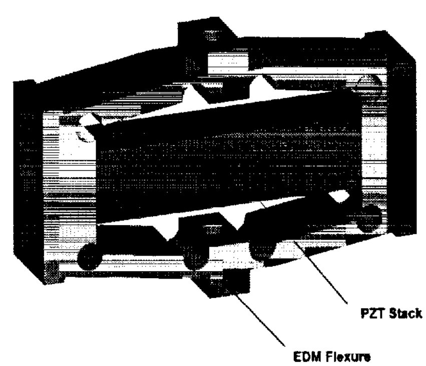


Figure 3: Actuator detail

A second advance in PZT materials that bears on this design is the development of single-crystal ceramics. These ceramics yield four to five times as much strain for a given applied voltage as the conventional polycrystalline materials (0.5% compared to 0.1% conventional). While the modulus in these materials is reduced from about 45 to 30 gPa, the energy delivered by the actuator, which is proportional to the square of the strain, is greatly improved. Burleigh Instruments, Inc. is heavily involved in developing actuators using this technology.

In future DULCE developments it would be desirable to investigate the use of these materials together with a redesigned displacement amplifying flexure as noted in section 6.1.5.2 above. This appears to be a feasible approach to building a robust, compact actuator for cryogenic use.

6.2 Optical coatings

DULCE has multilayer dielectric coatings over a 25 mm diameter aperture. These coatings are designed to minimize phase dispersion over the 3-5 μm wavelength range. As discussed in section 3.3, phase dispersion must be controlled for low order etalons, where the thickness of the coating is comparable to the separation of the plates. DULCE uses low phase dispersion coatings for the 3-5 μm wavelength range, which approach the properties of ideal metal reflectors. We plan to utilize similar coatings in our continuing development effort.

In order for curvature not to dominate the system finesse, the etalon plates must be flat to $\lambda/200$ at the temperature of operation. Plate curvature can arise from the optical polishing process as well as from stresses induced by the application of thin film multilayers. Upon cooling to cryogenic temperatures, uncoated plates may also distort. We intend to use single crystal or special substrates that contract uniformly under cool down and we have identified commercial optical fabrication companies that have metrology capabilities at or near the 5 nm level. The stresses imposed by multilayer coatings can be predicted accurately and a coating design may be adjusted to minimize plate curvature.

6.3 Electronics Design

The FPI tuning frequency will drift slowly over time unless active stabilization of the mirror separation is employed. Cavity stability is required to be within one-tenth of a resolution element, or 3 nm. The capacitance between the pads deposited on the outer annulus edges of both elements changes as the cavity spacing varies. This capacitance can be read out, and used by the controller to generate an error signal that can, in turn, be processed and fed to the PZT actuators to keep constant plate separation and parallelism. The controller for DULCE uses a Digital Signal Processor for flexibility. Control schemes can easily be modified by changing software. 16-bit analog-to-digital and digital-to-analog converters are used for the sensor and actuator driver interfaces, respectively. This approach provides for a sensing resolution of about 0.5 nm over the 30μm stroke. Capacitive sensors were chosen due to their low power dissipation.

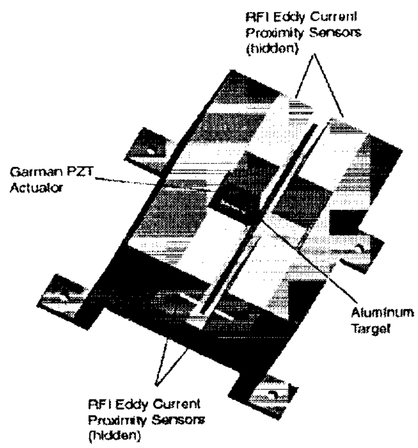
The DULCE control scheme is fully implemented in the digital domain. Importantly, these software algorithms will be readily transportable from the present controller to processor circuitry that has a clear path to flight hardware. GSFC has nearly completed an internally funded development of an eight input, eight output, flight-qualifiable DSP board with a sample rate of 20 kHz. This board is based on the rad-hard, floating point, Analog Devices AD21020 processor and has enough ram to accommodate sensor linearization, dither, and control algorithms.

7. TESTING

7.1 Actuator testing

The actuators used on DULCE were thoroughly cryogenically tested to assess stroke, gain, hysterisis, and CTE characteristics for the purpose of matching actuators for use on the etalon. Additionally, structural modes and stiffnesses were measured to understand possible resonance issues. This effort entailed putting the actuators into a test fixture that contained differential eddy current sensors and an optical cube. (See figure 4a.) The actuators were then brought to temperature and the eddy current sensors yielded positional information that was verified by a Zygo laser metrology system. A dedicated cryostat, all associated test fixtures, and a labVIEW data acquisition system specifically designed for this test were also used.

In this testing, as was noted in section 6.1.5 above, total actuator stroke is decreased to one fourth that of ambient. (See figure 4b.) A total CTE shrinkage of 500 microns was also recorded. Use of the manual gap adjustment prior to cryogenic operation to account for this expected shrinkage will allow the available actuator stroke to bring the sensors into their capture range.



Cryogenic Actuator Test Bed

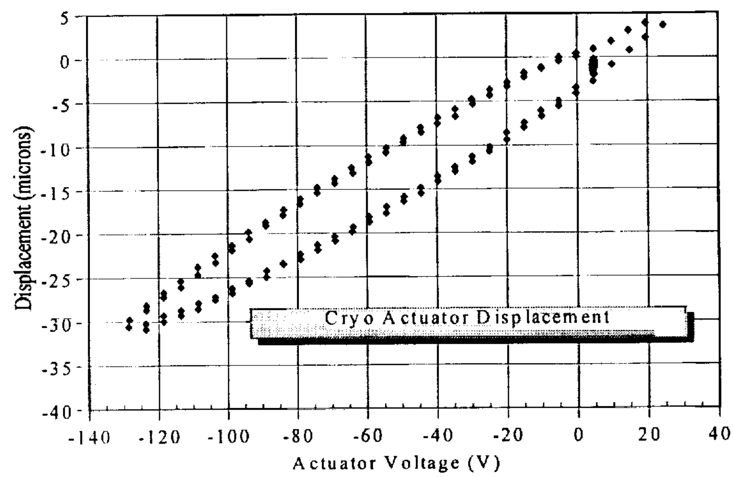


Figure 4a and 4b: Actuator test fixture and a typical result

7.2 System-Level Optical Testing

System level optical testing was carried out as follows. In Figure 5a and 5b we show our current optical bench setup. We use an IR-optimized Helium Neon laser with a single InSb detector to calibrate the Fabry-Perot gap spacing, determine the finesse, and evaluate the stability of our control system. Since the IR laser is invisible, a visible light HeNe laser is used to help with alignment. Here the laser light is expanded, collimated, and sent through the etalon and detected with the photodetector. By scanning the etalon, the closed-loop finesse was determined to be 25, identical to the reflectance-limited finesse of the optical plates used in DULCE. Our control system stability was determined by tuning the etalon to the half power point of a 3.39 μm interference peak and monitoring with the detector the calibrated laser amplitude as shown in Figure 6. This method yielded a control system stability of better than 0.6 nm, sufficient to meet our requirements.

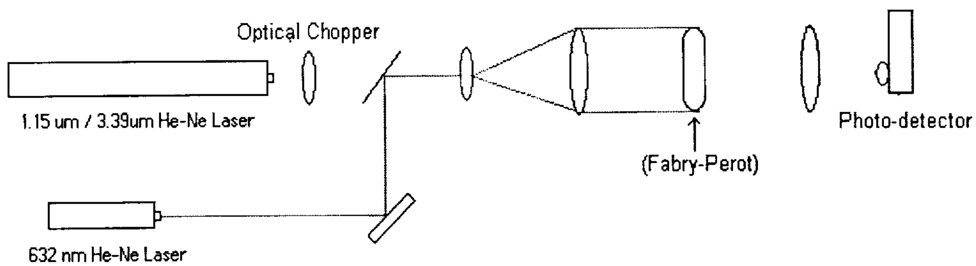


Figure 5a: Schematic representation of optical bench setup.

Figure 5b: Lab bench setup of system-level optical testing using an optical HeNe laser, an IR-optimized HeNe 3.39/1.15 micron laser and InSb detector.

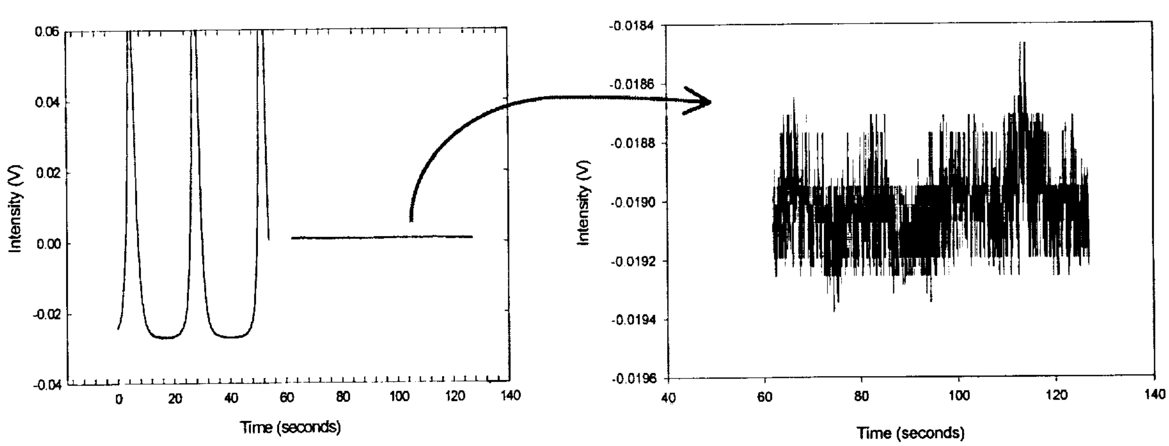


Figure 6: Control system stability testing with DULCE demonstrates better than a 0.6 nm stability.

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