University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

# SPECTROM
# Scientific Platform for Exact Control of Thermally Regulated Optical Mechanisms

## Approvals

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# I. Problem or Need

The objective of the SPECTROM project presented by Ball Aerospace and Technologies Corp. is to design, build, and validate the functionality of an optical focus correction system, which utilizes a material with a high coefficient of thermal expansion (CTE) as the control mechanism.

Precise and accurate alignment of optical instrumentation is often critical for gathering scientific data. Not only can misalignment of these elements cause a mission to be scrubbed completely, but on-orbit rectification of misaligned systems can cost hundreds of millions of dollars[1]. Variations in the position of a spacecraft's optical system can often be attributed to the expansion and contraction of materials under cyclic thermal loading.

Historically, precise optical benches are expensive carbon fiber composite structures that require extensive testing to ensure minimal deformation when exposed to the temperature gradients of space. Alternatively, an aluminum bench would be a cost-effective solution; aluminum, however, is susceptible to structural deformation when exposed to temperature loads, due to its high coefficient of thermal expansion. To eliminate the need for on-orbit maintenance, the successful implementation of an aluminum optical bench requires an active control system to counteract displacement introduced by thermal expansion. SPECTROM is a novel solution in the field of spacecraft optics, introducing intentional thermal expansion in order to dynamically correct the focus length and pointing error of optical instrumentation.

The purpose of SPECTROM is to design and manufacture a test demonstration unit, consisting of a thermally controlled aluminum test bed, integrated with optical instrumenation that can be adjusted by a high precision, material-driven control system. The precision of the control system must additionally be validated to demonstrate successful application of the technology. The demonstration unit will require two independent thermal control systems, one for maintaining and controlling the temperature of the aluminum test bed, and one for adjusting focus length and pointing alignment (tilt) of the optics.

A successful test bed design will allow for more than 100 microns of structural expansion when a 10°C temperature increase is applied to the structure via the thermal control system, from an initial temperature of 296.15K. Additionally the test bed thermal control system must be capable of inducing a customer-provided temperature profile, shown in Figure 3, as well as an alignment error of $10\mu$rad (TBR) to the optical system through differential heating of the bench. Temperature of the structural elements must be known to within 0.1K at all times.

Successful design of the focus correction system will maintain the best focus position with an accuracy of +/-$1\mu$m (TBR) and alignment (tilt) with an accuracy of +/-$1\mu$rad (TBR). Additionally, the focus correction system shall return the optical system to +/-$2\mu$m of best focus position within 120 seconds from when thermal equilibrium is reached in the test bed, or maintain best focus to within 5 microns when the test bed is subjected to the aforementioned temperature profile. These success criteria are customer provided requirements.

The benefits of a successful correction system are the increased control of an optical system with a reduction in risk and cost, compared to those afforded by composite buses. The corrective system employed by the SPECTROM project will further reduce costs by eliminating the need to manufacture, integrate, and test fine-tolerance shims necessary for the precise alignment of optical elements.

# II. Previous Work

SPECTROM is a test bed for demonstrating successful application of a high thermal coefficient material as the control mechanism for maintaining optical focus. Research suggests this technology has not previously developed or applied within the public domain.

One major part of SPECTROM involves creating an optical system for accurately measuring the distance that a high CTE material is able to move and tilt an optical instrument. The system must be able to measure distances to within 1 $\mu$m and angle deflections to within 1 $\mu$rad. One previously applied method of accomplishing this, is by using an optical element with knowledge of the focal length. Knowing the initial height of a laser and the final height of the laser in pixels, Eq 1 can be used to find the distance of the light source from the detector.

$$\frac{x}{f} = \frac{X}{d} \tag{1}$$

Where x is the size of the laser in the sensor, f is the focal length of the optical element, X is the size of the laser before going through the optical element, and d is the distance from the source of the laser to the sensor. Using a sensor to calculate the height of the laser after passing through the optical element, Eq 1 can be used in order to determine the amount of length the high CTE material has expanded in order to correct for thermal expansion of the aluminum bench. Eq 2 can be used to determine the magnification of the laser.

$$M = -\frac{S_1}{S_2} = \frac{f}{f - S_1} \tag{2}$$

Where M is the magnification factor, f is the focal length, $S_1$ is the distance from the optical element to the source of the laser, and $S_2$ is the distance from the optical element to the image of the laser.

Another method that has been previously implemented for measuring distance is by using eddy current sensors. These sensors adjust aperture by creating an electromagnetic field that induces eddy currents in a conductive measurement object, which change based on the proximity that the sensor is to the object. Multiple sensors can be used in order to measure the displacement and calculate the deflection change induced by the focus mechanism.

An additional method that has been used to measure displacement in past projects, is through implementation of strain gauges. These sensors are mounted on an expanding material, and measure the expansion of the material based on the strain that is being undergone. These could provide a good design solution for this project because of their ease of use, price point, and availability.

## III. Specific Objectives

The levels of success given in Table 1 will gauge the project's success over the course of the two semesters. The team will design, test, and integrate with the intention of meeting the first level objectives, with fulfillment of all Level 1 objectives being indicative of project success. Subsequent levels represent additional successes at a more refined level, involving higher levels of complexity. Some specific numbers are To Be Reviewed (TBR) by the customer after more in-depth design work has been accomplished.

| | **Test Bed Performance** | **Focus Mechanism Performance** | **Optical Test Equipment and Data Analysis** |
|---|---|---|---|
| **Level 1** | Aluminum test bed shall change the focus position by $> 100$ $\mu$m for a change in temperature of 10 K from a starting temperature of 296.15 K. | The focus mechanism shall return the optical system to the best focus position ($\pm$ 2 $\mu$m) for a displacement of 50 $\mu$m within 120 seconds. For this static demonstration the test bench shall start at ambient temperature and be held constant at the temperature that produces 50 $\mu$m displacement. | The optical test equipment shall be able to measure the focus position to an accuracy of 1 micron. This position data and temperature data shall be recorded at a rate at least 1 sample per minute. (TBR) |
| **Level 2** | The test bed shall imitate the customer provided temperature profile to within 0.5 K at all times during the profile and the temperature of the bench must be known to an uncertainty of $\pm$ 0.1 K | The focus mechanism shall maintain the best focus position to within $\pm$ 5 $\mu$m when the test bench is subjected to the customer provided temperature profile at all times during the profile. | |
| **Level 3** | The test bed shall be capable of inducing a tilt error of 10 $\mu$ radians in the optical system. (TBR) | The focus mechanism shall maintain the best focus position to within $\pm$ 5 $\mu$m and maintain tip and tilt angle to within $\pm$ 5 $\mu$ radians when the test bench is subjected to the customer provided temperature profile at all times during the profile. | The optical test equipment shall be able to measure best focus, tip and tilt to $\pm$ 1 micron and $\pm$ 1 $\mu$ radians respectively. This position data and temperature data shall be recorded at a rate of at least 1 sample per minute and displayed in real time. (TBR) |

Table 1: Levels of Success for Specific Objectives

# IV. Functional Requirements

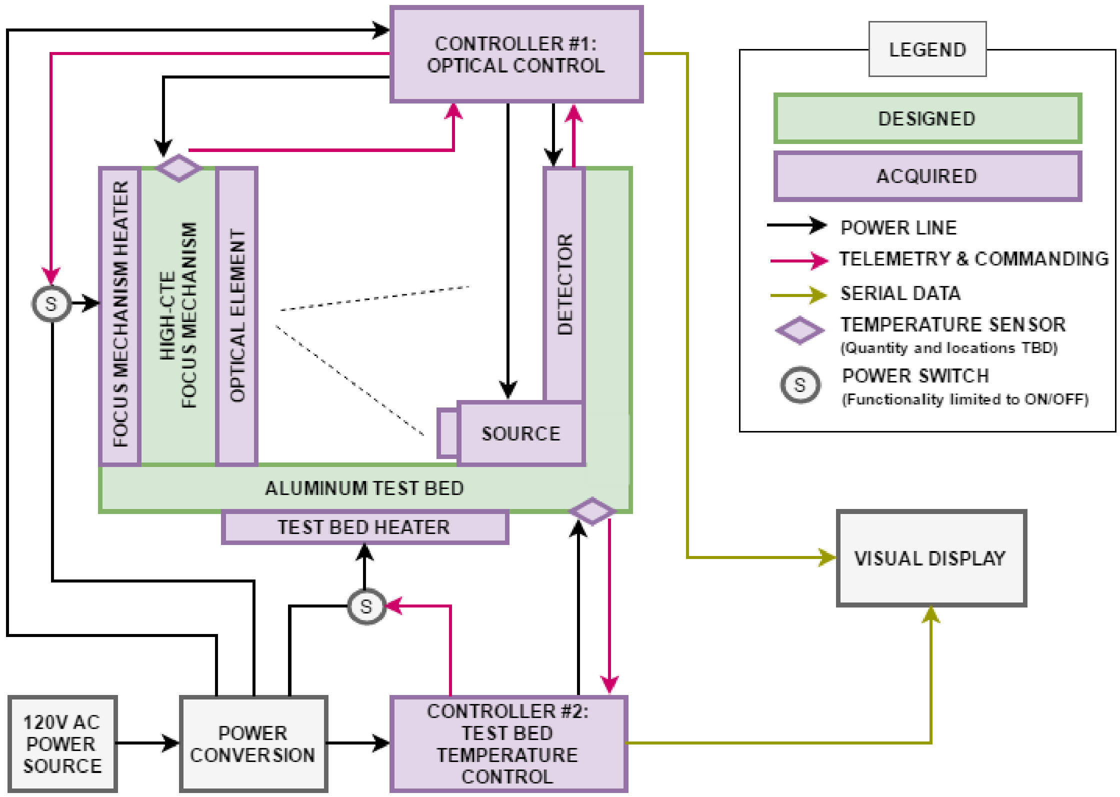


Figure 1: Functional Block Diagram

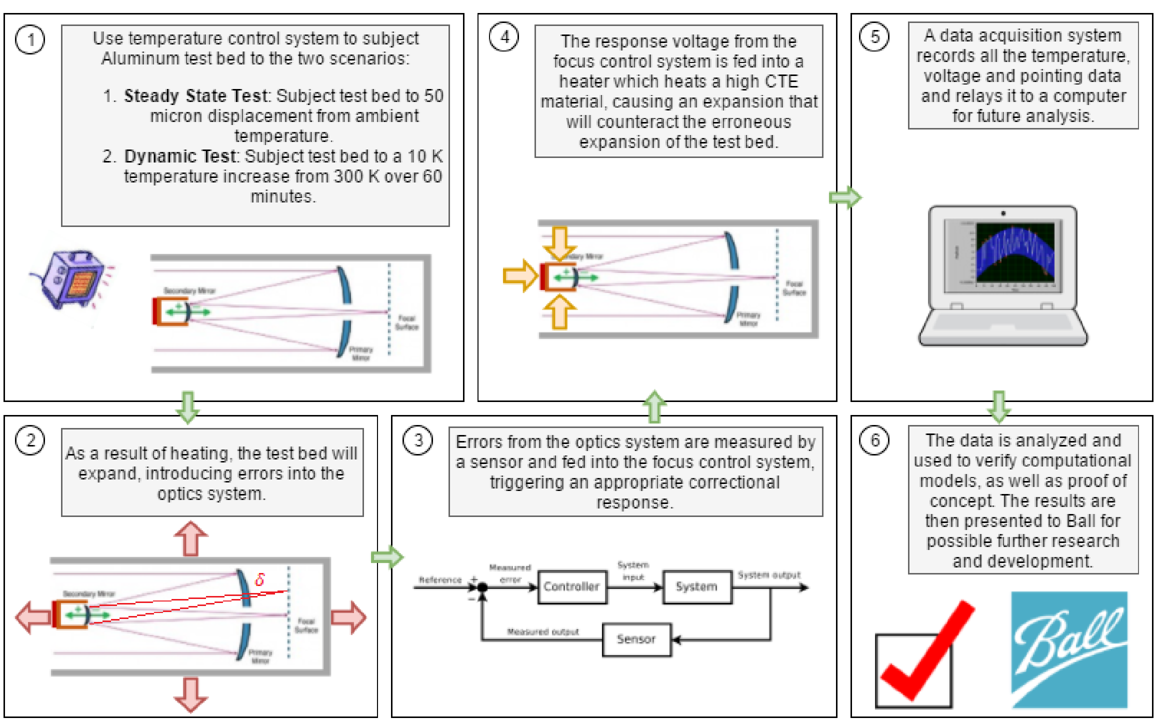


Figure 2: Concept of Operations

# V. Critical Project Elements

### A. Design and Control of Aluminum Test Bed

An aluminum test bed must be designed, containing a heating system for maintaining thermal control of the test bed structural elements. The heating system must be designed to maintain temperature within the required tolerances, governed by an active control loop. The test bed must be sized to produce measurable thermal expansion, and to accommodate mounting of selected optical instrumentation and the focus control system.

### B. Focus Correction System

An active focus length correction and tilt adjustment system must be designed, utilizing expansion of a material with a high coefficient of thermal expansion as the adjustment mechanism. The system encompasses design of the mechanism, thermal heating system, and the active feedback control loop for maintaining precise control of material expansion. Failure to accurately predict and control movement of the correction system will result in failure to demonstrate material expansion as a viable control mechanism.

### C. Optical System Design

An optical system comprised of at least a source, optical element, and detector must be designed to integrate with the aluminum test bed. The system must demonstrate and measure changes in focus length and tilt, when adjustments are made by the Focus Correction System. Off-the-shelf components will be sourced and and integrated to meet the system requirements. Failure of design will prevent accurate resolution of the focus correction system measurement capabilities.

### D. Focus Measurement System

Corrective adjustments to the optical focus distance and alignment (tilt) introduced by the focus correction system, must be precisely measured for closed loop feedback control. A system must be developed to accurately resolve the adjustment capabilities of the focus correction system to the precision tolerances specified by the document. Failure to precisely measure changes will prevent successful implementation of a closed loop control law, and validation of the control system.

### E. Data Acquisition and Software Package

A data collection system must be selected and designed to interface with all temperature sensor telemetry feeds as well as the focus measurement feed. The software package must interpret the results, and implement the necessary control law for applying corrective heating to the specified system. Failure to collect and process data will result in the inability to control the Correction System and Test Bed expansion.

# VI. Team Skills and Interests

| **Critical Project Elements** | **Skills Needed** | **Team Members** |
|---|---|---|
| Design and Control of Aluminum Test Bed | • Solidworks and ANSYS Modeling<br>• Electrical<br>• Closed loop control design<br>• Thermal analysis<br>• Machining | Eli, Jeff, Sarah, Zach, Whipkey |
| Focus Correction System | • Solidworks and ANSYS Modeling<br>• Electrical<br>• Closed loop control design<br>• Thermal analysis<br>• Machining | Whipkey, White, Mellin, Jaevyn, Tyler, Sarah, Eli |
| Optical System Design | • Optics and physics knowledge<br>• Electrical | Mellin, Jeff, Jaevyn, Sarah |
| Focus Measurement System | • Electrical | Zach, White, Whipkey, Tyler, Jaevyn, Jeff |
| Data Acquisition and Software Package | • Controller programming knowledge<br>• Labview VI development<br>• Sensor calibration<br>• Software programing | White, Whipkey, Tyler, Jaevyn, Jeff |

Table 2: Critical Project Elements and Team Member Skills

# VII. Resources

| Critical Project Elements | Resource | Source |
|---|---|---|
| Design and Control of Aluminum Test Bed | • Solidworks and ANSYS software<br>• Machineshop<br>• Thermal analysis knowledge | • Trudy Schwartz, Matt Rhode, Bobby Hodgkinson, Jelliffe Jackson<br>• Aerospace/ ITLL machine Shop<br>• ITLL Electronics Shop |
| Focus Correction System | • Precision manufacturing<br>• Control law modeling<br>• Solidworks and ANSYS software<br>• Material Database | • Aerospace/ ITLL Machine Shop<br>• Campus provided student software<br>• Matweb.com |
| Optical System Design | • Optics hardware<br>• Optical system design knowledge | • Jeffrey Thayer, Joe Lopez, Xinchau Chu |
| Focus Measurement System | • High precision measurement knowledge | • Ball Aerospace |
| Data Acquisition and Software Package | • DAQ hardware<br>• NI LabVIEW Student Software | • Trudy Schwartz<br>• CU Aerospace Department |

Table 3: Project Resources

# VIII. Appendix A

| Time (min) | Temperature |
|---|---|
| 0 | 300 |
| 5 | 300 |
| 10 | 300 |
| 15 | 301 |
| 20 | 302 |
| 25 | 303 |
| 30 | 304 |
| 35 | 305 |
| 40 | 306 |
| 45 | 307 |
| 50 | 308 |
| 55 | 309 |
| 60 | 310 |
| 65 | Remove Bench Heating |
| 70 | Remove Bench Heating |
| 75 | Remove Bench Heating |
| 80 | Remove Bench Heating |
| 85 | Remove Bench Heating |
| 90 | Remove Bench Heating |
| 95 | Remove Bench Heating |
| 100 | Remove Bench Heating |

Figure 3: Customer Provided Temperature Profile

# References

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[4]”Eddy Current.” Glossary. Micro Epsilon, n.d. Web. 12 Sept. 2016. ¡http://www.micro-epsilon.com/glossar/Wirbelstrom.html¿.

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