

## PAN & TILT PLATFORM FOR A THERMAL VACUUM VIDEO CAMERA

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### ABSTRACT

The purpose of the Space Simulation Test Engineering (SSTE) Section at NASA Goddard Space Flight Center is “to provide full service test support, engineering expertise, and state-of-the-art facilities to perform simulated space and thermal cycle testing of Earth orbit and deep space flight hardware”(ref. 1). During the Integration & Testing phase of space flight projects, flight hardware must successfully demonstrate its functionality under conditions similar to the actual environment experienced in space. When testing hardware with mechanical components, such as antenna extensions, door openings, or solar panel deployments, visual observation would allow test personnel to verify mechanical operations in real-time.

A video camera can supply data that the usual sensors inside a TV chamber cannot provide. Since mechanical functional testing could affect multiple regions of a test item, a camera with a fixed position may not be able to monitor and record the performance of different components of a mechanism, especially for large test items. By mounting the camera to a Pan and Tilt Platform, the camera can cover a larger area and its field-of-view (FOV) will increase significantly. This paper details the design process for the Pan and Tilt Platform.

### INTRODUCTION

A primary objective of Code 549.4, the Space Simulation Test Engineering Section of the Environmental Test & Integration Branch, is to create space environments to test hardware for space flight or the ground support equipment for space flight missions. To simulate environments experienced during flight, Code 549.4 uses thermal vacuum (TV) chambers to replicate the temperature and pressure of outer space.

Sensors inside a TV chamber typically provide pressure, temperature, and contamination (outgassing) data during testing. If a test includes mechanical functional testing, the ability to visually monitor the test item would provide additional information on the performance of the item. Code 549.4 has a vacuum-compatible video camera that has been used for such tests. However, the camera's usage is limited because its position and FOV are fixed after the chamber door is closed. Therefore, the camera can only observe a fraction of large test items.

To expand the FOV, the camera will be mounted to a platform designed and built to adjust the orientation of the camera inside the chamber. The platform will rotate the camera with respect to two axes (panning and tilting) and will be controlled by a user-friendly interface. Because it will be used in a thermal vacuum environment, the platform must be fabricated from vacuum-compatible materials and operate in the temperature extremes of a TV chamber.

### SYSTEM REQUIREMENTS

The Pan and Tilt Platform system has various requirements based on its operating conditions and its performance. First, the Platform will be designed for use with the existing in-house video camera. To increase its FOV, the Platform will rotate the camera 120° ( $\pm 60^\circ$  from centerline) in each axis. A user-friendly interface will control the mechanical system used to rotate the camera; easy-to-use controls will also simplify and promote the use of the camera.

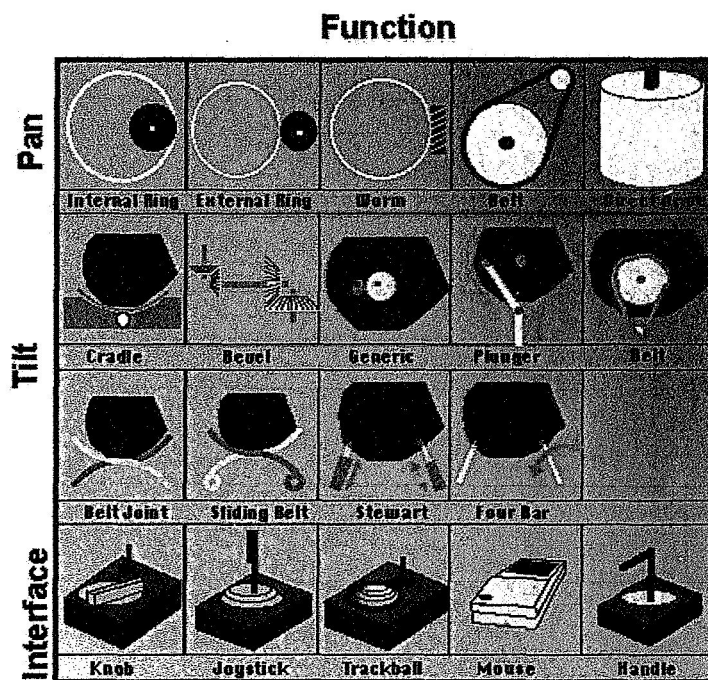
Next, all system components must be able to withstand the range of temperatures inside TV chambers, from -180°C to +100°C. Additionally, all components must be made of materials compatible with a vacuum environment of less than  $1 \times 10^{-5}$  torr. Because the camera's minimum and maximum operating temperatures, -10°C and +50°C respectively, are less extreme than the thermal environment of the TV chambers, a thermal control system must maintain the temperature of the camera within its limits. To minimize the space required inside a TV chamber, the complete Pan and Tilt Platform system will fit within a 30.5 cm x 30.5 cm x 30.5 cm (1 ft x 1 ft x 1 ft) volume. Finally, the design will use readily available "off-the-shelf" products as much as possible to decrease the time and cost for fabrication and assembly.

## MECHANICAL CONTROL SYSTEM

Various methods used to control other camera systems, such as security cameras, were evaluated to design the Pan and Tilt Platform. Figure 1 (ref. 2) shows different mechanisms for panning and tilting the camera, as well as types of interface for user control. Each method has advantages and drawbacks for controlling the Platform.

Methods with gears, rings, or belts may use a smaller motor for a given load than a motor for the direct drive method because the mechanisms amplify the torque supplied by the motor. With the addition of a transmission, a single motor could possibly be used to control both rotational axes of the camera. However, the additional components would increase the complexity of the system, for both assembly and maintenance. Another disadvantage would be a larger volume required for the overall system due to the greater number of parts.

The direct drive method, using stepper motors, was selected to enable the movement of the Platform. Stepper motors have previously been used in TV chambers during testing for various flight programs, including MAP, MESSENGER, and ST-5. Using the direct drive method reduces the number of components versus other options. A smaller number of components also simplifies the assembly process and provides greater reliability by decreasing the number of failure points.



**Figure 1 – Mechanical System Evaluations**

Three options were considered for the user interface – the knob/handle, the mouse/trackball, and the joystick. The knob and the handle are very similar; a handle is basically a knob with an attached extension. Both are simple devices that control movement limited to one dimension or a single degree-of-freedom (DOF). However, the Pan and Tilt Platform would require two knobs or handles because the Platform rotates in two axes. The mouse and the trackball are also very similar controllers. A mouse is basically a trackball rolling on a surface instead of the ball being rolled by hand. A mouse or trackball offers multiple DOF to control multi-dimensional movement in a single unit. But because the Platform only moves in two axes, the software to control a mouse/trackball would have to interpret off-axis input.

Because of the user interface tradeoffs, the joystick was chosen as the controller for the Platform. The joystick has the advantages of the knob/handle and the mouse/trackball without the disadvantages of either type of controllers. A single joystick can control movement in both axes without the off-axis input. Also, a joystick provides intuitive control for the user. Tilting motion is analogous to pitch – moving the stick forward and backward; panning motion is analogous to yaw – moving the stick left and right.

### Stepper Motor Sizing

Each major component of the Platform contributes an inertial load to the stepper motors that pan and tilt the video camera. To simplify inertial load calculations, all major components are modeled using rectangular blocks and cylinders or sections of such shapes. The Parallel Axis Theorem was used to find the actual inertial load of a component when the component's centroidal axis does not coincide with the rotational axis. The inertial load (or mass moment of inertia) of each component was determined using the equations shown in Appendix A.

The moment (or torque) required for each motor is the product of the total inertial load applied to the motor and the angular acceleration required:  $M = I \times \alpha$ . In addition to the inertial load, the total load applied to the tilt motor includes a component from the moment induced by gravity with respect to the perpendicular distance from the axis of rotation:  $M = F \times d$ . From these equations (ref. 3), four basic steps are used to find the minimum torque required for each motor.

- Find the load of each component with respect to the rotational axis of the motor
- Sum the loads of all components for the motor
- Specify the angular acceleration
- Calculate the torque required

See Appendix B for a summary of the loads of components and the torques required for each motor at various angular accelerations.

### Mechanical System Selection

Stepper motors from MDC Vacuum Products (ref. 4) were selected to maneuver the Pan and Tilt Platform. These motors function at  $1 \times 10^{-10}$  torr and from  $-40^{\circ}\text{C}$  to  $+250^{\circ}\text{C}$ . The motors can produce 0.42 N-m (60 oz-in) of torque for the load applied to each axis at a maximum angular acceleration of 0.1 rad/s ( $60^{\circ}/\text{s}$ ). Weighing 0.68 kg (1.5 lbs) and measuring  $\phi 5.6$  cm x 5.8 cm length (2.2 in x 2.3 in); the tilt motor accounts for approximately 20% of the total inertial load for the pan motor.

The joystick controller system from Optimal Engineering Services (OES) (ref. 5) was selected to control the pan and tilt motors. This off-the-shelf product “integrates the power supplies, the drivers, and the controllers” for both motors. In this integrated system, a single joystick controls movements in each axis. The motor speed varies in proportion to the tilt angle of the joystick. This system also provides programmable limit switches for each axis.

## THERMAL CONTROL

### Thermal Environment For Camera Operation

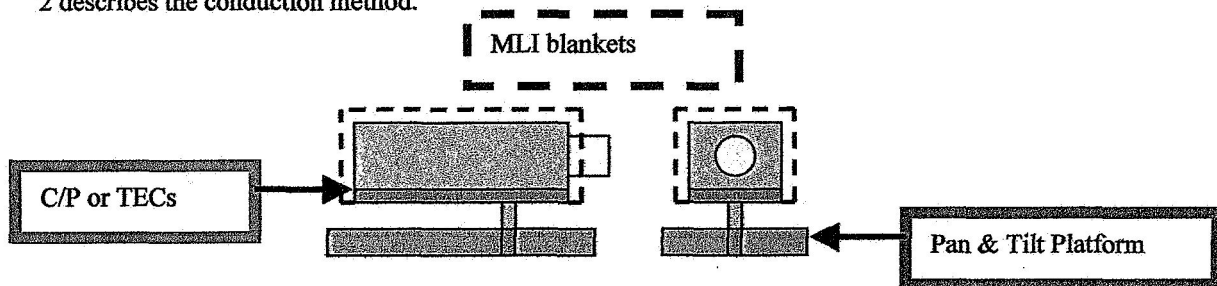
Because the chamber environment operates at a wider envelope (from  $-180^{\circ}\text{C}$  to  $+100^{\circ}\text{C}$ ) than the operating limits of the camera (from  $-10^{\circ}\text{C}$  to  $+50^{\circ}\text{C}$ ), a thermal control system is essential to maintain the camera's temperature. The Pan and Tilt Platform will integrate a thermal control system for the video camera.

Inside a chamber colder than  $-10^{\circ}\text{C}$ , Kapton heaters will be used to warm the camera. These camera heaters are wired to a temperature-controlled circuit on a standard TV facility heater power supply rack that automatically activates when feedback thermocouples are below the minimum temperature limit of the camera. Additionally, the camera dissipates approximately 6 W of power during operation.

In contrast to a cold chamber, a chamber above  $+50^{\circ}\text{C}$  is a more difficult thermal scenario. Because the environment is hotter than the video camera's maximum temperature limit, heat transfers from the chamber to the camera. The heat must be removed by conduction or radiation inside a vacuum.

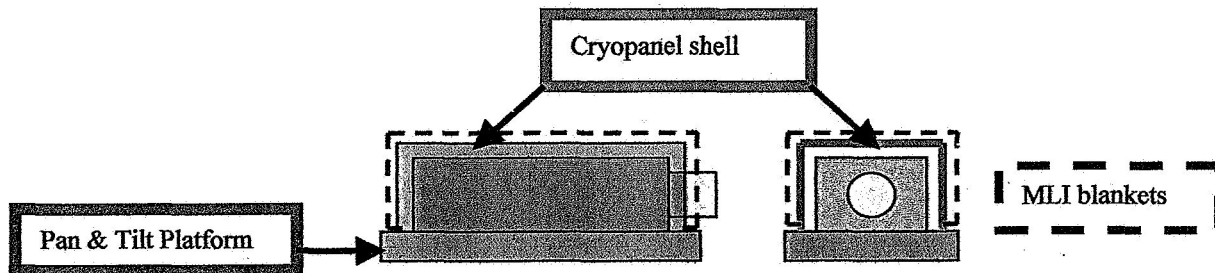
### Active Thermal Control Options

Devices must be used to actively remove heat from the camera, either by conduction or by radiation. Thermoelectric coolers (TECs) or a cold plate (C/P) acts as the active thermal controller and enables conductive heat transfer. A C/P or a number of TECs would be attached to the bottom of the camera. The active thermal controller maintains its temperature at ambient temperature and removes heat from the camera. Multi-layer insulation (MLI) material would cover and thermally isolate the camera and its active thermal control device from the chamber environment by reducing the thermal emissivity. Figure 2 describes the conduction method.



**Figure 2 – Conductive Heat Transfer Method**

For radiative heat transfer, the camera would reject its heat to an enclosure that is thermally controlled. A shell cooled by  $\text{GN}_2$  would surround the camera as much as possible to remove the heat from the camera. Again, MLI material would provide passive thermal control by covering the camera and its active thermal control device. Figure 3 describes the radiation method.



**Figure 3 – Radiative Heat Transfer Method**

## Calculating Heat Transfer

The heat transfer between the camera and its environment or its thermal control devices is calculated for both conductive and radiative methods. With the camera in both hot and cold chambers, the calculations show that the conductive method transfers approximately 100 times the amount of heat as the radiative method for active thermal control.

Furthermore, by using MLI for passive thermal control, the heat transfer from the environment to the camera decreases by a factor of 10. Therefore, a conductive method will be used for the camera's active thermal control and MLI material will also be used to isolate the camera from the chamber. See Appendix C (ref. 6) for the equations and the results from the calculations.

## Active Thermal Control Selection

Two options were considered for active thermal control by conduction, thermoelectric cooler (TEC) or cold plate (C/P). A TEC is a solid state heat pump that transfers thermal energy using the Peltier effect (ref. 7). The TEC can heat or cool depending on the direction of the current flowing through the device. TECs are very light weight and allow precision temperature control. However, multiple TECs would be required for the video camera for two reasons. The surface area of a single TEC is small; multiple units are needed to cover one surface on the camera. The maximum temperature difference between the hot and cold side of a TEC is less than the temperature difference between the camera and the chamber; multiple units must be used to handle large  $\Delta T$ . Another disadvantage of TECs is that effective heat rejection requires convection. In vacuum conditions, an additional heat sink must be utilized to remove heat rejected from the device. Without a heat sink in vacuum, a TEC would overheat and be destroyed.

A cold plate could also be used for conductive heat transfer. A C/P is simply an aluminum plate with tubing welded on one surface. Temperature-controlled  $\text{GN}_2$  flows through the tubing. With a thin profile relative to a large surface area for conduction, the surface on the front side of the C/P matches the  $\text{GN}_2$  temperature. Consequently, the C/P easily transfers thermal energy to and from the camera. The drawback of a C/P is that a Thermal Conditioning Unit (TCU) is required to control the  $\text{GN}_2$  flowing to the C/P. Fortunately, C/Ps have been used in many TV tests and all support equipments, including TCUs, are already in place. Because of the pros and cons between using TECs or C/Ps, the C/P was selected as the active thermal controller for the video camera.

## Stepper Motor Thermal Control

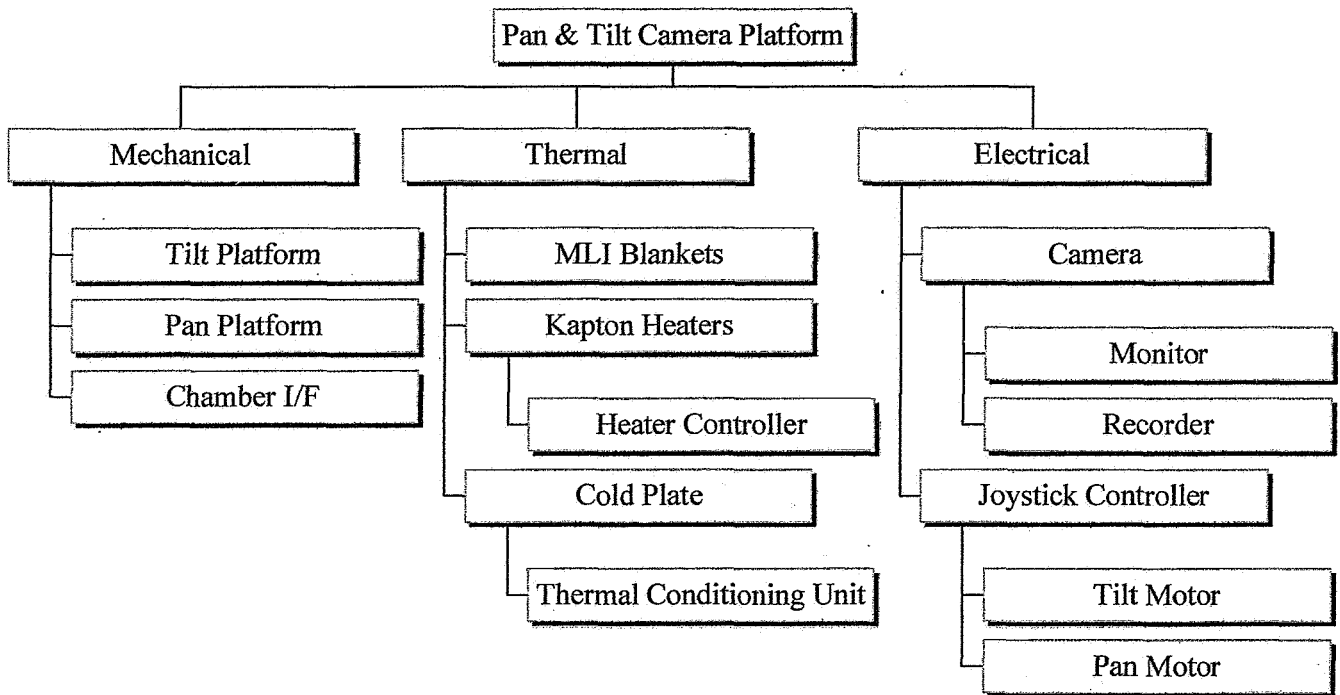
Because the temperature limits of the stepper motors (from  $-40^\circ\text{C}$  to  $+250^\circ\text{C}$ ) do not correspond to the limits of the camera (from  $-10^\circ\text{C}$  to  $+50^\circ\text{C}$ ), thermal control for the motors requires a different approach than for the camera.

At  $+100^\circ\text{C}$ , the maximum temperature of the chamber is  $150^\circ\text{C}$  colder than the upper limit of the motors. As a result, the chamber actually functions as a radiative heat sink for the motors during the hot case. Increasing the emissivity of the motors by using black paint or Kapton tape will allow the motors to radiate more thermal energy to the chamber.

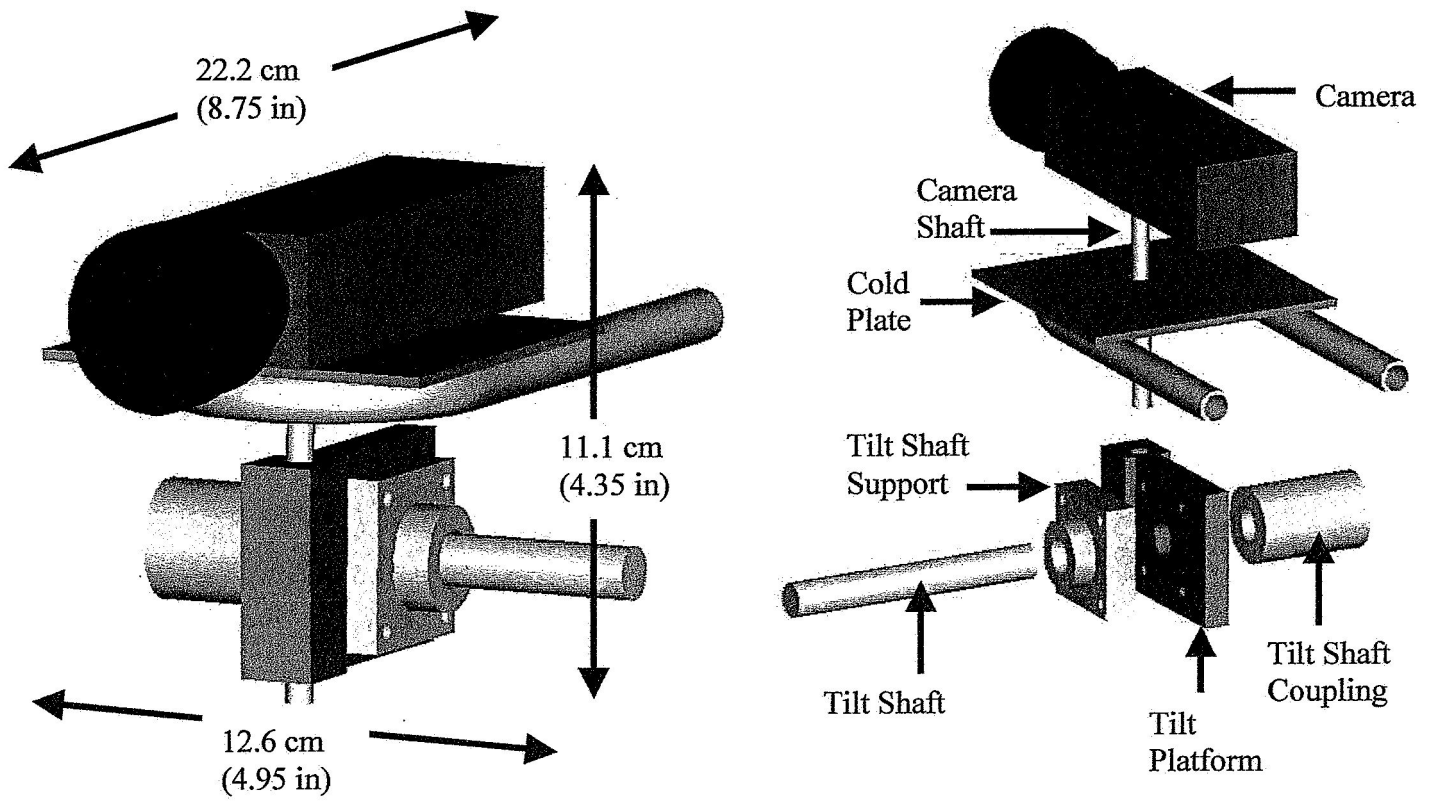
Conversely, the minimum temperature of the chamber, at  $-180^\circ\text{C}$ , is  $140^\circ\text{C}$  colder than the lower limit of the motors. In this case, the motors must be heated to stay warmer than its lowest operating temperature. Kapton heaters on each motor, wired to temperature-controlled circuits, will apply heat automatically when feedback thermocouples indicated motor temperatures below its lower limit. Also, each motor dissipates approximately 8 W of power during operation. Keeping the motors powered in a cold chamber would provide a second heat source. See Appendix C for the heat transferred by radiation between a stepper motor and the chamber.

## SYSTEM COMPONENTS

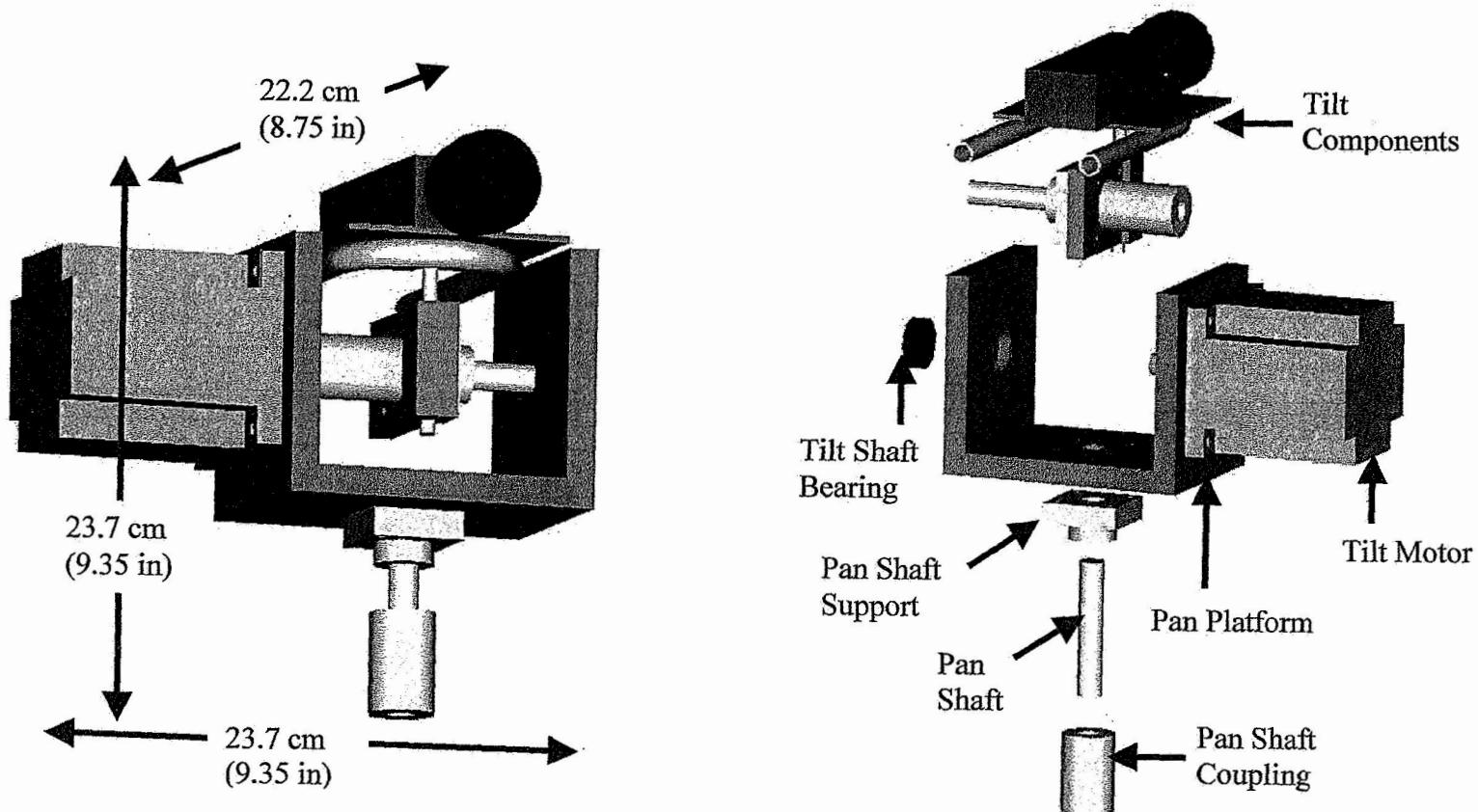
The Pan and Tilt Platform has three major subsystems – mechanical, thermal, and electrical. The components of the subsystems are outlined in Figure 4. Figures 5-9 (ref. 8) graphically detail the components and the overall dimensions that make up the Pan and Tilt Platform. Figure 5 contains the components that apply loads to the stepper motor rotating the tilt axis. Components loading the panning motor are illustrated in Figure 6. In Figure 7, the complete Pan and Tilt Platform is assembled. Figure 8 demonstrates one possible interface used to secure the entire Platform to the payload table inside a TV chamber. Two views of the Pan and Tilt Platform inside a  $\phi 2.1 \text{ m} \times 2.4 \text{ m}$  length (7 ft x 8 ft) TV chamber can be seen in Figure 9.



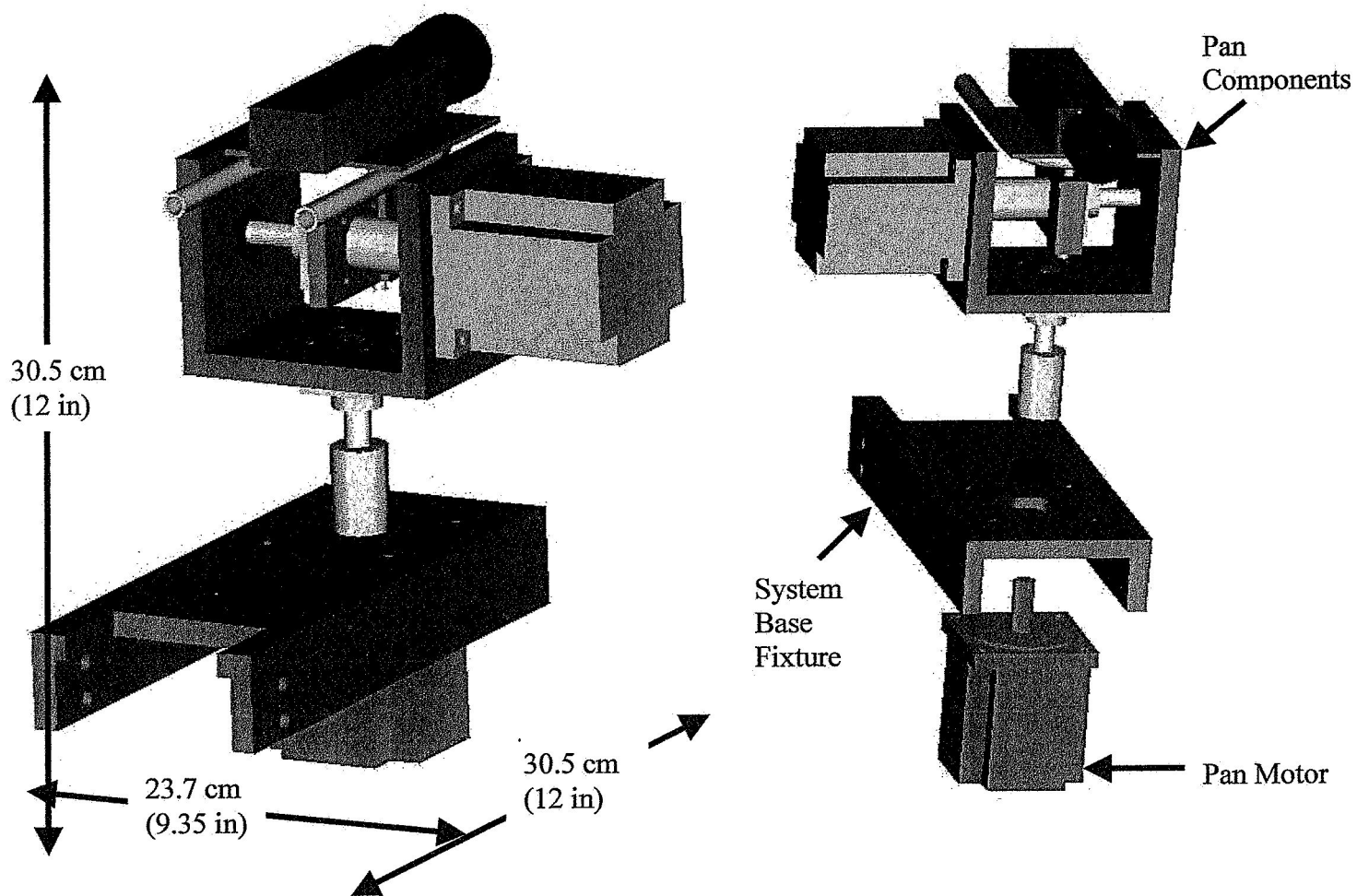
**Figure 4 – System Diagram**



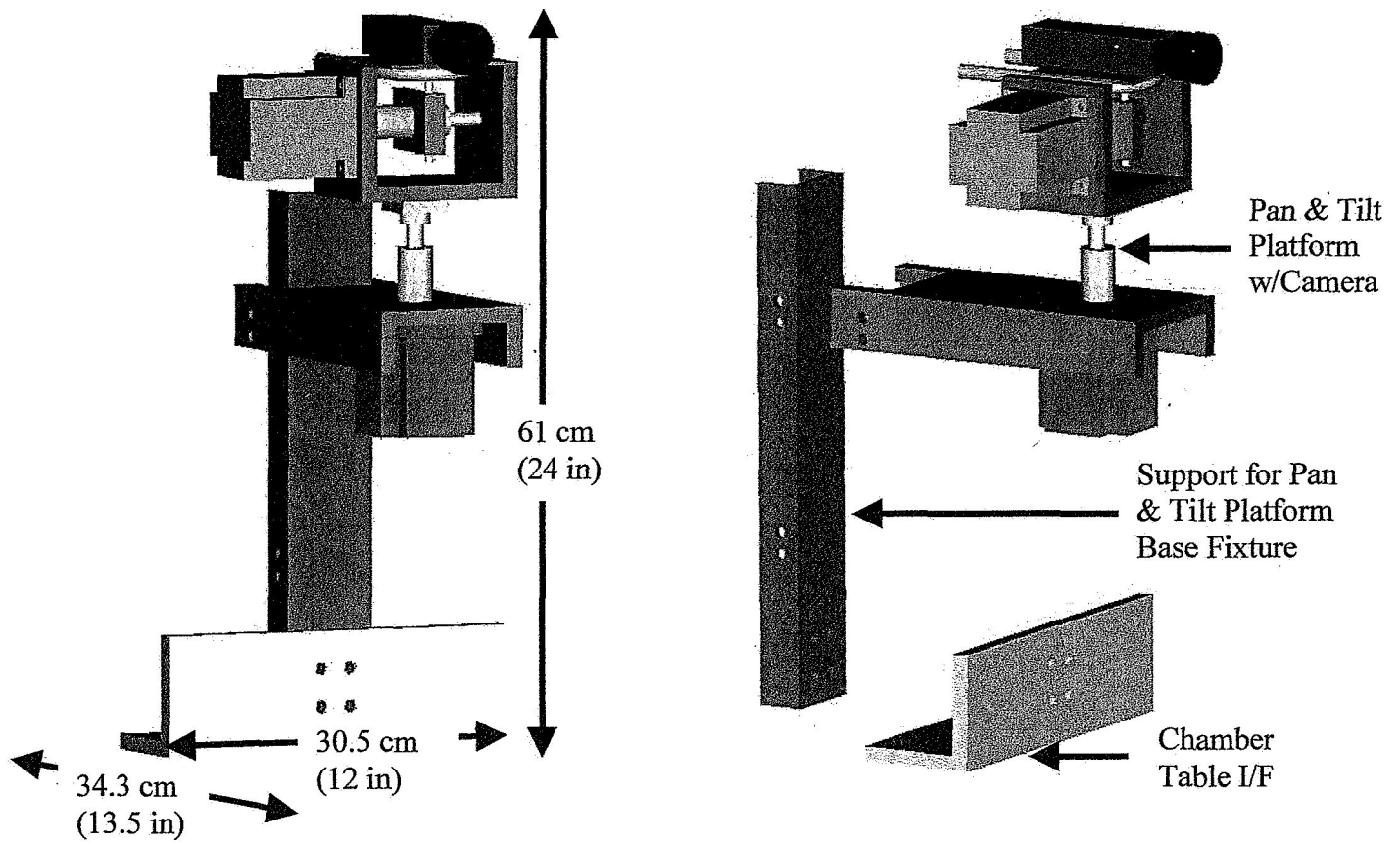
**Figure 5 – Tilt Components**



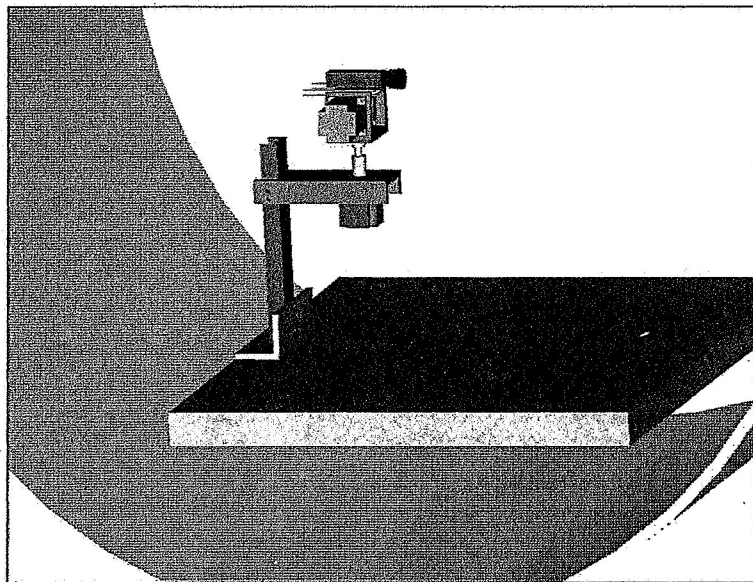
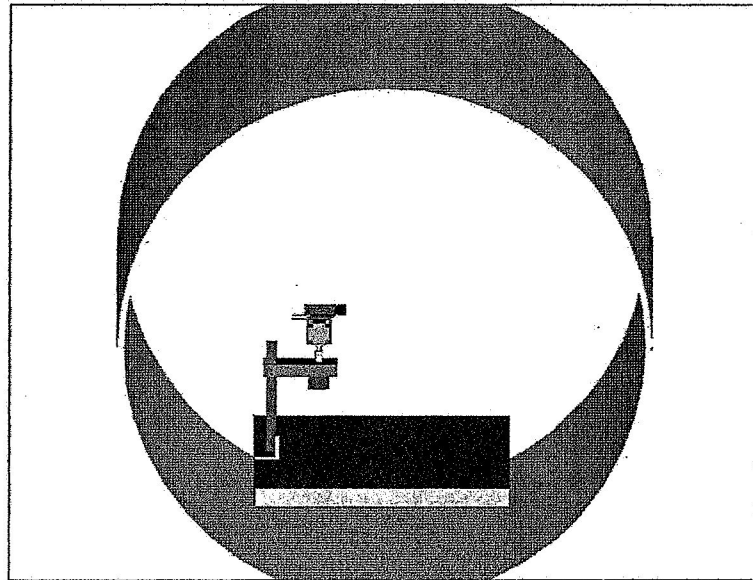
**Figure 6 – Pan Components**



**Figure 7 – Pan and Tilt Platform**



**Figure 8 – Platform with Chamber Interface**



**Figure 9 – Platform inside TV Chamber**

## **COST ANALYSIS**

The cost of the materials for the Platform is \$7500, with the stepper motors and the joystick controller system accounting for over 90% of the cost. Labor cost, including fabrication, assembly, integration, and testing, is estimated at \$13500. The total cost of the Pan and Tilt Platform is \$21000. See Appendix D for an itemized list of the costs.

As a cost savings measure during the I&T phase, the Pan and Tilt Platform will be tested inside a TV chamber during the standard post-test certification after a test. This method saves approximately \$7000 that a chamber would have cost if it was used only to test the Platform.

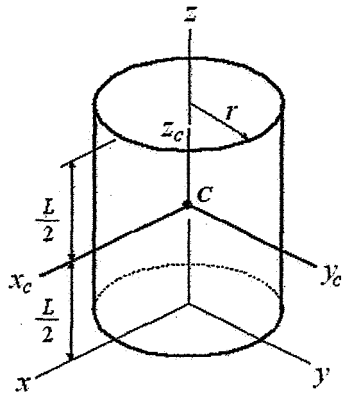
## **SUMMARY**

The Pan and Tilt Platform will augment the capability of the Space Simulation Test Engineering Section's in-house thermal vacuum video camera. The Platform will survive and function in a TV chamber at pressures below  $1 \times 10^{-5}$  torr and at temperatures between -180°C and +100°C. Using a joystick system to control two stepper motors, the Platform will rotate the video camera's field-of-view up to  $\pm 60^\circ$  from its initial centered position along two axes, at a maximum angular velocity of 60° per second. The Platform will integrate thermal control systems, actively with a cold plate and Kapton heaters and passively with MLI blankets, to maintain the camera's temperature limits. For the stepper motors, Kapton heaters will add heat when the chamber temperature falls below -40°C; high emissivity coating on the stepper motors will efficiently radiate heat from the motors when the chamber tops out at +100°C.

The Pan and Tilt Platform will increase the use of the camera during TV tests, especially ones that involves mechanical functional testing. With a greater FOV, test personnel will be able to observe a larger area of the payload in the TV chamber. This ability could be invaluable to monitor mechanisms, e.g. to verify the clearance of a door in motion, that the previously static camera could not see. With real-time visual data available for multiple sections of a large payload, it may not be necessary to open the chamber in the middle of a test for inspection if anomalies occur, saving time and money to complete the test. The Pan and Tilt Platform, used with the TV video camera, will add value to TV testing services provided by the SSTE Group.

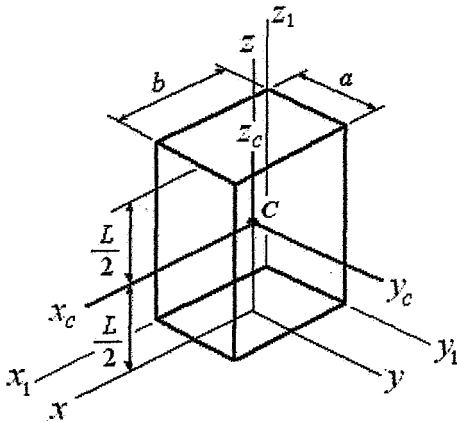
## APPENDIX A –MOMENT OF INERTIA EQUATIONS

### Cylinder



| Moment of Inertia                        | Axis of Rotation |
|------------------------------------------|------------------|
| $I = (1/4) * M * r^2 + (1/3) * M * L^2$  | x axis           |
|                                          | y axis           |
| $I = (1/4) * M * r^2 + (1/12) * M * L^2$ | $x_c$ axis       |
|                                          | $y_c$ axis       |
| $I = (1/2) * M * r^2$                    | z axis           |
|                                          | $z_c$ axis       |

### Rectangular Block



| Moment of Inertia                        | Axis of Rotation |
|------------------------------------------|------------------|
| $I = (1/12) * M * a^2 + (1/3) * M * L^2$ | x axis           |
| $I = (1/12) * M * b^2 + (1/3) * M * L^2$ | y axis           |
| $I = (1/12) * M * (a^2 + L^2)$           | $x_c$ axis       |
| $I = (1/12) * M * (b^2 + L^2)$           | $y_c$ axis       |
| $I = (1/12) * M * (a^2 + b^2)$           | z axis           |
|                                          | $z_c$ axis       |

### Parallel Axis Theorem

$$I_{\text{Parallel Axis}} = I_{\text{Centroidal Axis}} + (M * d^2)$$

- M = mass of body
- d = perpendicular distance from the centroidal axis to the parallel axis
- Parallel axis = actual axis of rotation

## APPENDIX B – LOADS AND TORQUES

**Table B1 – Inertial Loads of Tilt Components**

| Item                | Dimensions<br>cm<br>(inches)                    | Weight<br>N<br>(lb)     | Mass<br>kg<br>(slug)     | Inertial Load<br>$10^{-3}$ kg * m<br>( $10^{-3}$ slug * ft) |
|---------------------|-------------------------------------------------|-------------------------|--------------------------|-------------------------------------------------------------|
| Camera              | 12.7 x 4.19 x 3.18<br>(5 x 1.65 x 1.25)         | 2.22<br>(0.50)          | 0.234<br>(0.016)         | 4.622<br>(1.039)                                            |
| Cold Plate          | 10.16 x 10.16 x 0.51<br>(4 x 4 x 0.2)           | 2.00<br>(0.45)          | 0.204<br>(0.014)         | 53.450<br>(12.016)                                          |
| Camera Shaft        | 9.53 L x 0.64 $\phi$<br>(3.75 L x 0.25 $\phi$ ) | 0.80<br>(0.18)          | 0.009<br>(0.0006)        | 0.050<br>(0.011)                                            |
| Tilt Platform       | 7.62 x 1.91 x 5.08<br>(3 x 0.75 x 2)            | 2.58<br>(0.58)          | 0.263<br>(0.018)         | 0.565<br>(0.127)                                            |
| Tilt Shaft          | 10.16 L x 1.27 $\phi$<br>(4 L x 0.5 $\phi$ )    | 0.98<br>(0.22)          | 0.102<br>(0.007)         | 0.0009<br>(0.0002)                                          |
| Tilt Shaft Support  | 4.19 x 4.19 x 1.27<br>(1.65 x 1.65 x 0.5)       | 0.53<br>(0.12)          | 0.058<br>(0.004)         | 0.058<br>(0.013)                                            |
| Tilt Shaft Coupling | 4.45 L x 3.18 $\phi$<br>(1.75 L x 1.25 $\phi$ ) | 1.78<br>(0.40)          | 0.175<br>(0.012)         | 0.071<br>(0.016)                                            |
| <b>TOTAL</b>        |                                                 | <b>10.89<br/>(2.45)</b> | <b>1.051<br/>(0.072)</b> | <b>58.817<br/>(13.222)</b>                                  |

**Table B2 – Inertial Loads of Pan Components**

| Item               | Dimensions<br>cm<br>(inches)                    | Weight<br>N<br>(lb)     | Mass<br>kg<br>(slug)     | Inertial Load<br>$10^{-3}$ kg * m<br>( $10^{-3}$ slug * ft) |
|--------------------|-------------------------------------------------|-------------------------|--------------------------|-------------------------------------------------------------|
| Tilt Components    |                                                 | 10.89<br>(2.45)         | 1.051<br>(0.072)         | 64.317<br>(14.459)                                          |
| Tilt Motor         | 5.66 x 5.66 x 5.59<br>(2.23 x 2.23 x 2.2)       | 6.67<br>(1.50)          | 0.686<br>(0.047)         | 19.425<br>(4.367)                                           |
| Tilt Shaft Bearing | 0.79 L x 3.18 $\phi$<br>(0.31 L x 1.25 $\phi$ ) | 0.31<br>(0.07)          | 0.029<br>(0.002)         | 0.320<br>(0.072)                                            |
| Pan Platform       | 13.97 x 11.43 x 11.43<br>(5.5 x 4.5 x 4.5)      | 11.03<br>(2.48)         | 1.124<br>(0.077)         | 44.540<br>(10.013)                                          |
| Pan Shaft          | 7.62 L x 1.27 $\phi$<br>(3 L x 0.5 $\phi$ )     | 0.76<br>(0.17)          | 0.073<br>(0.005)         | 0.004<br>(0.001)                                            |
| Pan Shaft Support  | 4.19 x 4.19 x 1.27<br>(1.65 x 1.65 x 0.5)       | 0.53<br>(0.12)          | 0.058<br>(0.004)         | 0.058<br>(0.013)                                            |
| Pan Shaft Coupling | 4.45 L x 3.18 $\phi$<br>(1.75 L x 1.25 $\phi$ ) | 1.78<br>(0.40)          | 0.175<br>(0.012)         | 0.071<br>(0.016)                                            |
| <b>TOTAL</b>       |                                                 | <b>31.98<br/>(7.19)</b> | <b>3.196<br/>(0.219)</b> | <b>128.736<br/>(28.941)</b>                                 |

**Table B3 – Torques Required For Specified Angular Acceleration**

| Item       | Inertial Load<br>$10^{-3}$ kg * m<br>( $10^{-3}$ slug * ft) | Time<br>sec | Acceleration<br>rad/s <sup>2</sup> | Torque<br>$10^{-3}$ N-m<br>( $10^{-3}$ lb * ft) | Torque<br>(oz * in) |
|------------|-------------------------------------------------------------|-------------|------------------------------------|-------------------------------------------------|---------------------|
| Tilt Motor | 58.817<br>(13.222)                                          | 10          | 0.10                               | 1.88<br>(1.39)                                  | (0.27)              |
|            |                                                             | 5           | 0.21                               | 3.76<br>(2.77)                                  | (0.53)              |
|            |                                                             | 1           | 1.05                               | 18.78<br>(13.85)                                | (2.66)              |
| Pan Motor  | 128.736<br>(28.941)                                         | 10          | 0.10                               | 3.08<br>(2.27)                                  | (0.44)              |
|            |                                                             | 5           | 0.21                               | 6.16<br>(4.54)                                  | (0.87)              |
|            |                                                             | 1           | 1.05                               | 30.79<br>(22.71)                                | (4.36)              |

## APPENDIX C – HEAT TRANSFER CALCULATIONS

Conduction:  $q = \kappa * A * \Delta T / d$

Radiation:  $q = A * \epsilon * \sigma * (T_{\text{camera}}^4 - T_{\text{environment}}^4)$

- $q$  = heat transfer (W)
- $A$  = surface area ( $\text{m}^2$ )
- $\kappa$  = thermal conductivity (W / m / K)
- $\Delta T$  = temperature difference (K)
- $d$  = thickness of material across  $\Delta T$  (m)
- $\epsilon$  = emissivity
  - > 0.1 with MLI
  - > 0.9 without MLI
- $\sigma = 5.67 \times 10^{-8} \text{ W / (m}^2 * \text{K}^4)$  Stefan-Boltzmann constant

Conditions:

- Camera = +40°C
- $\epsilon = 0.1$  w/MLI
- $\epsilon = 0.9$  w/o MLI

Table C1 – Effect of Multi-Layer Insulation

| Chamber | Heat Transfer (W) |         |
|---------|-------------------|---------|
|         | w/MLI             | w/o MLI |
| +100°C  | 1.2               | 10.5    |
| -180°C  | -1.1              | -10.2   |

Conditions:

- Camera = +40°C
- Thermal Controller = +22°C
- Camera and Thermal Controller covered with MLI

Table C2 – Conduction versus Radiation

| Chamber | Conduction        | Heat Transfer (W) | Radiation            | Heat Transfer (W) |
|---------|-------------------|-------------------|----------------------|-------------------|
| +100°C  | Chamber to C/P    | 0.9               | Chamber to Cryoshell | 1.1               |
|         | Camera to C/P     | 113.5             | Camera to Cryoshell  | 2.5               |
|         | Chamber to Camera | 1.2               |                      |                   |
|         | <b>TOTAL</b>      | <b>115.6</b>      | <b>TOTAL</b>         | <b>3.7</b>        |
| -180°C  | Chamber to C/P    | -0.5              | Chamber to Cryoshell | -0.7              |
|         | Camera to C/P     | 113.5             | Camera to Cryoshell  | 2.5               |
|         | Chamber to Camera | -1.1              |                      |                   |
|         | <b>TOTAL</b>      | <b>111.9</b>      | <b>TOTAL</b>         | <b>1.8</b>        |

Conditions:

- Motor hot limit = +250°C
- Motor cold limit = -40°C
- $\epsilon = 0.9$  w/o MLI

Table C3 – Radiation from Motor to Chamber

| Motor  | Chamber | Heat Transfer (W) |
|--------|---------|-------------------|
| +250°C | +100°C  | 39.9              |
|        | -180°C  | 53.8              |
| -40°C  | +100°C  | N/A               |
|        | -180°C  | 2.1               |

## APPENDIX D – COST ANALYSIS DATA

Table D1 – Cost Breakdown

| Item                      | Cost           | Notes                                                 |
|---------------------------|----------------|-------------------------------------------------------|
| <b>Materials Costs</b>    |                |                                                       |
| Stepper Motors            | 5900           | 2 units                                               |
| Joystick System           | 995            | 1 unit controls both motors                           |
| Pan and Tilt Shafts       | 18             | Both items cut from same shaft                        |
| Shaft Couplings           | 63             | 2 units                                               |
| Shaft Supports            | 44             | 2 units                                               |
| Radial Bearings           | 12             | 2 units                                               |
| Aluminum Channel          | 74             | Pan Platform, System Base Fixture                     |
| Aluminum Bar              | 98             | Tilt Platform                                         |
| Fasteners                 | 36             |                                                       |
| MLI Material              | 260            |                                                       |
| <b>Materials Subtotal</b> | <b>\$7500</b>  |                                                       |
|                           |                |                                                       |
| <b>Labor Costs</b>        |                |                                                       |
| Fabrication               | 4500           | Includes machining components and building harnesses  |
| Integration               | 9000           | Includes assembly and T/C, heater, & C/P installation |
| Testing                   | 0              | To be tested during post-test chamber certification   |
| <b>Labor Subtotal</b>     | <b>\$13500</b> |                                                       |
|                           |                |                                                       |
| <b>Cost Summary</b>       |                |                                                       |
| <b>Materials Subtotal</b> | <b>7500</b>    |                                                       |
| <b>Labor Subtotal</b>     | <b>13500</b>   |                                                       |
| <b>TOTAL COST</b>         | <b>\$21000</b> |                                                       |

## APPENDIX E – ABBREVIATIONS, ACRONYMS, AND SYMBOLS

|                 |                                                               |
|-----------------|---------------------------------------------------------------|
| $\alpha$        | Angular acceleration                                          |
| A               | Area                                                          |
| °C              | Celsius                                                       |
| cm              | centimeter                                                    |
| C/P             | Cold Plate                                                    |
| $\phi$          | Diameter                                                      |
| $\varepsilon$   | Emissivity                                                    |
| ft              | Foot                                                          |
| FOV             | Field-of-View                                                 |
| GN <sub>2</sub> | Gaseous Nitrogen                                              |
| GSE             | Ground Support Equipment                                      |
| GSFC            | Goddard Space Flight Center                                   |
| hr              | Hour                                                          |
| Hz              | Hertz                                                         |
| in              | Inch                                                          |
| I               | Moment of Inertia                                             |
| I&T             | Integration & Testing                                         |
| I/F             | Interface                                                     |
| K               | Kelvin                                                        |
| kg              | Kilogram                                                      |
| L               | Length                                                        |
| lb              | Pound                                                         |
| LN <sub>2</sub> | Liquid Nitrogen                                               |
| M               | Mass                                                          |
| m               | Meter                                                         |
| MAP             | Microwave Anisotropy Probe                                    |
| MESSENGER       | MErcury Surface, Space ENvironment, GEochemistry, and Ranging |
| MLI             | Multi-Layer Insulation                                        |
| N               | Newton                                                        |
| NASA            | National Aeronautics and Space Administration                 |
| P/L             | Payload                                                       |
| rad             | Radian                                                        |
| $\sigma$        | Stefan-Boltzmann constant                                     |
| s or sec.       | Second                                                        |
| SSTE            | Space Simulation Test Engineering                             |
| ST-5            | Space Technology 5                                            |
| T               | Temperature                                                   |
| T/C             | Thermocouple                                                  |
| TCU             | Thermal Conditioning Unit                                     |
| TEC             | Thermoelectric Cooler                                         |
| $\kappa$        | Thermal Conductivity                                          |
| TQCM            | Thermoelectric Quartz Crystal Microbalance                    |
| TV or T/V       | Thermal Vacuum                                                |
| TVDS            | Thermal Vacuum Data System                                    |
| UPS             | Uninterrupted Power Supply                                    |
| W               | Watt                                                          |

## APPENDIX F – REFERENCES

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