Fermi National Accelerator Laboratory
Particle Physics Division

Mechanical Department Engineering Note

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Project: *DES*

Project Internal Reference: *DES DocDB 2630*

Title: ***DES Imager Vessel Design***

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Reviewer(s):

Key Words: *DES*

Abstract/Summary:

The DES imager is a vacuum vessel with an optical window in one end for the camera optics. Elements of the imager vessel design are discussed, including a comparison to alignment requirements, an estimation of the total weight, and verification of cover bolt size. The Engineering Note addressing vacuum safety is documented separately in MD-ENG-179.

Applicable Codes: *N/A*

1.0 INTRODUCTION

WBS 1.5.2.2.1.1 covers the imager vessel design, meaning the vacuum vessel minus the flange into which the optical window is mounted. Additional hardware, such as the mounts used to support the electronics crates, has also been included in this task. The relevant assembly drawings are listed below:

Top level assembly	438890
Vessel shell machined weldment	436361
Back cover assembly	436802
V2 Focal Plate assembly	436874
VIB assemblies	436865
Monsoon crate mounts	436757 & 436764
Vessel feet	436751, 436752 & 436748
55-pin connector feedthrough	436842
32-pin connector feedthrough	436854

This report will document the following items in support of this effort:

2.0 EVALUATION

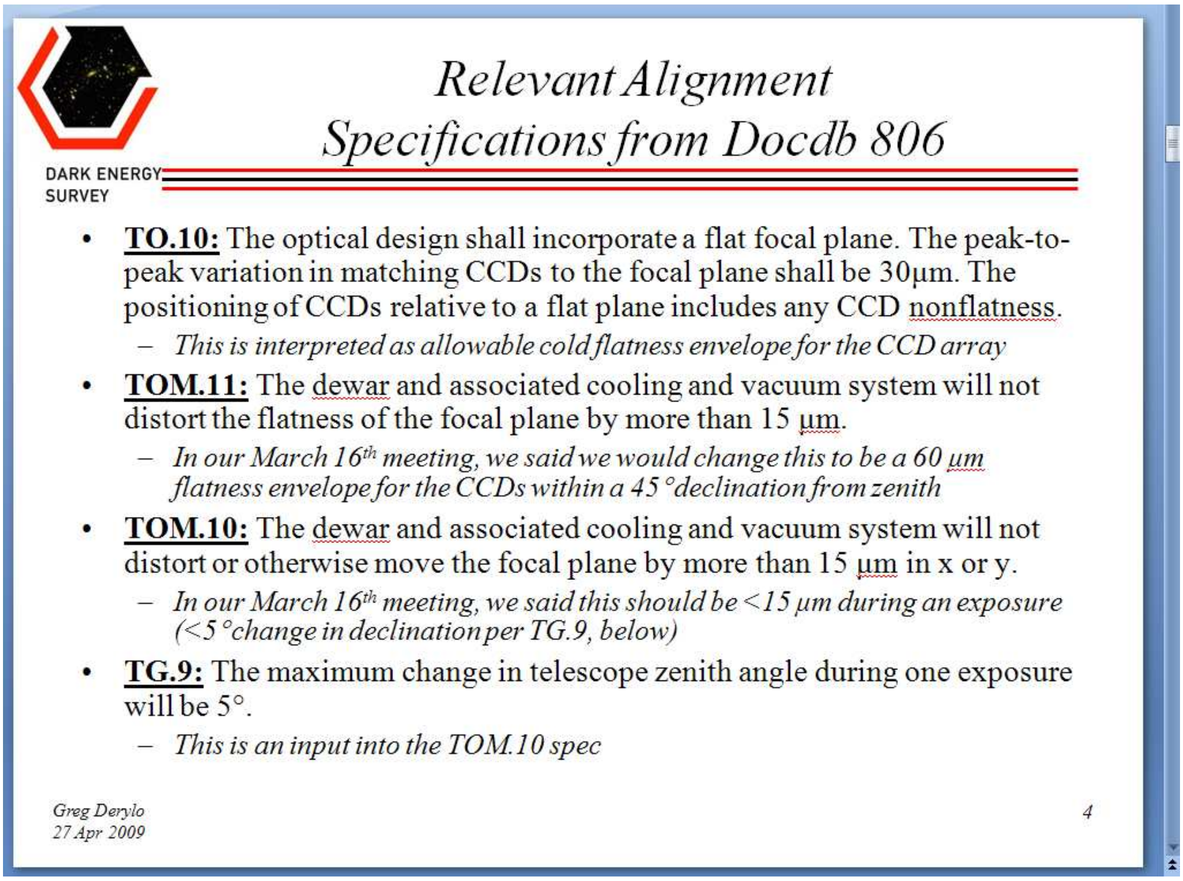
Different aspects of the design are addressed in the sections below.

2.1 VACUUM VESSEL SAFETY

MD-ENG-179 documents the vacuum vessel safety of the imager, including protection from accidental pressurization. As explained there, the imager is technically exempt from the FESHM 5033 requirement due to its small volume, but a note was still written to document the design. A copy of this report is documented in docdb 2841.

2.2 ALIGNMENT REQUIREMENTS

The alignment requirements are listed below (slide taken from docdb 2821).

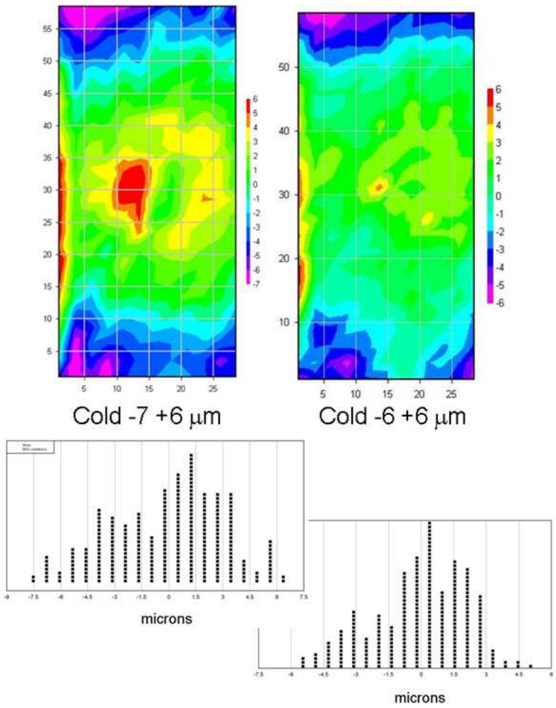


Each of these requirements will be addressed separately below.

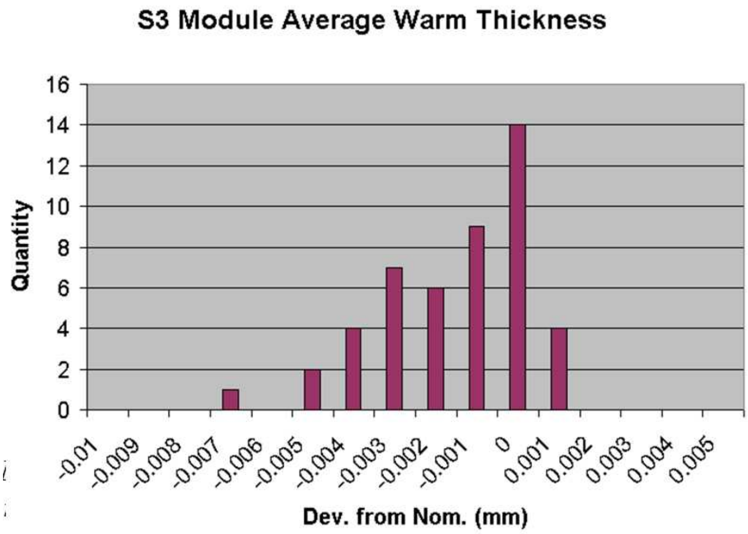
SPECIFICATION TO.10: Cold Focal Plane Flatness

There are several factors that contribute to the overall unflatness of the focal plane (light-collecting surface of the CCDs). These are addressed individually below:

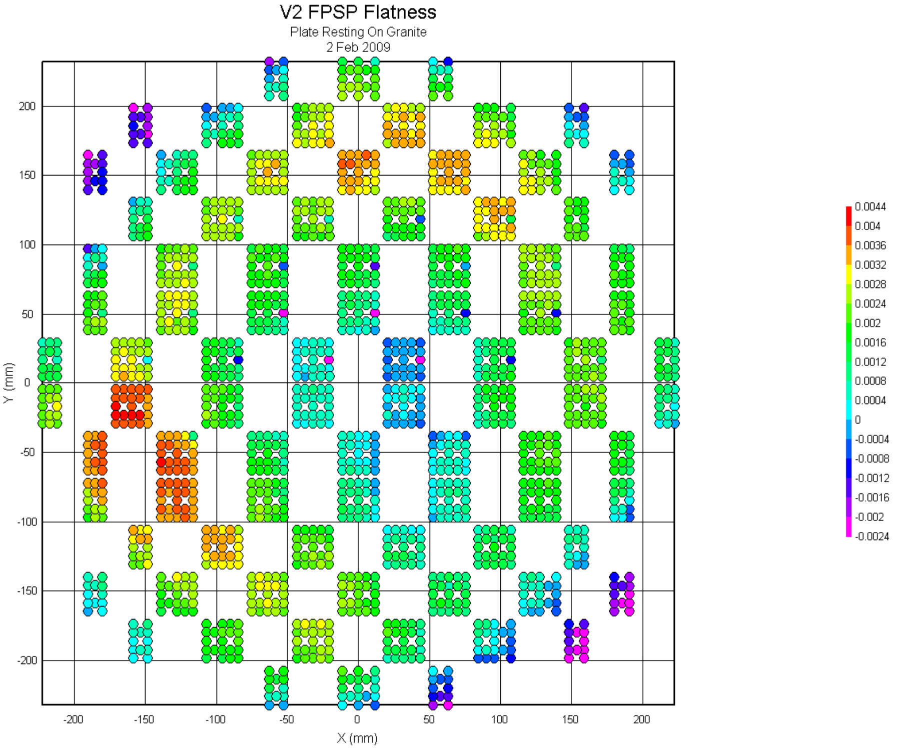
CCD Cold Flatness – The CCDs modules experience some thermal warpage as they are cooled. This behavior has been measured by Tom Diehl, as documented in docdb 3008. He found a surface flatness variation of 13 microns with a standard deviation of about 3 microns.



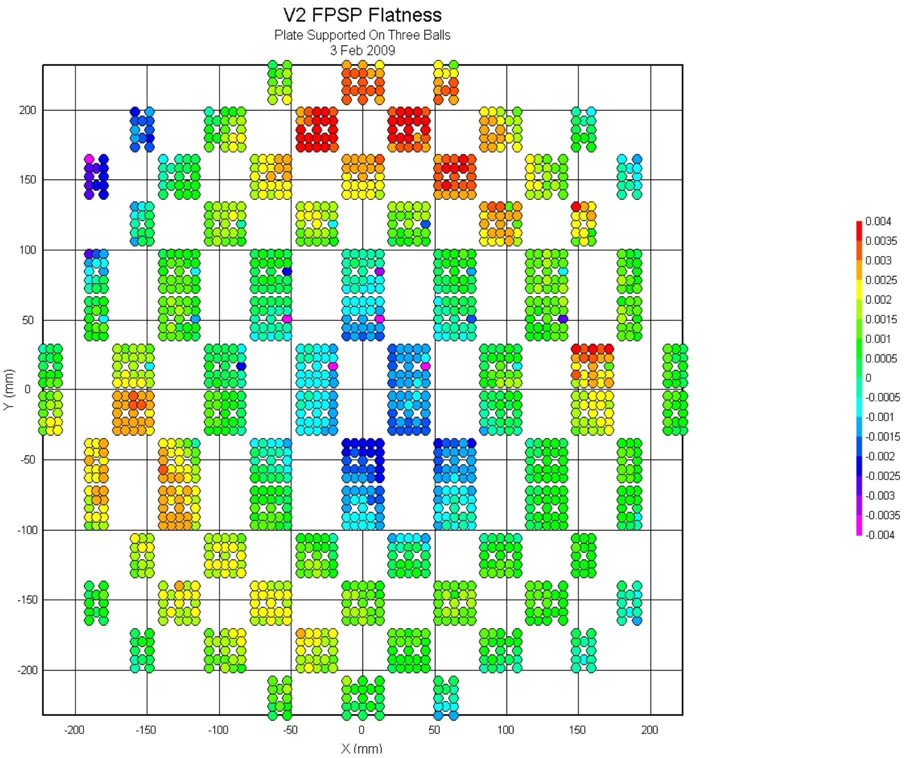
<u>CCD Module Thickness</u> – Each module is expected to have a slightly different thickness, which adds to the total unflatness of the focal plane. The warm flatness of the V3 production CCD modules has been inspected by John Krider, whose data indicates a 6 micron variation with a standard deviation of 1.8 microns.



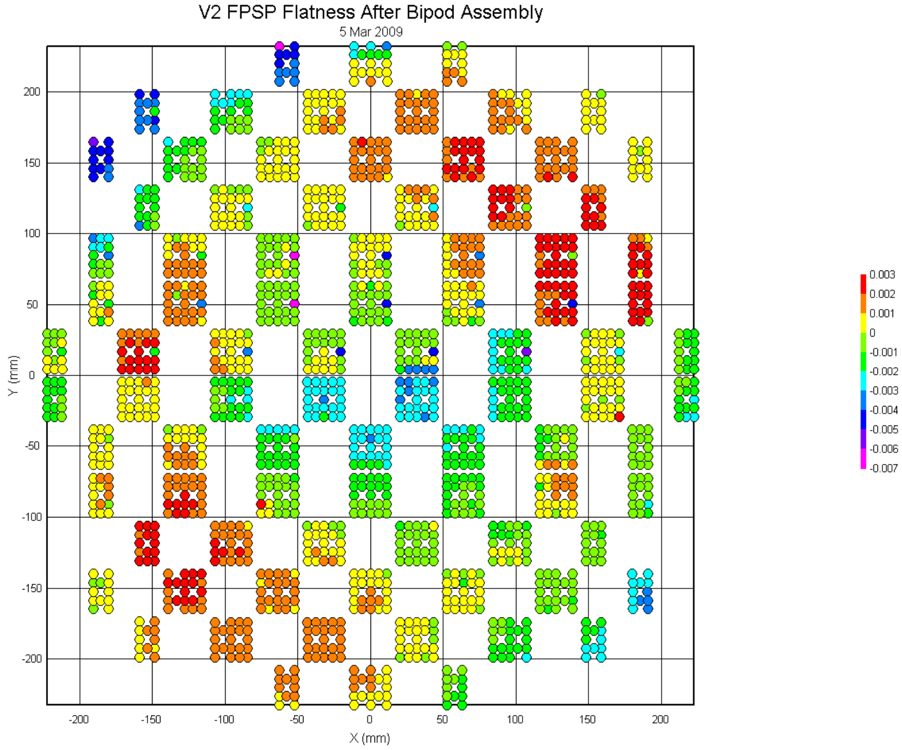
<u>FPSP Warm Flatness</u> – The V2support plate flatness was inspected using a grid of approximately 1800 points on the elevated module mounting areas using the touch probe CMMs in Lab C. The plots below show the results for three different mounting scenarios:



6.8 micron flatness with the FPSP resting on the granite table



8.0 micron flatness with the FPSP resting on 3 balls 120deg apart



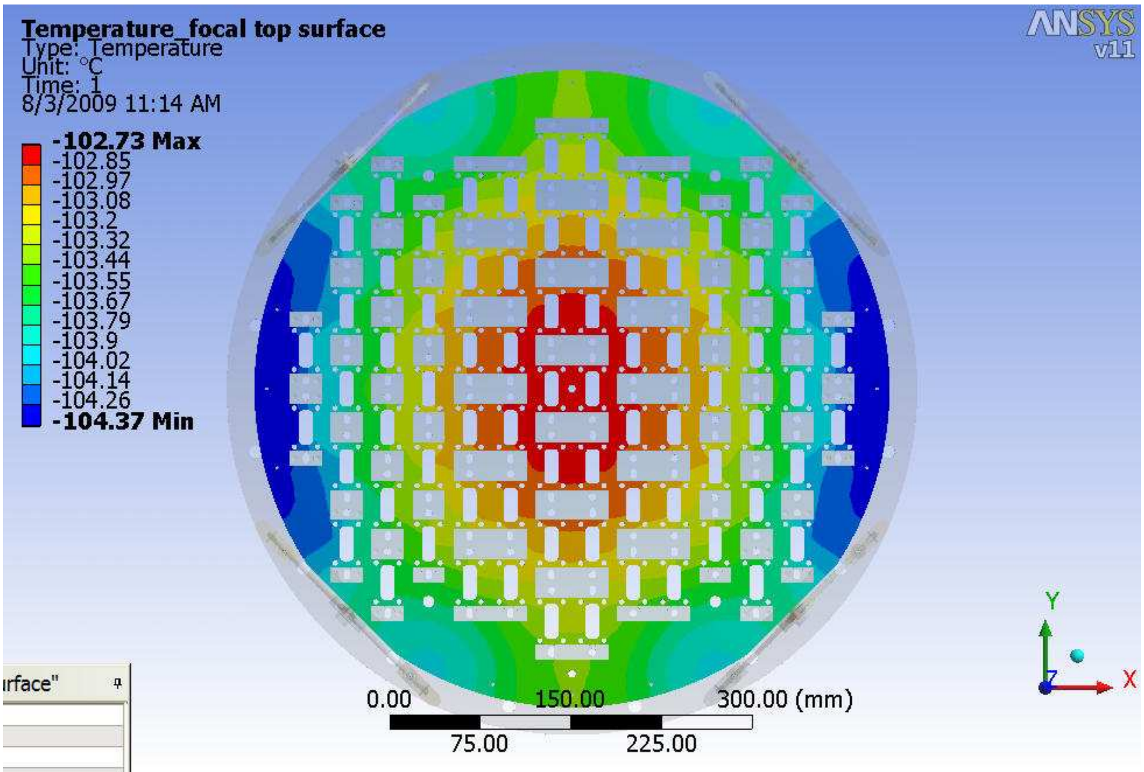
10.0 micron flatness after mating to the bipod legs & support ring (horizontal orientation)

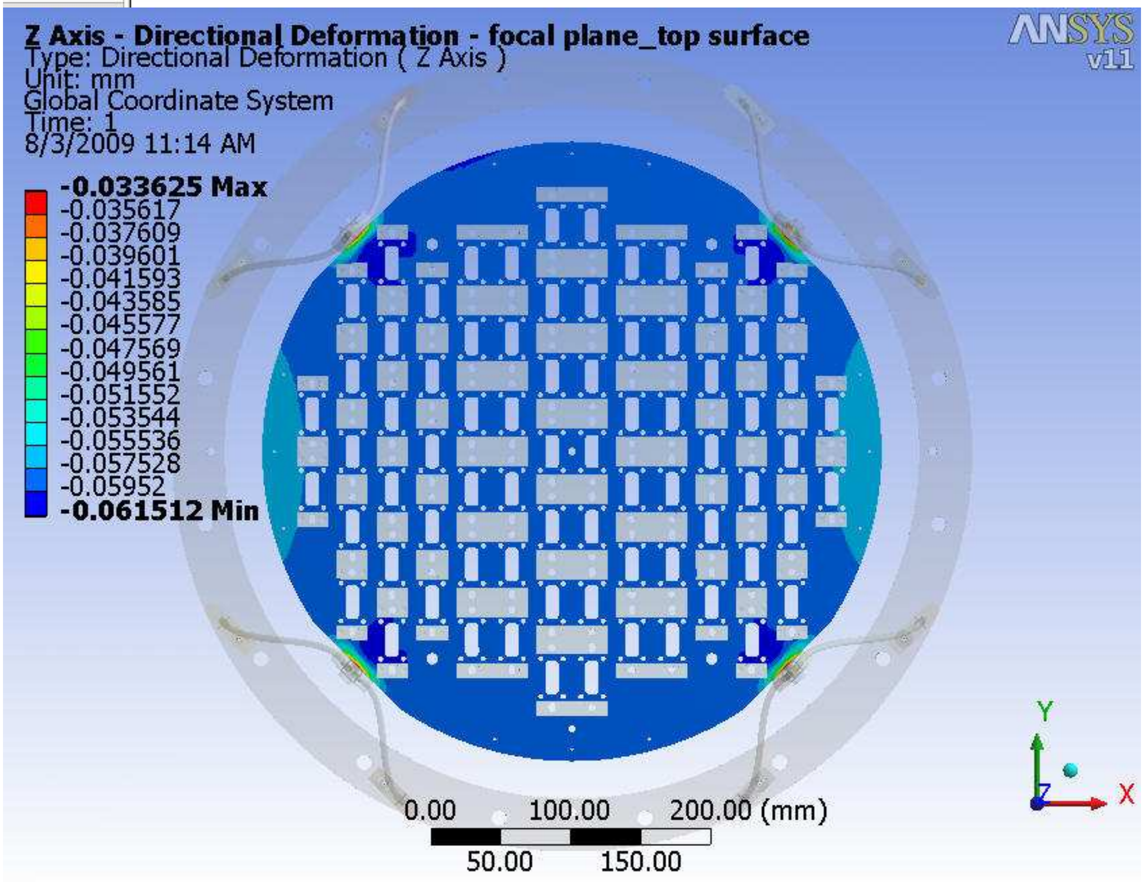
Effect of CCD Module Weight on the FPSP – The total combined weight of the modules, VIBI cards, and cable restraints is about 10 kg. A set of weights was made to mimic this load and the FPSP surface, positioned horizontally, was measured with and without this load. The CMM results are included in docdb 2339 and indicate a 5 micron flatness without weights and 5.8 microns with weights (using a 54-point plane). The effect of the CCD gravity load is therefore about 1 micron.

FPSP Thermal Distortion – There are two different cooldown factors that lead to distortion here. The first is the temperature gradient in the FPSP itself, with the front surface being warmer than the back, which is cooled at 10 locations on the back face near the OD of the plate. This temperature gradient will tend to create a convex shape on the front surface of the plate.

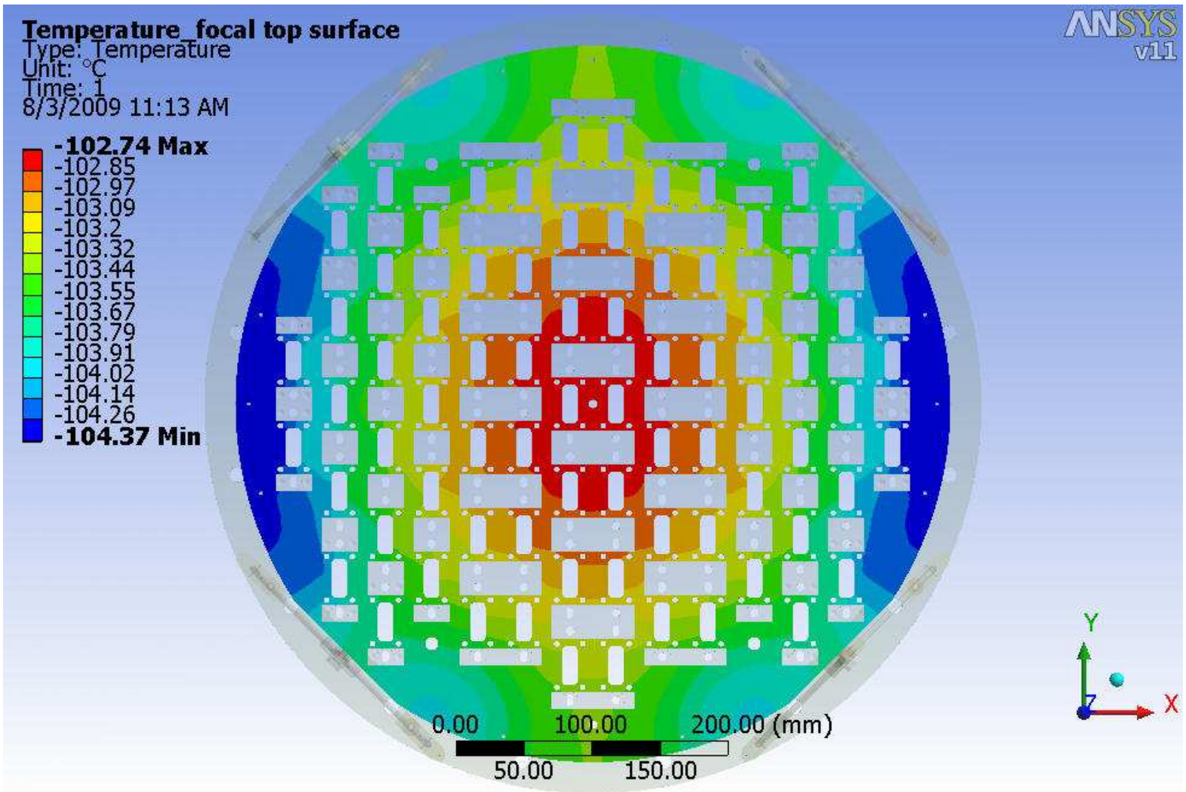
The second factor is due to the radial shrinkage of the FPSP by almost a millimeter. Since the bipod base ring is the same temperature as the vessel shell, the bipod rods must bend into an ‘S’ shape in order to accommodate the plate shrinkage. Bending the rods in this way applies a moment on the edge of the plate, which wants to react by taking a slightly concave shape.

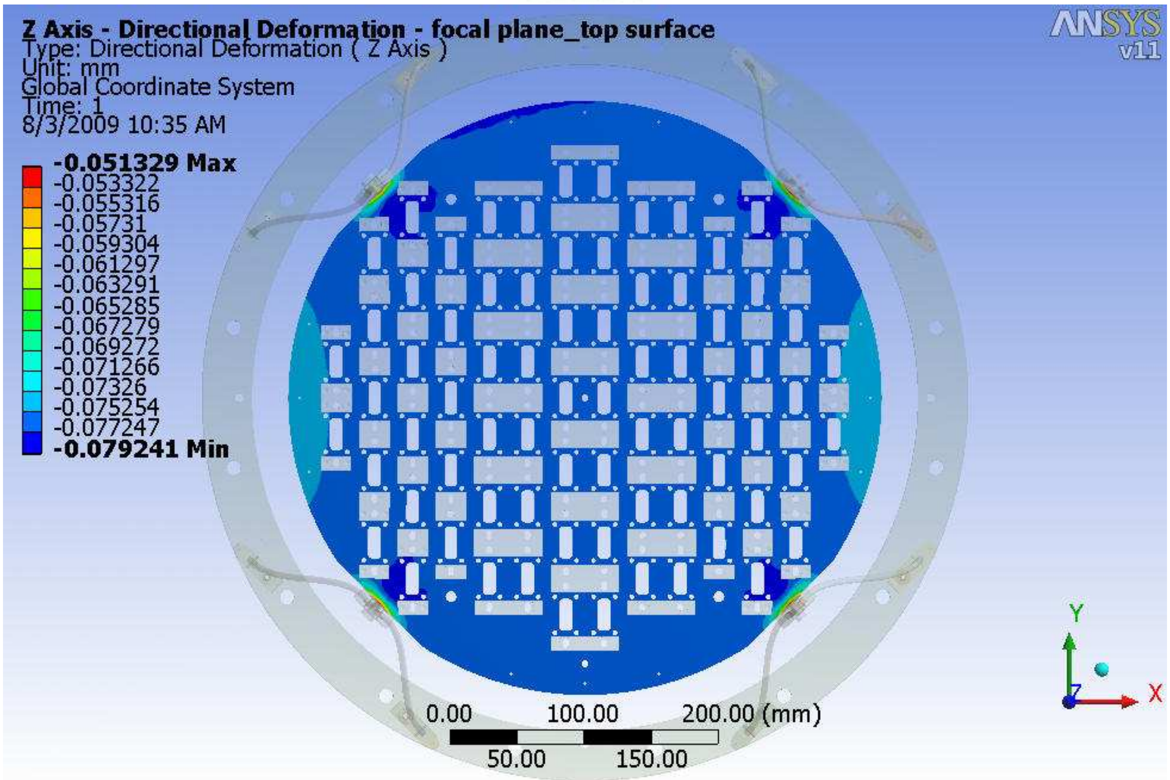
These two effects are therefore at least partially offsetting. An FEA analysis of the combined effect was performed by Ingrid Fang and found the following results:





Effect of FPSP Thermal Gradient and Radial Shrinkage with Bipod Base Ring at +20ºC
Front Surface Temperatures and Z Distortions
Z Variation over Survey Area ~ 2 microns





Effect of FPSP Thermal Gradient and Radial Shrinkage with Bipod Base Ring at -5ºC
Front Surface Temperatures and Z Distortions
Z Variation over Survey Area ~ 2 microns

The separate contributions listed above are summarized below and are added both linearly and in quadrature. Gravity is not included here since its effect on the FPSP shape has been predicted to be small and it is already part of the warm FPSP CMM flatness measurements.

Contributor	Variation	Variation Squared
CCD Flatness	13	169
CCD Module Thickness	6	36
FPSP Warm Flatness	10	100
Effect of CCD Weight on FPSP	1	1
FPSP Thermal Distortion	2	4
Summation:	32	18

These results indicate that when added linearly, the combined effects slightly exceed the 30 micron limit. However, assuming a linear addition is overly conservative. As discussed during the 27 April 2009 review, the CCD flatness & thickness terms could be statistically combined. Linearly adding this combination (14 microns) to the other effects results in a total of 27 microns, which does satisfy the specification.

A small additional improvement could also be potentially gained by matching module thickness to the warm FPSP flatness data.

SPECIFICATION TOM.11: Tilting of the Focal Plane

Many factors go into maintaining the perpendicularity of the focal plane to the optical axis of the camera.

- Focal plane flatness
- Assembly parallelism between the FPSP and the front face of the C5 cell
- Parallelism stiffness of the FPSP bipod supports
- Parallelism stiffness between the bipod mounting points and the C5 cell

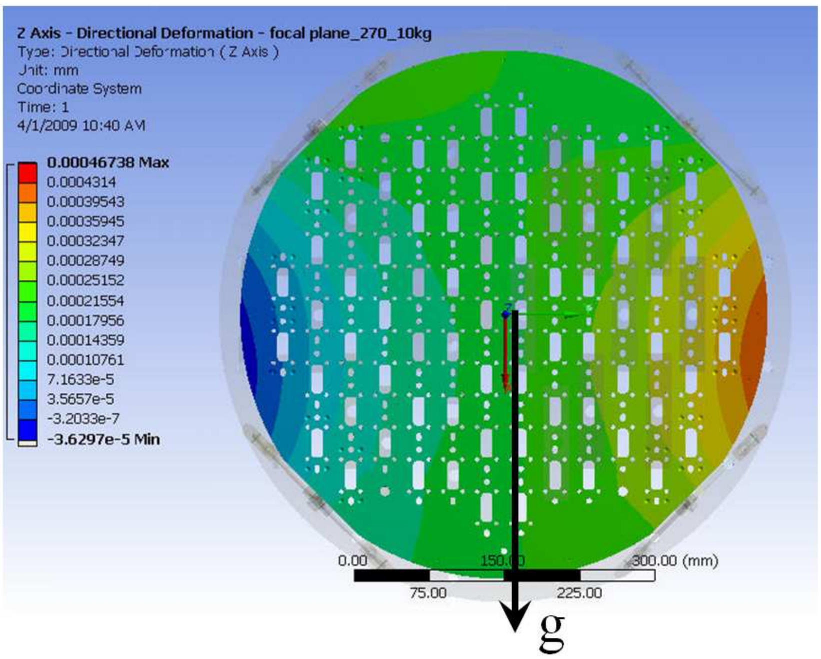
The flatness of the focal plane was discussed above as part f the TO.10 specification. The remainder of the items are covered below and will be compared to an introduced tilt limit of 30 microns.

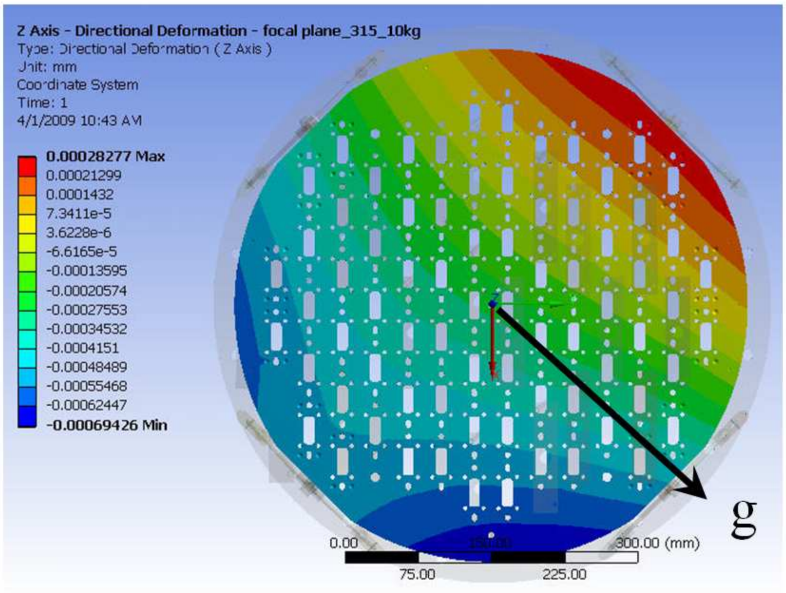
Regarding assembly alignment, the plan is to align the FPSP to be parallel to the front surface of the C5 flange that mounts to the back end of the optics barrel. This is anticipated to proceed as follows:

- Assemble FPSP / bipod assembly
- Install in the imager shell with a set of 16 precision shims between the bipod base ring and the mounting ring that is part of the vessel weldment
- Install the C5 cell (without the lens)
- Survey the relative alignment of the C5 flange and the FPSP and determine the modifications needed for the 16 shims in order to achieve the proper parallelism
- Remove the C5 flange and the FPSP assy from the imager
- Have the individual shims lapped to desired thicknesses
- Reassemble with the shims in the correct locations
- Repeat survey to verify alignment

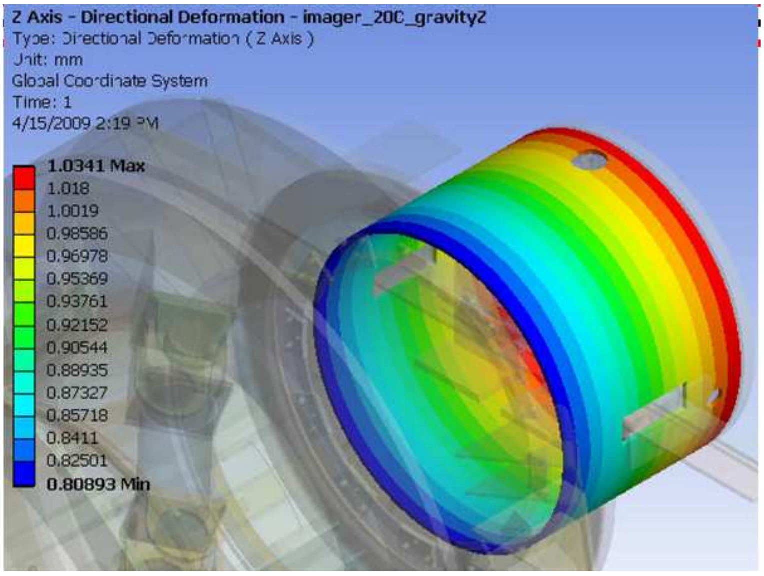
Aligning the parallelism of two surfaces, each with a flatness of about 10 microns, will be difficult to do accurately. A parallelism of 20 microns is assumed here.

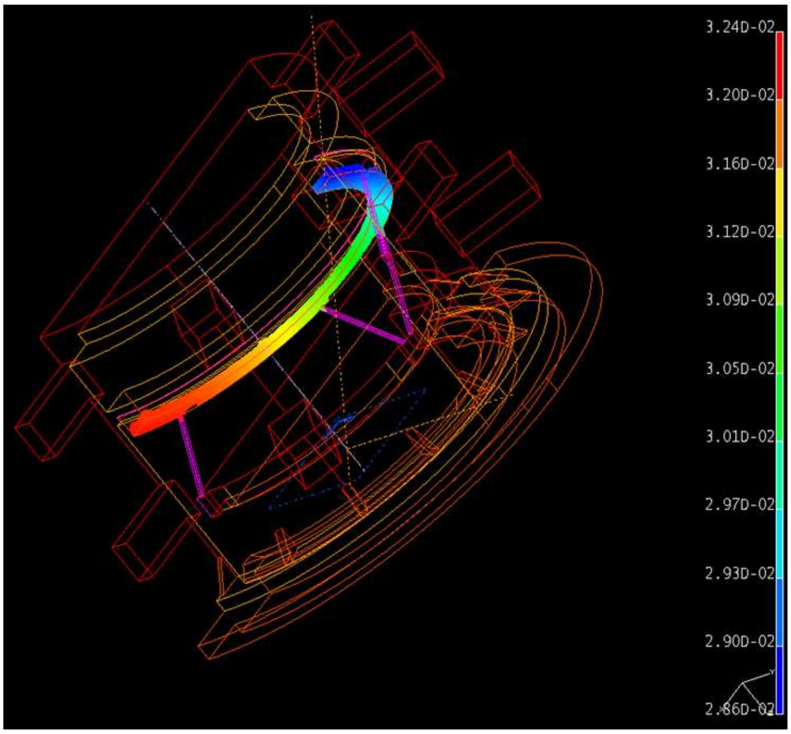
The stiffness of the bipod support system is also to be considered. The tests that were performed with the V2 FPSP are not a good indicator of tilt behavior due to variations in the way the bipod ring was mounted. ANSYS studies were performed on the FSP / bipod system using a detailed model. A 10kg load was added to simulate the weight of the CCDs and a 90° declination (pointing at the horizon) was assumed. The results indicate a tilt on the order of 1 micron, indicating that the bipods do a good job of preserving this orientation.





The <u>stiffness of the imager shell</u> between the bipod mounting ring and the C5 flange was investigated with both ANSYS and IDEAS models. The ANSYS study included the combined barrel / imager assembly and was performed at a 45° declination in two different directions (declination in the XZ and YZ planes). Both cases reported tilts of 2 microns or less. A simple IDEAS model was also constructed and run at one 45° declination position. A 4 micron tilt was predicted. Three microns is assumed below for this contribution.





Adding up the additional contributions (beyond flatness of the focal plane itself):

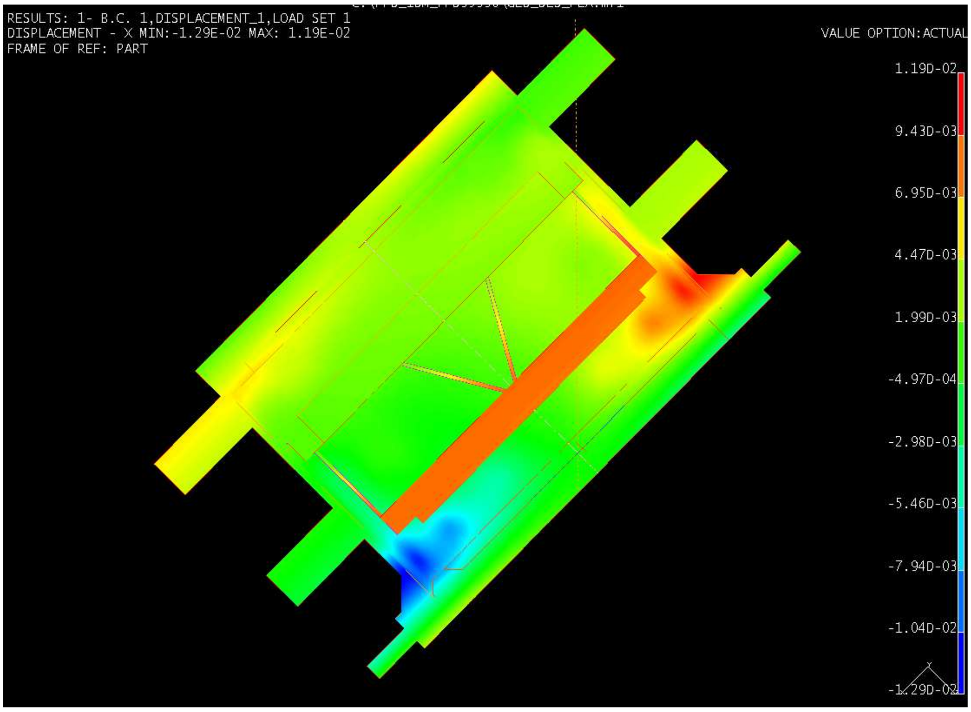
Assembly alignment	20
Bipod stiffness	1
Imager shell stiffness	3

This results in a total additional tilt factor of 24 microns, which is consistent with the additional 30 microns allowed for in the specification. Initial alignment of the assembly is the critical factor – this process must be done accurately in order to achieve the necessary result.

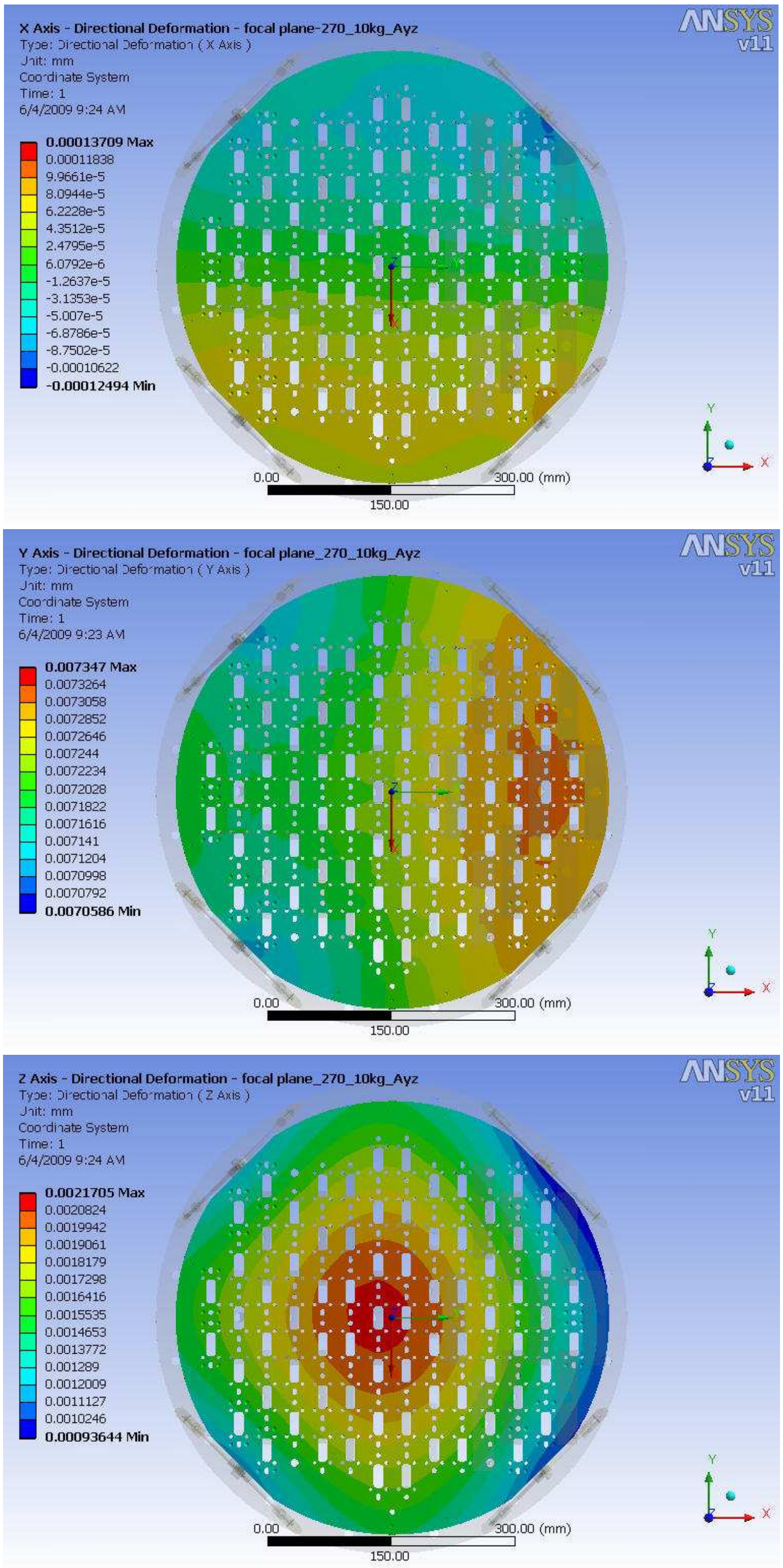
SPECIFICATION TOM.10: Operational Transverse Motion of the Focal Plane

As the telescope is pointed around the sky, some transverse motion of the CCDs is expected relative to the camera axis due to the relatively flexible nature of the bipod supports. This behavior has been investigated with an FEA study and with direct measurement using the V2 FPSP. The specification has been clarified, as described in docdb 2821, to define the transverse motion allowed over a single exposure while within 45° of zenith. TG.9 specifies that the maximum change in zenith angle during an exposure is 5°.

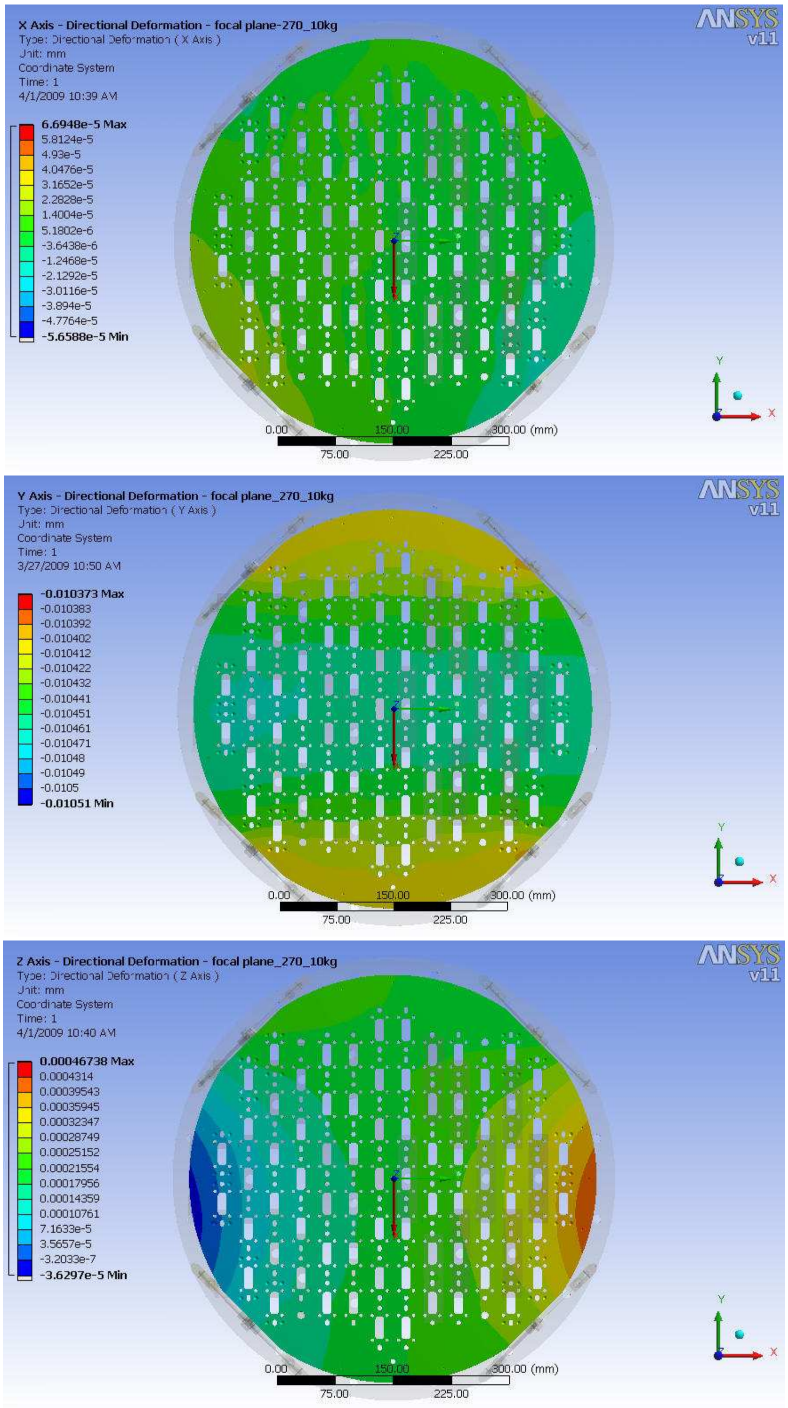
Vessel Study – Investigations of vessel shell stiffness (both with ANSYS and IDEAS) indicate that the mid-ring used to mount the bipod base ring experiences only small motions as a function of pointing angle. Only about 3 microns of transverse motion is predicted at 45° declination.



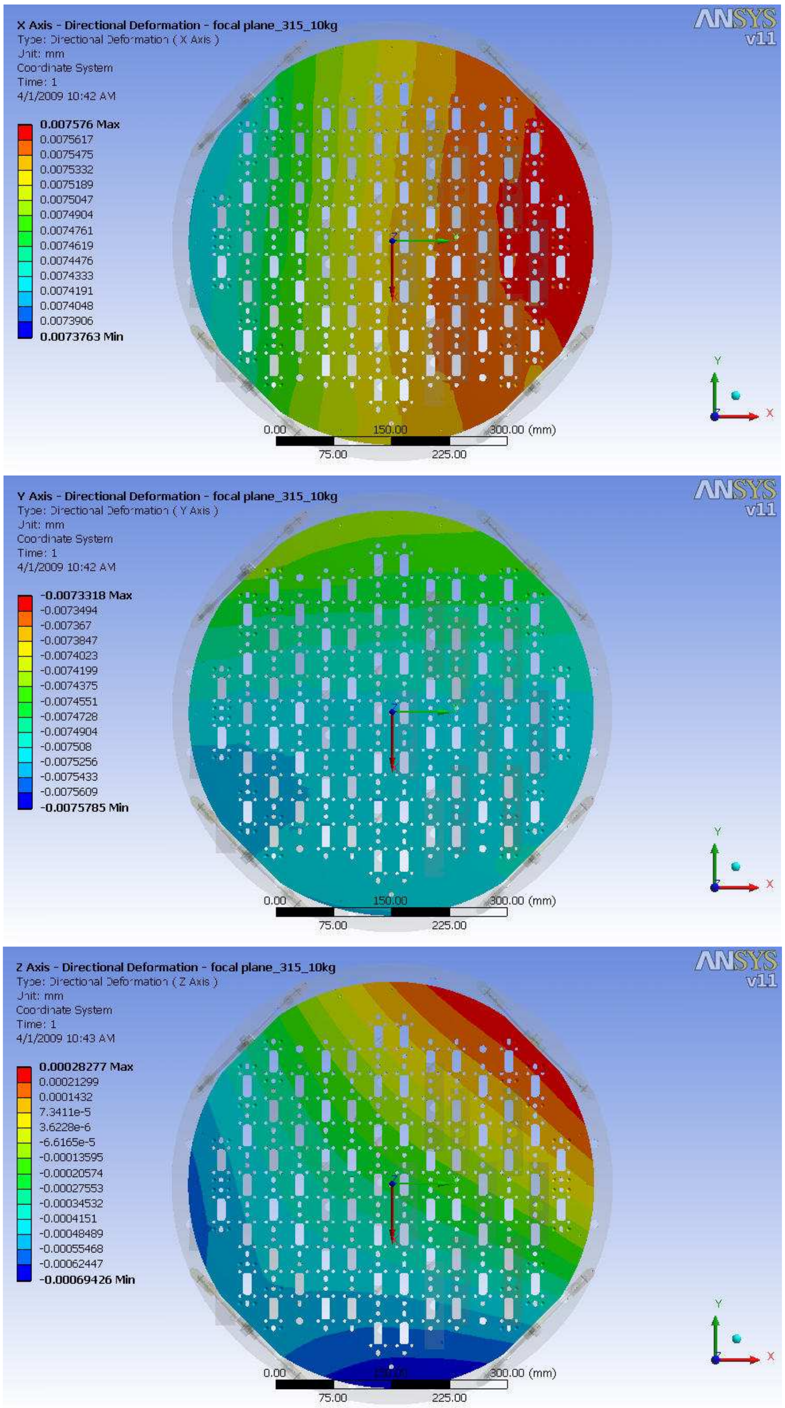
Bipod FEA Study – A very detailed model of the FPSP / bipod arrangement has been developed by Ingrid Fang, and this model was used to investigate transverse motion due to the bipods at two different declination angles. All of these cases use 10kg of dummy weights on the FPSP to mimic the weight of the CCDs.



Bipod transverse motion at 45° declination in the YZ plane
[Transverse motion ~ 7 microns]

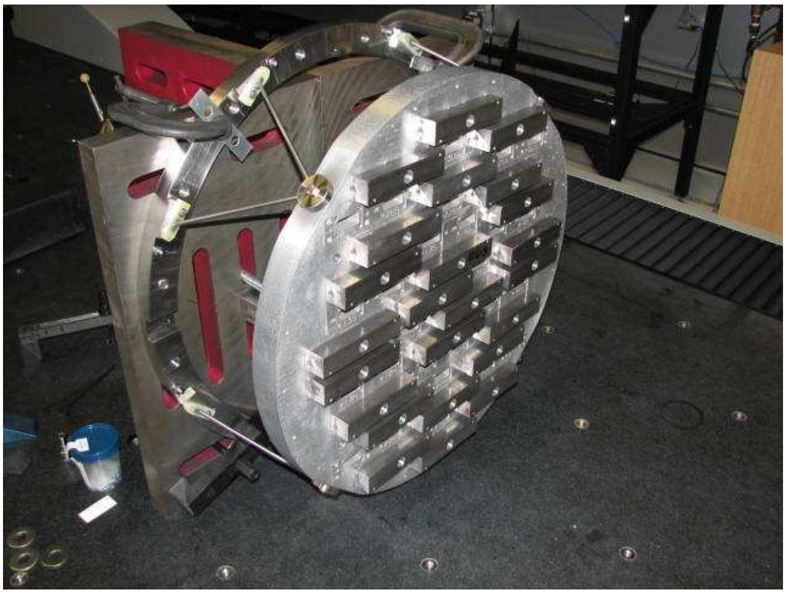


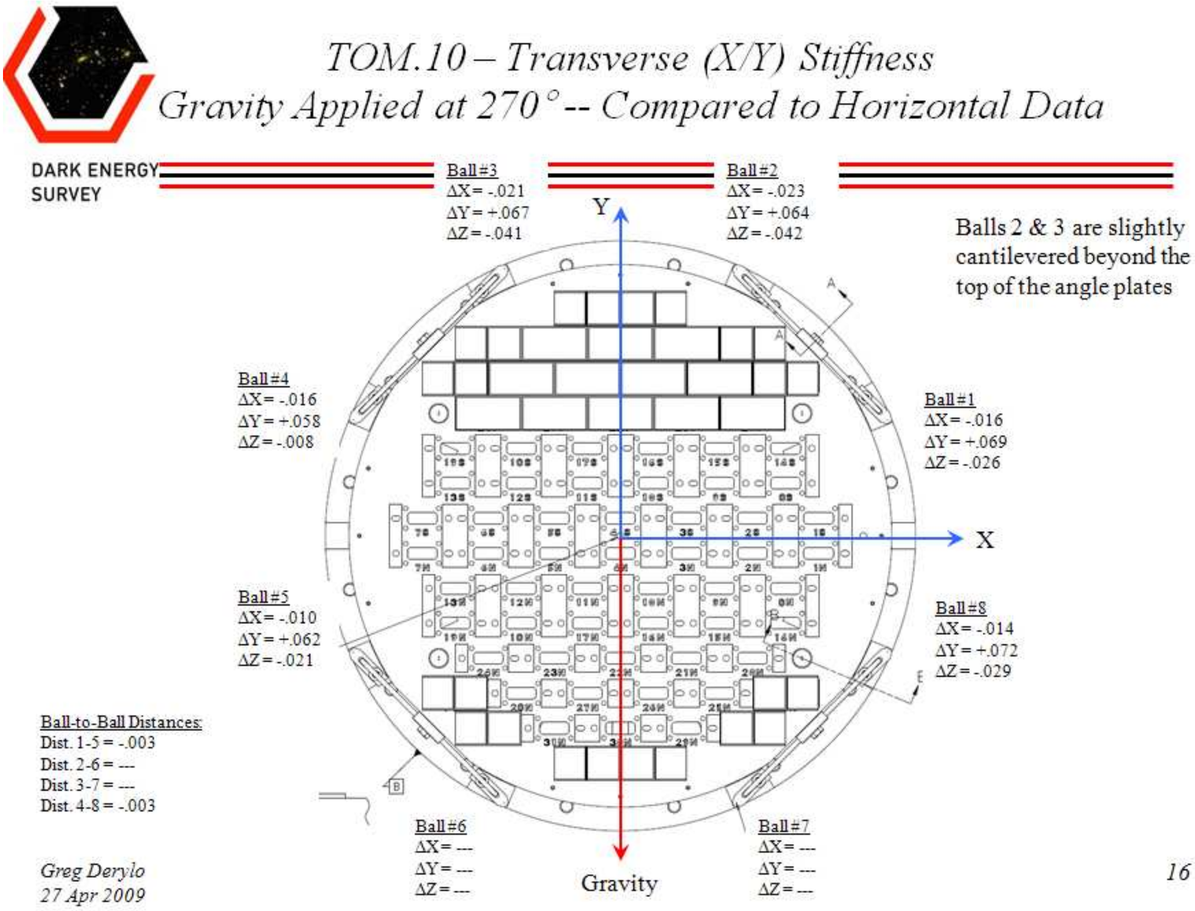
Bipod transverse motion at 90° declination in the YZ plane
[Transverse motion ~10 microns]

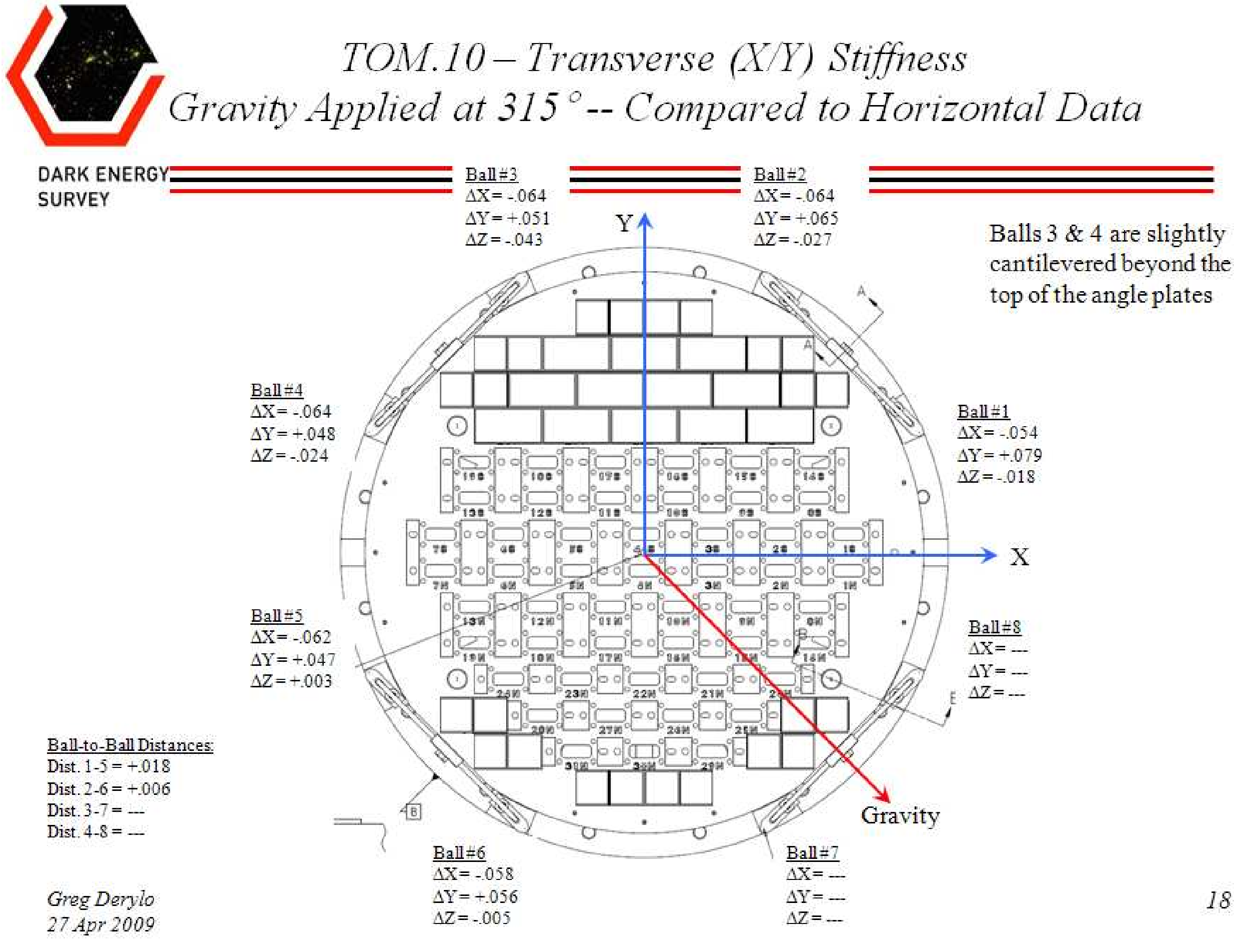


Bipod transverse motion at 90° declination 45° to the YZ plane
[Transverse motion ~ 11 microns]

Bipod CMM Survey – After assembly of the V2 FPSP with its bipod rings, the system was inspected on a CMM to check bipod transverse stiffness. 10kg of dummy weights were used to simulate the CCD weight. The positions of tooling balls mounted to the bipod support ring were measured relative to a coordinate system established on the FPSP. The measurement results indicate larger transverse deflections than predicted by the FEA. Additional detail, including the pinned & glued bipod rod joints, added to the model did not dramatically change the predicted results (shown above).







The imager shell and bipod studies indicate that the transverse motion resulting from a 5° change in declination angle (while remaining above 45°) is smaller than the 15 micron limit. The differences between the ANSYS and V2 FPSP CMM results do not change this conclusion.

2.3 ESTIMATED WEIGHT

The estimated weight of the vessel is documented in docdb 3204 and is about 1,300 pounds. That estimate also shows the center of gravity predictions for the full imager and with various items removed (end covers, Monsoon crates, etc.).

2.4 BOLT CIRCLE ANALYSES

Two different bolts circles are of note here:

Imager Vessel to C5 Flange

During operation on the telescope, the entire imager hangs from the C5 cell. The bolts were considered in an analysis performed by Ingrid Fang. A copy of her summary is provided below under “C5-cell to Imager”:

Barrel Jointed Ball Joints at Both Ends Model Connection Design by Ingrid Fang on 6/10/09

Cone to Body Bolted Connection

The maximum load combination under case1, case2, case4, case5 and casel in the Barrel Jointed Ball Jointed FEA are listed below

Fx=1505 Lbs(shear)
Fy=1259 Lbs (shear)
Fz=1064Lbs (tension)
Mx=34827 Lbs-in (tension or compression)----> 34827/32.79=1062 Lbs
My=29418Lbs-in(tension or compression) ----->29418/32.79=879 Lbs
Mz=0 Lbs-in (shear)

My hand calculation shows the maximum tension for the bolt is 1128Lbs (1062+1064/16). The maximum shear for the bolt is 122 Lbs. The allowable tension for 5/8 bolt is 6kips and the allowable shear is 3 kips.

Body to C5 cell

The maximum load combination under case1, case2, case4, case5 and casel in the Barrel Jointed Ball Jointed FEA are listed below

Fx=1367 Lbs(shear)
Fy=1144 Lbs (shear)
Fz=966 Lbs (tension)
Mx=14965 Lbs-in (tension or compression))----> 14965/32.79=456 Lbs
My=17880 Lbs-in(tension or compression))----> 17880/32.79=545Lbs
Mz=0 Lbs-in (shear)

My hand calculation shows the maximum tension for the bolt is 605.375Lbs (966/16+545). The maximum shear for the bolt is 111 Lbs. The allowable tension for 5/8 bolt is 6kips and the allowable shear is 3 kips.

C5 cell to Imager

The maximum load combination under case1, case2, case4, case5 and casel in the Barrel Jointed Ball Jointed FEA are listed below

Fx=1027 Lbs(shear)
Fy=859 Lbs (shear)
Fz=726 Lbs (tension)
Mx=13450 Lbs-in (tension or compression))----> 13450/27=498 Lbs
My=16070 Lbs-in(tension or compression))----> 16070/27=595Lbs
Mz=0 Lbs-in (shear)

My hand calculation shows the maximum tension for the bolt is 640 Lbs (726/16+595). The maximum shear for the bolt is 84 Lbs. The allowable tension for 3/8 bolt is 2kips and the allowable shear is 1 kips.

Back Cover to Imager Vessel

Two different situations are of note here. In regular operation, the weight of the back cover (~250 lb) is bolted to the back of the vessel. But the more limiting case occurs during installation / removal in the telescope cage when the imager is picked up by the back cover (< 1100 lb). The bolt calcs are as follows (using the EES equation solver). As shown, there is considerable margin between the bolt loads and their proof strengths.

```
{  =====================  Bolt Tension Calculator -- Blind Holes  =====================  }
{  ==============================  Back Cover Bolts  ==============================  }

{ From Mechanical Engineering Design, 5th ed., by Shigley & Mischke }

D_bolt = .375                                       {! Major diameter (in)}
A_bolt_tsa = .0775                                  {! Tensile stress area from TABLE 8-2 (sqin)}
E_bolt = 28.5e6                {304 SS}             {! Modulus (psi)}
S_proof = 31.2e3 * 0.9         {304 SS, 90% of yield}  {! Maximum limit stress (psi)}
L_bolt_unthd = .06                                  {! Length of unthreaded section (in)}
    L_bolt_thd = (t_plate + t_washer) - L_bolt_unthd

Torque = 10 * 12                                    {! Assembly torque (in-lbf)}

t_washer = .06                                      {! Washer thickness (in)}

t_plate = .97                                       {! Plate thickness (in)}
d_plate = .406                                      {! Clearance hole diameter (in)}
E_plate = 28.5e6               {304 SS}             {! Plate modulus (psi)}

(3 * P_joint * 21) =  (2 * 1100 * 9)                {! Tensile load on bolted joint (lbf)}
    {Momemt balance, with uppermost 3 bolts
    assumed to carry 200% of the weight
    estimate, which is 7" offset from the joint.
    Weigh & CG estimate do not include the
    back cover}

{  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -  }


{Spring Constants}

    k_bolt = (k_thd * k_unthd) / (k_thd + k_unthd)          {Eqn 8-9 & 8-10}
        k_thd = A_bolt_tsa * E_bolt / L_bolt_thd
        k_unthd = (0.25 * pi * D_bolt^2) * E_bolt / L_bolt_unthd

    {k_member = 0.5 * (pi*E_plate*d_plate*tan(alpha)) / ln(((L_eff*tan(alpha)+D_washer-
d_plate)*(d_washer+d_plate)) / (L_eff*tan(alpha)+D_washer+d_plate)*(d_washer-d_plate))
    {Eqn 8-15}}
    k_member = 0.5 * (0.577 * pi * E_plate * d_plate) / ln (5 * (0.577*L_eff + 0.5*d_plate) /
(0.577*L_eff + 2.5*d_plate))  {Eqn 8-16}
        L_eff = t_plate + 0.75 * D_bolt                     {Assumed effective clamping
length}
        alpha = 30                                          {Assumed stress cone angle, S&M pg
339}
```

```
    C_joint = k_bolt / (k_bolt + k_member)                    {Eqn 8-21}


{Bolt Loads}

    Torque = 0.2 * F_preload * D_bolt                         {Eqn 8-20}
    F_bolt = C_joint * P_joint + F_preload                    {Eqn 8-17}

    (C_joint * P_max / A_bolt_tsa) + (F_preload / A_bolt_tsa) = S_proof         {Eqn 8-22c}
    (1 - C_joint) * P_joint_separation - F_preload = 0                          {Eqn 8-23d}

    eta_load = P_joint / P_max
    eta_proof = F_bolt / F_proof
    eta_preload = F_preload / F_proof
        F_proof = A_bolt_tsa * S_proof                        {Eqn 8-26}


{===========================================================================================}

{OUTPUT:        eta_load              < 1            (P / P_max for the given preload)
                eta_proof             < 1            (F / F_proof)
                P_joint_separation    > P_joint
                eta_preload           ~ 0.75         (Preload / Proof, recommended value from
Eqn 8-25)}



alpha=30 [degrees]
A_bolt_tsa=0.0775 [in^2]
C_joint=0.1693 [---]
D_bolt=0.375 [in]
d_plate=0.406 [in]
eta_load=0.09234 [---]
eta_preload=0.7352 [---]
eta_proof=0.7597 [---]
E_bolt=2.850E+07 [psi]
E_plate=2.850E+07 [psi]
F_bolt=1653 [lbf]
F_preload=1600 [lbf]
F_proof=2176 [lbf]
k_bolt=2.182E+06 [lbf/in]
k_member=1.070E+07 [lbf/in]
k_thd=2.277E+06 [lbf/in]
k_unthd=5.246E+07 [lbf/in]
L_bolt_thd=0.97 [in]
L_bolt_unthd=0.06 [in]
L_eff=1.251 [in]
P_joint=314.3 [lbf]
P_joint_separation=1926 [lbf]
P_max=3404 [lbf]
S_proof=28080 [psi]
Torque=120 [in-lbf]
t_plate=0.97 [in]
t_washer=0.06 [in]
```

APPENDIX

Additional Copies of ANSYS FEA Study Results

Analysis by Ingrid Fang based on
input provided by Herman Cease

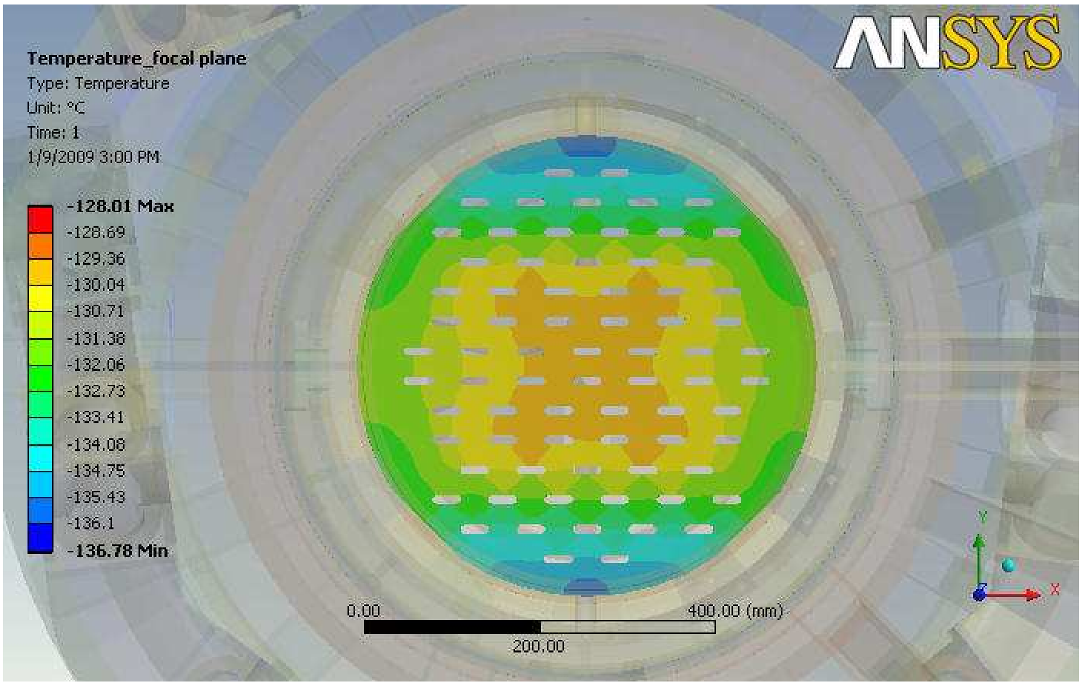
An FEA model consisting of the DES imager vessel and lens barrel was created to study behavior in several situations. Later work was performed with an improved model of just the FPSP & bipod arrangements (and inclusion of the 10kg CCD weights, which were not originally accounted for). But the results of this earlier work are included here for completeness.

Six cases were considered, as described in the table below. Coordinate system +Z is towards the mirror

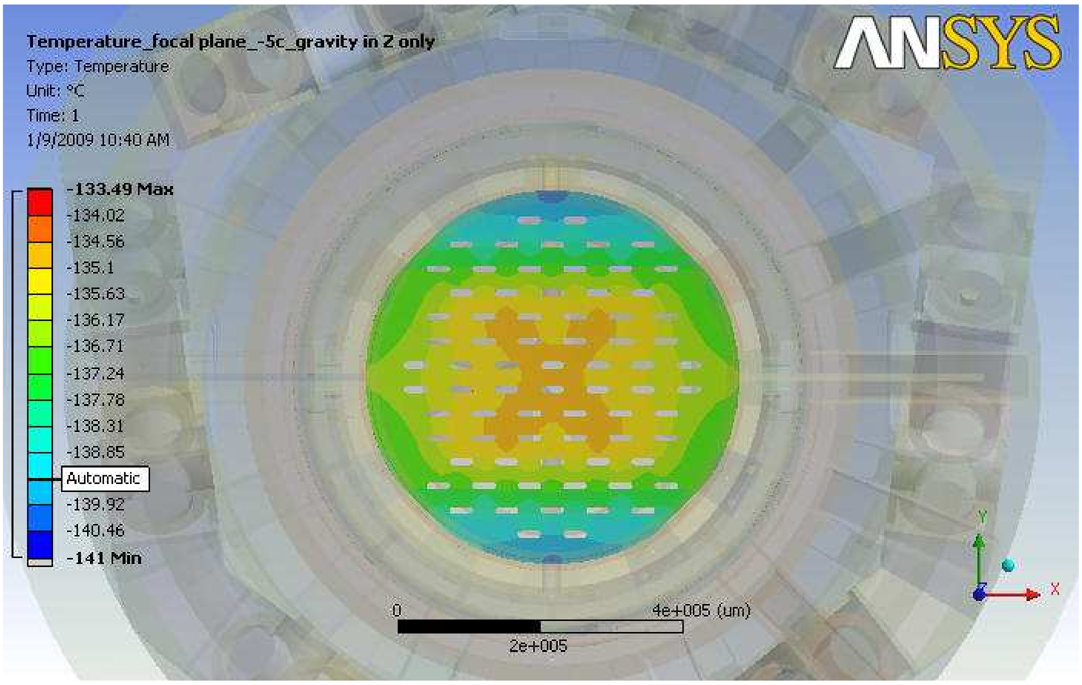
Case #	Declination	Ambient T (°C)
WZ	Zenith	+20
W1	45° in Y/Z	+20
W2	45° in X/Z	+20
CZ	Zenith	-5
C1	45° in Y/Z	-5
C2	45° in X/Z	-5

TEMPERATURE RESULTS – FPSP

+20°C Ambient



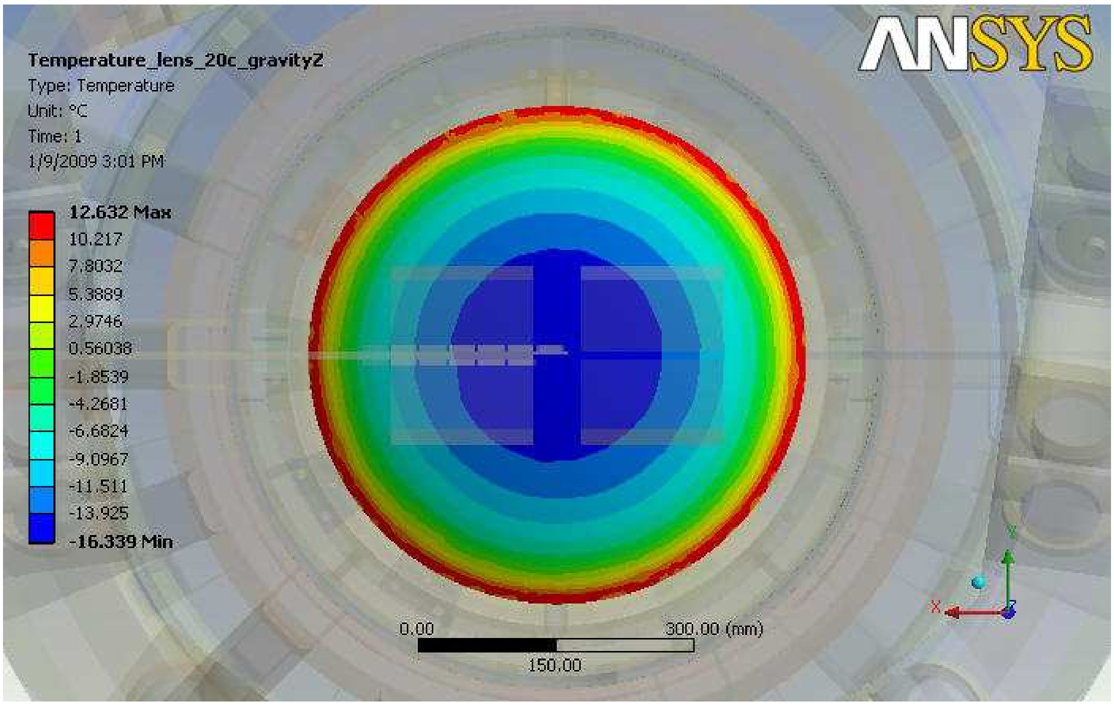
-5°C Ambient



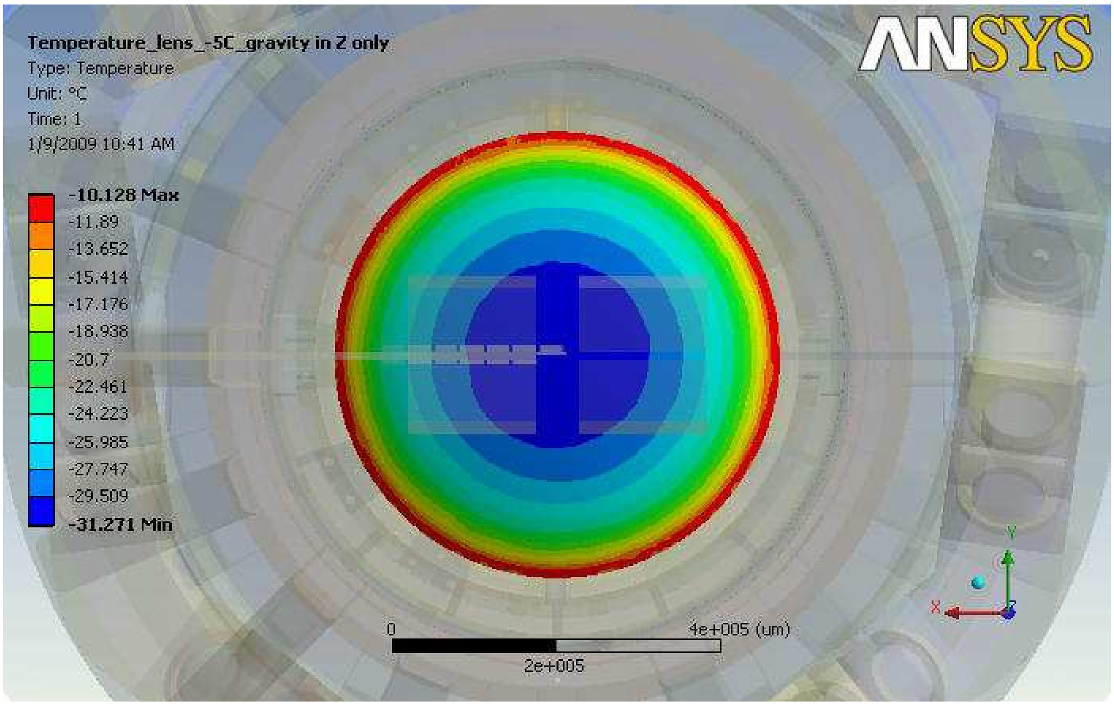
Actual FPSP temps will be modulated by the heater control system to control the CCD temperature. Also, note that CCD cable conductivity is applied as a lumped link rather than being more realistically distributed.

TEMPERATURE RESULTS – C5 LENS

+20°C Ambient

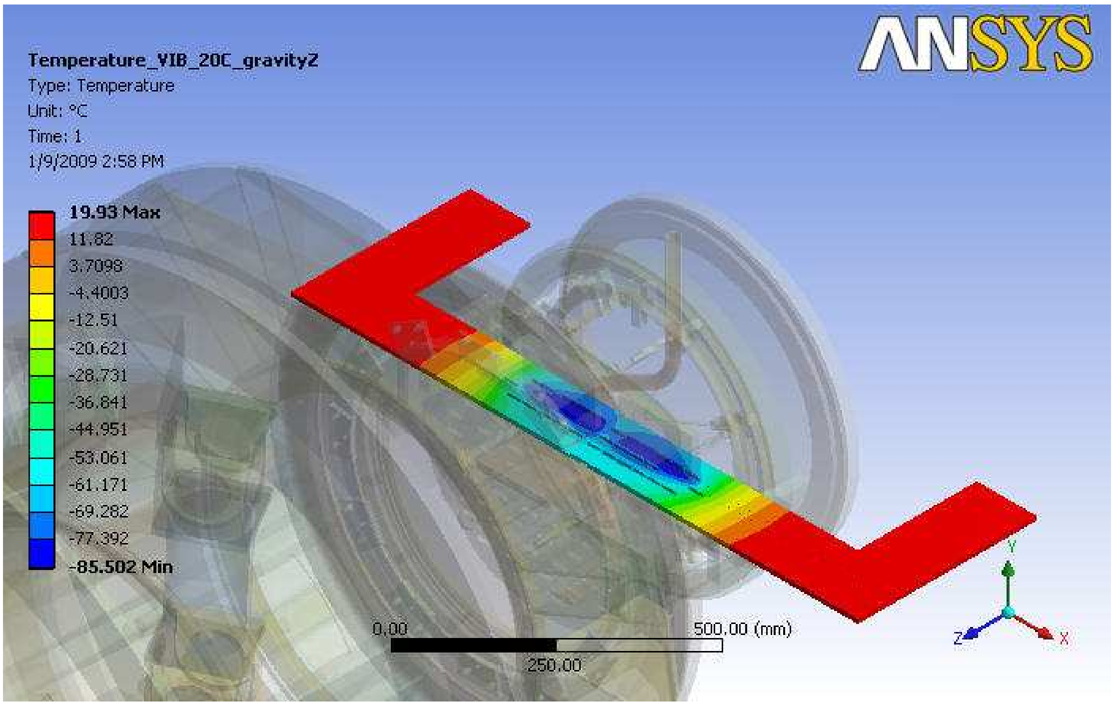


-5°C Ambient

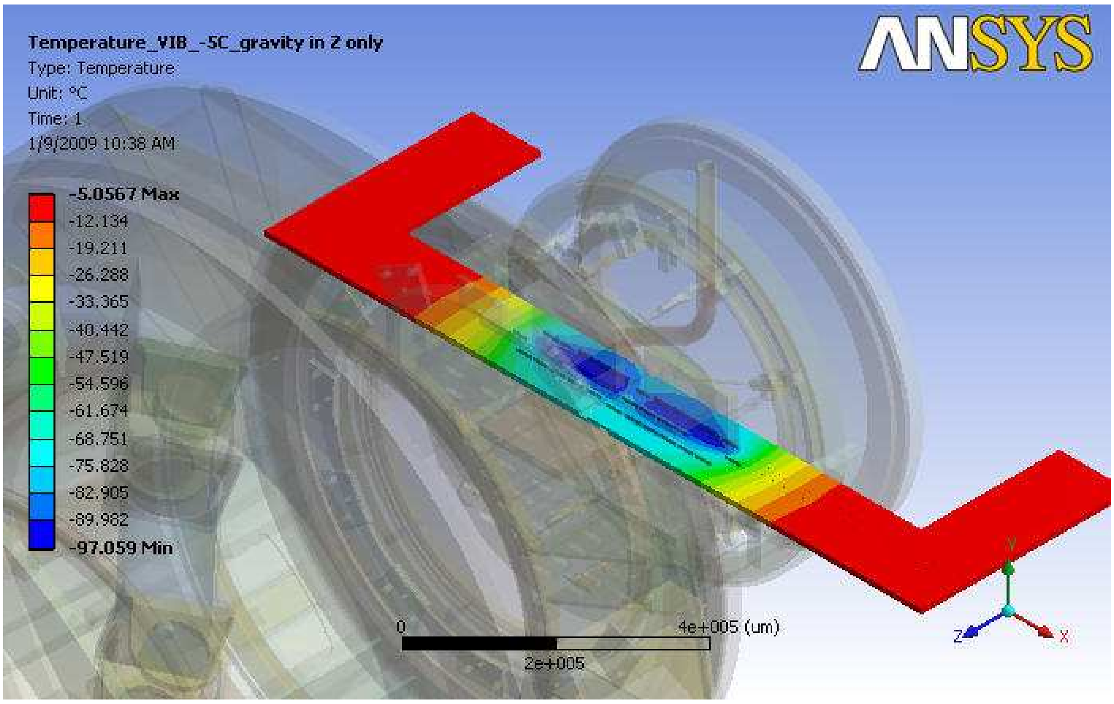


TEMPERATURE RESULTS – VIB

+20°C Ambient



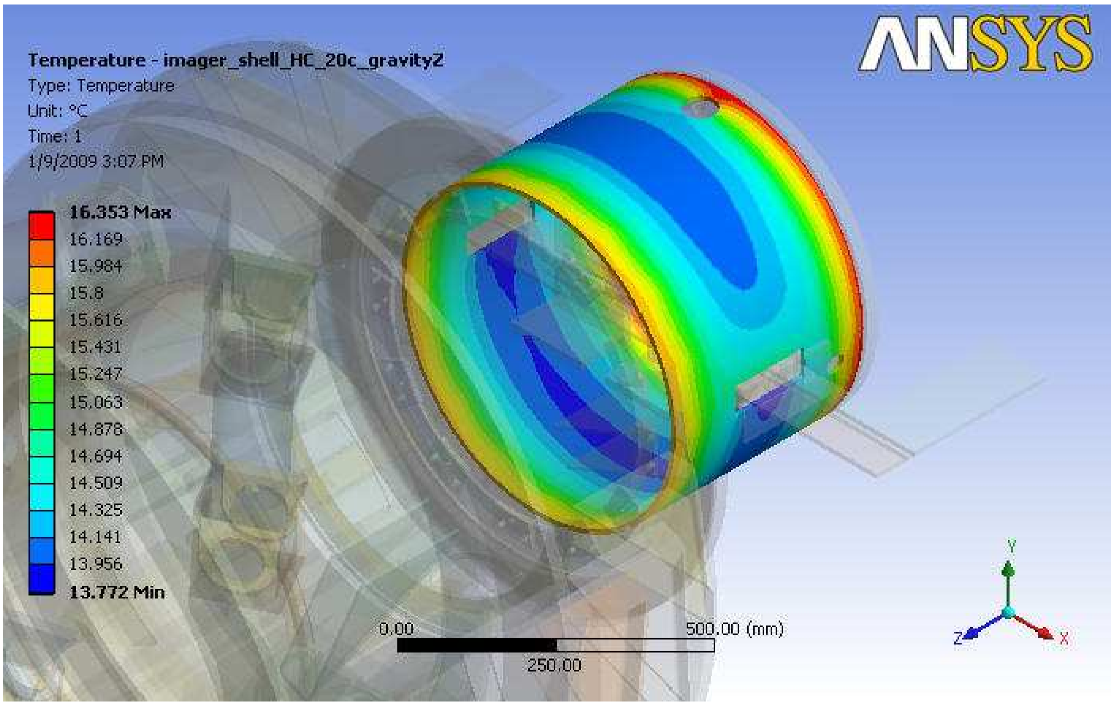
-5°C Ambient



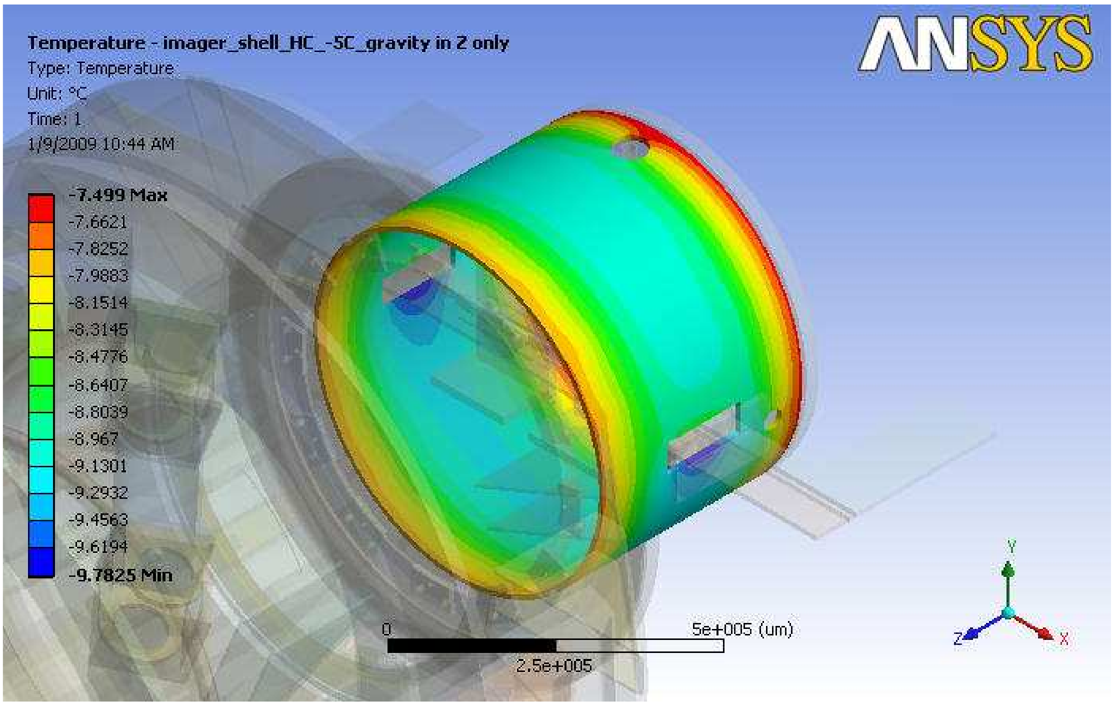
Note that simplified CCD cable modeling concentrates the heat transfer over a limited VIB area. Real cables are more evenly-distributed over the VIB surface.

TEMPERATURE RESULTS – IMAGER SHELL

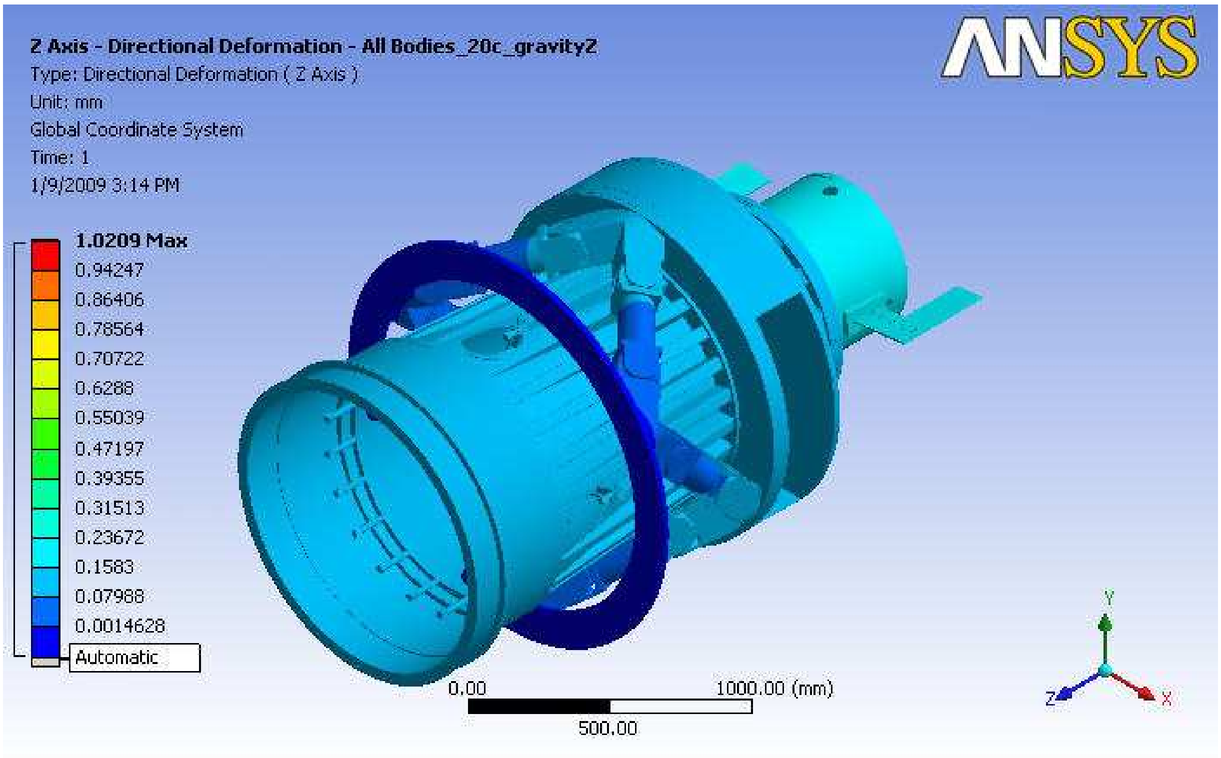
+20°C Ambient



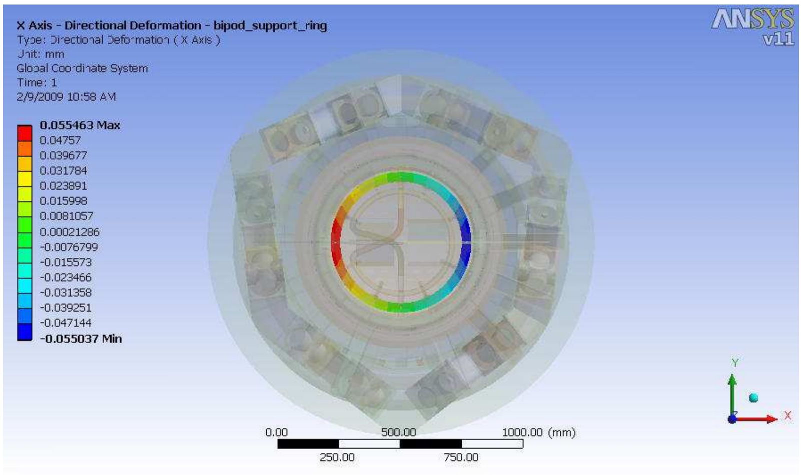
-5°C Ambient

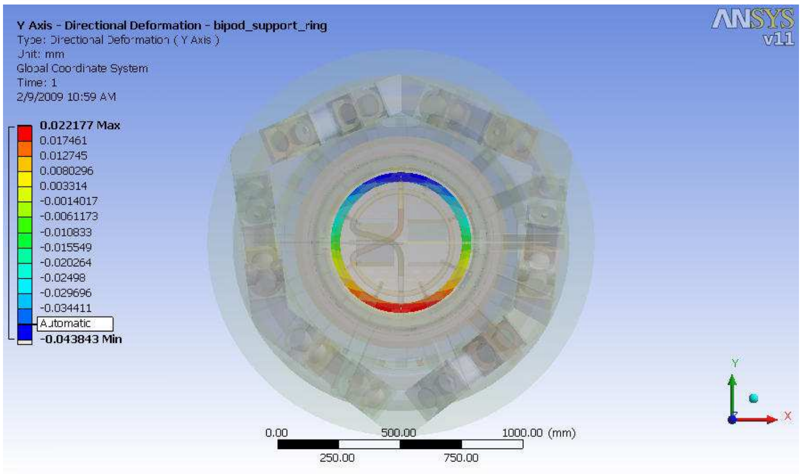


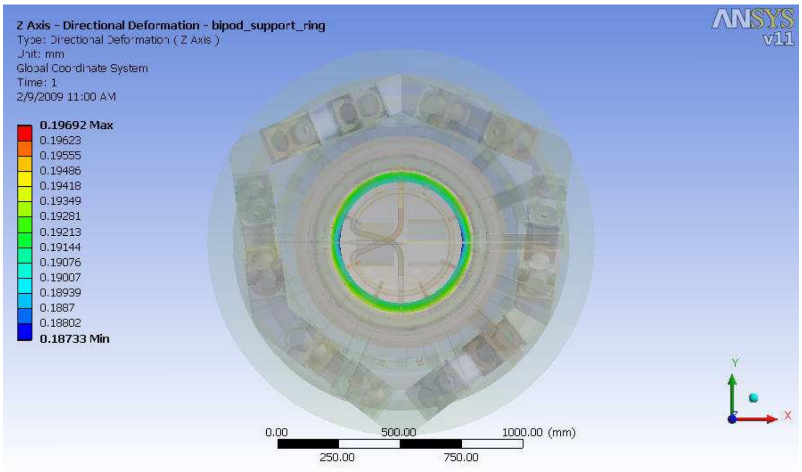
DEFORMATION RESULTS – IMAGER/BARREL ASSEMBLY
CASE WZ – +20°C AT ZENITH



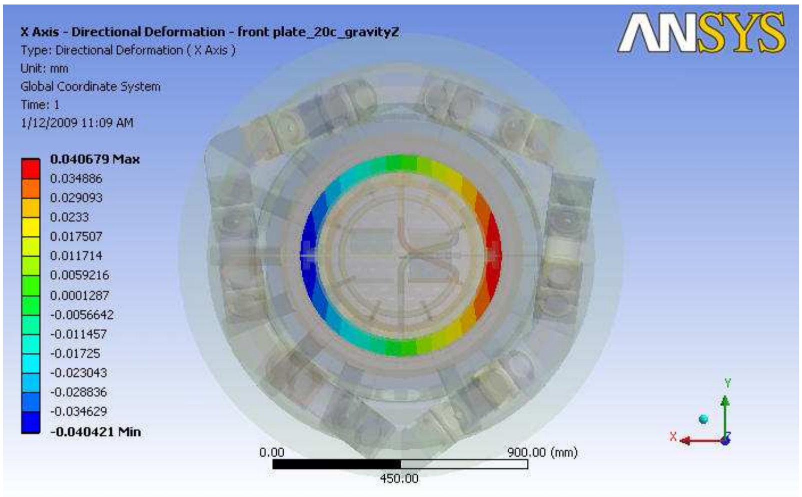
DEFORMATION RESULTS – BIPOD MOUNTING FLANGE
CASE WZ – +20°C AT ZENITH

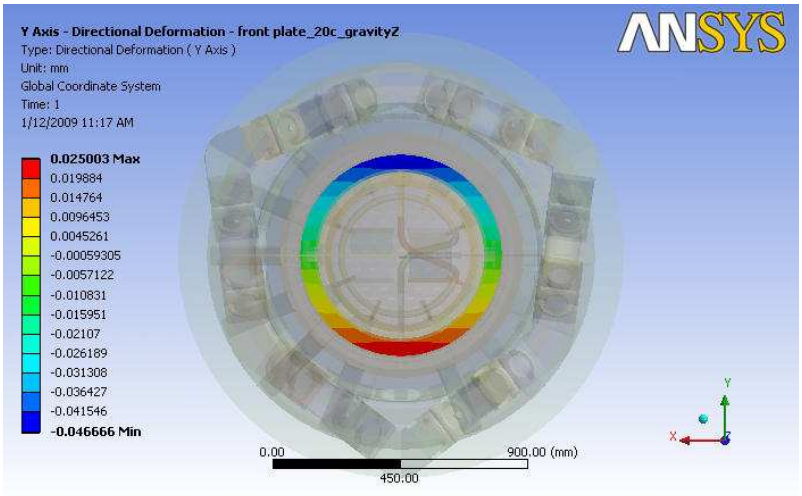


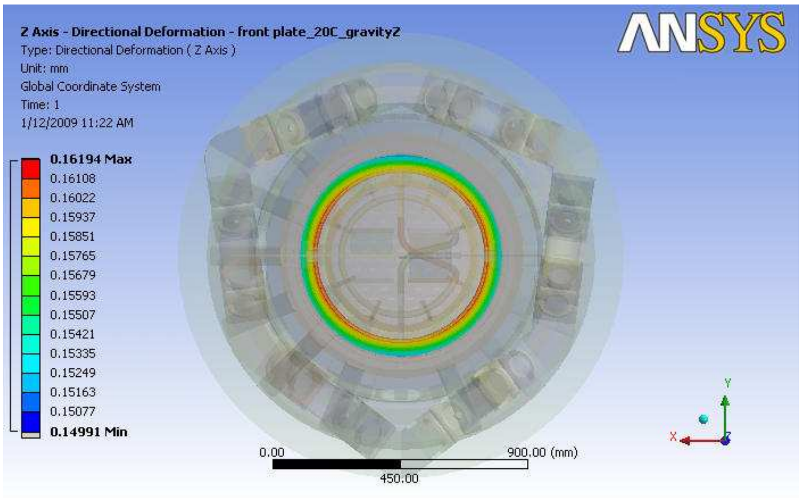




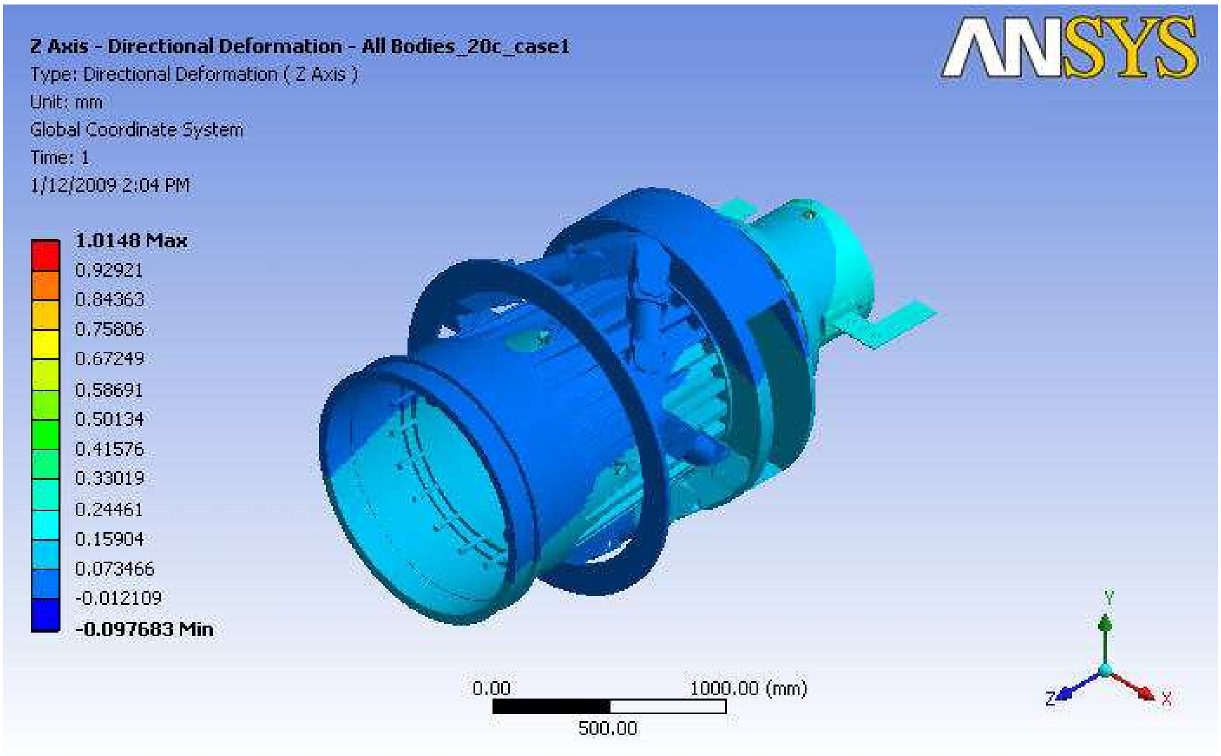
DEFORMATION RESULTS – IMAGER FLANGE
CASE WZ – +20°C AT ZENITH



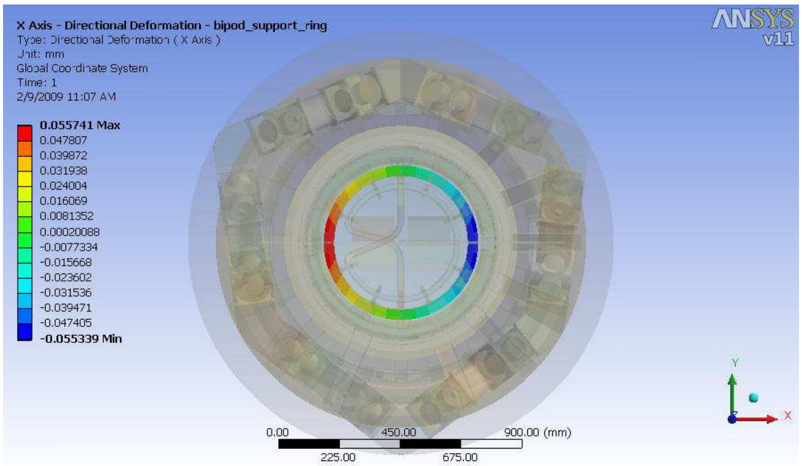


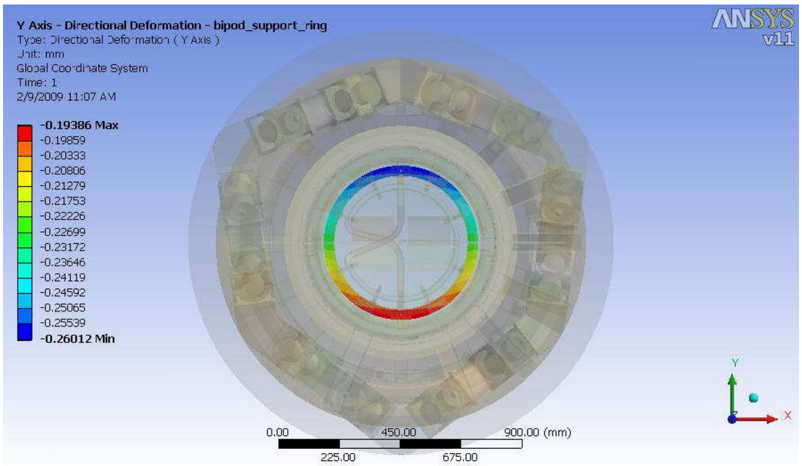


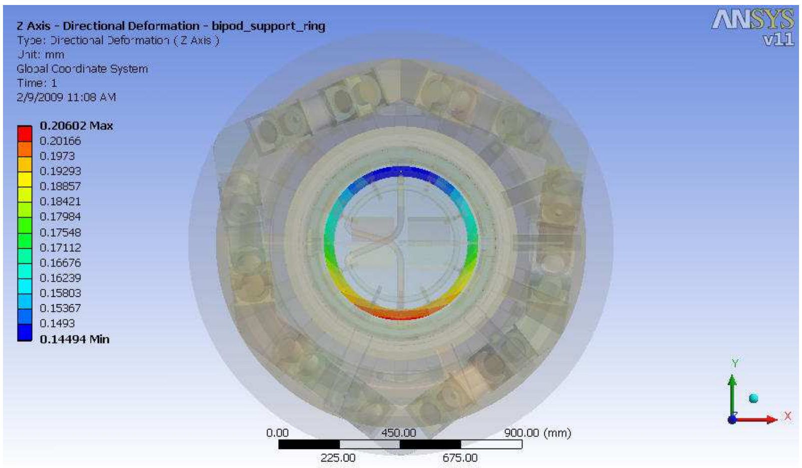
DEFORMATION RESULTS – IMAGER/BARREL ASSEMBLY
CASE W1 – +20°C AT 45° DELINATION IN THE Y/Z PLANE



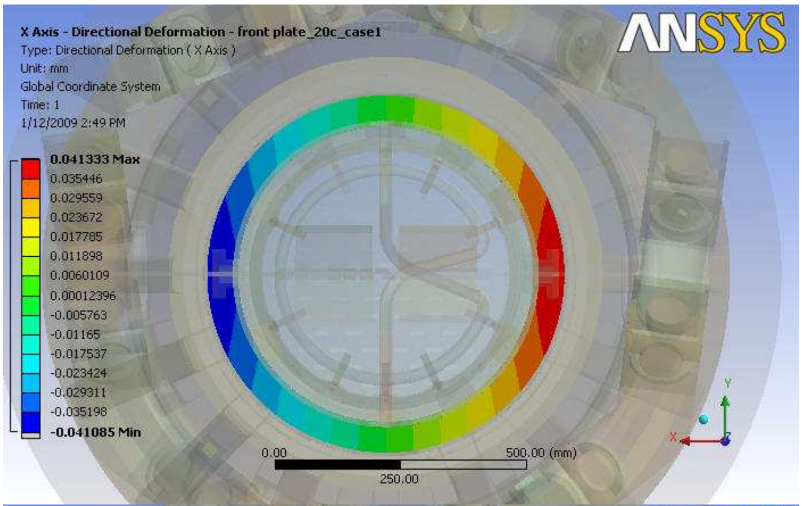
DEFORMATION RESULTS – BIPOD MOUNTING FLANGE
CASE W1 – +20°C AT 45° DELINATION IN THE Y/Z PLANE

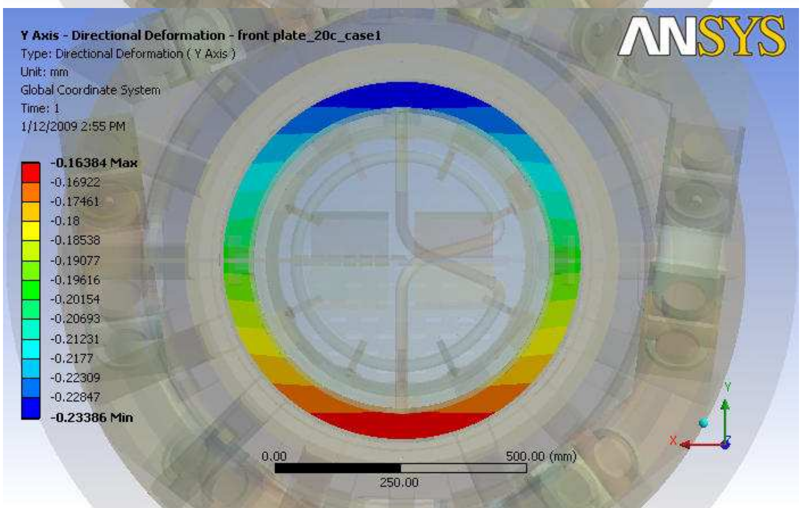


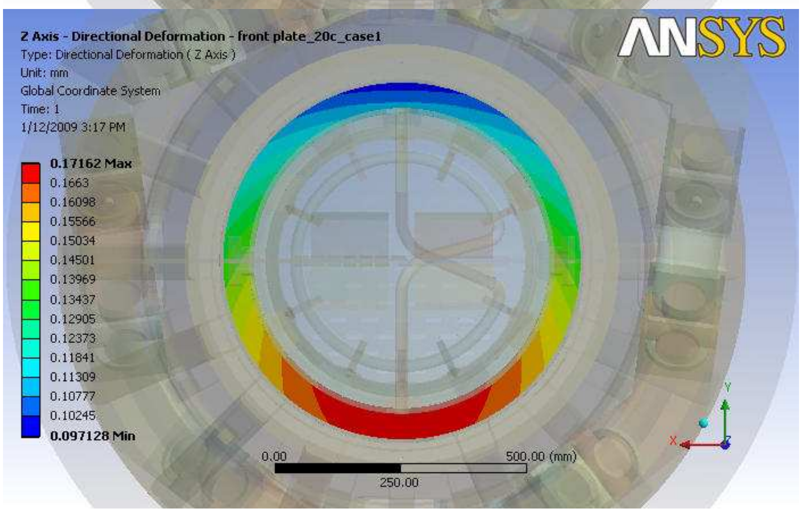




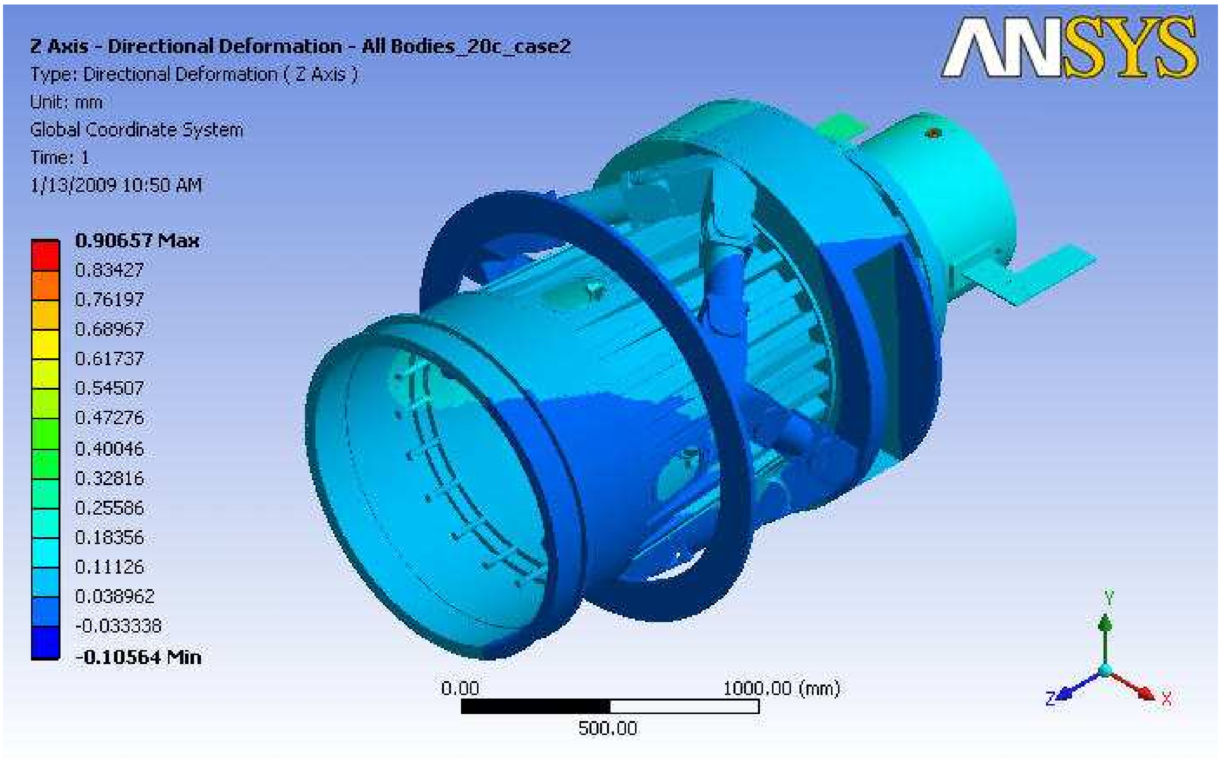
DEFORMATION RESULTS – IMAGER FLANGE
CASE W1 – +20°C AT 45° DELINATION IN THE Y/Z PLANE



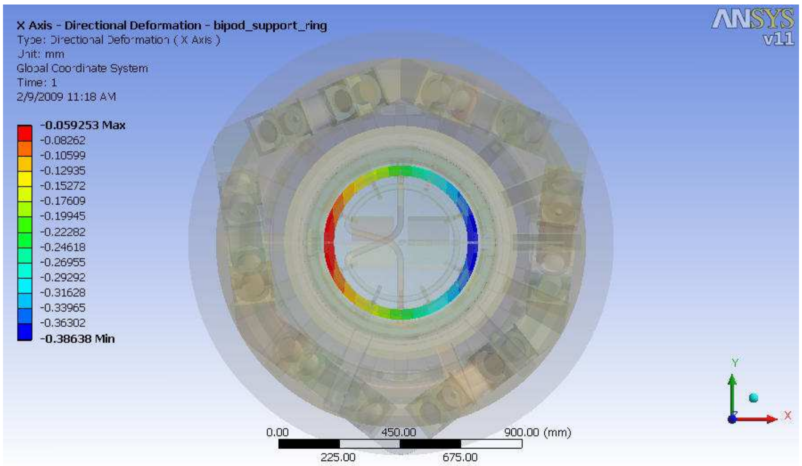


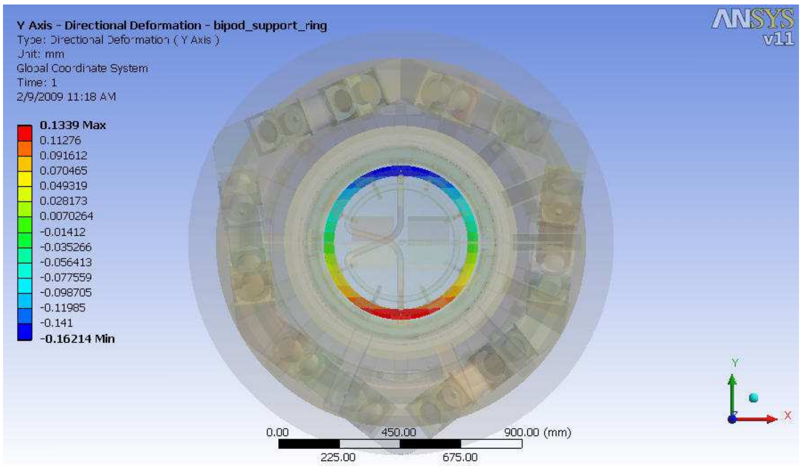


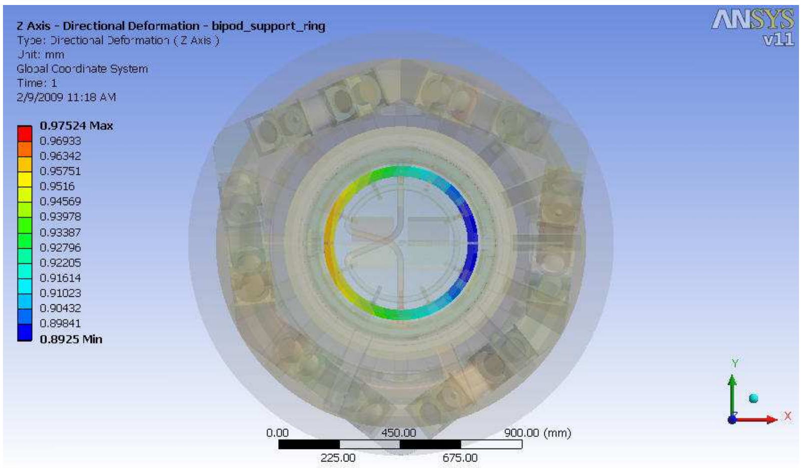
DEFORMATION RESULTS – IMAGER/BARREL ASSEMBLY
CASE W2 – +20°C AT 45° DELINATION IN THE X/Z PLANE



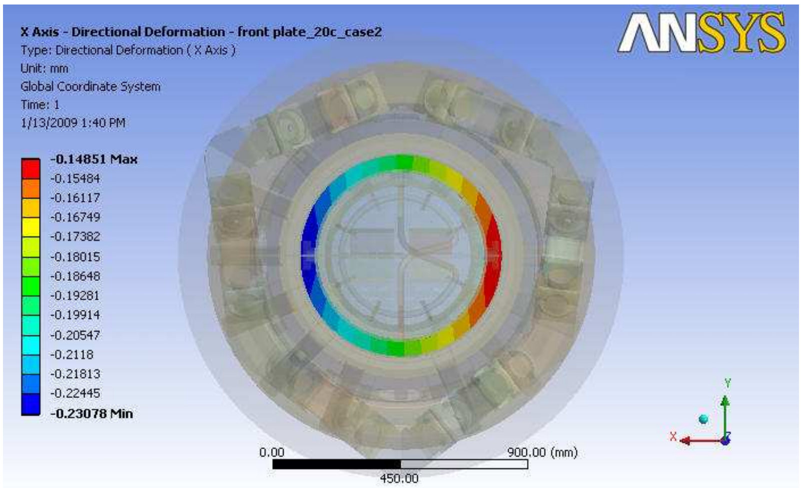
DEFORMATION RESULTS – BIPOD MOUNTING FLANGE
CASE W2 – +20°C AT 45° DELINATION IN THE X/Z PLANE

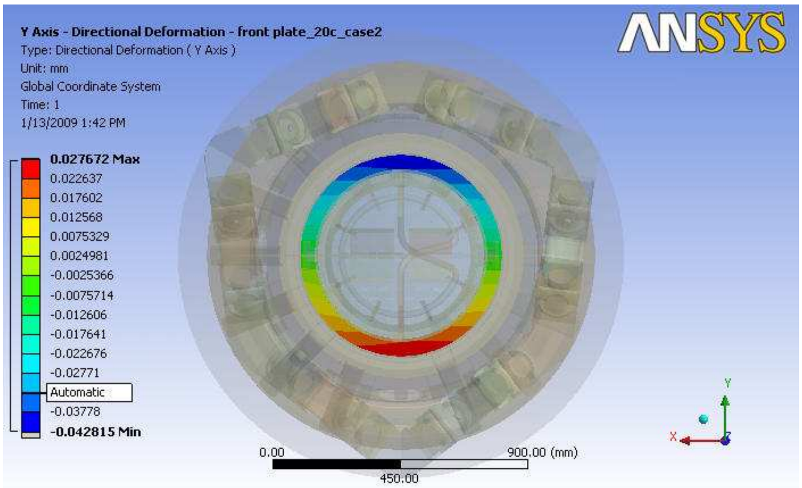


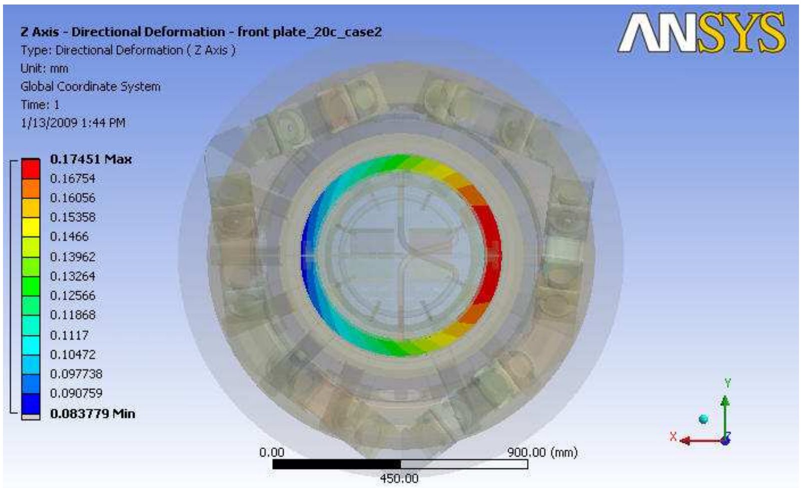




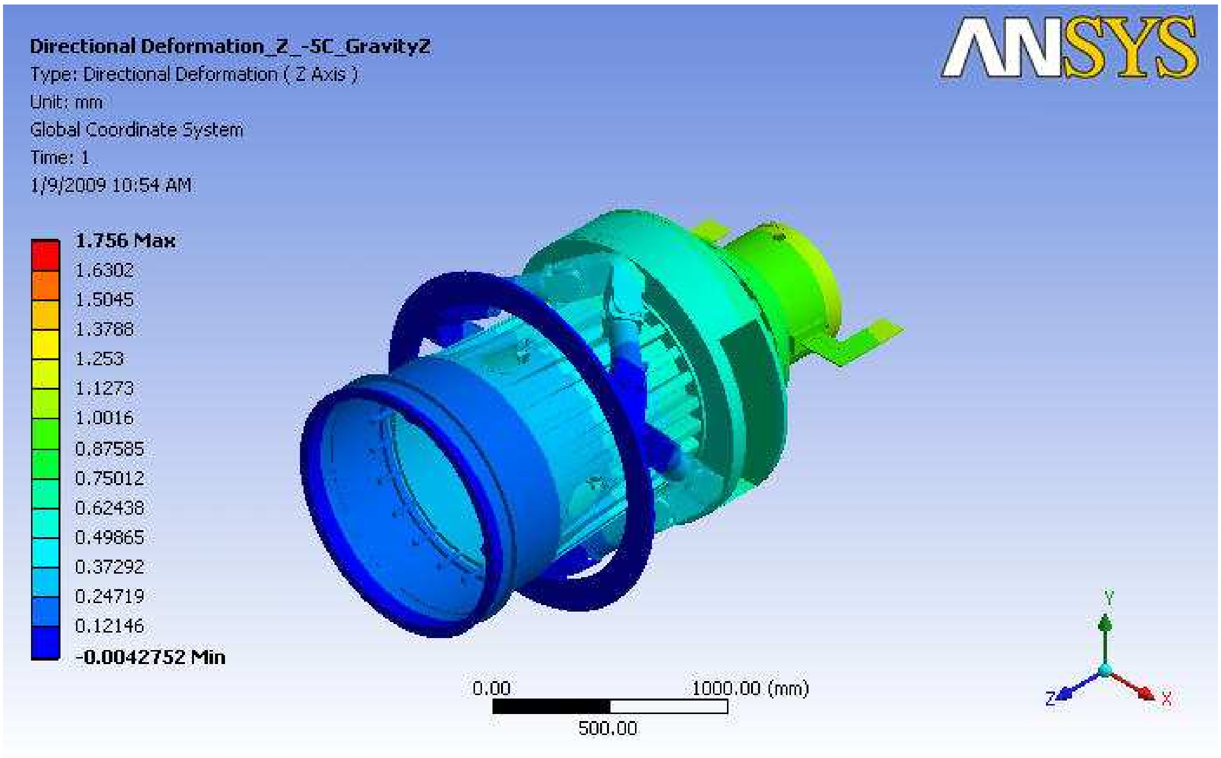
DEFORMATION RESULTS – IMAGER FLANGE
CASE W2 – +20°C AT 45° DELINATION IN THE X/Z PLANE



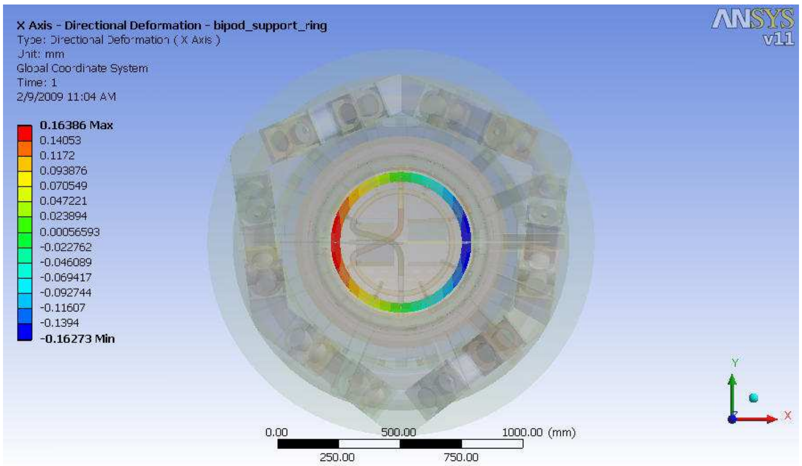


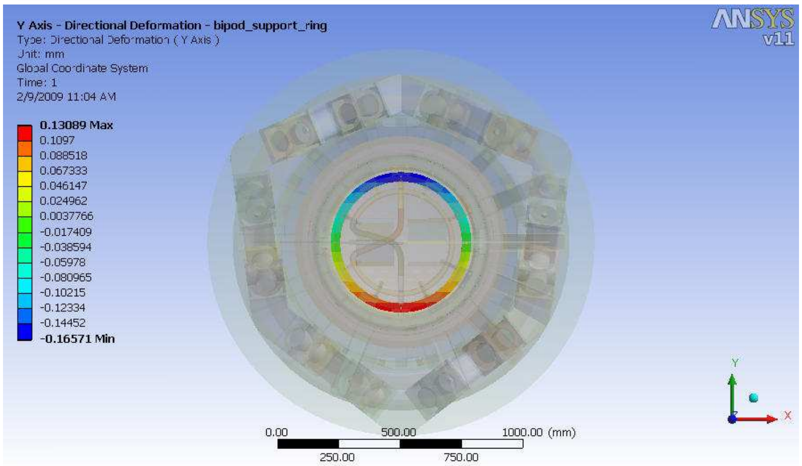


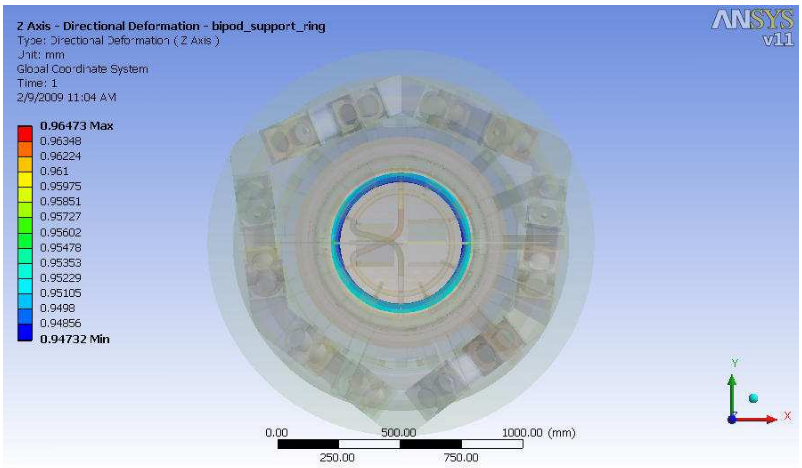
DEFORMATION RESULTS – IMAGER/BARREL ASSEMBLY
CASE CZ – -5°C AT ZENITH



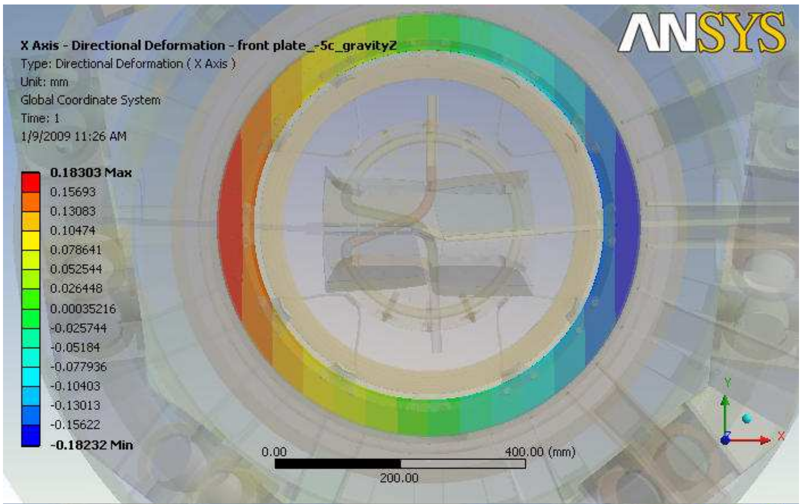
DEFORMATION RESULTS – BIPOD MOUNTING FLANGE
CASE CZ – -5°C AT ZENITH

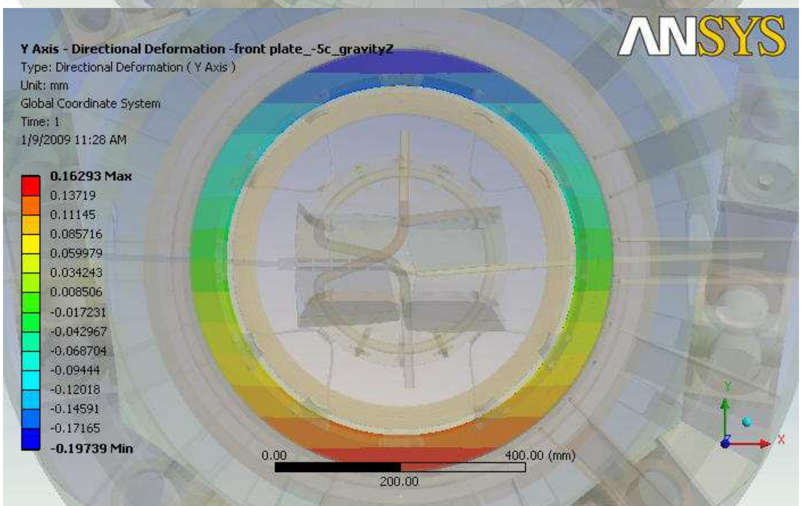


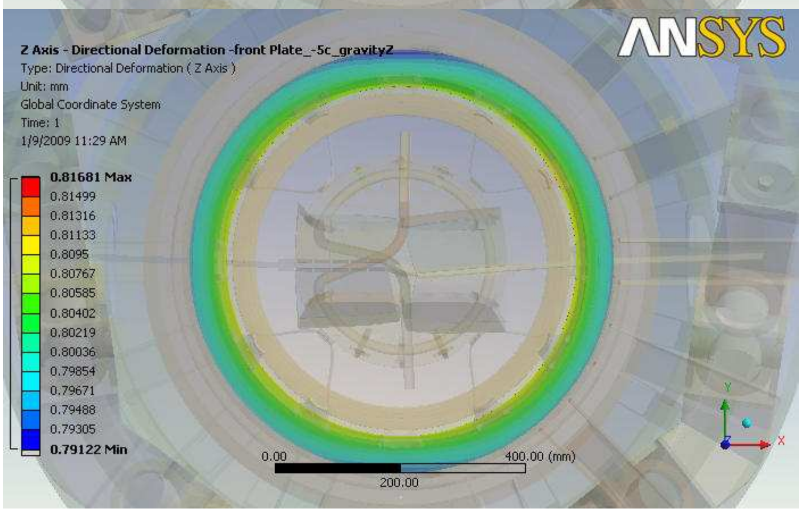




DEFORMATION RESULTS – IMAGER FLANGE
CASE CZ – -5°C AT ZENITH



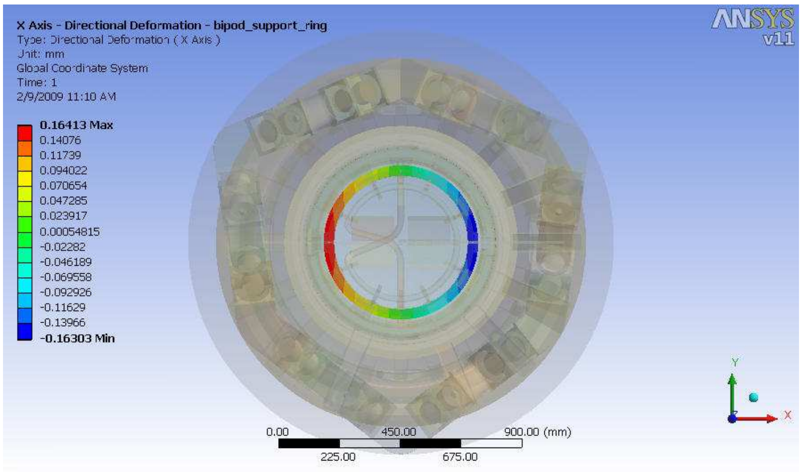


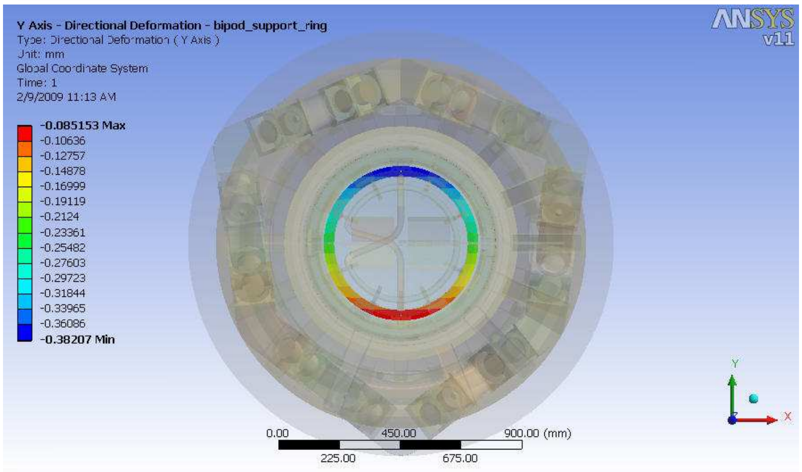


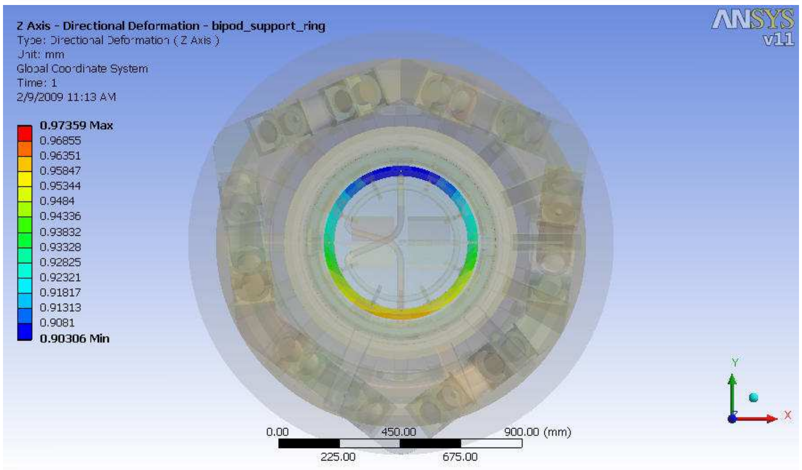
<u>DEFORMATION RESULTS – IMAGER/BARREL ASSEMBLY</u>
<u>CASE C1 – -5°C AT 45° DELINATION IN THE Y/Z PLANE</u>

[Plot not provided]

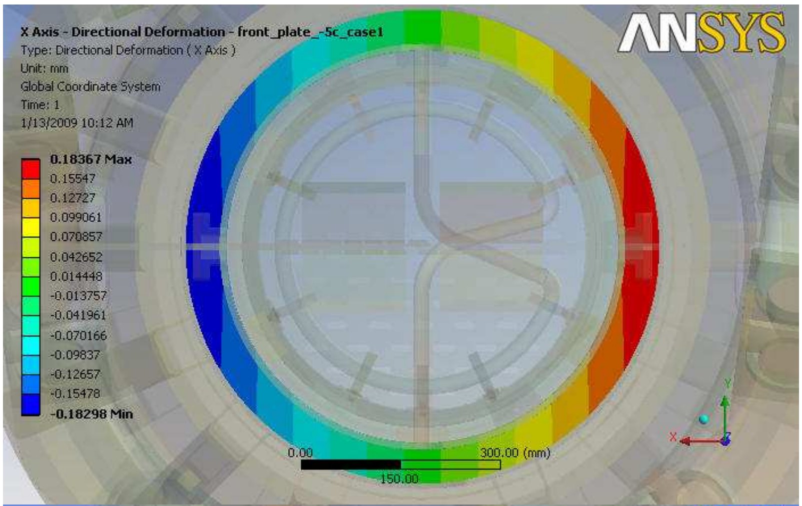
DEFORMATION RESULTS – BIPOD MOUNTING FLANGE
CASE C1 – -5°C AT 45° DELINATION IN THE Y/Z PLANE

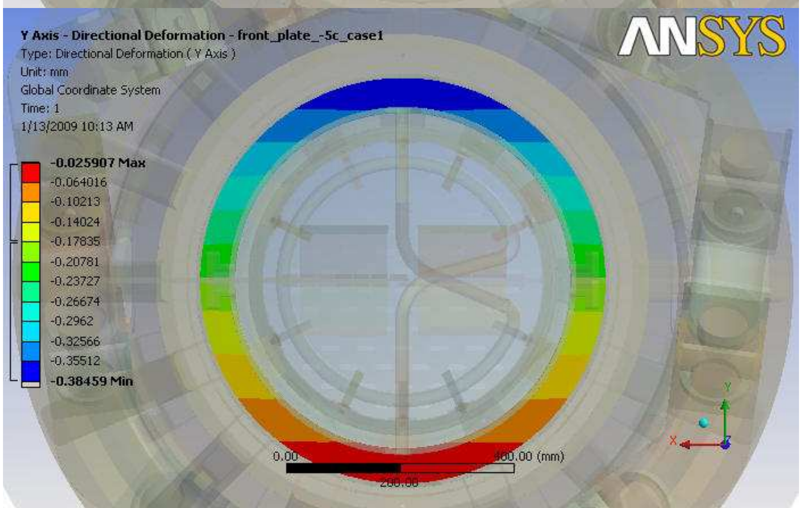


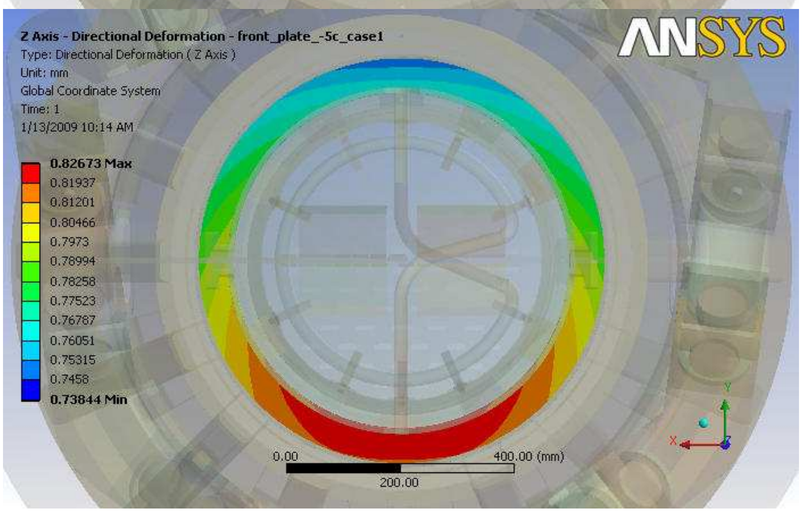




DEFORMATION RESULTS – IMAGER FLANGE
CASE C1 – -5°C AT 45° DELINATION IN THE Y/Z PLANE







DEFORMATION RESULTS – IMAGER/BARREL ASSEMBLY
CASE C2 – -5°C AT 45° DELINATION IN THE X/Z PLANE

[Plot not provided]

DEFORMATION RESULTS – IMAGER FLANGE
CASE C2 – -5°C AT 45° DELINATION IN THE X/Z PLANE