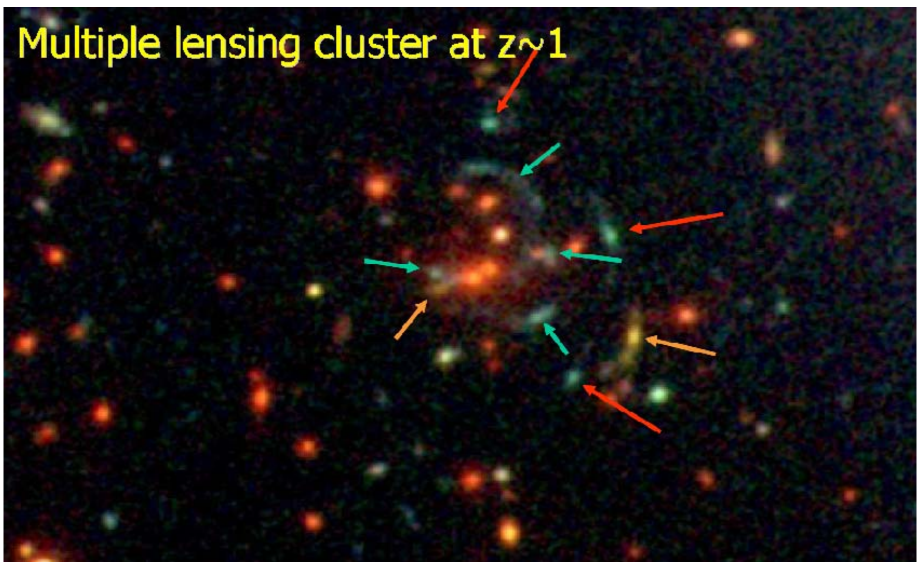
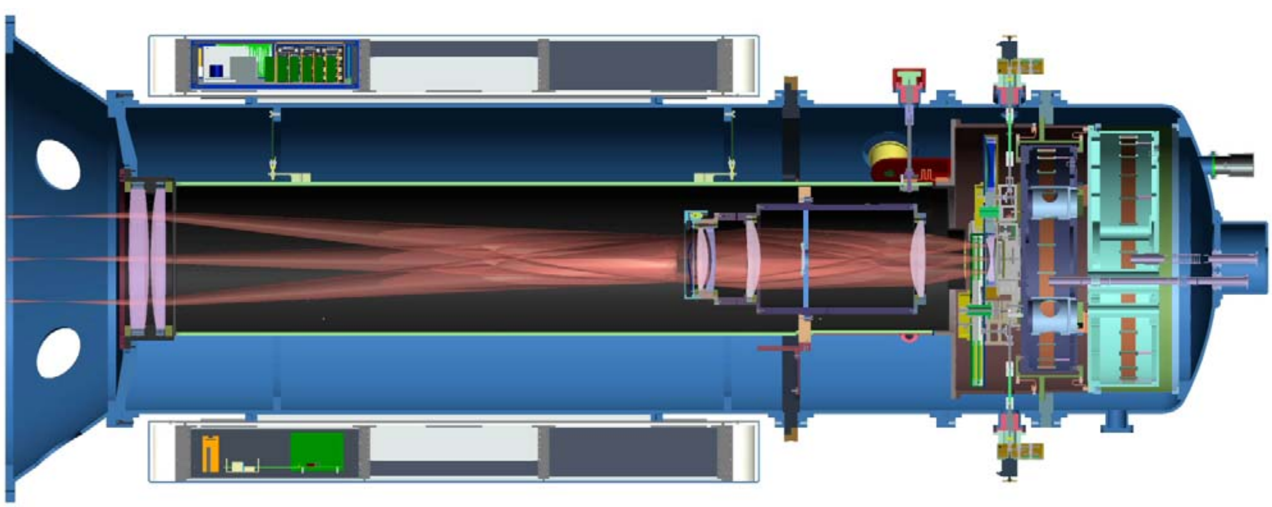
FourStar Critical Design Review

Carnegie Observatories
September 21-22, 2006

http://www.ociw.edu/instrumentation/FourStar





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Charge to Reviewers

Overview

FourStar is a 4K x 4K JHKs imager currently under construction for the Magellan 6.5 meter telescopes at Las Campanas Observatory. Intended to provide a deep extragalactic survey capability, it is also expected to see service in more focused situations.

FourStar uses an all-refractive optical system similar to the proven PANIC imager installed at Magellan and employs Rockwell Hawaii-2RG detectors. Carnegie has partnered with the Johns Hopkins University Instrument Development group for work on the mechanical and opto-mechanical design and maintains close contact with Rockwell Scientific on detector and readout electronics issues.

Scope

This review should identify problems that would severely impact the schedule, budget, scientific productivity, or observatory operations. The time-line ends at successful testing in Pasadena. Shipping, installation, and commissioning will not be explained in detail, but reviewers *should* comment on issues that impact those steps.

Although a preliminary design review was not held, we believe the design fundamentals are sound because it builds on existing examples. Consequently, topics of a philosophical nature are less interesting than those of practical import. For example, the cooling system and detector choices are unlikely to change but we are ready to receive advice about implementation and execution. We are especially interested in tapping your knowledge and experience on design, materials, process, and vendors.

Procedure

FourStar team members will present technical details on FourStar. During the presentations, panelists will note issue items (*discoveries*), write *remarks*, and provide *recommendations*. The panel chair will write and present to the instrument team a closeout report that includes the recommendations in priority order.

Table of Contents

TAB 1

1. Welcome and Purpose of the Review

Reviewers, Team, and Participants/Invitees

Review Committee

Tom O'Brien	OSU (Chair)
Keith Matthews	Caltech
James Larkin	UCLA

Carnegie Observatories

Eric Persson	PI
David Murphy	Co-I
Pat McCarthy	Science, Data Refinery
Alan Uomoto	Project Management
Christoph Birk	Software/control
Dan Kelson	Software/refinery
Greg Walth	Software/refinery
Tyson Hare	Mechanical Engineer
Jennifer Marshall	Post Doc
Wendy Freedman	OCIW Director
Steve Shectman	Optical Design and Advice
Charlie Hull	Telescope Interface Consultant
Vince Kowal	Shop Foreman
Robert Storts	Machinist
Jerson Castillo	Machinist

Instrument Development Group at Johns Hopkins University

Stephen Smee	Chief Engineer
Robert Barkhouser	Optical Engineer
Randy Hammond	Mechanical Engineer
Joe Orndorff	Electronics Engineer
Gregg Scharfstein	Thermal & Mechanical Engineer
Al Harding	CAD

Las Campanas Observatory

Frank Perez	Integration/Deployment
Miguel Roth	Integration/Deployment
Mark Phillips	Scientific Management Support

Dedicated Micro Systems, Incorporated

Erich Koch	CAD

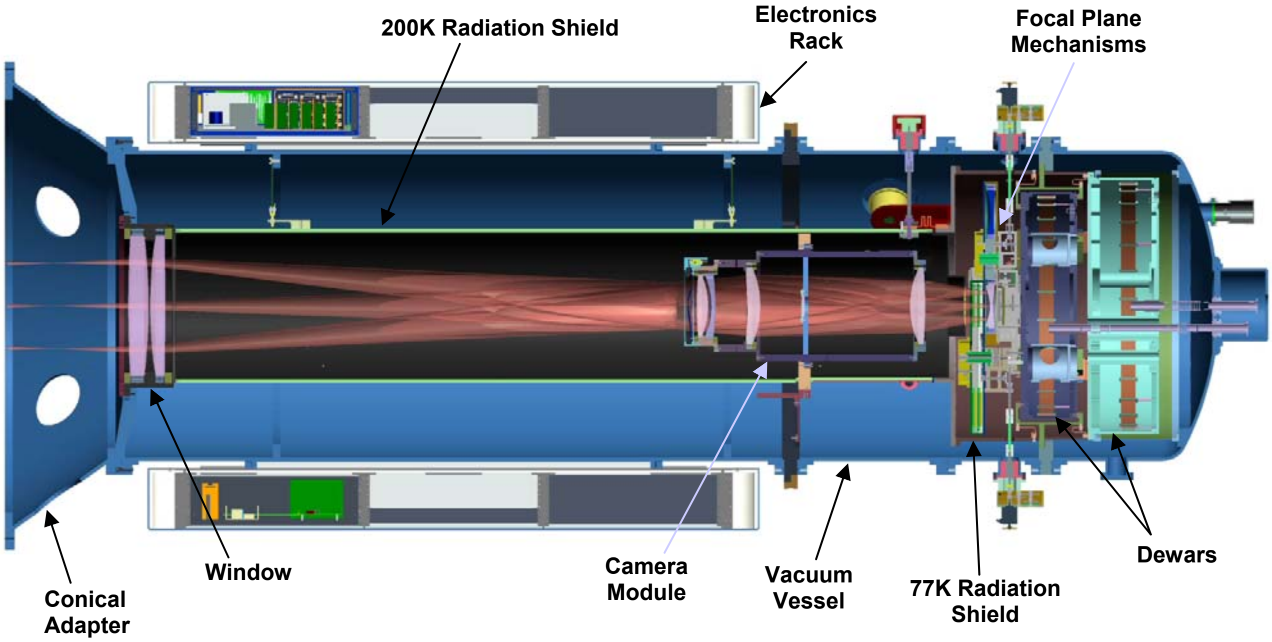
Rockwell Scientific

James Garnett	Project Manager for HAWAII-2RG
Markus Loose	ASIC Developer
Jonathan Clarke	Electronics
Jim Beletic	Management

TAB 2

2. Introduction and Overview

FourStar is the name of a wide-field near-infrared camera that the Carnegie Observatories is building for the Baade (Magellan 1) 6.5-m telescope at Las Campanas Observatory, Chile. FourStar is designed and optimized for wide-band imaging in the J, H, and Ks bands. The design has been done in close collaboration with the Instrument Development Group at The Johns Hopkins University. This brief introduction will give an overview of the instrument and thus provide a context for the individual sections that follow.



We began thinking about a survey camera for Magellan in 2001, when McCarthy and Persson concluded that an imager should precede any sort of multi-obect IR spectrograph. We applied for NSF/ATI funding to buy six Rockwell HAWAII-2RG detectors, and were awarded sufficient funding to buy four. Given the long lead-times involved in obtaining the detectors, we built a near infrared camera called PANIC as a stopgap measure. This instrument has a single 1024x1024 detector, 0.125" pixels, a 2x2 arcmin field of view, and mounts at an F/11 focus of the telescope.

The possible foci at Magellan are the following: two F/11 Nasmyth ports and platforms, and three F/11 folded ports, per telescope. The latter have seen very little use because of poor accessibility. In practice one of the four Nasmyth ports will be used indefinitely by IMACS - the Observatory’s primary optical wide-field spectrograph/CCD camera. There will be, in addition, an F5 Cassegrain focus on the Clay Telescope (Magellan 2). Current plans are to use the F/5 focus three months of the year, and they could in principle be used for a wide-field camera. Dan Fabricant is leading the effort at Harvard/SAO to build MMIRS, a combination IR camera/multi-object spectrograph for the F/5 Cassegrain focus. In our original NSF proposal we showed our own F/5 design, but the advent of MMIRS and the advantages of an F/11 camera in terms of time available for use, were compelling. Just as important, we wanted an instrument that could be mounted on the telescope and kept cold and operational for many months at a time.

Steve Shectman originated the design for the optics in PANIC which he showed could be scaled to the large 10.8′ X 10.8′ field of FourStar with a modest increase in the number of optical surfaces and the introduction of one aspheric surface. The FourStar plate scale is 0.159" per 18 micron pixel which corresponds to final speed of F/3.6. The Four Star optical design is shown in Figure 1.

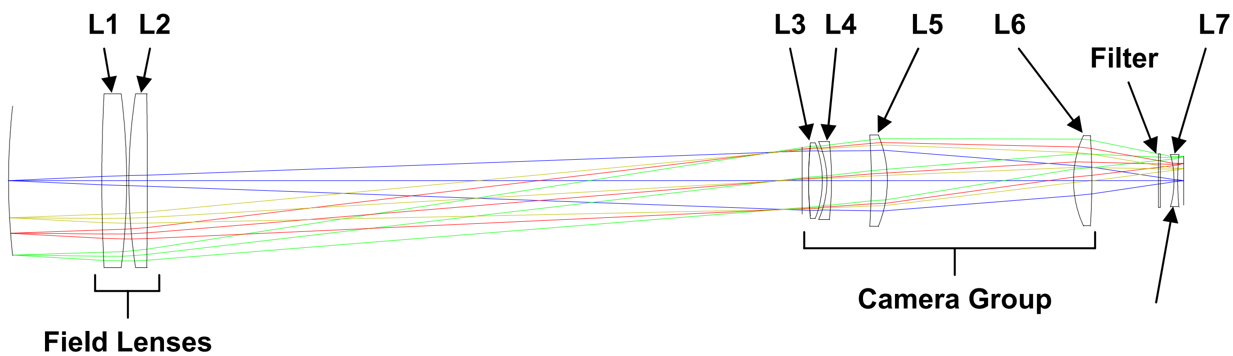


Figure 1 – FourStar optical design

The two-element vacuum vessel entrance window is also a Fabry lens that images the telescope pupil onto a cold stop inside the instrument. The two-lens choice resulted from modeling the thermal gradients in a single window, and the resulting cold section near the center which would be extremely prone to icing. Four lenses and a field flattener follow and bring the beam to a flat field focus at a speed appropriate to deliver a pixel scale still suitable for the 2-micron median seeing at Las Campanas, which is about 0.35". The design trades off a slightly undersampled seeing disk to obtain a large gain in field area for moderately deep imaging.

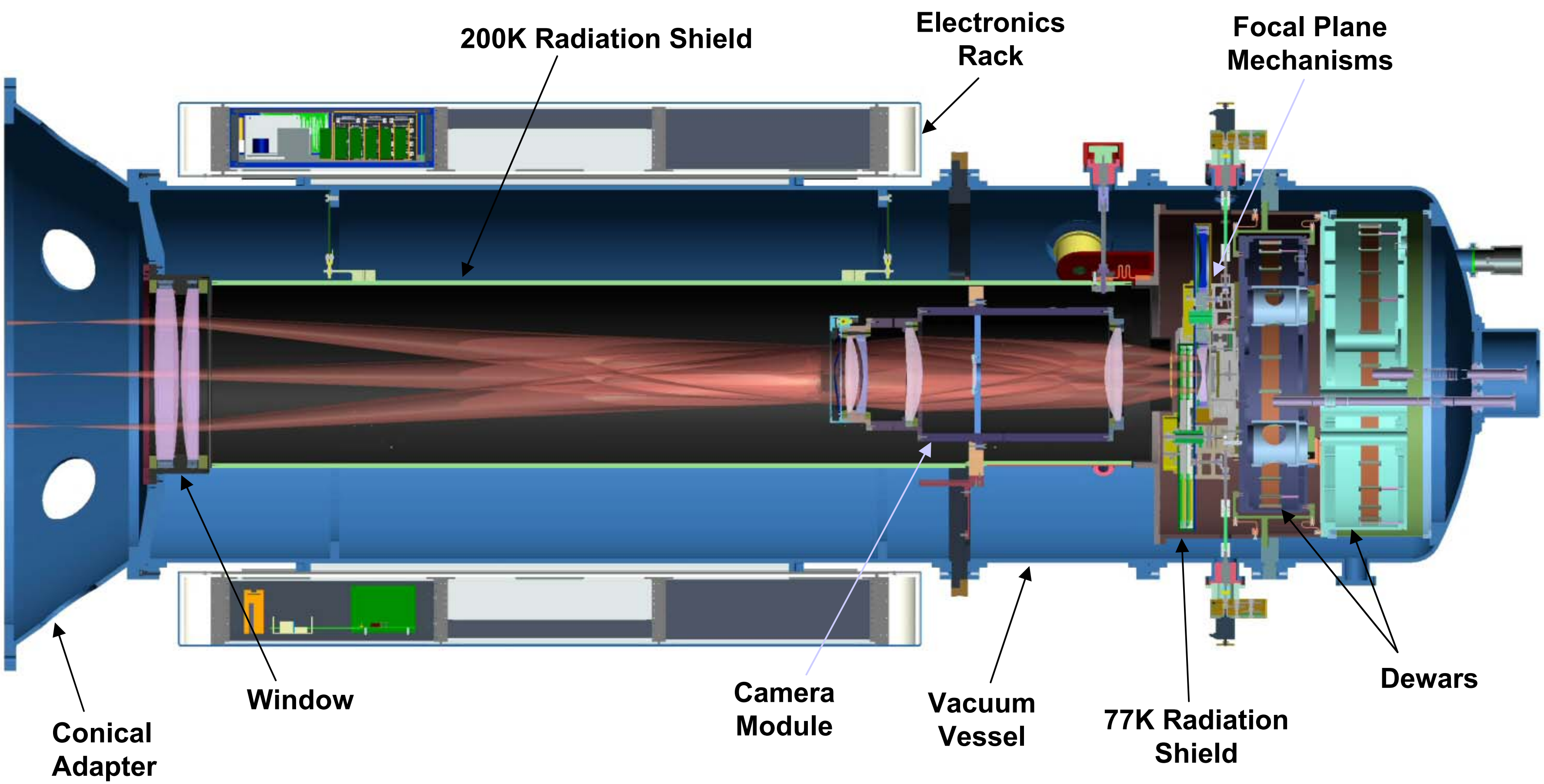
FourStar will be a heavy and long instrument (of order 10 feet in length). Because of this suspending it from the Nasmyth guider was rejected in favor of a plan to offload most of the weight onto the Nasmyth platform and use the attachment to the instrument mounting ring/guider only to (precisely) locate the instrument in space.

We adopted some ideas from PANIC. First, we wanted to cool the camera optics only as much as necessary. This minimizes uncertainties in the refractive indices of our chosen materials, shortens cool down times, reduces thermal contractions, and lowers material stresses. By modeling the flux seen by a detector illuminated by surfaces at various temperatures inside the instrument, we concluded that 200K was sufficiently cool for the optical elements ahead of the band pass filters. That is, the interior of the instrument will contribute only a few percent of the total thermal background under the coldest ambient conditions. This also reduces the heat load on the interior by 40%, compared to an instrument cooled entirely to 77K. FourStar will be cooled with liquid nitrogen (LN2). Motivating factors for this choice were the portability of LN2, the potential difficulties and complexities anticipated for cooling a rotating instrument with mechanical refrigeration, and the greater expense and long term maintenance challenge of mechanical refrigeration. The proven concept of a dewar with an independently cooled radiation shield (as pioneered by IR Labs) was adopted.

Much of the rest of the design details follow from these initial concepts and various essential constraints. The main opto-mechanical-thermal tradeoffs are between mounting the optics stiffly, but without introducing excessive heat loads. There are, however, other factors, the most important of which is the safety and handling of the detectors and associated internal electronics. The dangers to these devices are electrostatic discharge, rapid temperature cycling, mechanical stresses, and contamination. Each of these requires that we handle the detectors as little as possible, follow strict ESD protection procedures, and develop benign and robust cooling and warming procedures. Early estimates indicated that cooling or warming the dewar would take more than a day, so a further design constraint was to minimize the number of such cycles, especially in Chile. Ultimately our goal is to maintain the instrument at cryogenic temperatures and ready to work for many months, if not years at a time.

Finally, our design required a systematic set of procedures for testing the subassemblies, aligning the optics, and testing the detectors and readout electronics. The design goal is to test and certify all functions of the instrument before it is mounted on the telescope. This minimizes the use of valuable telescope for commissioning. These considerations have influence many of the basic choices adopted for instrument sub-assemblies.

Instrument Overview



Overall Description

- Wide-field JHKs survey camera for the Baade 6.5-m telescope at Las Campanas Observatory

- 4 2048x2048 HAWAII-2RG detectors (substrate removed)
- RWSC Sidecar ASICs
- Scale = 0.159”/pixel
- Format on the sky of 10.8’x10.8’
- Will remain at the f/11 Nasmyth port for long periods of time
- All-refractive optical design
- Operates the detectors at 77K and some of the optics at 200K
- Compensates for field rotation by rotating the entire instrument

Developers

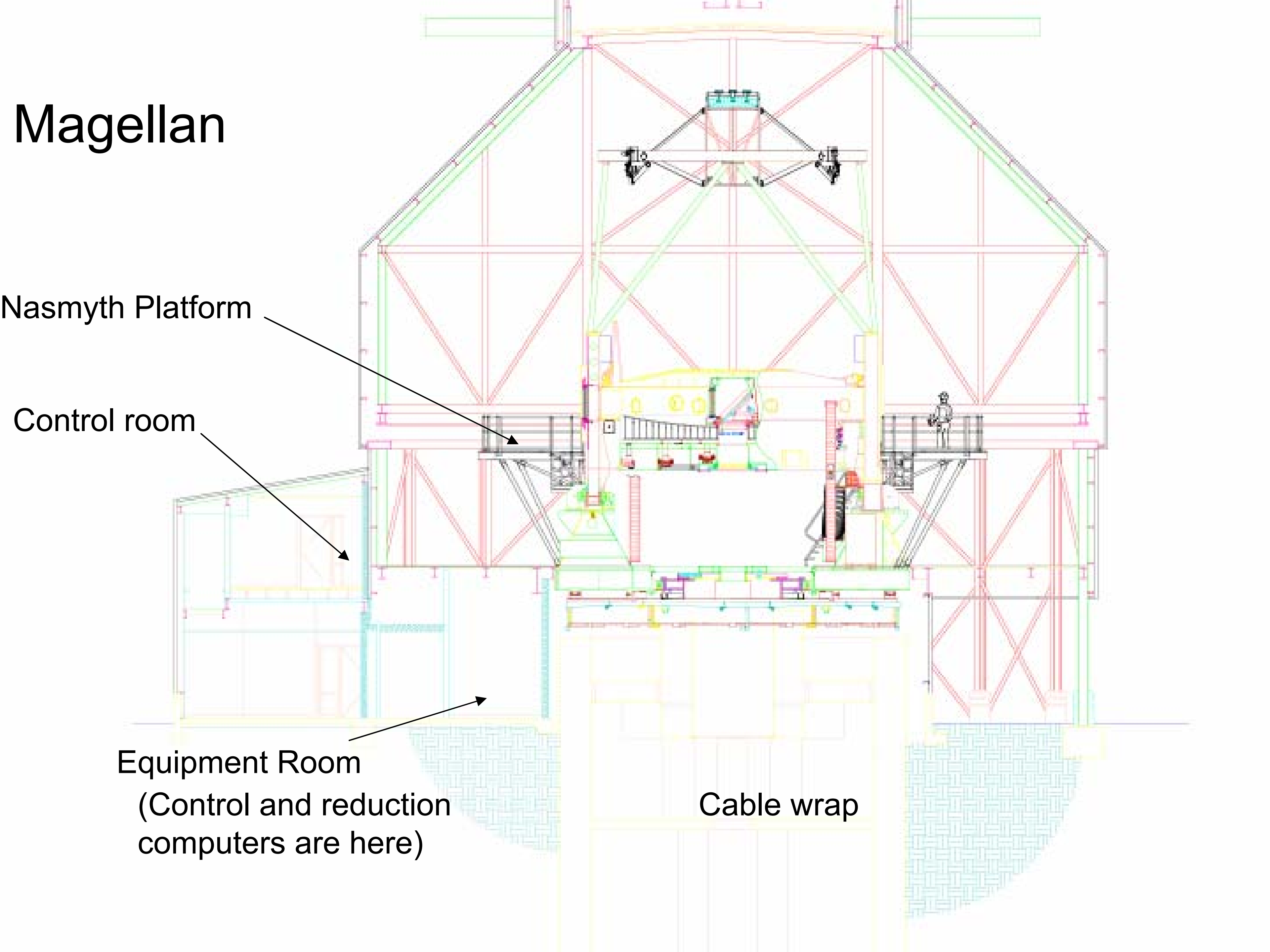
Eric Persson
David Murphy
Christoph Birk
Eric Koch
Alan Uomoto
Dan Kelson

Stephen Smee
Robert Barkhouser
Gregg Scharfstein
Joe Orndorff
Randy Hammond

Wendy Freedman
Charlie Hull, Steve Shectman, Frank Perez, …
Our machinists

Rockwell Scientific

Magellan


Nasmyth Platform
Control room
Equipment Room
(Control and reduction
computers are here)
Cable wrap

Science Capabilities

1. Deep JHKs, intermediate- or narrow-band imaging:
   High redshift galaxies, clusters, QSOs, …
2. Competition is tough: HAWK-I, WFCAM, NEWFIRM, and VISTA
3. Many extragalactic programs must therefore be done in the sweet spot between the factors of depth and area.
4. Available to a large user group in the Magellan Consortium.
5. This will be a “facility instrument”, i.e., one that can be handled on a routine basis by mountain staff.

Science/Engineering Requirements

Optical

1. The camera optics will not degrade the native image quality delivered by the telescope (best ever is 0.21” FWHM at Ks) by more than 0.03”. So instrument contribution should be less than 0.116” = 0.73 pixel.
2. The camera will operate in the JHKs bands. It was found during the design that the theoretical Y-band images did not meet the spec in #1.
3. The camera shall not increase the Ks (thermal) background from the telescope and sky by more than 10% under median conditions.
4. The images shall be excellent everywhere in the field and shall not move on the detector by more than 1/3 of a pixel over a 20 degree rotation of the instrument.
5. The scale shall be in the range 0.13 - 0.17 arcsec/pixel, with a coarser scale favored.
6. The FPAs shall be baffled so that only science plus sky photons entering the telescope pupil are detected, apart from those unavoidably produced by the dewar window, telescope optics, and secondary spiders.

Science/Engineering Requirements (cont'd)

Mechanical

1. The instrument shall weigh less than 4000 lbs.
2. It shall put no more load upon the guider/instrument rotator than is necessary.
3. All the optical, internal dewar, and mechanism designs shall be consistent with the image motion requirement above (#4).
4. There will be baffles and surface preps to guarantee #6 above.
5. There shall be enough filter positions to allow future additions for medium- and narrow-band observations.

Science/Engineering Requirements (cont'd)

Thermal

1. The camera optics shall reside at their design temperatures within 5K.
2. The thermal load on the inside of the instrument shall be minimized in order to reduce consumption of liquid nitrogen.
3. The above requirement (#2) must be satisfied simultaneously with the mechanical and image motion requirements.
4. The amount of attention given to IN2 filling by mountain staff shall be minimized.

Science/Engineering Requirements (cont'd)

Focal Plane Array (FPA) and Electronics

1. The FPAs will be four Rockwell Science Center (RWSC) HAWAII-2RGs.
2. The readout electronics will be based upon the RWSC "Sidecar" ASIC.
3. The FPAs shall be protected from temperature rates of change that could potentially cause fatal damage.

Control System and Software

1. The entire instrument shall be computer controlled so that minimal observer interaction will be required to execute a pattern of telescope moves and exposures such as is standard practice in near-infrared observations.
2. A data reduction system will be part of the instrument in the sense that fully reduced pictures will be finished by the next day, following a night's observing.

Optical/Mechanical/Thermal Design Overview

- 7 lenses, L3 - L6 are controlled at 200K, L7, filters, and detectors are at 77K
- Two lN_2 dewars, one filled automatically, one manually
- Larger dewar shields the inner (smaller) one
- Instrument rotates on its cart
- Cooldown and warmup are serious
- Design minimizes handling of detectors

TAB 3

3. Sample Science Programs

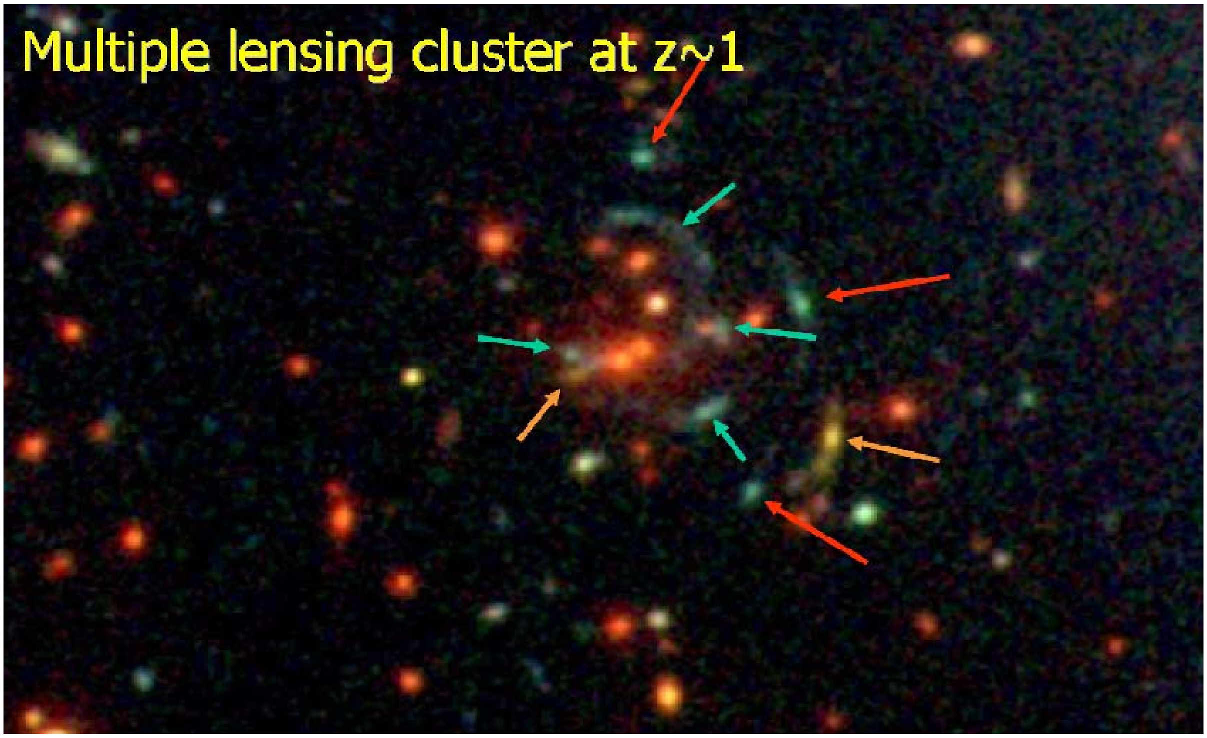
The FourStar instrument will provide the Magellan community with a powerful new scientific capability. The outstanding image quality of Magellan and the Las Campanas site, coupled with the high performance and large field of view of FourStar will enable a range of survey and targeted science programs. Near-IR imaging programs will advance the study of cool and obscured objects within the Milky Way and local universe, and will enable a wide range of science at intermediate and high redshift.

Magellan's location at a premier southern hemisphere site will enable FourStar to carry out studies of star formation and early stellar evolution in the largest and nearest star forming complexes. The Orion, Taurus and Ophiuchus molecular complexes are prime laboratories for star formation studies. The galactic center and bulge offer well-placed targets for stellar evolution studies, as do the Magellanic Clouds. FourStar will enable synergistic studies with ALMA and space-based mid-IR missions in the coming decade.

The strongest science motivations for FourStar within OCIW center on studies of the distant universe. Near-IR imaging surveys allow one to select galaxies on the basis of their stellar mass and to trace the evolution of rest-frame visible light to early epochs. We will use FourStar to study the growth of stellar mass and assembly of galaxies in the critical $1 < z < 2$ epoch with surveys of intermediate area and depth. Many of these will build on existing surveys at other wavelengths. The near-IR wavelengths provide critical leverage in determining the mass and star formation histories of passively evolving systems. Ultra-deep surveys will allow us to trace the evolution of the most massive galaxies in the $2 < z < 4$ era when the first massive stellar systems may have appeared. FourStar will complement the spectroscopic capabilities of IMACS and LDSS3 and allow powerful surveys over a wide range of redshifts.

Galaxy clusters provide convenient laboratories for studies of early star formation and rapid dynamical evolution. A new generation of distant cluster surveys are either now underway or in advanced planning stages. Large area surveys with the Dark Energy Camera at Cerro Tololo will yield hundreds of candidate clusters at $z > 1$. Similarly, surveys using the South Pole S-Z Array will produce samples of thousands of galaxy clusters. Near-IR imaging provides and efficient means of selecting the most interesting clusters on the basis of photometric redshifts and richness estimators.

The most massive clusters offer the additional benefit of being powerful gravitational telescopes. Cluster arcs provide a unique window on intrinsically faint galaxies in the early universe. The most distant cluster-arc-sources are best detected in the near-IR as most of their optical flux is absorbed by the IGM. Y, J and K imaging, combined with I or z' imaging in the visible will allow one to identify the highest redshift arcs and gauge their stellar populations.



FourStar provides a new set of capabilities for the large and diverse Magellan users community. The programs described above offer just small sampling of the science that will be enabled by this instrument.

FourStar

Science With Magellan & FourStar

Patrick McCarthy
Carnegie Observatories

JOHNS HOPKINS
UNIVERSITY

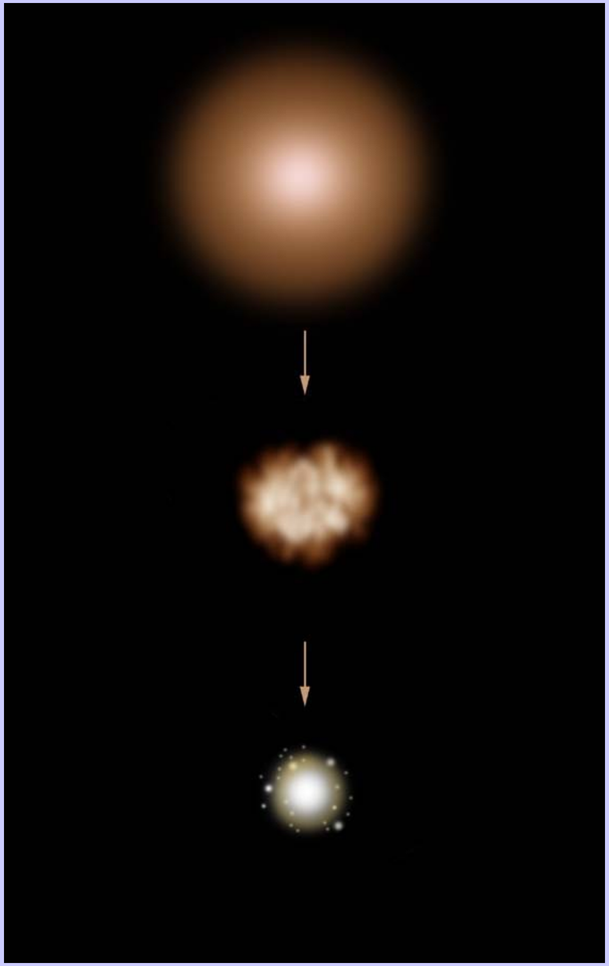
Key Attributes of FourStar & Magellan

- **Large field of view and collecting area**
  - *Largest field IR imager on an 8-m class telescope*
- **Outstanding image quality**
  - *Median K-band seeing ~ 0.4”, best 1/4^{tile} ~ 0.25”*
- **State of the art detectors and electronics**
  - *Hawaii 2RG, reference pixels, ASIC controllers*
- **Steady access to telescope and instrument**
  - *Enables long-term ambitious programs*

Key Science Drivers

- **Stellar Populations in Obscured Environments**
- **Star Formation**
- **Planets and other sub-stellar mass objects**
- **Galaxy Formation and Evolution**
  - Growth of structure
  - Assembly of stellar mass
  - Star formation histories
  - Cluster evolution and lensing

Science with FourStar



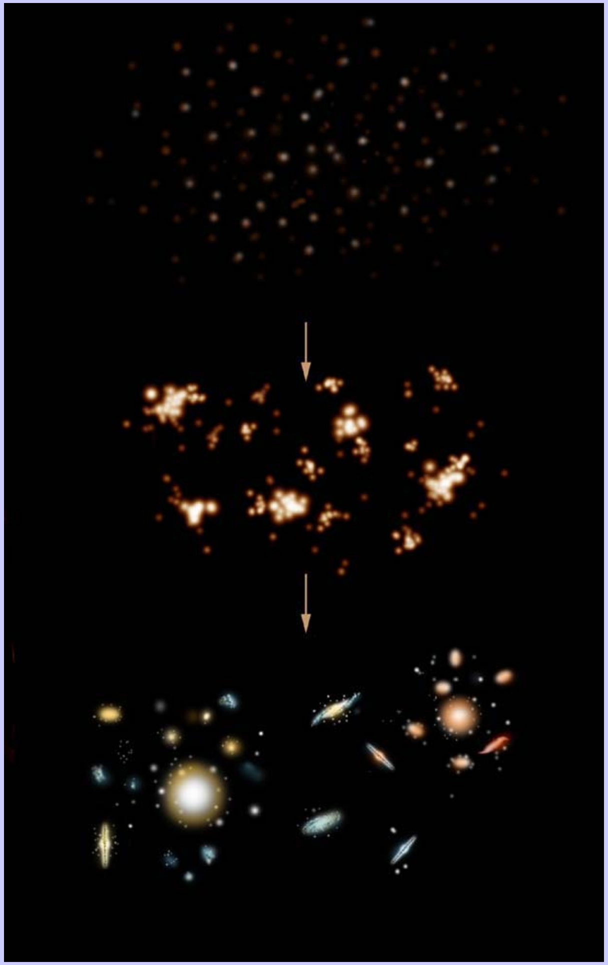
Monolithic Collapse
ala ELS

How

Did

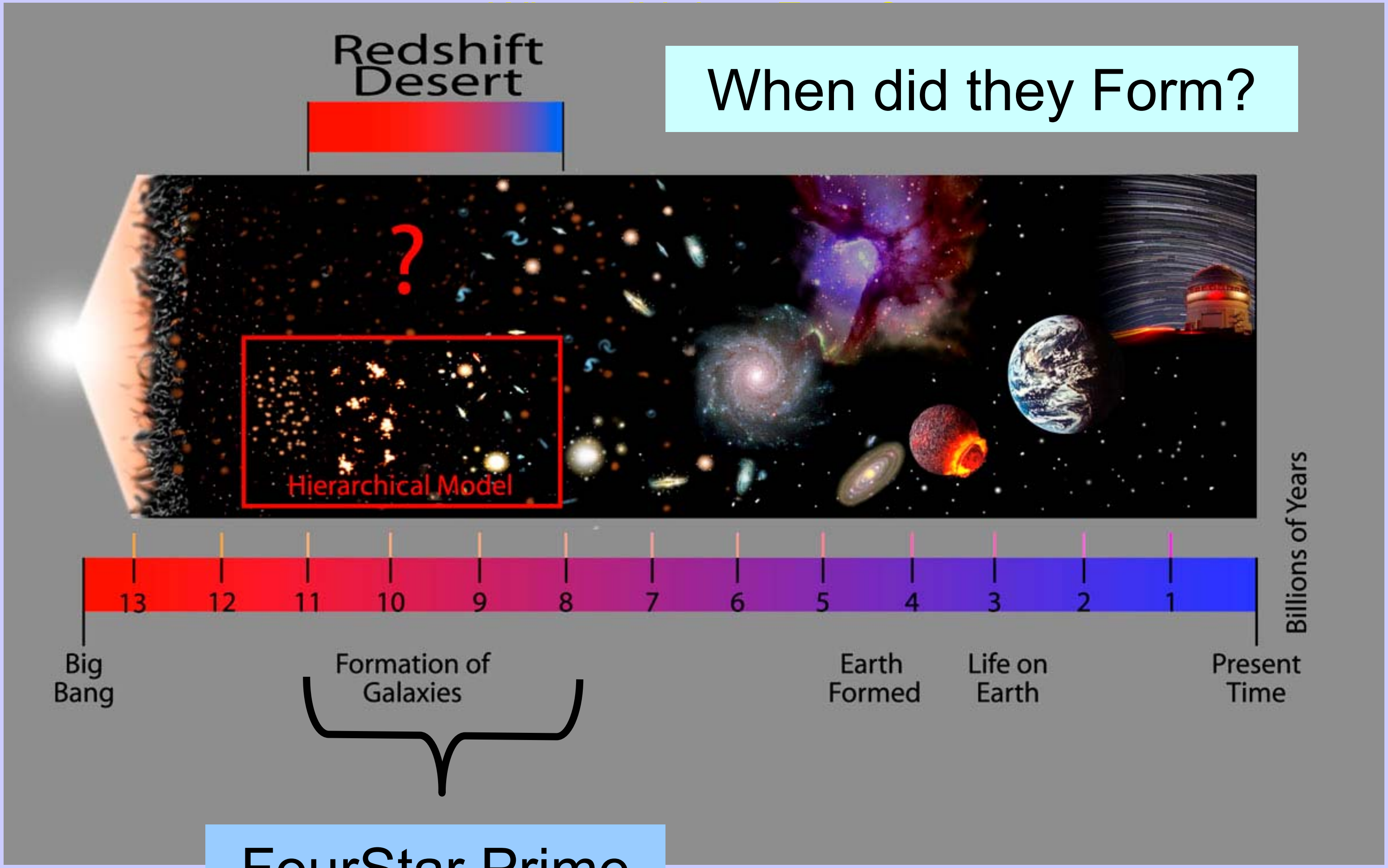
Galaxies

Form?



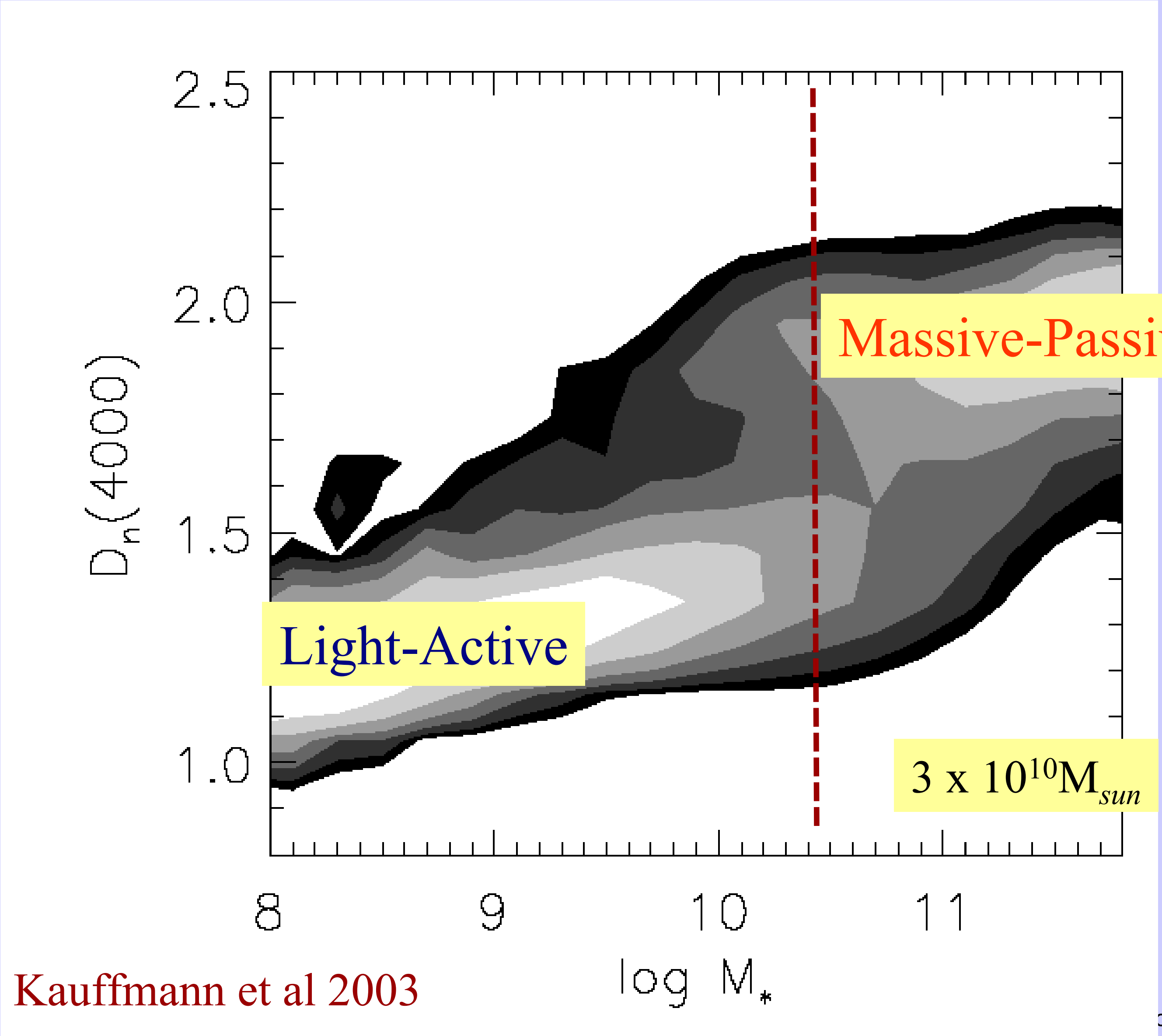
Hierarchical
Assembly

Science with FourStar



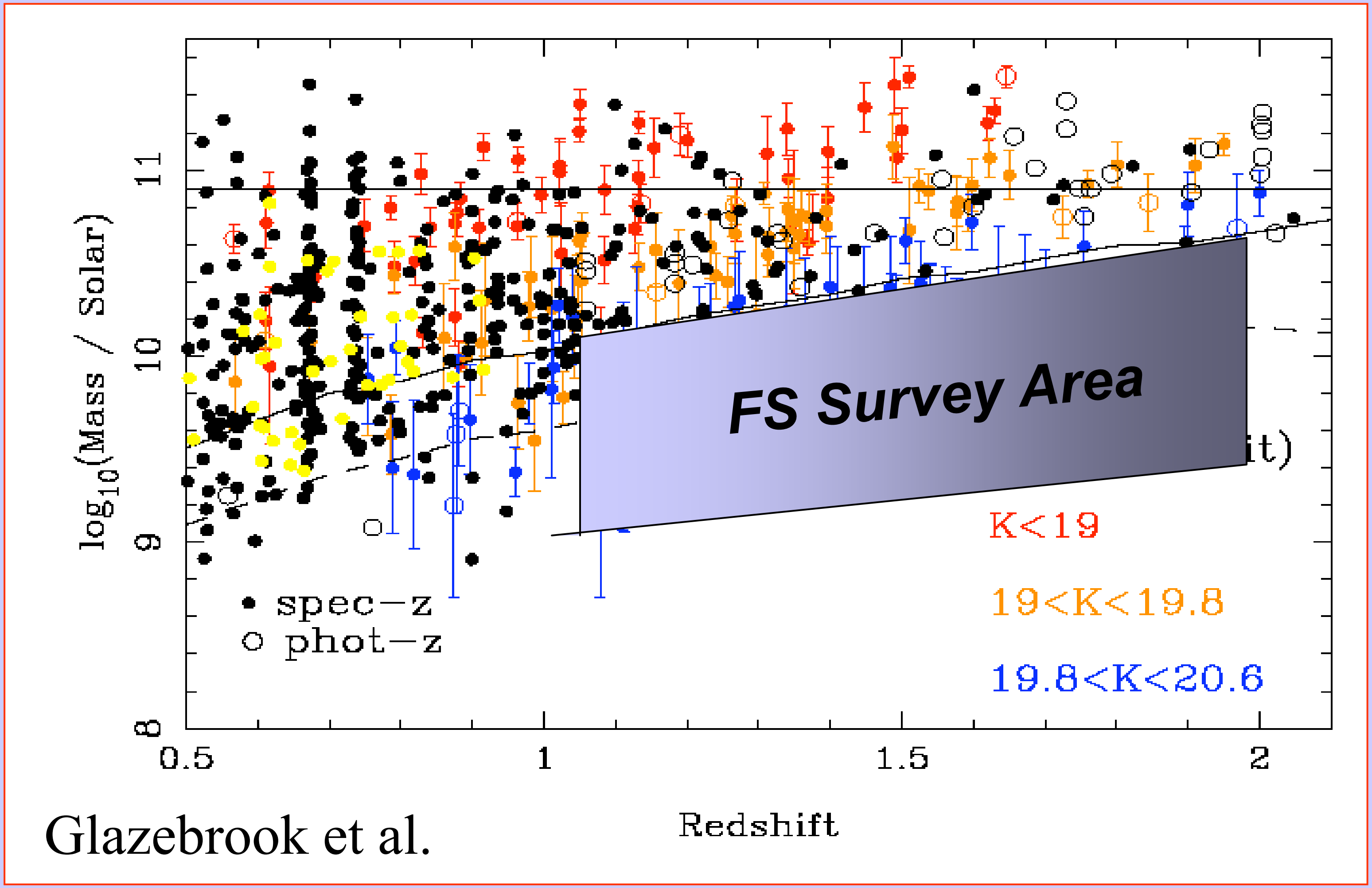
FourStar Prime Sensitivity

Science with FourStar



Science with FourStar

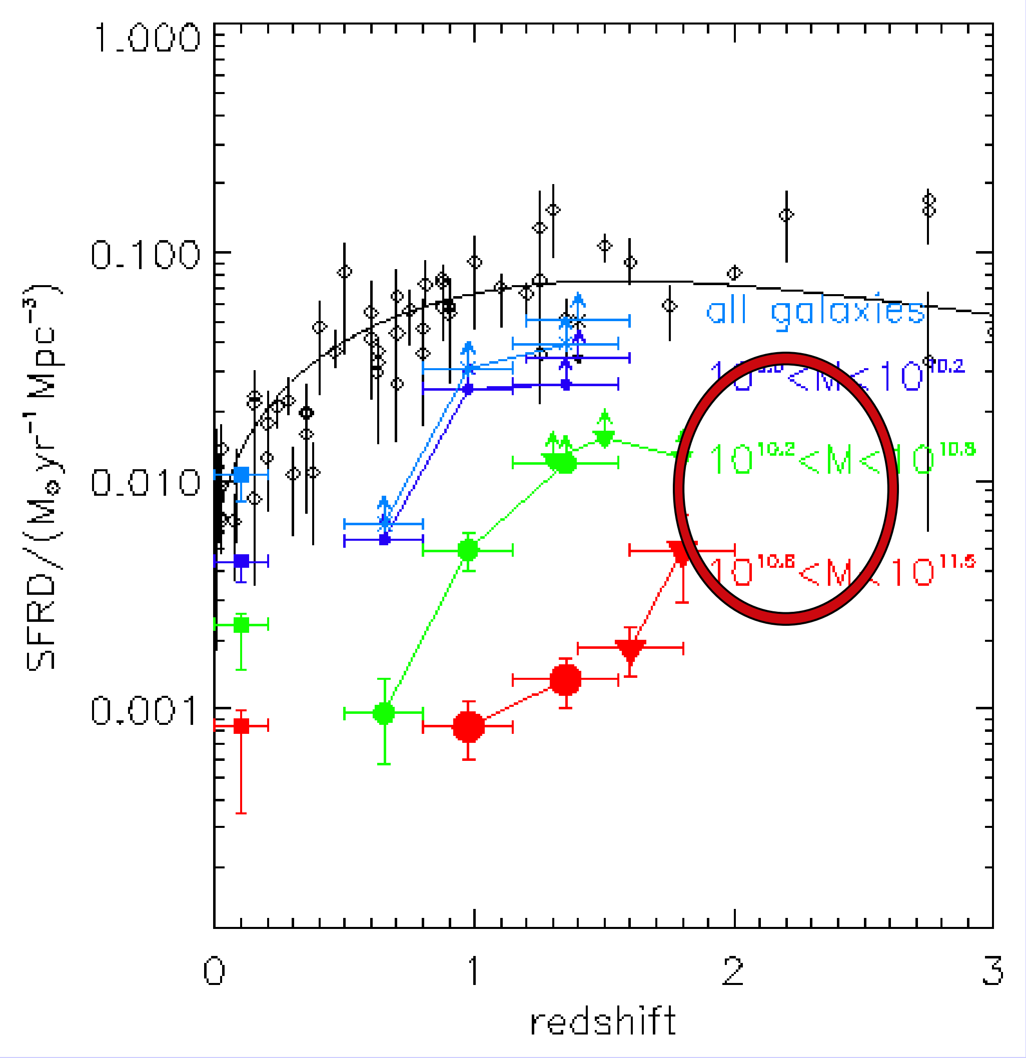
Probing Galaxy Assembly below M^*



Science with FourStar

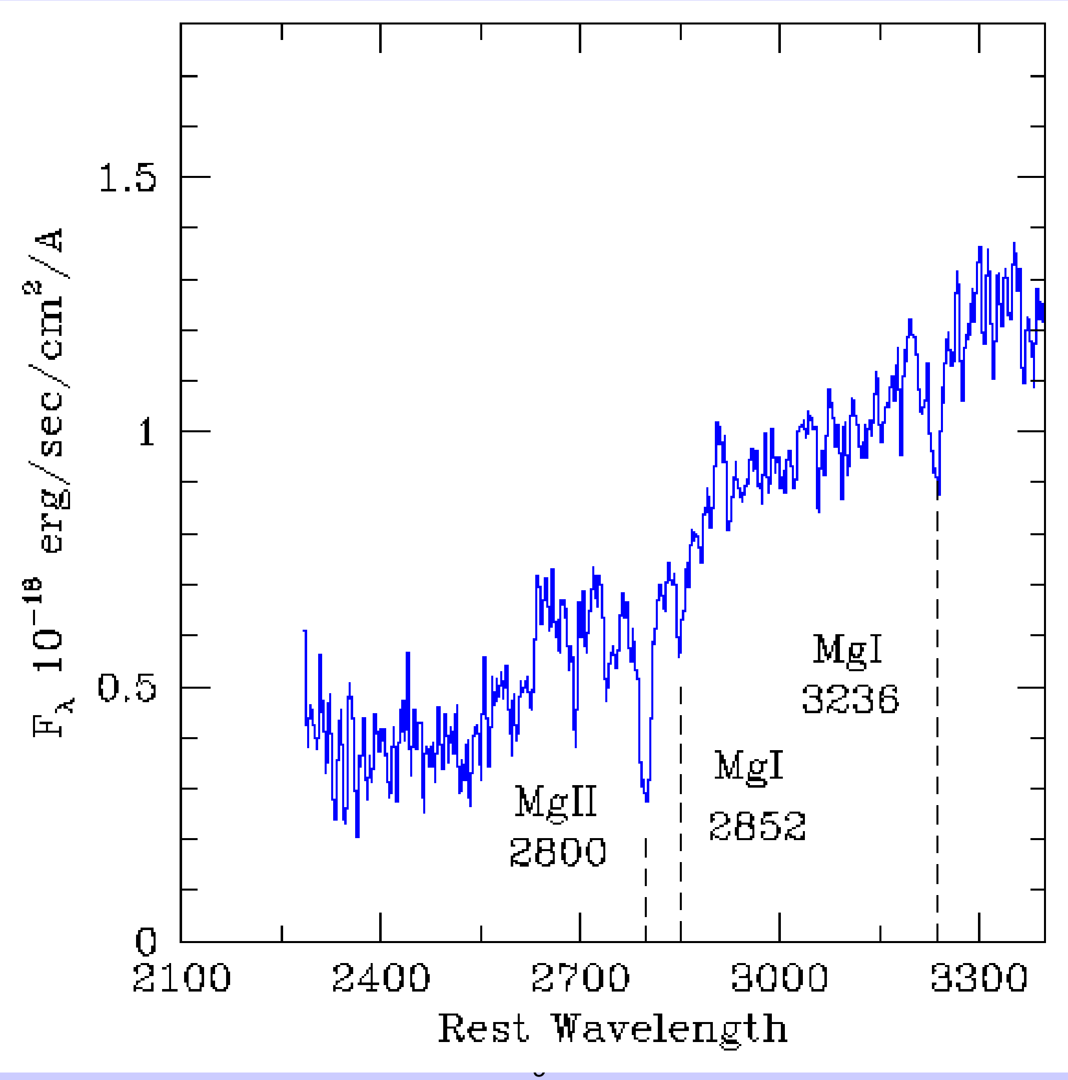
The Epoch of Massive Galaxy Formation

Juneau et al.



Science with FourStar

Old Galaxies at z ~ 2



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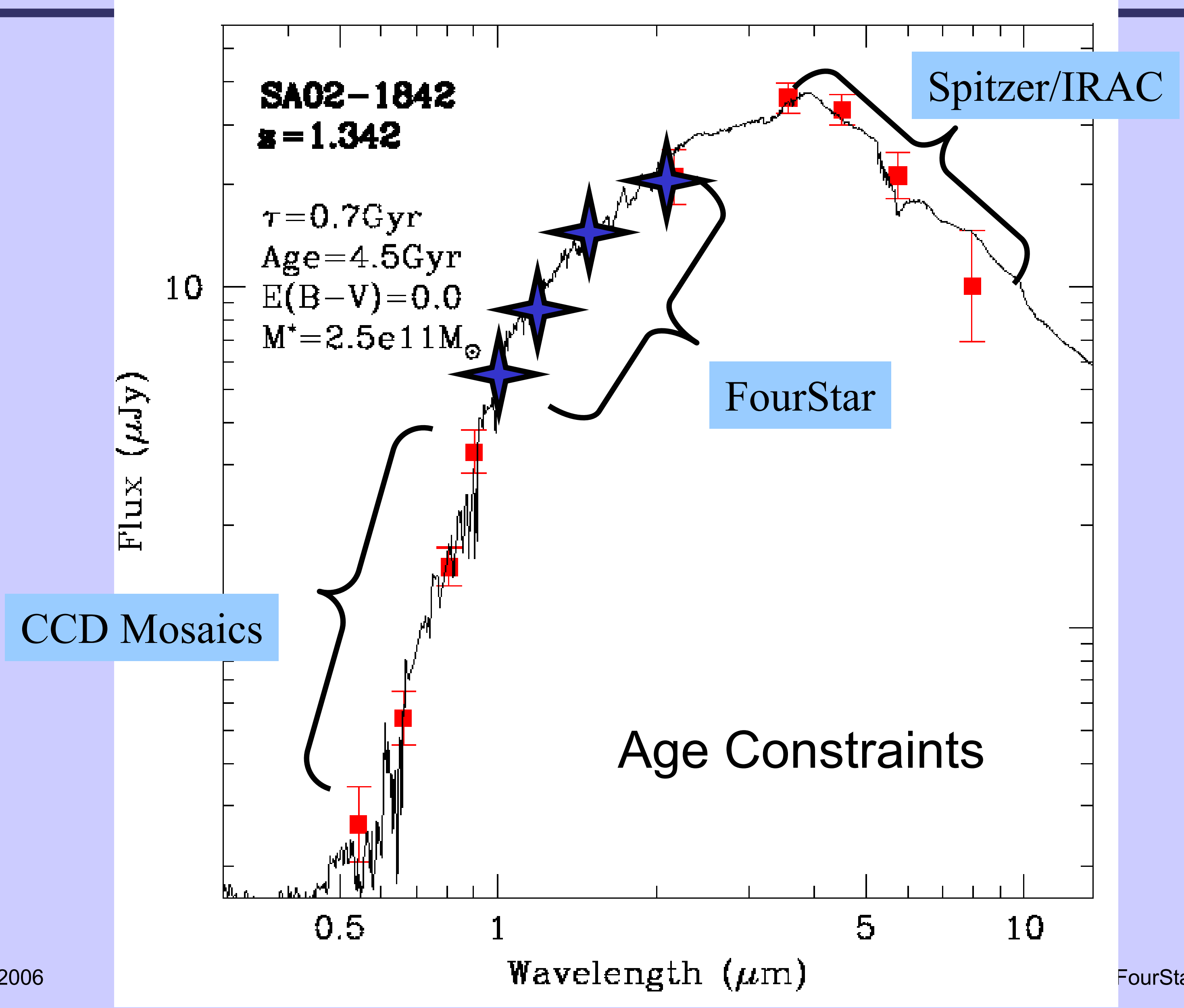
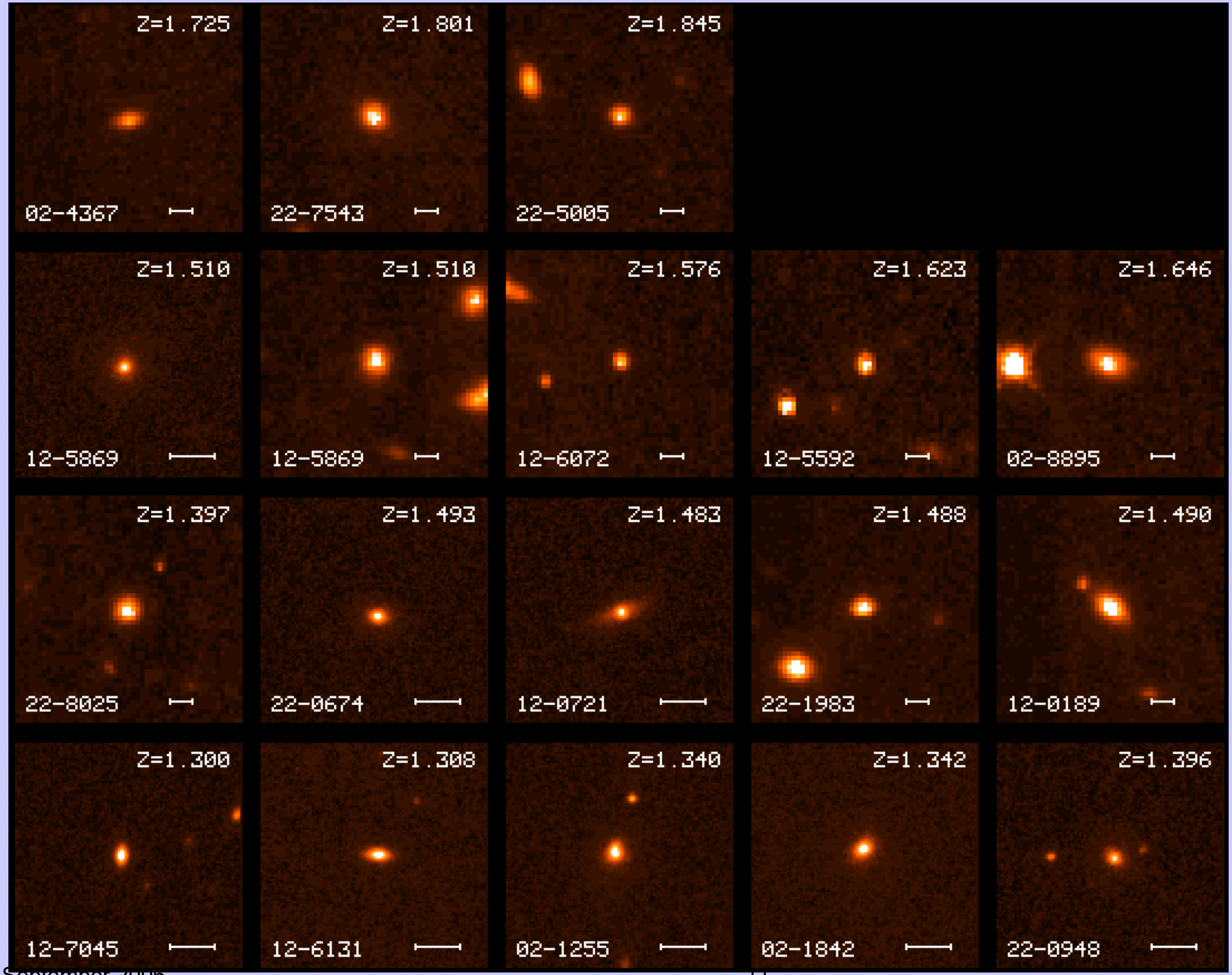


Science with FourStar



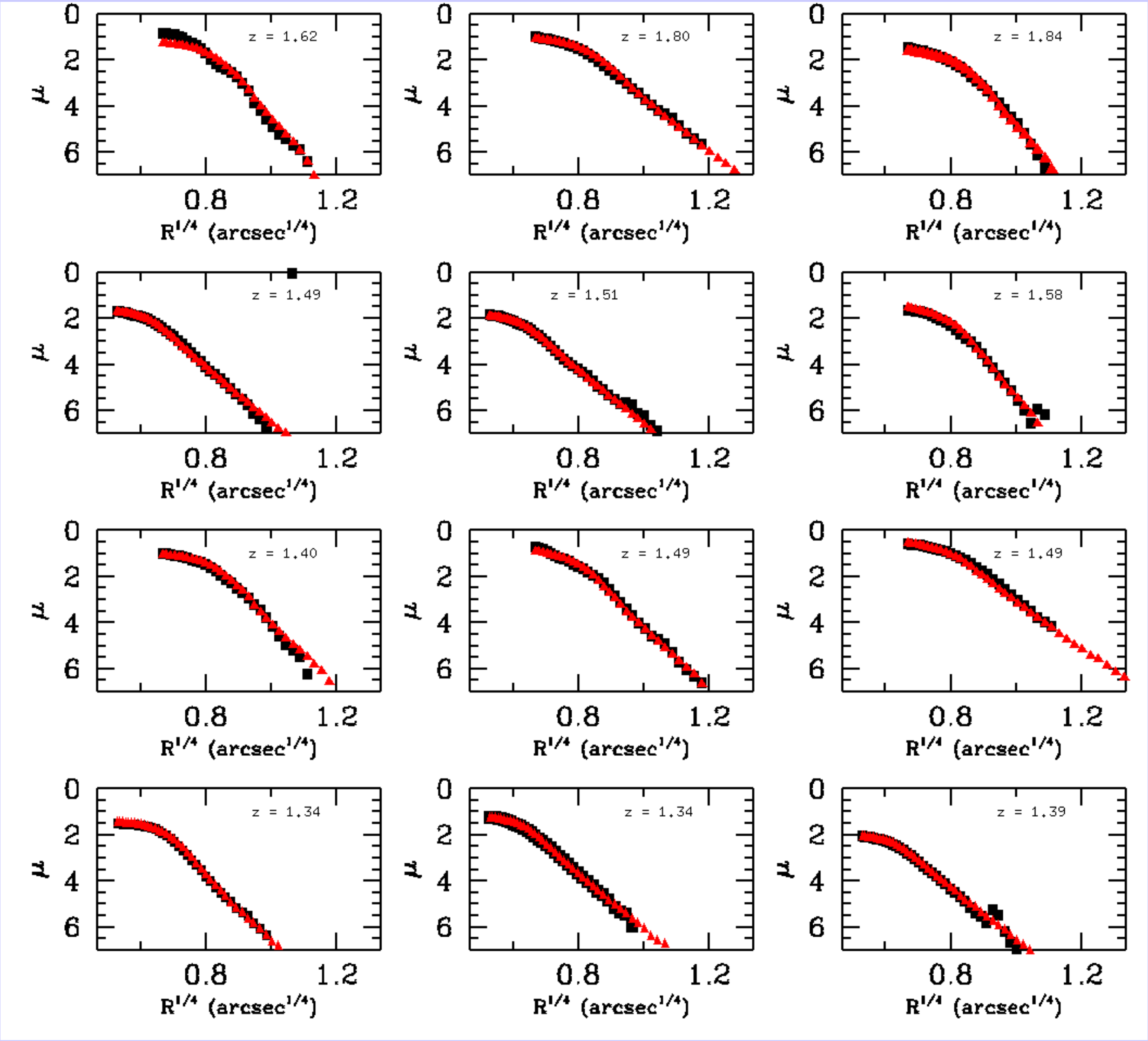
NICMOS

Images of distant passive galaxies

75-80%

Spheroids

Science with FourStar



Distant

Massive

Galaxies

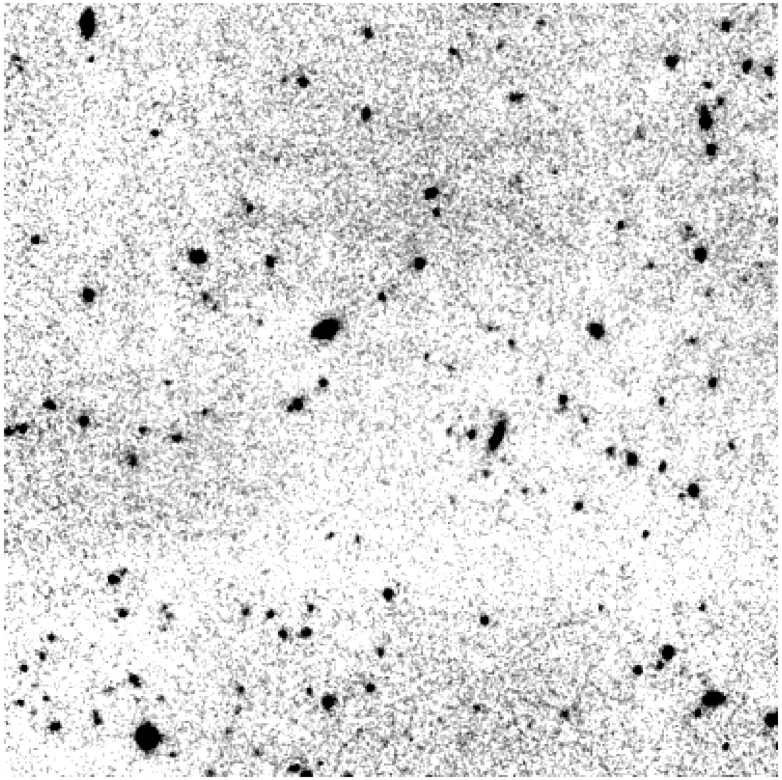
are

Small

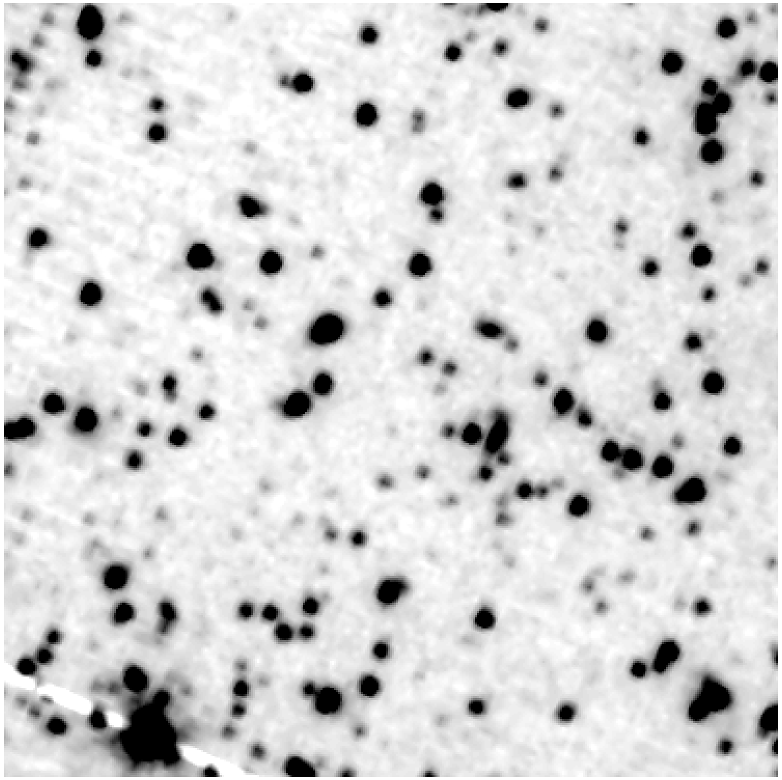
$0.3 < R_e < 1''$

Science with FourStar

Spitzer provides deep survey fields…..

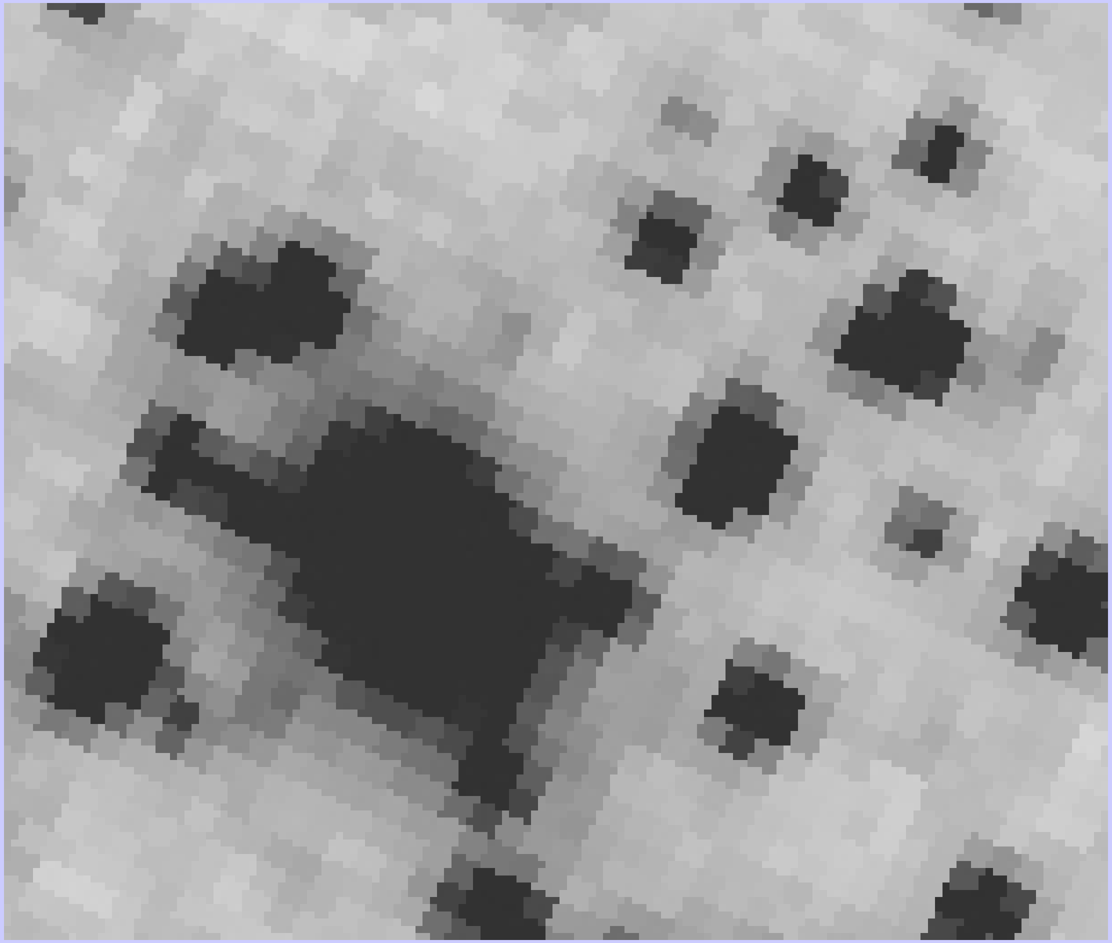


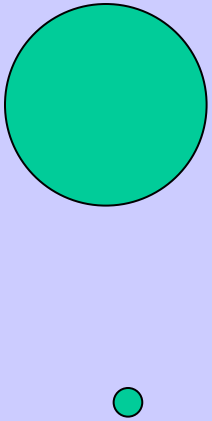
du Pont WIRC



Spitzer IRAC

…but a very soft PSF



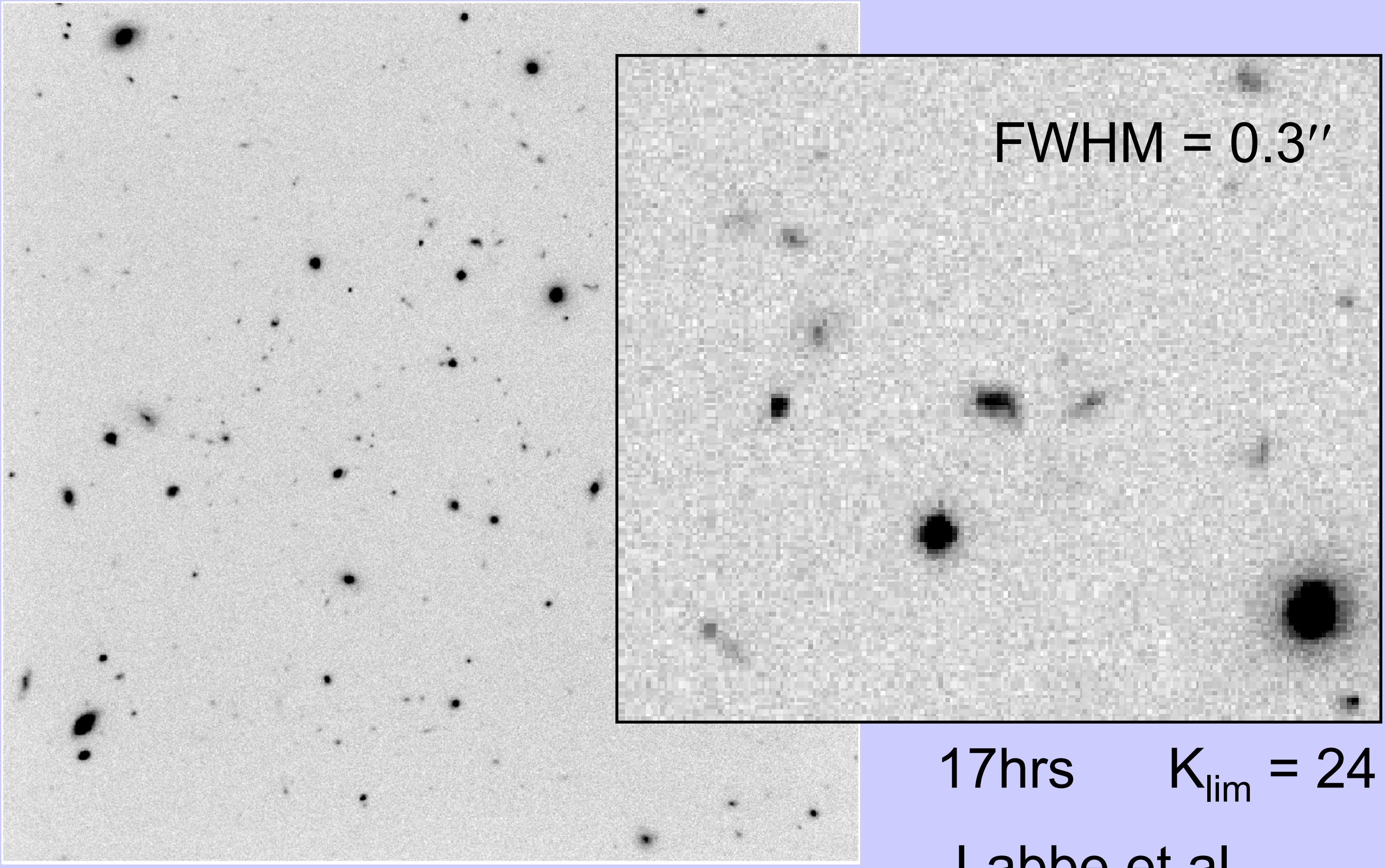


IRAC 3.6μm
2″ FWHM

PANIC 2.2 μm
0.3″ FWHM

Science with FourStar

Magellan near-IR Seeing



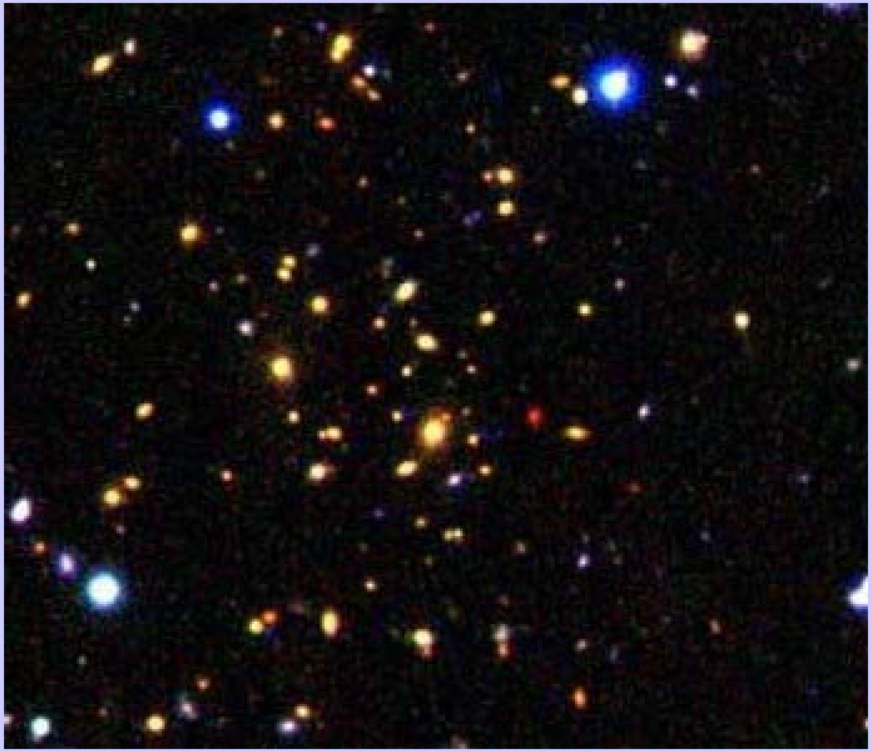
17hrs $K_{lim} = 24$

Labbe et al.

Science with FourStar

The Red-Sequence Method:
Galaxy Evolution from z=0 to 1.0

Coma   z=0.02 (optical)

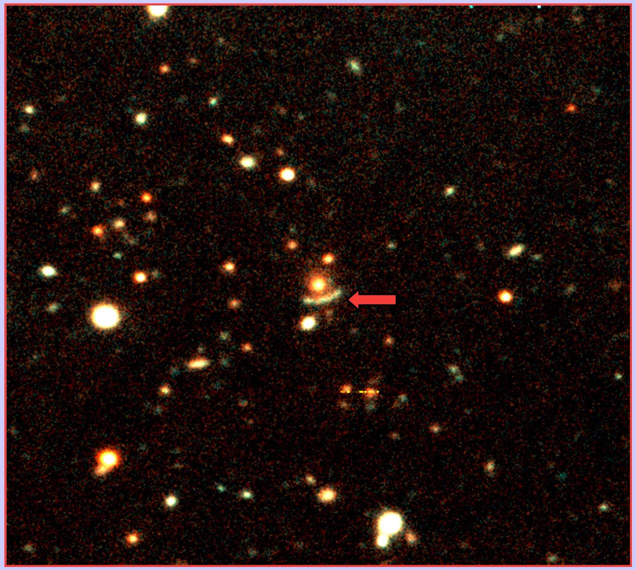


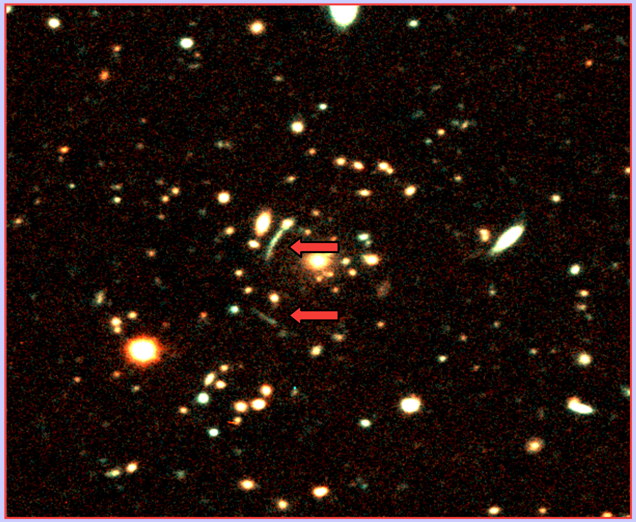
RCS 0439-2904 z=0.97 (IR)

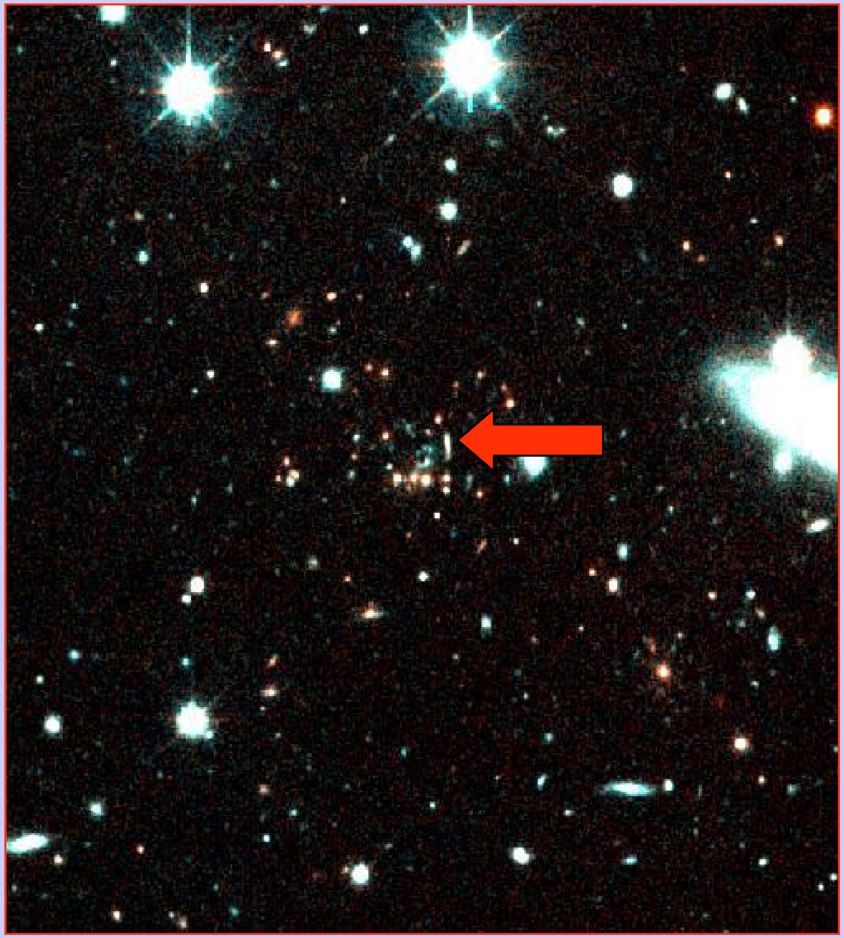
Science with FourStar

Rich Galaxy Cluster at Z=1.10

Science with FourStar







Science with FourStar

Science with FourStar

Representative FourStar Science Programs

- Deep JHK_s Survey of COSMOS 2° ACS field
  - *probing large scale structure at 0.8 < z < 2*
- Deep JKs Survey of ECFS
  - *galaxy evolution at z ~ 3*
- Follow-up of DEC Cluster Survey
  - constraining dark energy
- Imaging of South Pole SZ sources
  - galaxy evolution in very distant clusters

TAB 4

4. Optical Design

FourStar

Optical Design

Robert Barkhouser

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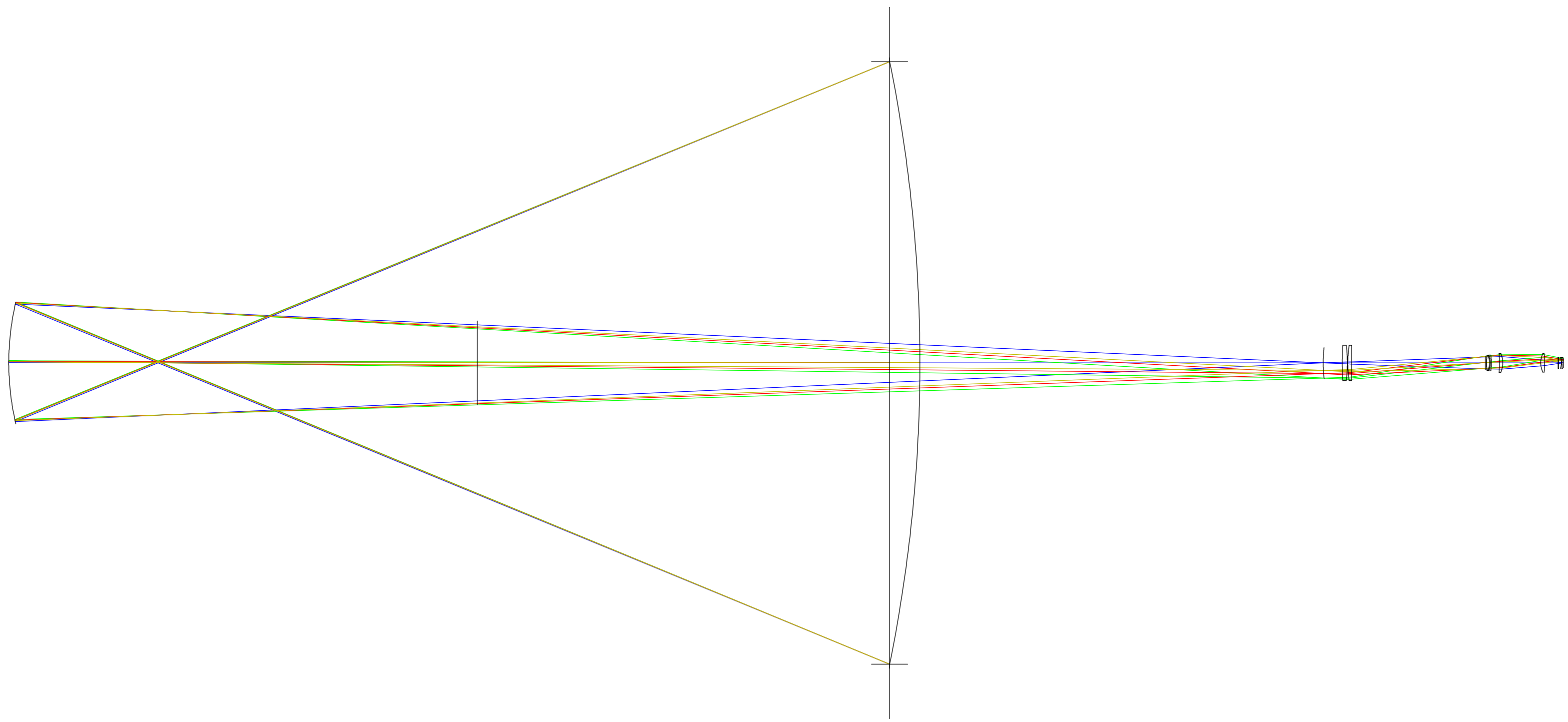
JOHNS HOPKINS
UNIVERSITY

Optical Design

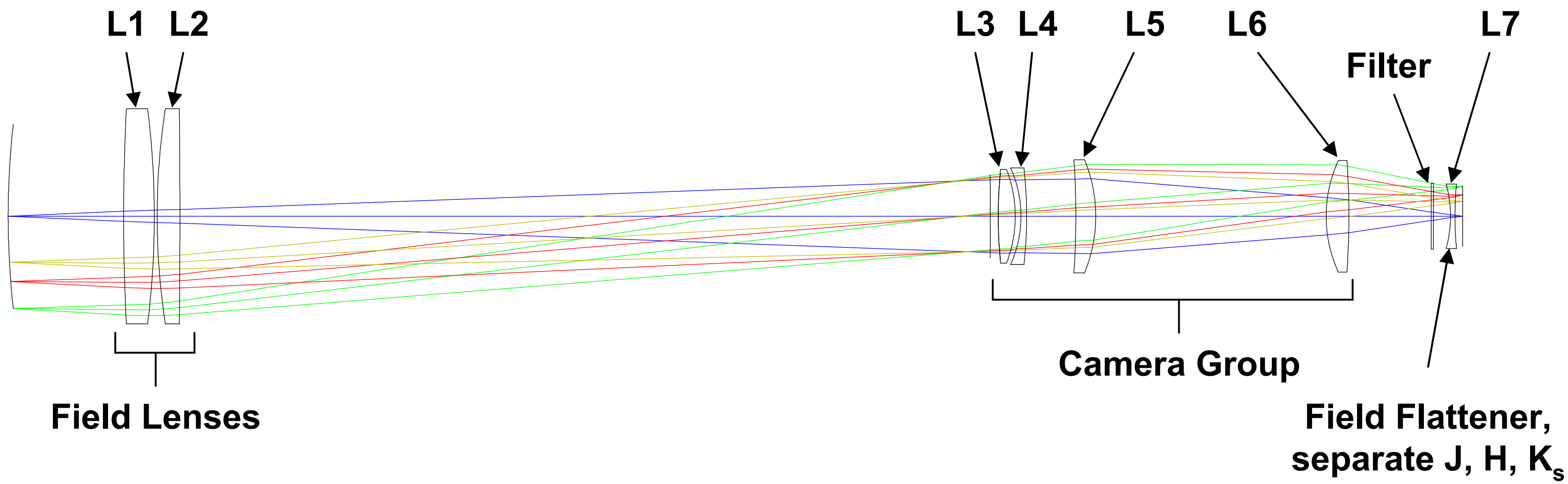
Layout with Magellan Telescope



- 6.5 m, f/1.25 primary with f/11 Gregorian secondary
- Telescope plate scale is 2.88"/mm or 347 μm/arcsec
- Telescope capable of delivering 0.3" FWHM images

Optical Design

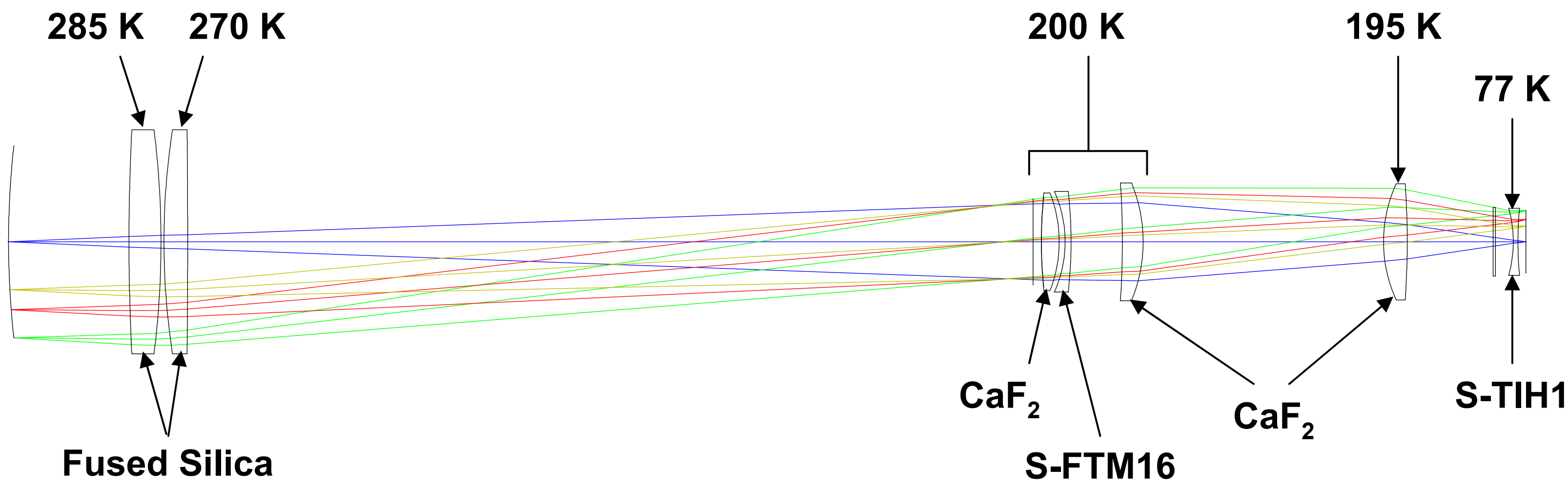
Overview



- f/3.6 imager (magnification = 0.33)
- Optical design is similar to PANIC in spirit
- Plate scale of 0.16"/pixel over an 11' x 11' field of view
- Optimized for J (1.25 µm), H (1.65 µm), and K_s (2.15 µm) bands
- Single asphere (front surface of L3) greatly increases field of view
- Field lens doublet reimages pupil in front of camera group; split to reduce thermal gradients; first element acts as vacuum window

Optical Design

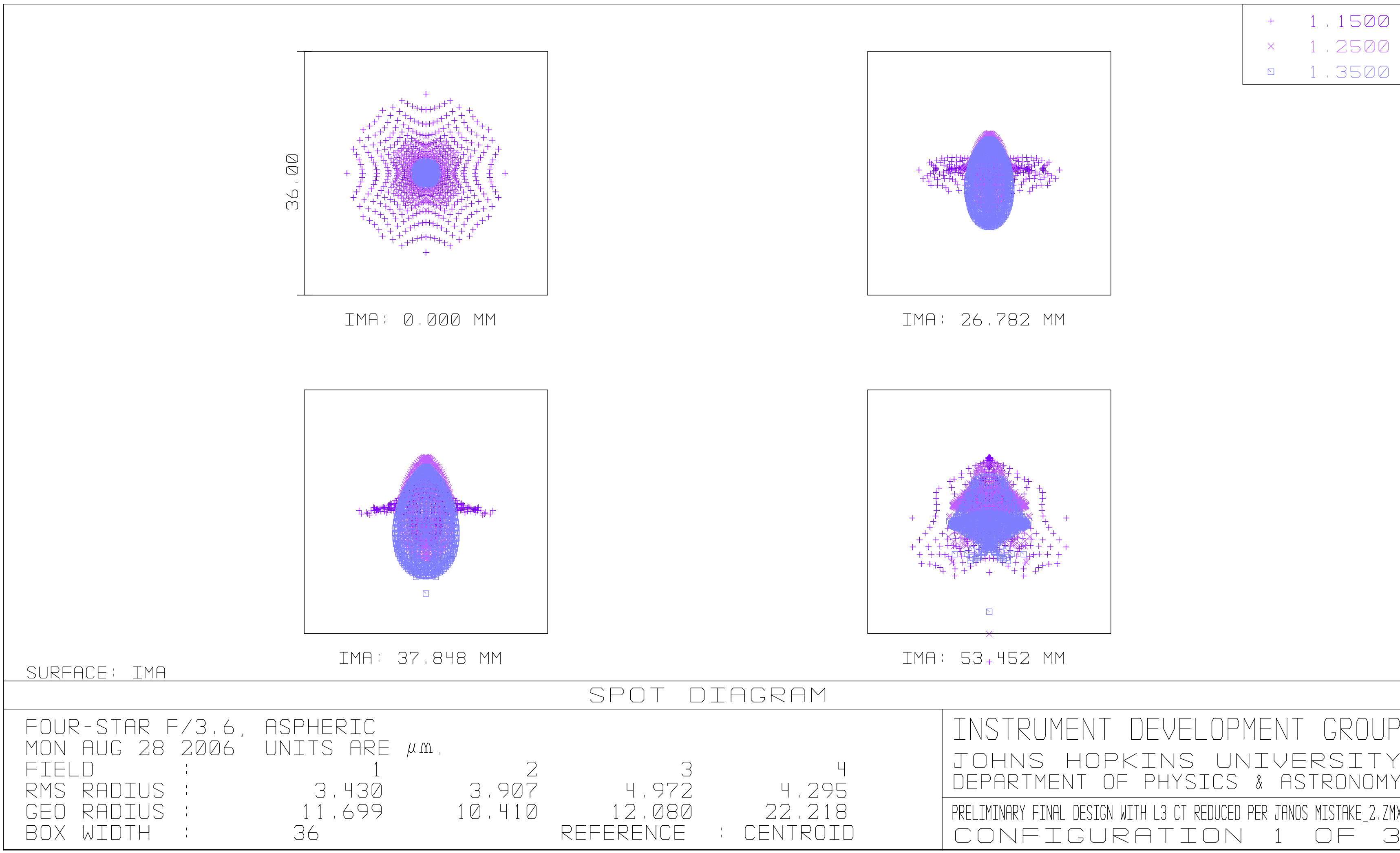
Overview (cont.)



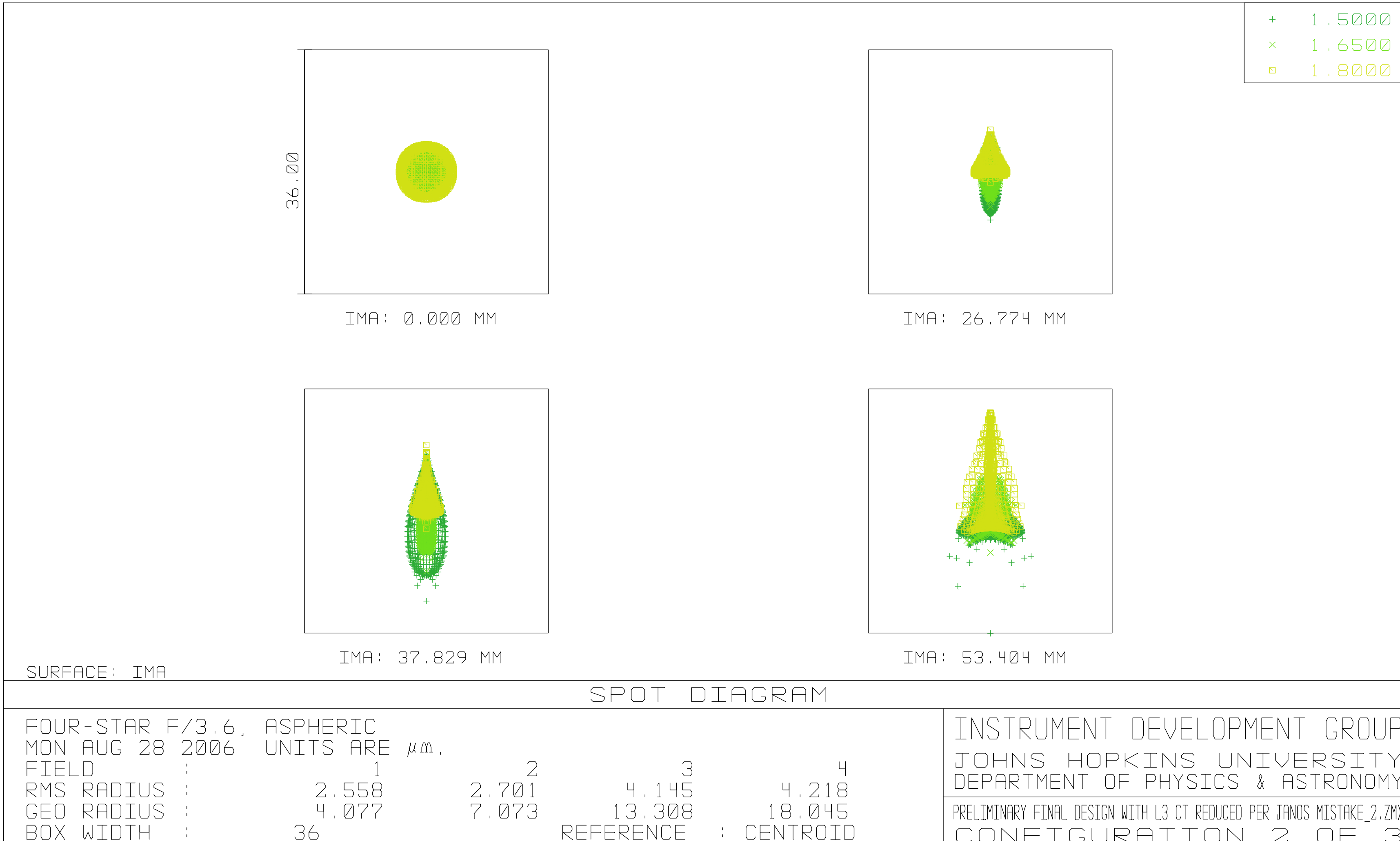
- Distance from L1 to detector is ~ 2.4 m
- 380 mm Ø fused silica field lens; 200 mm Ø CaF_2 camera elements
- Temperature decreases from first element to last:
  - Field lenses near room temperature
  - Camera elements ~ 200 K
  - Field flattener ~ 77 K

Optical Design

Spot Diagrams – J

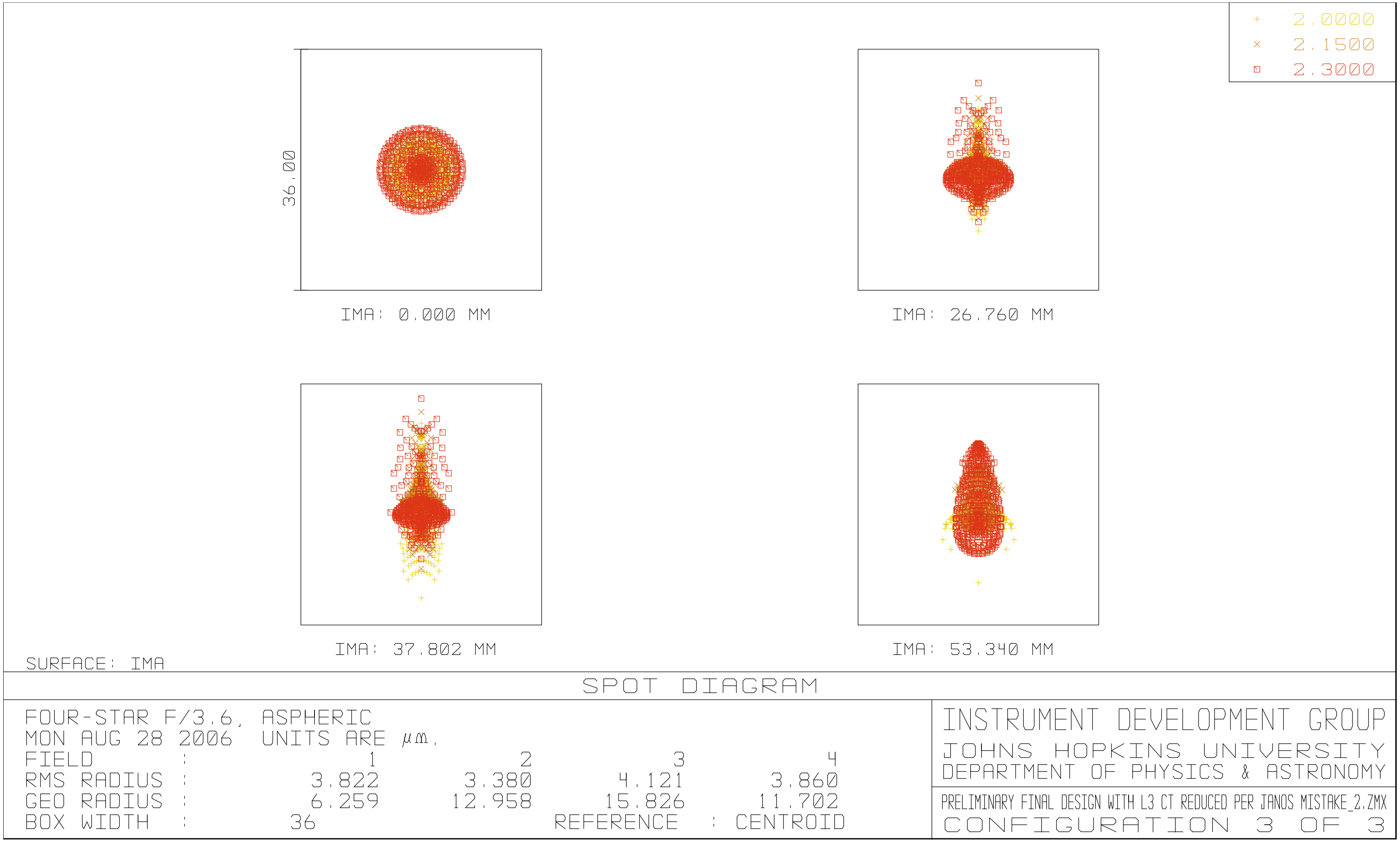


Spot Diagrams – H



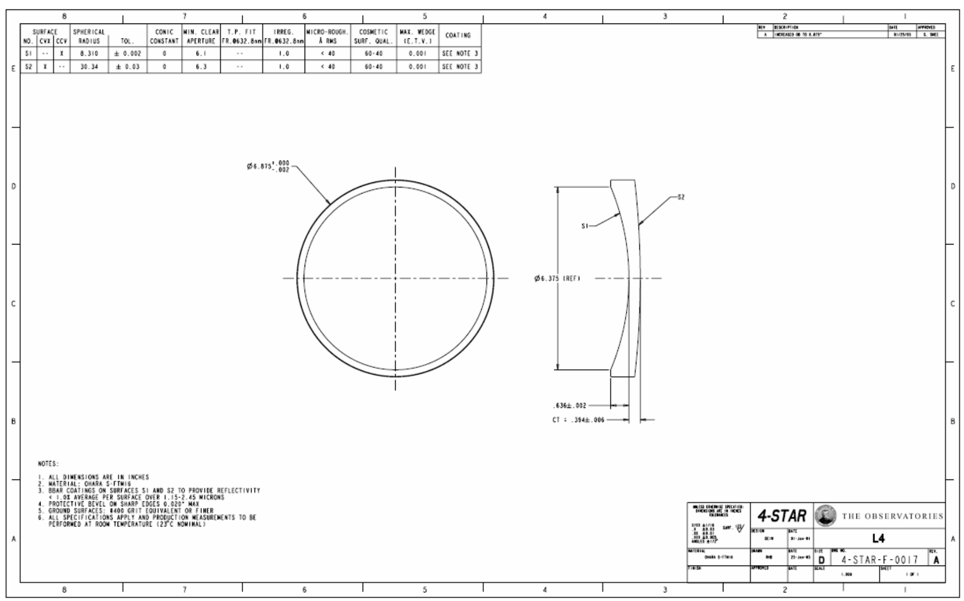
Optical Design

Spot Diagrams – K_s



Tolerance Analysis Goals

- **Establish decenter, tilt, and spacing sensitivities to help guide the optomechanical design**
- **Establish a set of fabrication tolerances for each element which balances manufacturing difficulty against performance degradation**



Optical Design

Tolerance Errors Considered

- **Optomechanical**
  - Element decenter
  - Element tilt
  - Element spacing
  - Group decenter
  - Group tilt
  - Group spacing
- **Optical fabrication**
  - Index of refraction
  - Surface radius of curvature
  - Surface irregularity
  - Wedge
  - Center thickness
  - Asphere surface decenter

144 individual tolerance errors were included in the analysis

Optical Design

Tolerance Analysis

- **ZEMAX used for this work**
- **Sensitivity analysis:**
  - **Considers the effect of each tolerance applied individually**
  - **Indicates which tolerances must be tight, which can be loose**
- **Monte Carlo analysis:**
  - **Applies a random amount of error for each tolerance to the system, within the limits set for that particular tolerance**
  - **The combined effect of all tolerances simultaneously can then be analyzed, for the given set of random errors**
  - **Many such systems are simulated to build meaningful statistics**
  - **The results provide insight into the likelihood that our *one* system will deliver the desired optical performance**

Optical Design

Tolerance Analysis

What is the allowable performance degradation?

Assume telescope can deliver 0.3" images, or 2 pixels.

Then a 1 pixel blur due to optics gives approximately:

$$\sqrt{(2^2 + 1^2)} = 2.2 \text{ pixels}$$

For a Gaussian with HWHM = 1, σ = 0.85.

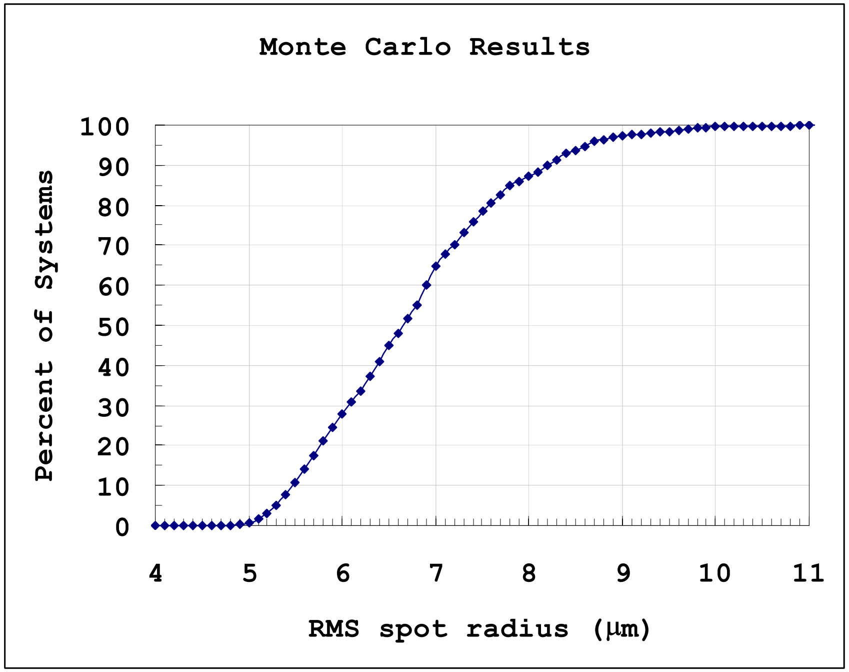
If we want optics FWHM < 1 pixel, then we need σ < 7.65 μm.

Monte Carlo Results

```
Monte Carlo Analysis:
Number of trials: 1000

Initial Statistics: Normal Distribution

Nominal      0.004606
Best         0.004739 Trial     80
Worst        0.011570 Trial    122
Mean         0.006743
Std Dev      0.001051

Compensator Statistics:
Change in back focus:
Minimum            :        -1.484133
Maximum            :         1.552783
Mean               :        -0.013451
Standard Deviation :         0.480224

98% <=       0.009300
90% <=       0.008181
50% <=       0.006654
10% <=       0.005469
 2% <=       0.005121

End of Run.
```

Nominal merit function:
RMS spot radius (σ) = 4.6 μm

>80% of the systems are better than σ = 7.65 μm



Optical Design

Optical Tolerance Diagram

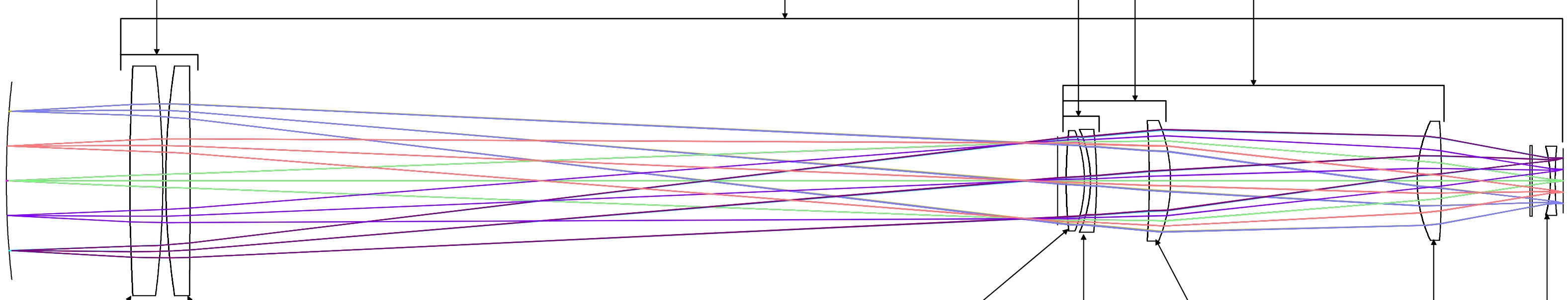
SYSTEM	Tolerance
Spacing	N/A (focus telescope)
Decenter	0.040"
Tilt	0.02 deg.

L3-L6	Tolerance
Spacing	0.020"
Decenter	0.005"
Tilt	0.01 deg.

L3-L5	Tolerance
Spacing	0.003"
Decenter	0.001"
Tilt	0.01 deg.

L1-L2	Tolerance
Spacing	0.020"
Decenter	0.020"
Tilt	0.015 deg.

L3-L4	Tolerance
Spacing	0.003"
Decenter	0.001"
Tilt	0.01 deg.



L1	Tolerance	
	S1	S2
Radius	1/100	1/100
Irregularity	8 fringes	8 fringes
Wedge	0.010" TIR	0.010" TIR
Index	0.0005	
Thickness	0.020"	
Spacing	From group	
Decenter	0.002"	
Tilt	0.0085 deg.	

L2	Tolerance	
	S1	S2
Radius	1/200	1/100
Irregularity	8 fringes	8 fringes
Wedge	0.010" TIR	0.010" TIR
Index	0.0005	
Thickness	0.020"	
Spacing	0.003"	
Decenter	0.002"	
Tilt	0.0085 deg.	

L3	Tolerance	
	S1	S2
Radius	1/1000	1/5000
Irregularity	0.25λ RMS	2 fringes
Wedge	1.0 arcmin	0.001" TIR
Decenter	0.004"	N/A
Index	0.0005	
Thickness	0.006"	
Spacing	From group	
Decenter	0.0015"	
Tilt	0.0085 deg.	

L4	Tolerance	
	S1	S2
Radius	1/5000	1/1000
Irregularity	2 fringes	2 fringes
Wedge	0.001" TIR	0.001" TIR
Index	0.0005	
Thickness	0.006"	
Spacing	0.003"	
Decenter	0.0015"	
Tilt	0.0085 deg.	

L5	Tolerance	
	S1	S2
Radius	1/200	1/5000
Irregularity	2 fringes	2 fringes
Wedge	0.001" TIR	0.001" TIR
Index	0.0005	
Thickness	0.010"	
Spacing	0.003"	
Decenter	0.002"	
Tilt	0.01 deg.	

L6	Tolerance	
	S1	S2
Radius	1/1000	1/200
Irregularity	8 fringes	8 fringes
Wedge	0.001" TIR	0.001" TIR
Index	0.0005	
Thickness	0.010"	
Spacing	0.003"	
Decenter	0.002"	
Tilt	0.01 deg.	

L7	Tolerance	
	S1	S2
Radius	1/1000	1/100
Irregularity	8 fringes	8 fringes
Wedge	0.001" TIR	0.001" TIR
Index	0.0005	
Thickness	0.006"	
Spacing	0.020"	
Decenter	0.005"	
Tilt	0.06 deg.	

FILTER	Tolerance	
	S1	S2
Flatness	50 fringes	50 fringes
Irregularity	8 fringes	8 fringes
Wedge	0.004" TIR	0.004" TIR
Index	0.0005	
Thickness	0.010"	
Spacing	0.020"	
Decenter	N/A	
Tilt	0.2 deg.	

Optical Design

Tightest Tolerances

- **Optomechanical**
  - **38 µm element decenter**
  - **25 µm group decenter**
  - **0.5 arcmin element tilt**
  - **0.6 arcmin group tilt**
  - **75 µm element spacing**
  - **75 µm group spacing**
- **Optical fabrication**
  - **0.0005 index of refraction**
  - **1/5000 radius of curvature**
  - **2 fringes irregularity (0.25λ RMS on asphere)**
  - **0.4 arcmin wedge (25 µm TIR)**
  - **±0.15 mm center thickness**

Optical Design

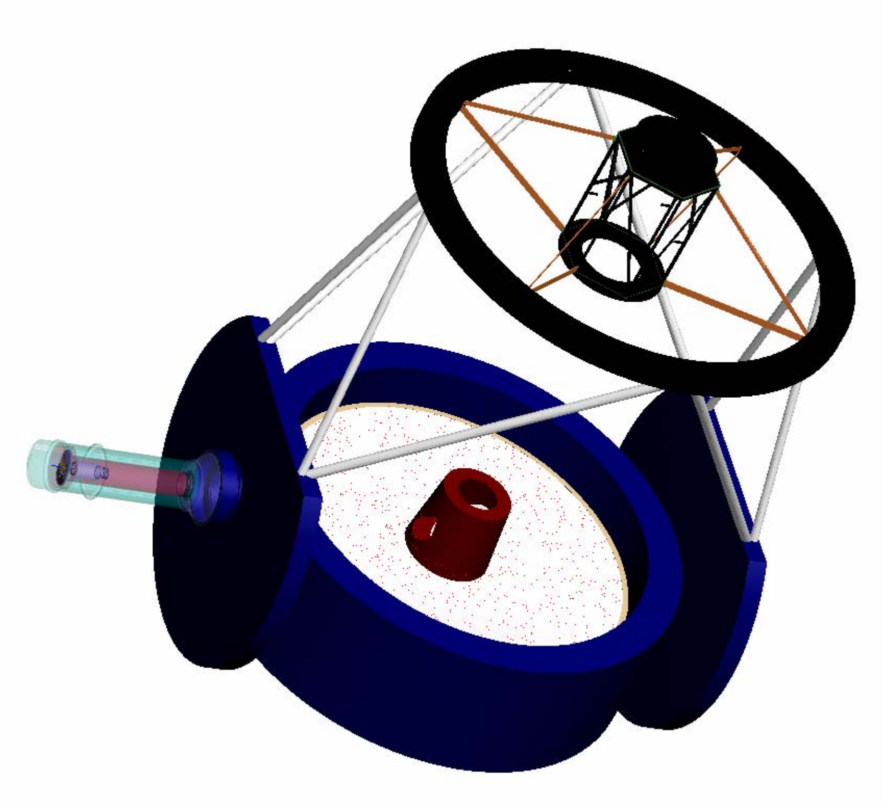
Stray Light Analysis

- Performed by Scott Ellis at Photon Engineering (developers of the FRED stray light analysis code)
- 44 page final report – only highlights will be presented
- Three types of analyses:
  - Ghost reflections from lenses
  - Scattered/stray light (including ghosts)
    - Instrument only
    - Instrument and telescope
  - Thermal self-emission

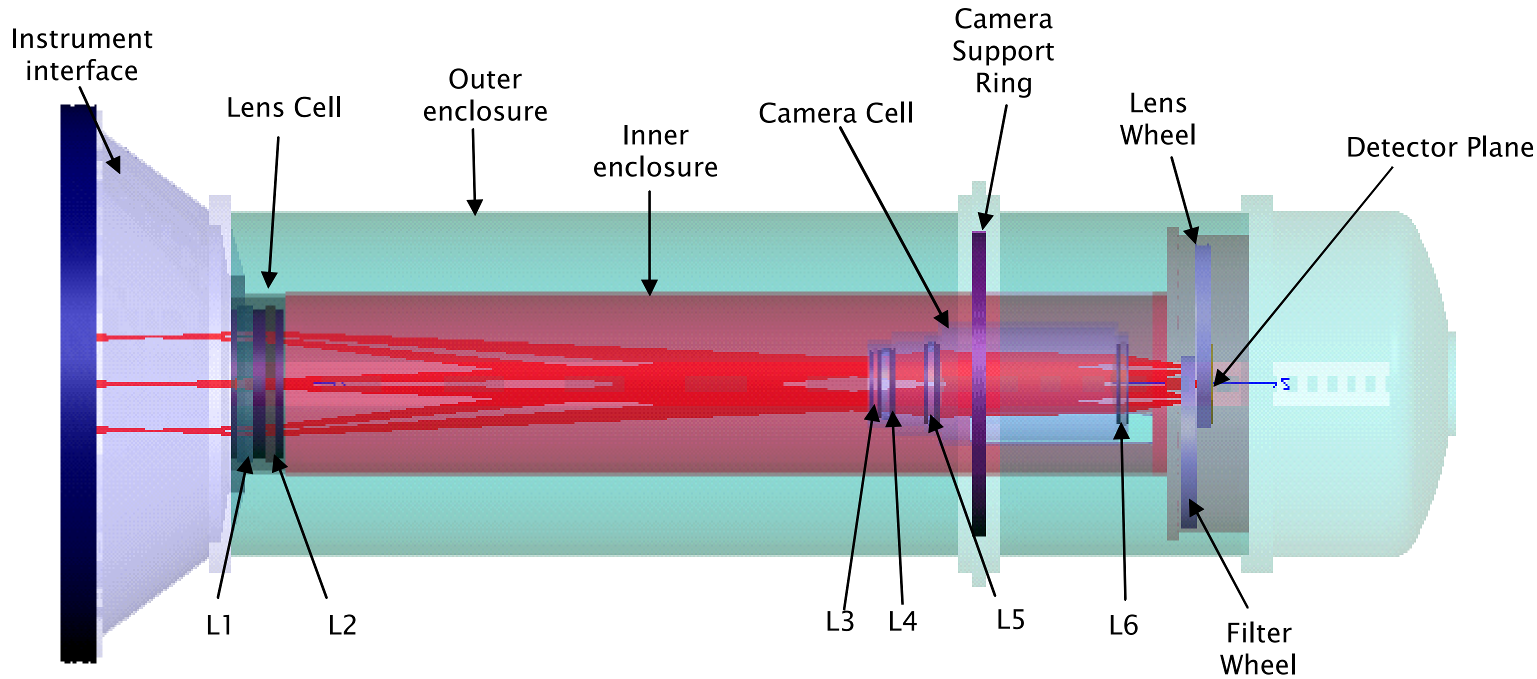
Optical Design

Stray Light Geometry Model – Magellan Telescope

- 2D line drawings and photos of various subassemblies were used to create an approximate representation
- Only mirrors and major support structures included:
  - Primary mirror cell
  - Secondary support structure
  - Tertiary mirror turret
- Dimensions scaled from 2D drawings if not otherwise specified
- Optical prescription from ZEMAX (Magellan 1 as-built)



Stray Light Geometry Model – Instrument

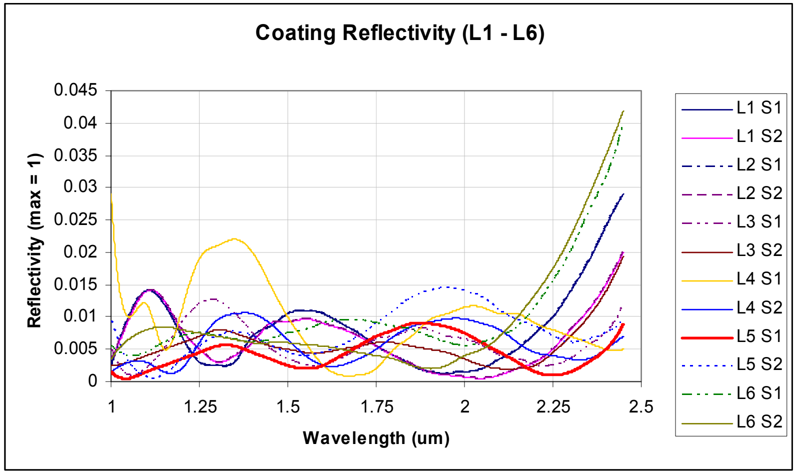


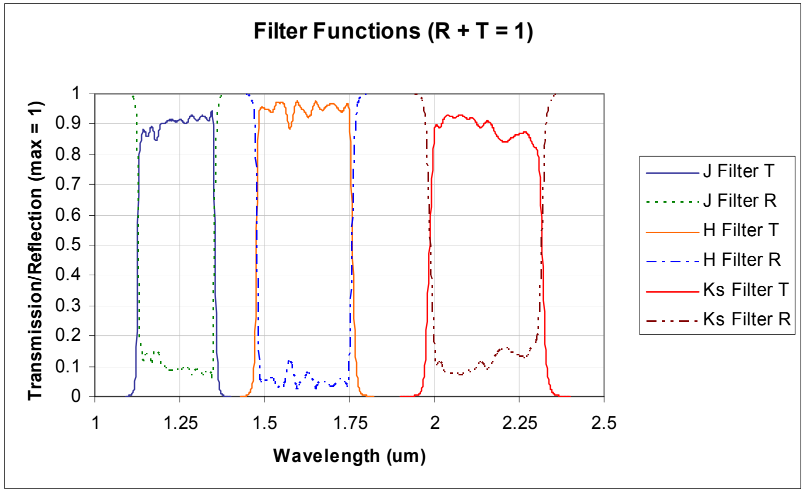
Model incorporates simple surfaces without complicated features unless they are close to the optical beam path (i.e., screw holes, cutouts, etc. are omitted)

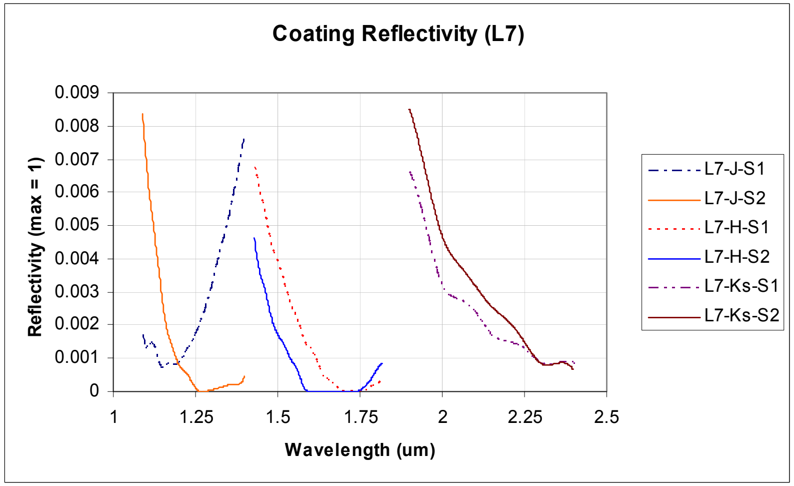
Optical Design

Optical Materials/Coatings

- Complex index (n, k) of lenses modeled to include material absorption
- Detector modeled with flat 92% QE, 8% reflectivity
- Coatings and filters as shown

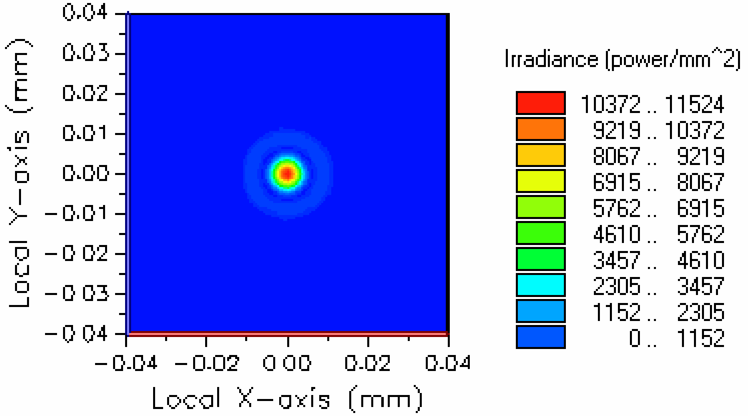






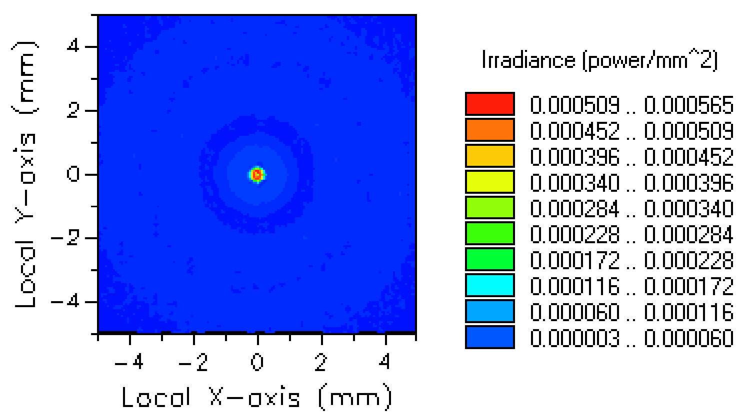
Ghost Analysis – Point Source

Coherent PSF



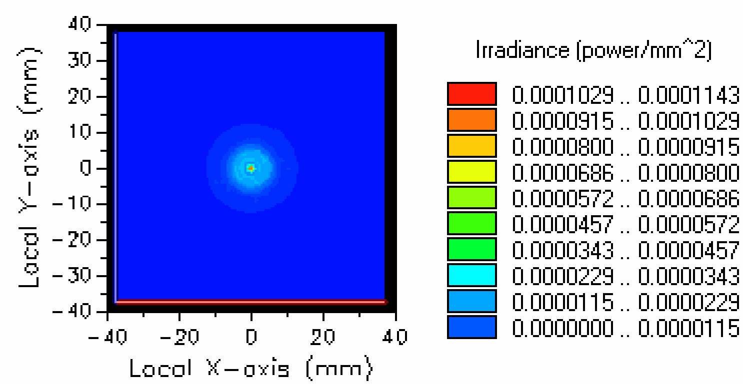
- Field angle: 0 arc-min
- Wavelength: 1.64 μm
- Source power: 1
- Transmission: 0.6

Incoherent Ghost (medium resolution)



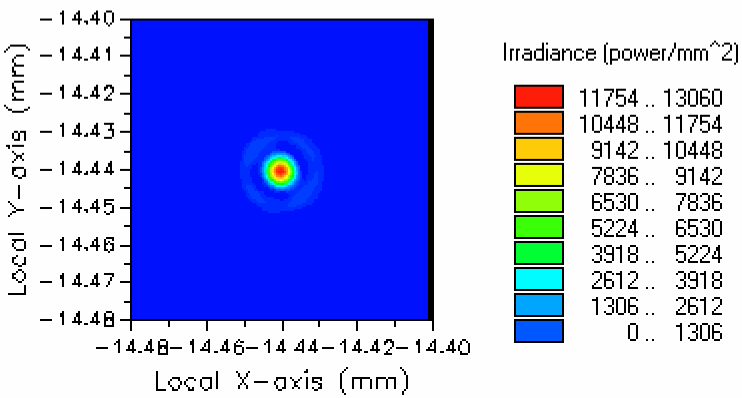
10mm x 10mm, centered on direct image

Incoherent Ghost Image (Full Focal Plane)



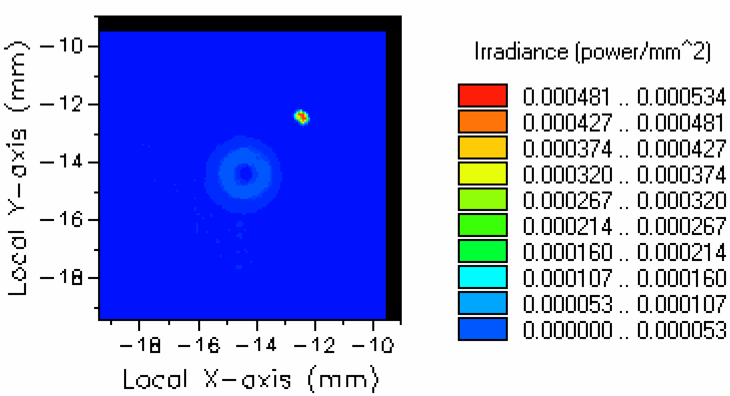
Ghost Analysis – Point Source

Coherent PSF



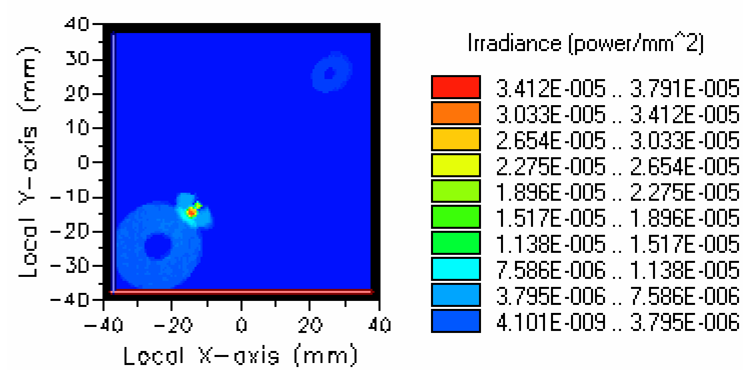
- Field angle: 3.0 arc-min
- Wavelength: 1.64 μm
- Source power: 1
- Transmission: 0.6

Incoherent Ghost (medium resolution)



10mm x 10mm, centered on direct image

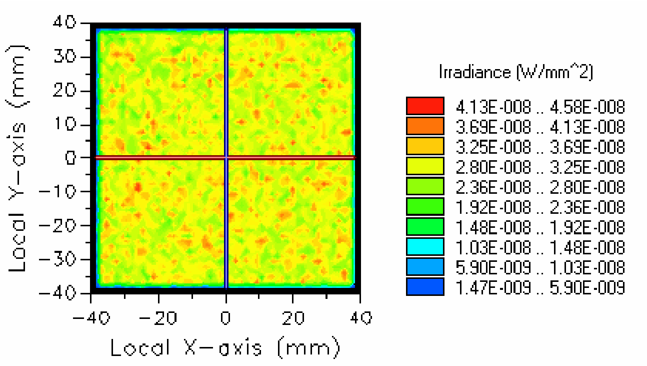
Incoherent Ghost Image (Full Focal Plane)



Ghost Analysis – Flat Field

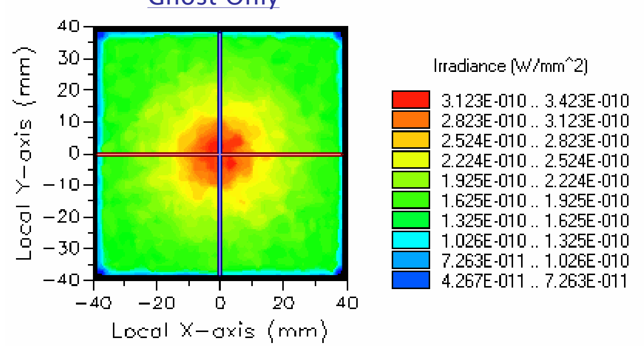
Unit Radiance Flood – Ks Band

Direct Only

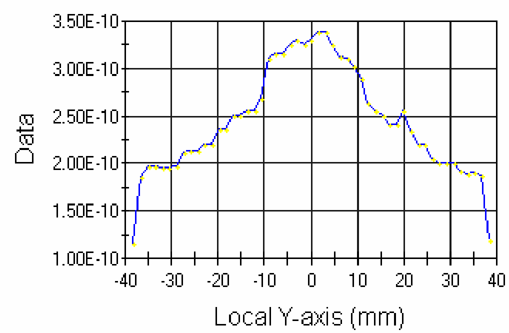


Direct average irradiance
3.05e−8 W/mm^2

Ghost Only



Ghost Only Profile



Optical Design

Ghost Analysis – Conclusions

- For point sources, the peak ghost irradiance is reduced from the peak source irradiance by at least six orders of magnitude
- The point source ghost images contribute very little to the total power accumulated on the focal plane (see table)

Field Angle (arc-min)	Total Power	Direct Fraction	Ghost Fraction
0	.65	99.155%	0.845%
1.5	.65	99.332%	0.668%
3	.65	99.429%	0.571%
4.5	.65	99.778%	0.222%
6	.65	99.941%	0.059%
7.5	.65	99.954%	0.046%

- In terms of total power, the strongest ghost is the bounce path between the detector and the front surface of the band pass filter
- For flat fields, the peak ghost image irradiance is 1% of the average direct irradiance

Optical Design

Stray Light Analysis

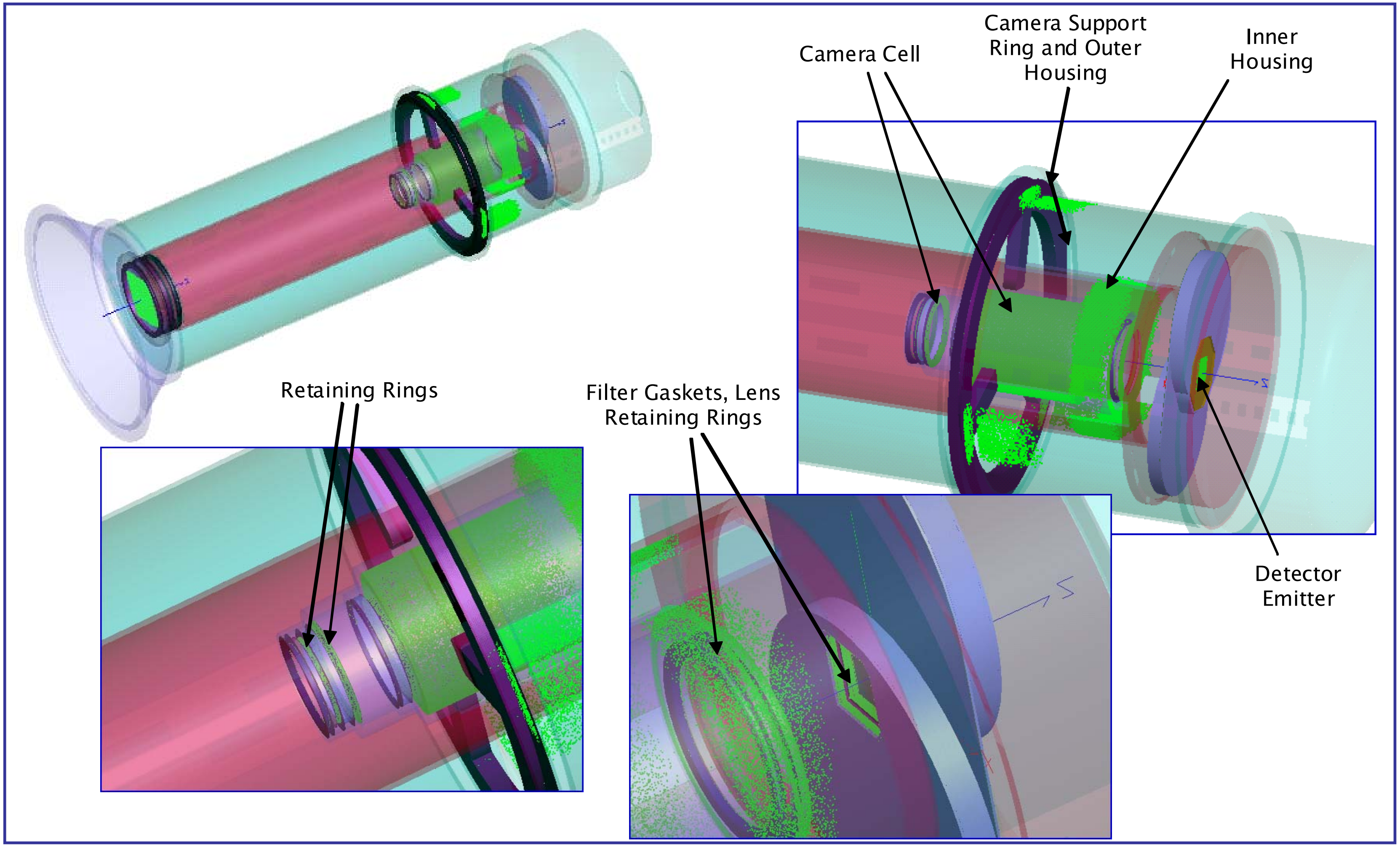
- Identify critical optomechanical surfaces (those which can be seen by the detector) with a reverse raytrace from the detector
- Identify illuminated optomechanical surfaces (those which can be seen directly by the “universe”)
- Assign scatter models to surfaces which appear on both lists – these are surfaces which can scatter light onto the detector with a single scatter event
- Run raytrace to calculate the Point Source Transmittance, the ratio between detected power and incident power:

$$PST(\theta, \phi) = \frac{E_{det}(\theta, \phi)}{E_{inc}(\theta, \phi)}$$

- The PST function of a well-baffled optical system exhibits a steep drop for objects just outside the field of view and a smooth, monotonic decrease with further increasing angle. We expect the optics to be the main contributor to stray light. Bumps in the function indicate an anomalous path, such as a glint or reflection from a piece of structure that is directly illuminated by the out-of-field source.

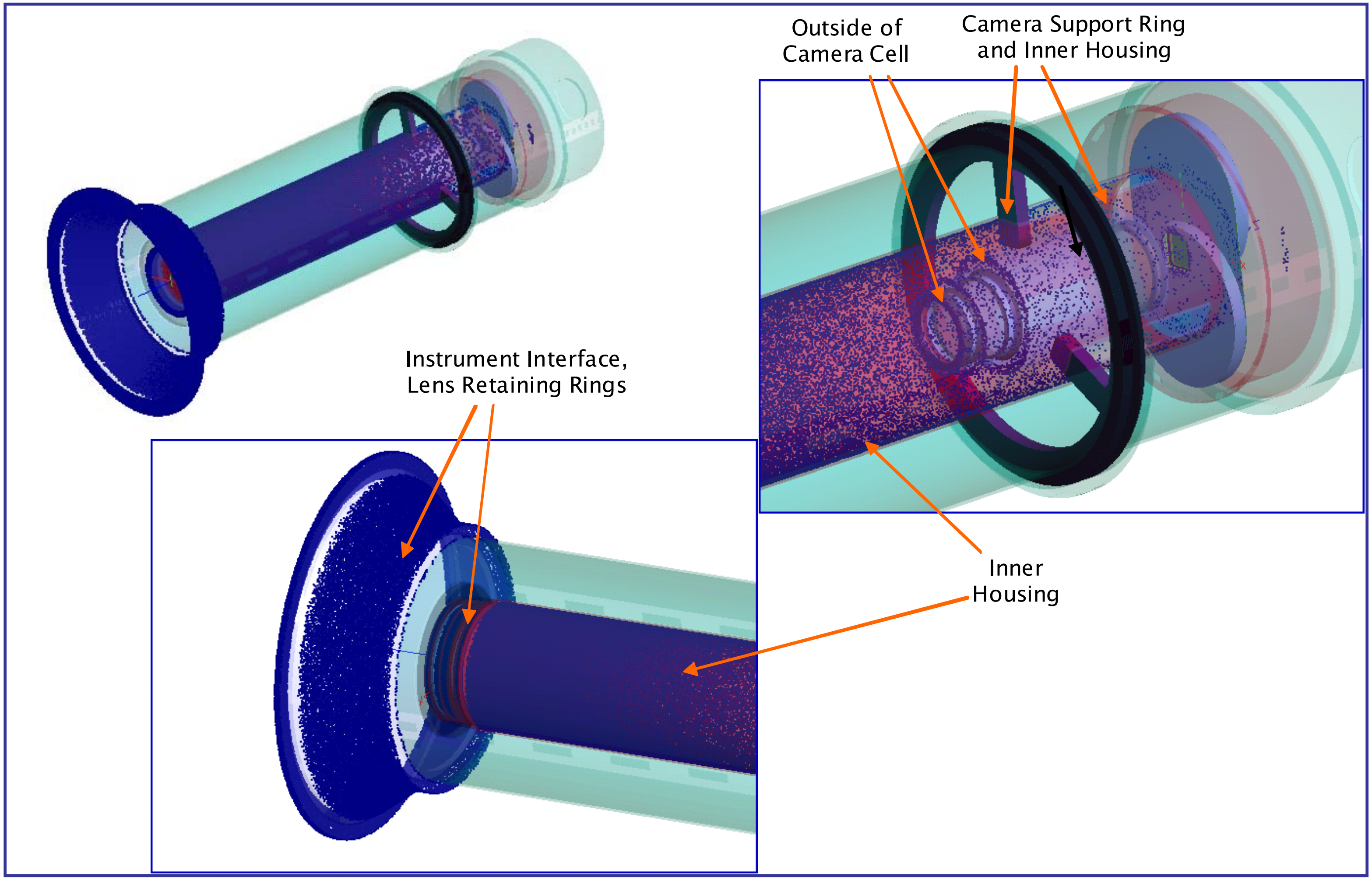
Optical Design

Critical Surfaces – Instrument Only



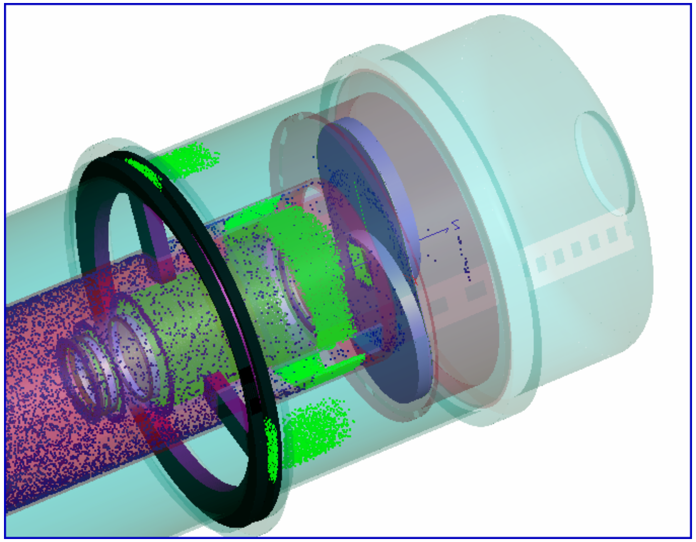
Optical Design

Illuminated Surfaces – Instrument Only



Optical Design

Critical ∩ Illuminated Surfaces – Instrument Only



Fraction of Universe	Fraction of Detector	Combined	Surface Name
7.596E-02	4.552E-02	1.215E-01	.4star.enclosures.inner enclosure.inner cylinder
2.828E-07	8.557E-02	8.557E-02	.4star.enclosures.wheel housing.middle plate.back face
2.829E-07	2.621E-02	2.621E-02	.4star.enclosures.wheel housing.filter wheel 2.mount plate.back aperture
2.932E-07	1.889E-02	1.889E-02	.4star.enclosures.wheel housing.filter wheel 1.mount plate.back aperture
8.781E-07	7.569E-03	7.570E-03	.4star.enclosures.wheel housing.filter wheel 1.empty filter gasket.tapered edge
9.446E-05	7.033E-03	7.128E-03	.4star.enclosures.wheel housing.middle plate.front face
1.119E-06	4.955E-03	4.956E-03	.4star.enclosures.detector mask.ID 2
1.845E-05	3.171E-04	3.355E-04	.4star.enclosures.wheel housing.filter cover.inside edge
9.231E-07	1.621E-04	1.630E-04	.4star.enclosures.inner enclosure.cutout 3
6.154E-07	9.515E-05	9.576E-05	.4star.enclosures.inner enclosure.cutout 2
2.237E-06	6.072E-05	6.296E-05	.4star.enclosures.detector mask.ID 1
5.648E-07	3.273E-05	3.329E-05	.4star.enclosures.wheel housing.filter wheel 2.mount plate.middle
5.862E-07	2.988E-05	3.047E-05	.4star.enclosures.wheel housing.filter wheel 1.mount plate.middle

Optical Design

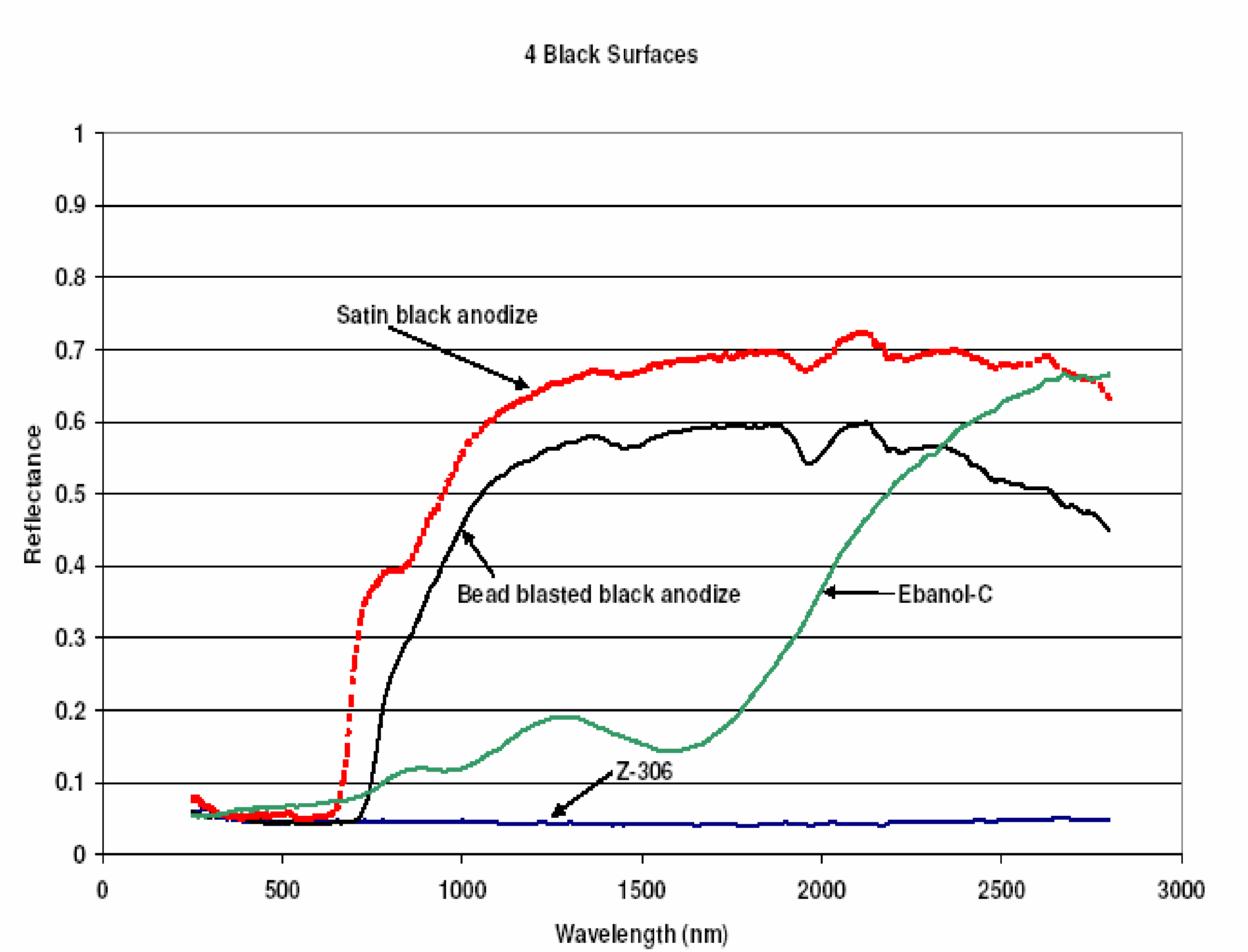
Surface Scatter Models

- **Optical surfaces all have two scatter models:**
  - Harvey-Shack BSDF – scatter due to RMS micro-roughness
  - Mie model BSDF – scatter due to particulate contamination

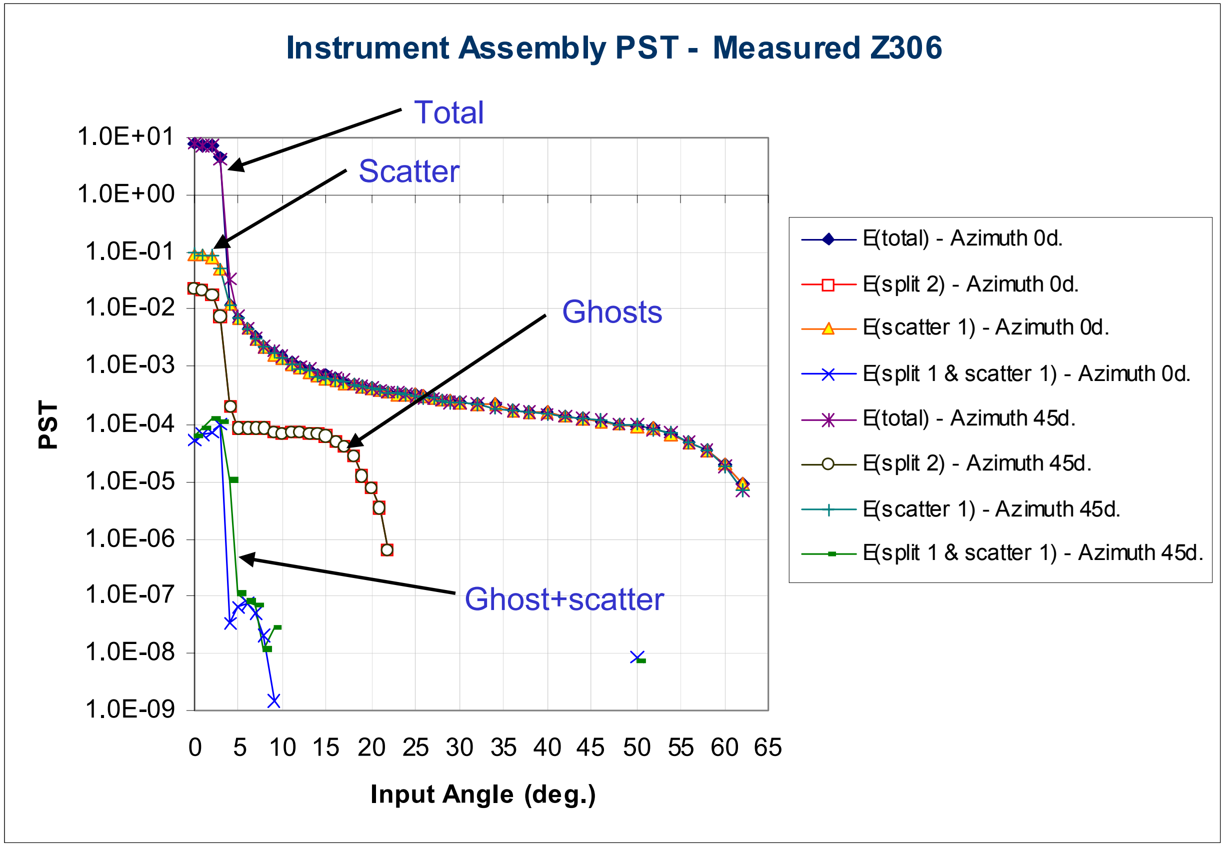
Surface(s)	Contamination Model	Normal Incidence TIS (%)
Filters and correctors	*CL 200*	*0.09%*
L1 S2 to L6 S2	*CL 400*	*0.22%*
L1 S1, all mirrors	*CL 600*	*1.64%*

- **Opto-mechanical surfaces (barrels, vanes, etc.) all have the same black surface model, either:**
  - Aeroglaze Z306
    - Model based upon actual BRDF measurements done for FourStar
  - Satin black anodize
    - Using a composite diffuse/specular model
    - BRDF measurements we had done were erroneous and corrected data were not available in time for the analysis

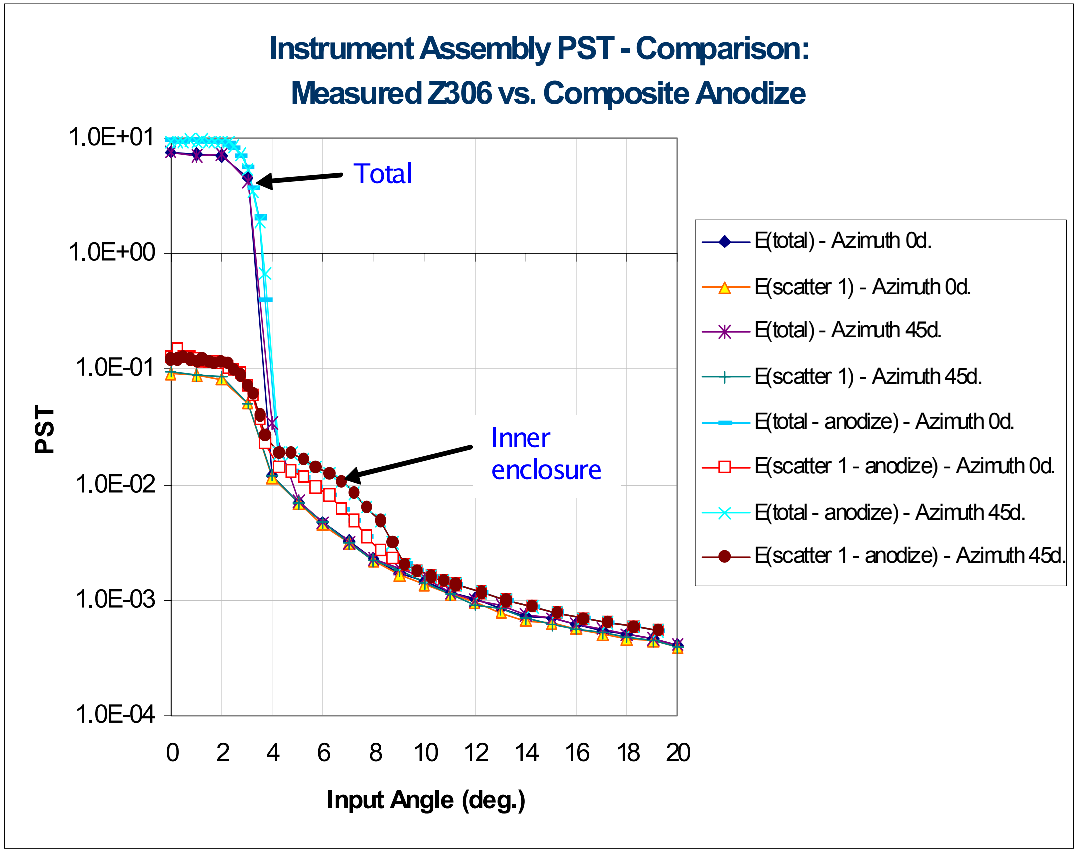
Total Integrated Scatter (TIS) Measurements



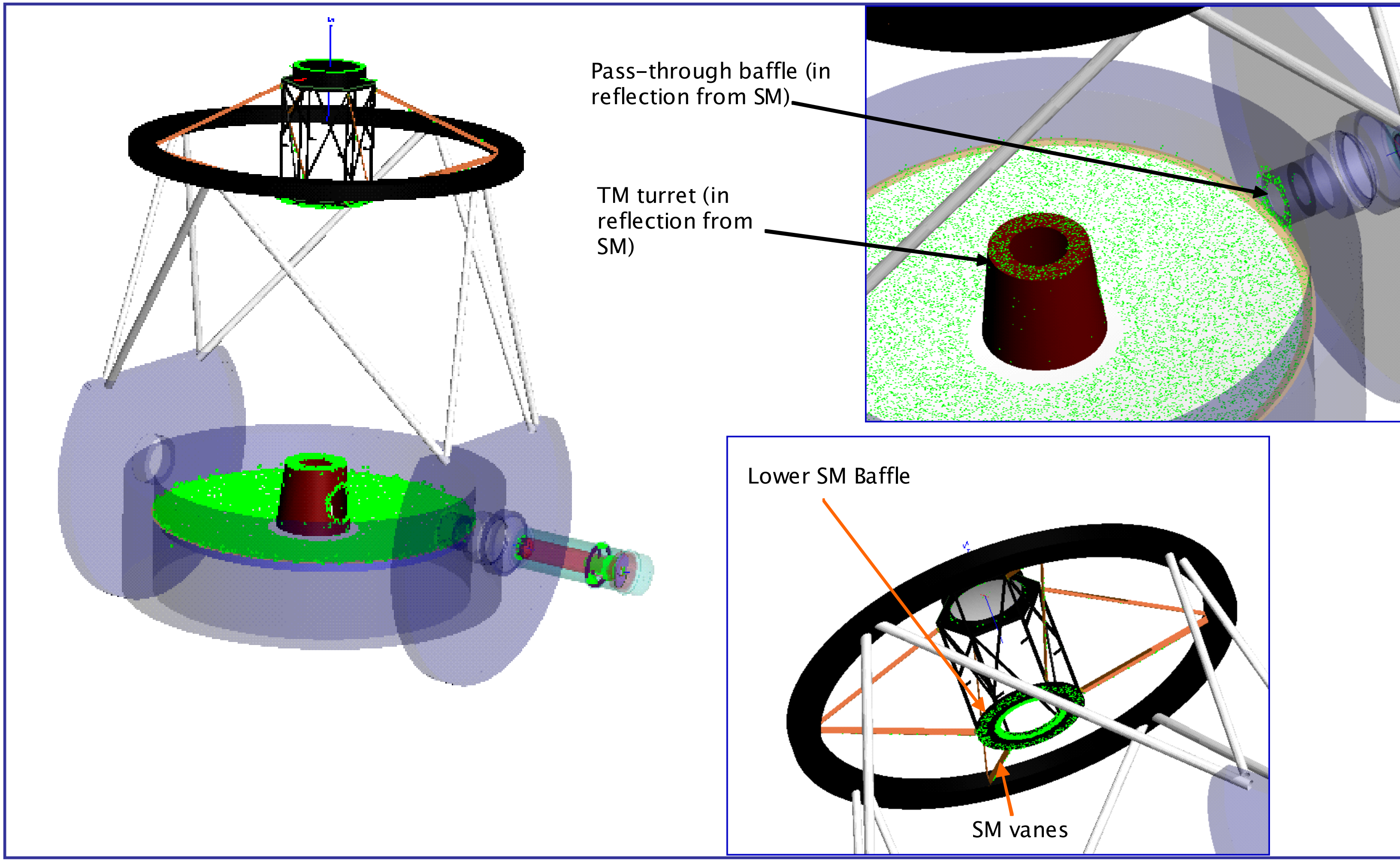
PST Results – Z306, Instrument Only



PST Results – Z306 vs. Anodize

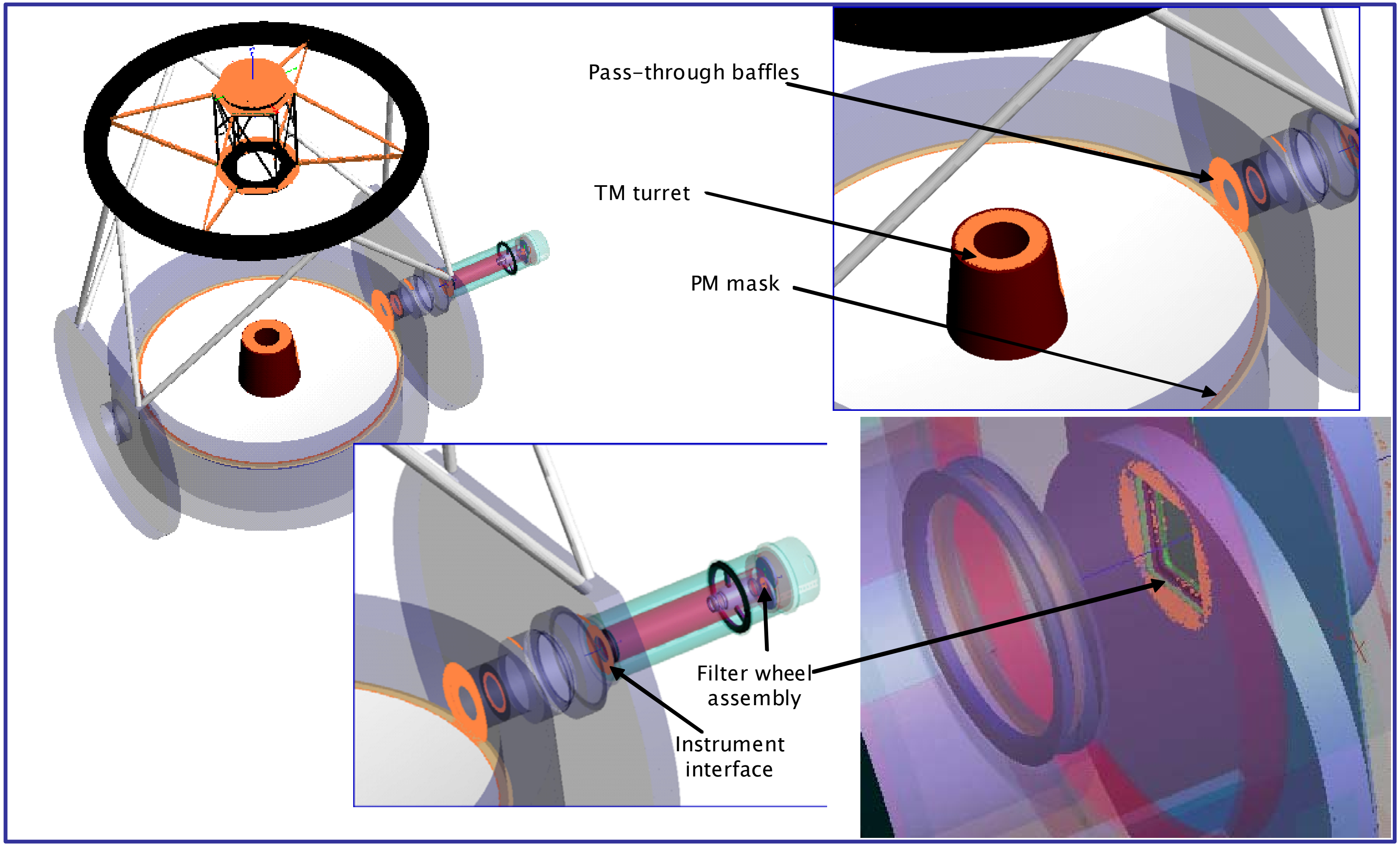


Critical Surfaces – Full System



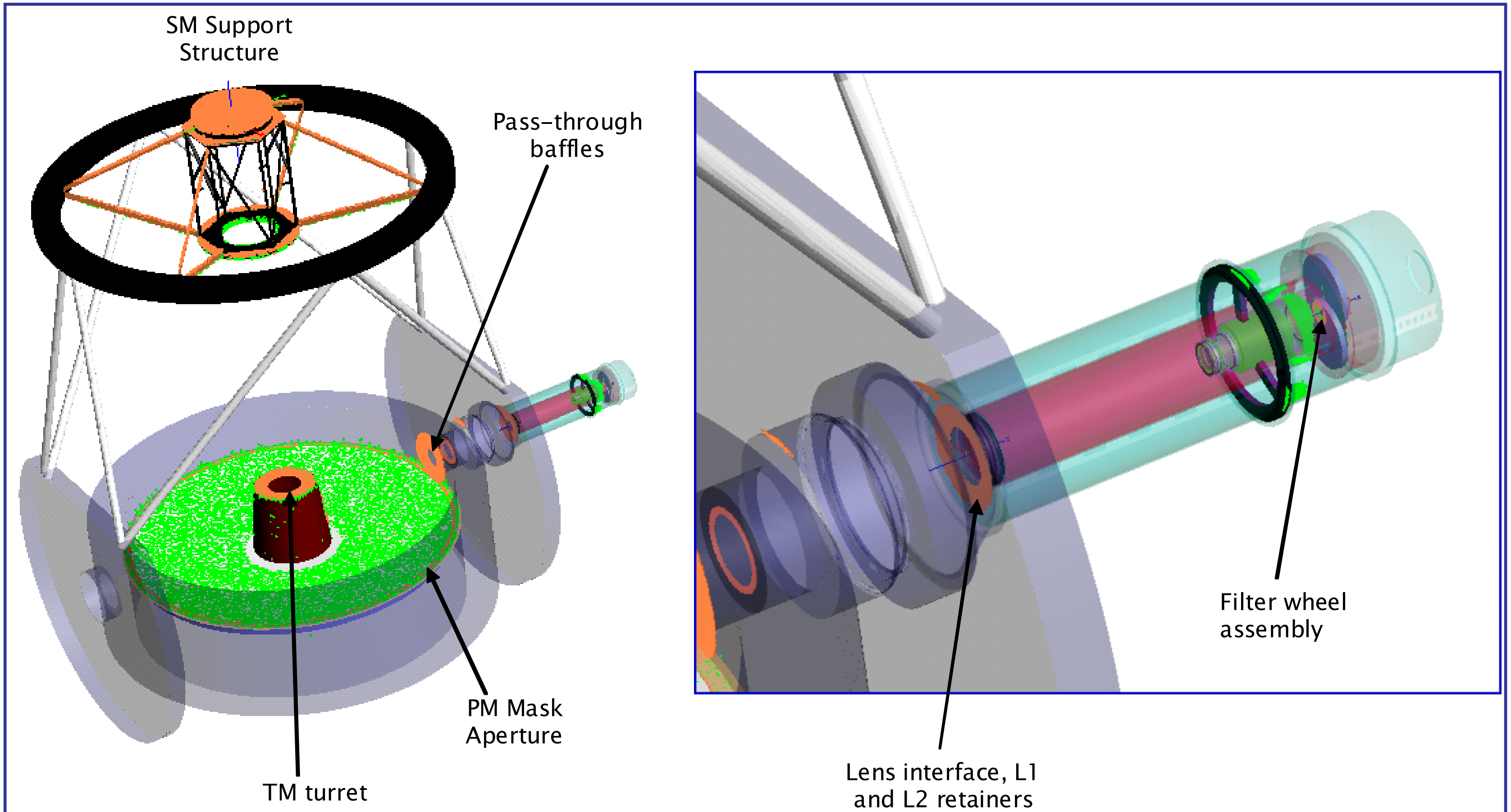
Optical Design

Illuminated Surfaces – Full System



Optical Design

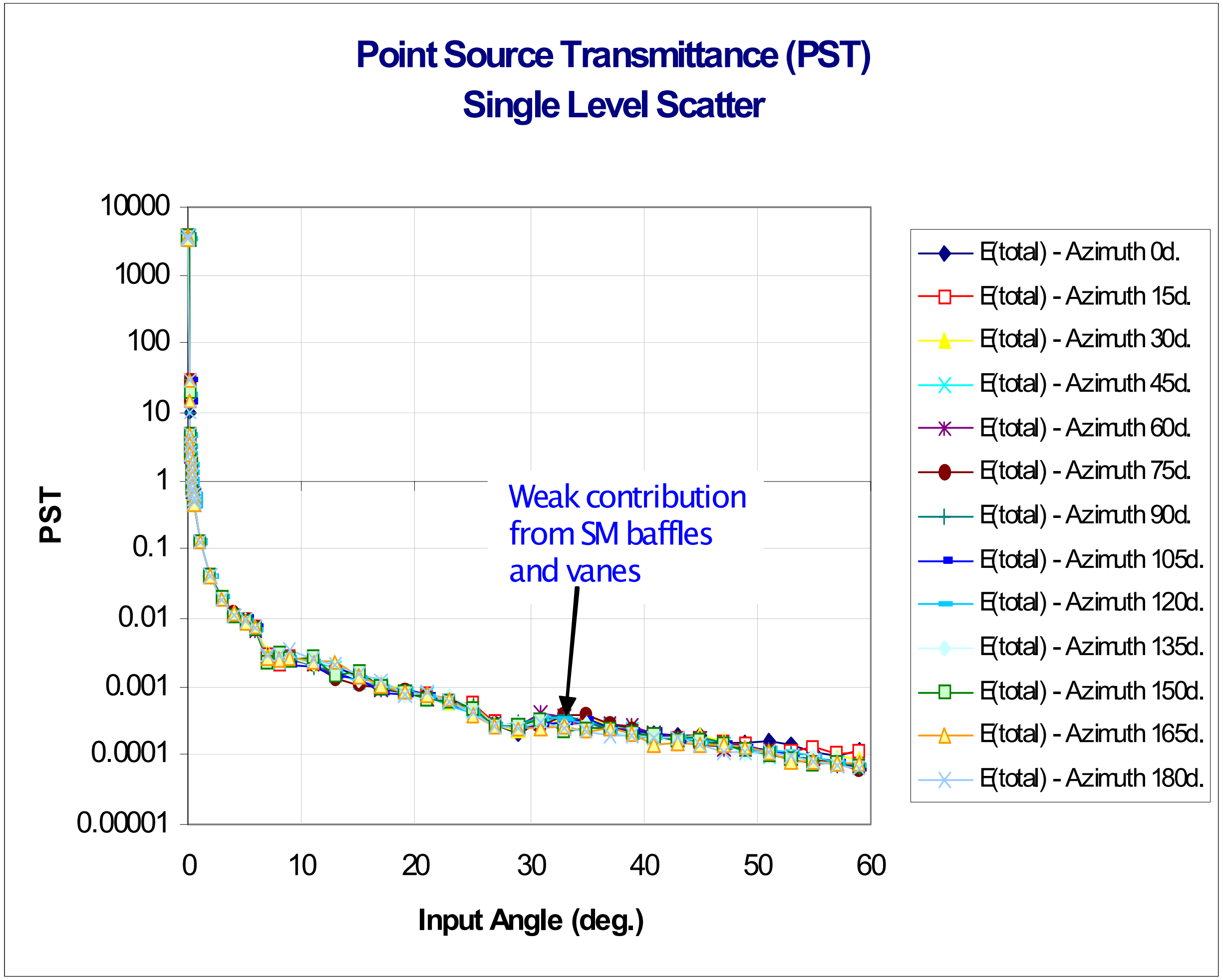
Critical ∩ Illuminated Surfaces – Full System



Very little inside the intrument assembly can be seen directly by both the detector and the universe

Optical Design

PST Results – Full System



Optical Design

Stray Light Analysis – Conclusions

- The PST is typical of a well-baffled system, even without the inclusion of the pupil stop and L6 baffle (not designed in time for the stray light analysis)
- The most significant scatter mechanism is from particulate contamination on the optical surfaces themselves
- Surface treatments on the interior of the instrument assembly, and, in particular, inside the camera module, are not critical to maintaining performance

Optical Design

Stray Light Control

- **Radiation shield (200K) serves as primary light baffle**
  - Interior painted with Z306
  - Beam-fitting apertures at each end of baffle tube
- **Pupil mask (200K)**
  - Iris mechanism allows remote optimization of O.D. stop
  - Fixed, spider-mounted central stop (obscuration)
  - Located at best focus of pupil image in K_s
- **Z306 on interior of camera module barrels**
- **Z306 on lens and filter spacers/retainers**

More details on these features will be provided in the mechanical presentation

- **Clean room assembly to maintain cleanliness level of optics**

Optical Design

Thermal Self-Emission Calculation

The power incident on the detector from the ith surface is

$$P_i(\lambda) = L_i(\lambda) A_{\det} \Omega_i$$

where L is the surface radiance, $A_{\det}$ is the area of the detector and Ω_i is the projected solid angle subtended by the surface from the detector. The radiance of the surface is derived from blackbody theory

$$L_i(\lambda) = \frac{\sigma_p T_i^3}{\pi} f_{BB}(\lambda_2 - \lambda_1)\varepsilon_i(\lambda_0)$$

where σ is the Stefan-Boltzmann constant (1.5205e+11 photons/sec-cm^2-K^3), T is the temperature in degrees Kelvin, $f_{BB}(\lambda_2-\lambda_1)$ is the energy (or photon) fraction under the blackbody curve between λ_2 and λ_1, and ε is the emissivity of the surface.

Thermal Self-Emission Calculation

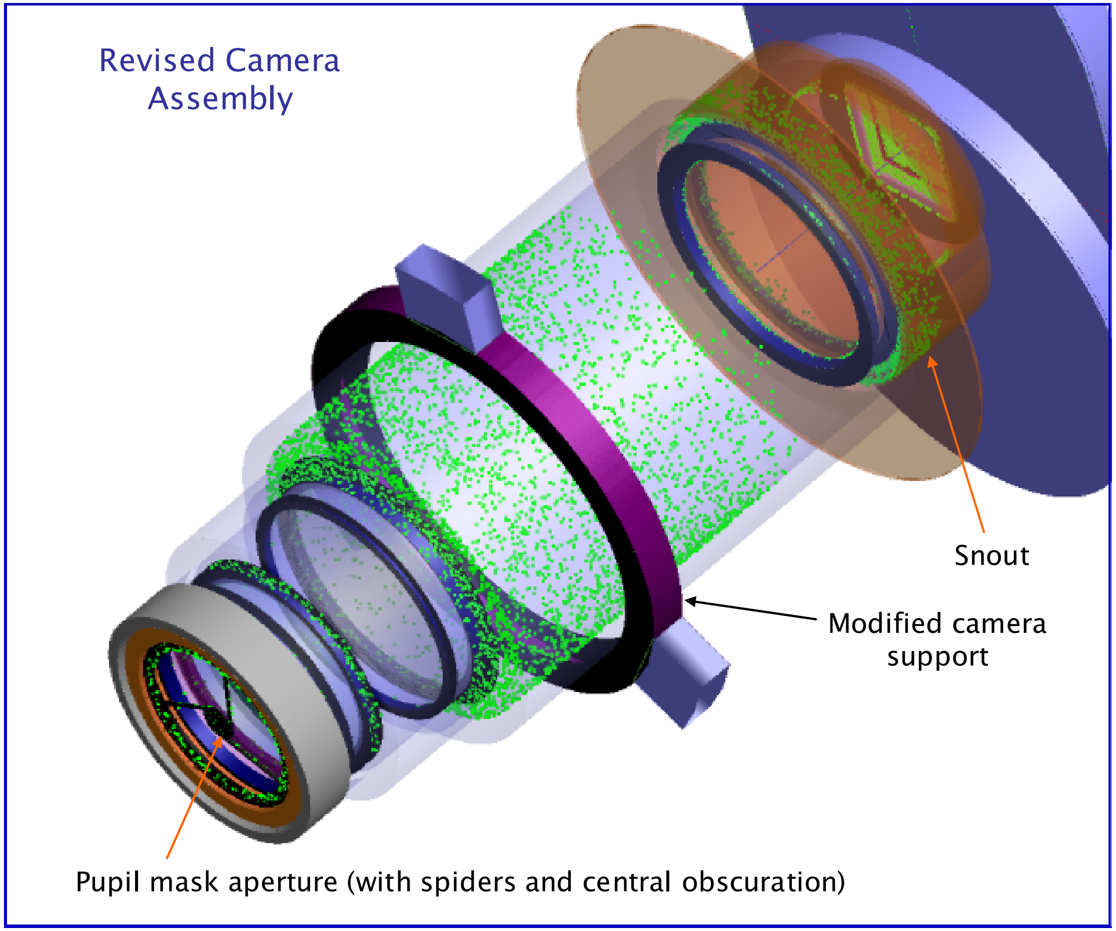
Defining the geometric configuration factor (GCF) as Ω/π, the power incident on the detector over a given wavelength band is the accumulated sum over all surfaces,

$$P_{total}(\lambda) = \sum_i \sigma_p T_i^3 f_{BB}(\lambda_2 - \lambda_1)\varepsilon_i(\lambda_0) A_{\det} GCF_i$$

The GCF is obtained via the raytrace. When a Lambertian source is configured to emit unit power into a hemisphere, then the power incident on any surface is numerically equivalent to the GCF. Transmission losses and the like are automatically taken into account during the raytrace.

Optical Design

Model for thermal calculation incorporates later modifications to the geometry



Optical Design

Surface Assignments

Objects	Temperature (K)	Emissivity (J Band)	Emissivity (H Band)	Emissivity (Ks Band)
Telescope hardware	*285*	*1*	*1*	*1*
Camera housing (including snout)	*200*	*1*	*1*	*1*
Inner enclosure	*200*	*1*	*1*	*1*
Filter & lens wheel	*77*	*1*	*1*	*1*
Mirror surfaces	*285*	*.058*	*.02*	*.02*
L1	*285*	*.005*	*.0004*	*.013*
L2	*270*	*.0035*	*.0003*	*.0095*
L3	*200*	*.0005*	*.0011*	*.0016*
L4	*200*	*.0035*	*.013*	*.047*
L5	*200*	*.0007*	*.0016*	*.0023*
L6	*195*	*.0007*	*.0016*	*.0022*
Filter	*77*	*.061*	*.0645*	*.002*
Corrector	*77*	*.0035*	*.011*	*.0457*

Optical Design

Thermal Self-Emission Results

Surfaces	J Band Photon Flux (photons/sec)	H Band Photon Flux (photons/sec)	Ks Band Photon Flux (photons/sec)
Telescope Support Structure	*6.99E+04*	*9.81E+07*	*7.58E+09*
Mirrors	*2.55E+04*	*4.01E+07*	*8.57E+09*
Instrument Optomechanics	*8.49E+00*	*4.81E+04*	*1.69E+08*
Instrument Optics	*2.98E+02*	*3.34E+05*	*2.87E+09*
Total	***9.57E+04***	***1.39E+08***	***1.92E+10***

With 16.8 million pixels in the focal plane, the estimated thermal background (instrument + telescope) in K_s is 1143 photons/sec-pixel.

FakeStar Alignment System

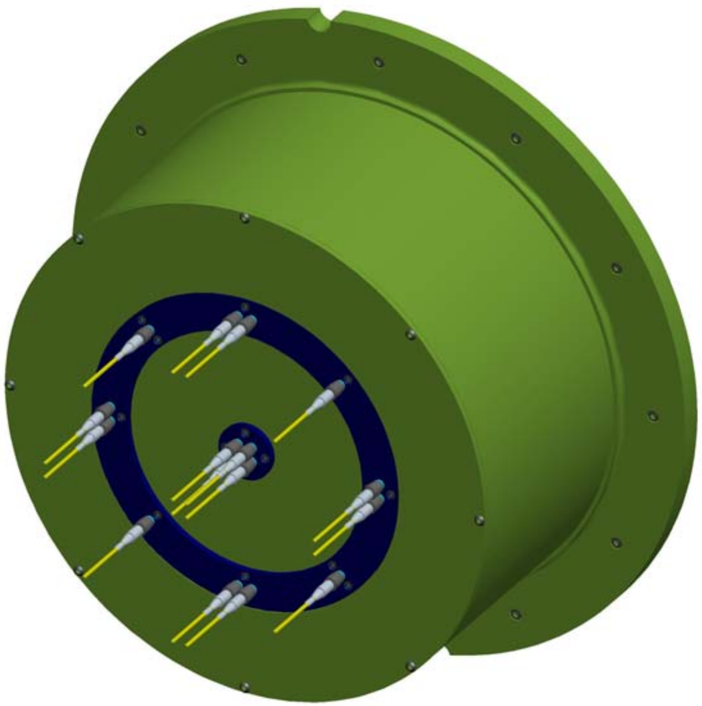
FakeStar is an alignment and imaging test setup designed for setting the focus/tip/tilt of the detector and verifying imaging performance in the lab. It consists of two components…

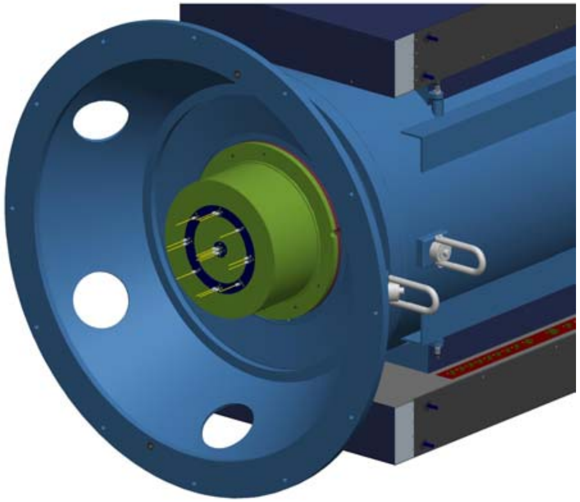
A diamond-turned, aspheric CaF_2 lens (shown in section view)

- **Mounts in the blank slot of the field corrector wheel**
- **Corrected for only two zones, one near the center of the FOV and one near the edge (not corner) of the FOV**
- **Within these two zones, the lens produces excellent H-band imaging from a flat object plane**

FakeStar Alignment System

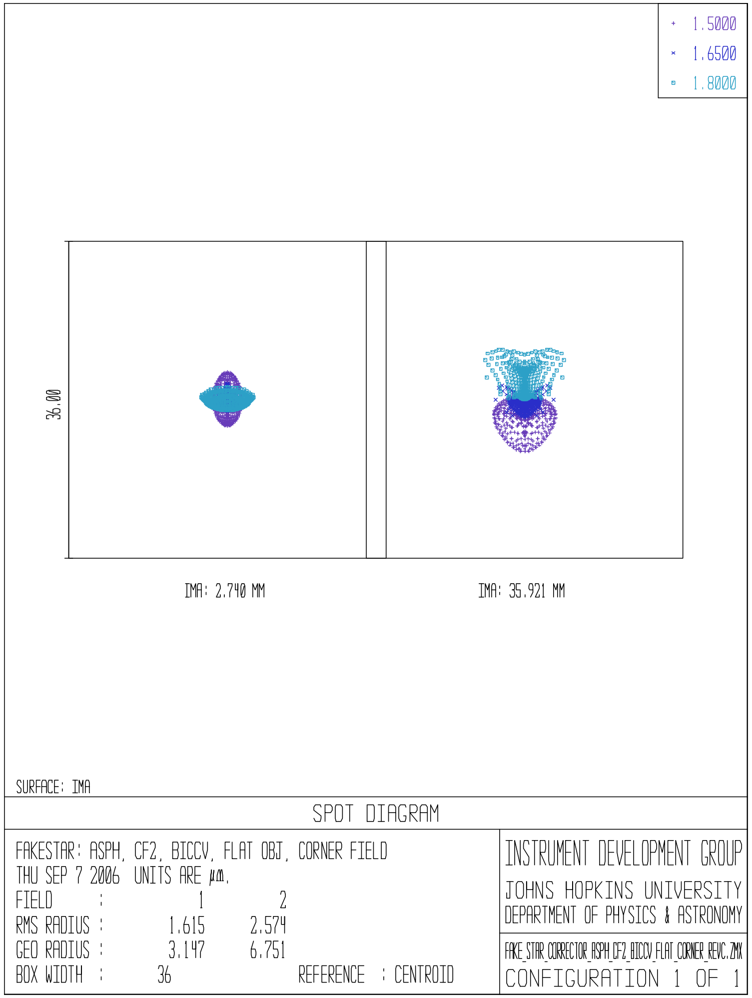
A fiber "plug plate" and top hat fixture mounted to the front flange



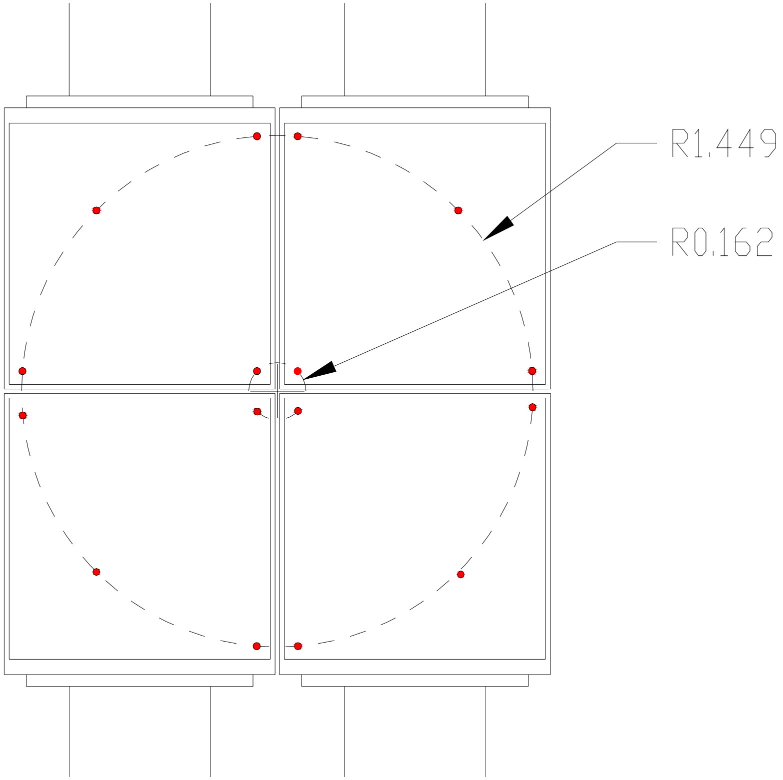


- **16 single mode IR fibers with 4 μm cores – "easy" pinhole sources**
- **A single light source (tungsten or laser diode?) will light up all fibers simultaneously**
- **Fibers will provide f/4 output, insuring full pupil illumination**

FakeStar Imaging Performance

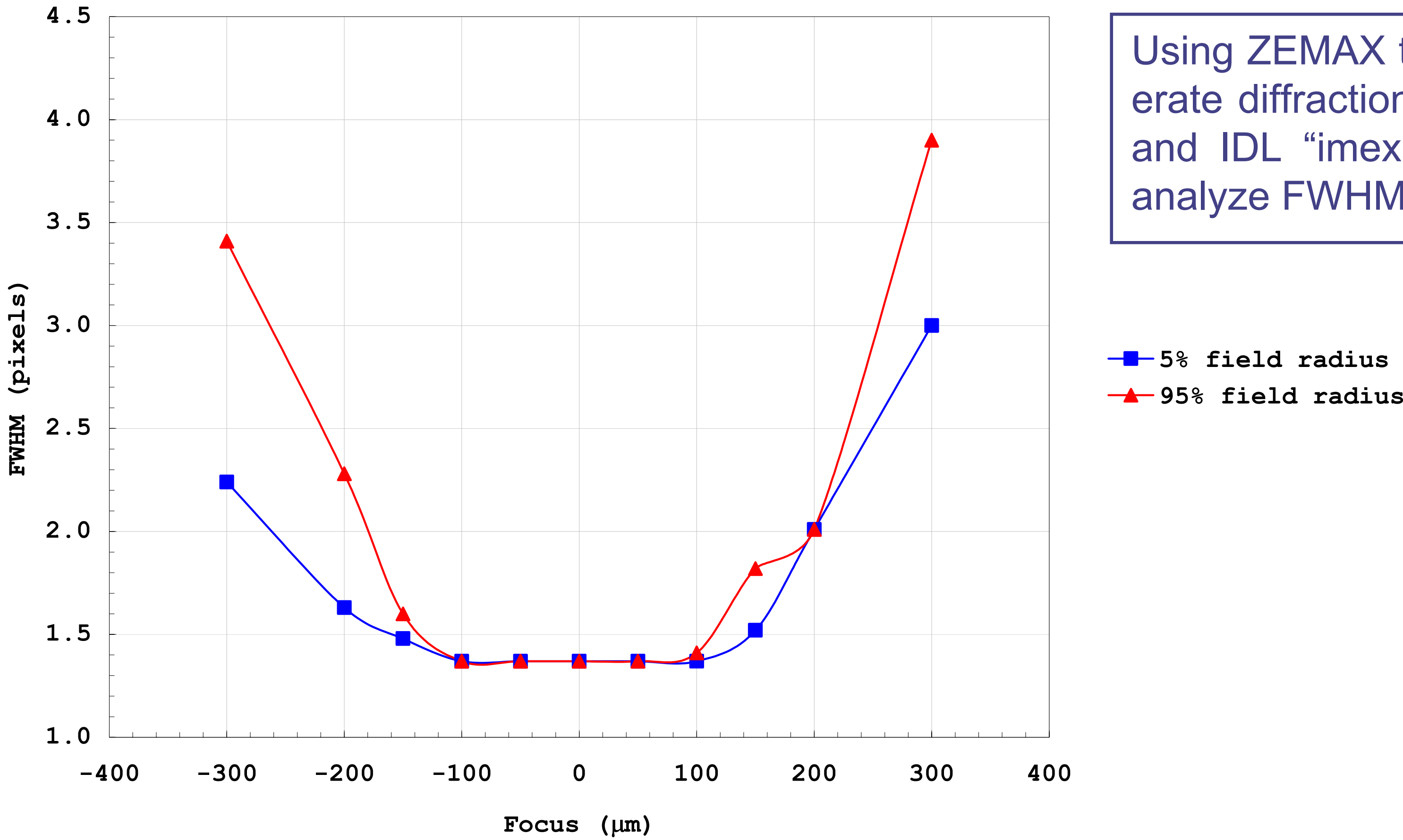


16 image locations on FPA indicated by red dots



Optical Design

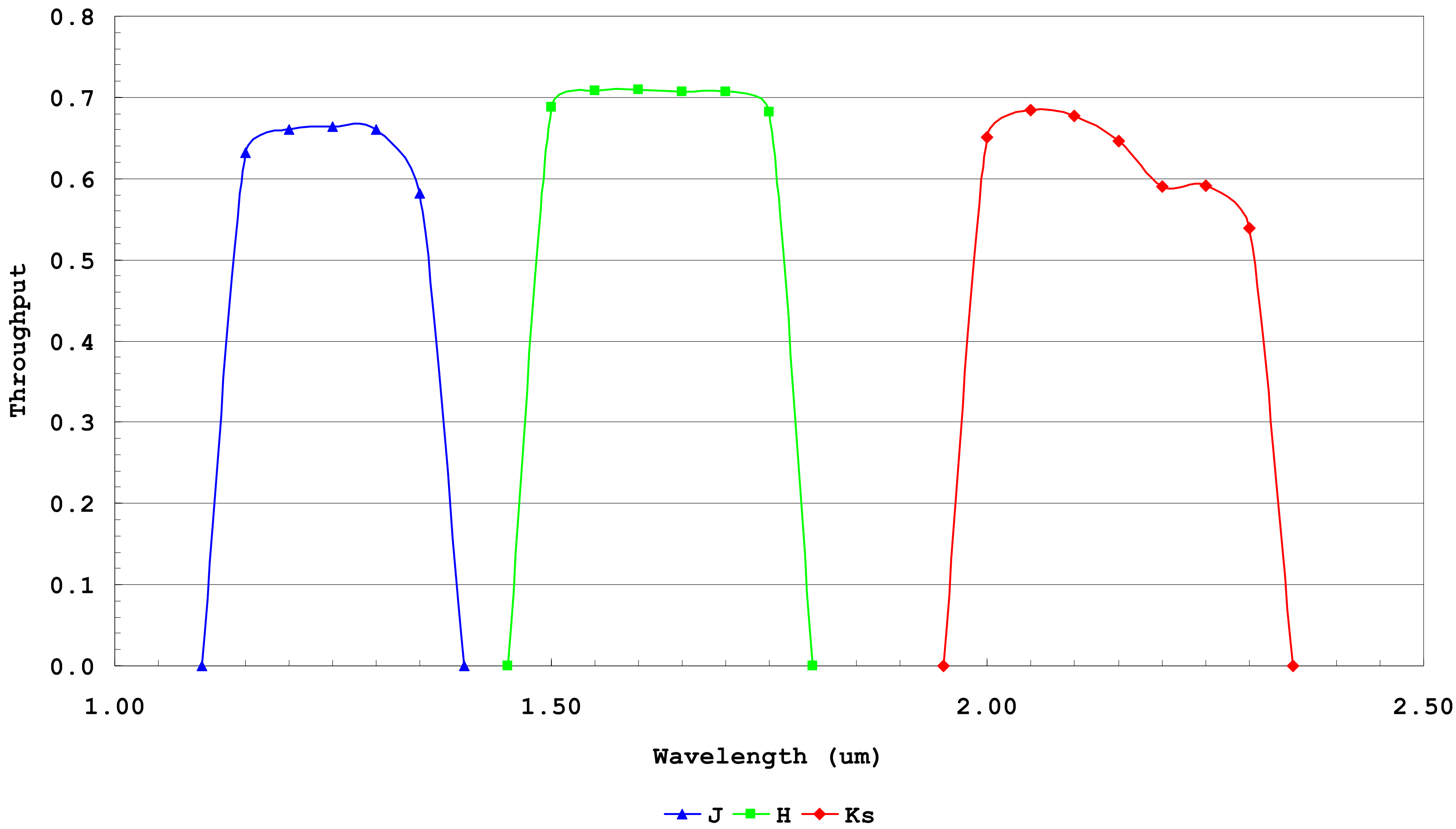
FakeStar Simulated Focus Sequence



Using ZEMAX to generate diffraction PSFs and IDL “imexam” to analyze FWHMs.

Optical Design

Predicted Instrument Throughput



TAB 5

5. Mechanical and Thermal Design and Models

FourStar

Optomechanical Design

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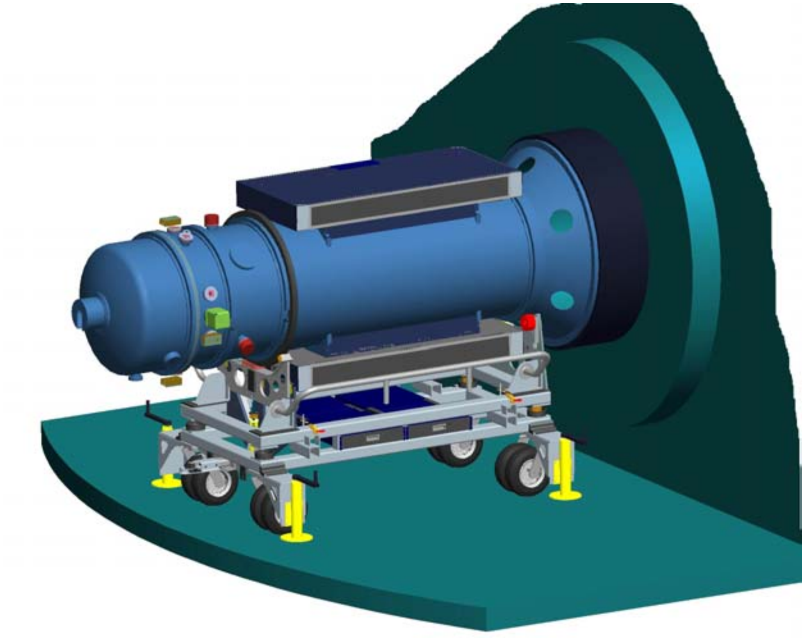
21 September 2006

JOHNS HOPKINS UNIVERSITY

Optomechanical Design

Outline

- General overview
- Vacuum Vessel
- 200K Radiation Shield
- Window
- Camera Module
- Focal Plane Mechanisms (Persson, later talk)
- Dewars & 77K shield
- Racks (Murphy/Smee, later talk)



Optomechanical Design

Requirements and Considerations

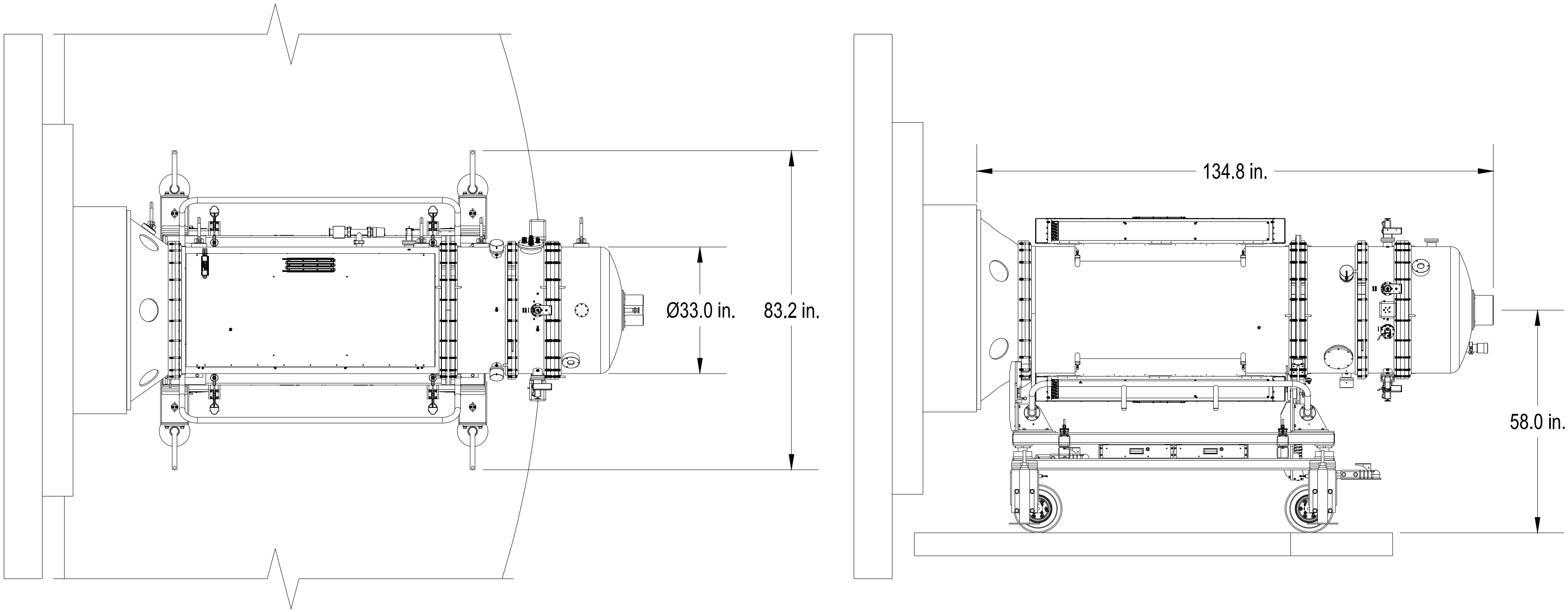
- **Field of View: 11' x 11'**
- **Wavelength range: 1 to 2.3 μm**
- **Filters: J, H, Ks, plus TBD narrow band**
- **Detector Array: 2 x 2 Hawaii 2RG w/sidecare ASICs**
  - Plate scale: 0.16" per pixel
- **Optical design: Seven elements, all refractive**
  - Fused Silica, CaF_2, S-FTM16
- **Optomechanical tolerances**
  - As determined by tolerance analysis
- **Flexure:**
  - < 1/3 pixel in-plane for a typical exposure
  - ± ~ 30 μm along the optical axis (diffraction limited DOF)
- **Thermal environment:**
  - L1 – L2: ambient
  - L3 – L6: 200K
  - L7, Filters, and detector: 77K

Requirements and Considerations Cont.

- Detector and optics cooled via LN_2
  - Usage should be within reasonable limits
- Electronics and cable management
  - PC's for detector readout
  - Motor controllers
  - Sensor monitoring
  - Thermal controllers
  - Communications
- Infrastructure required to operate the instrument
  - Control computers/software
  - Data reduction computers/software
  - AC power
  - Chilled water
- Reliability
- Maintainability

Optomechanical Design

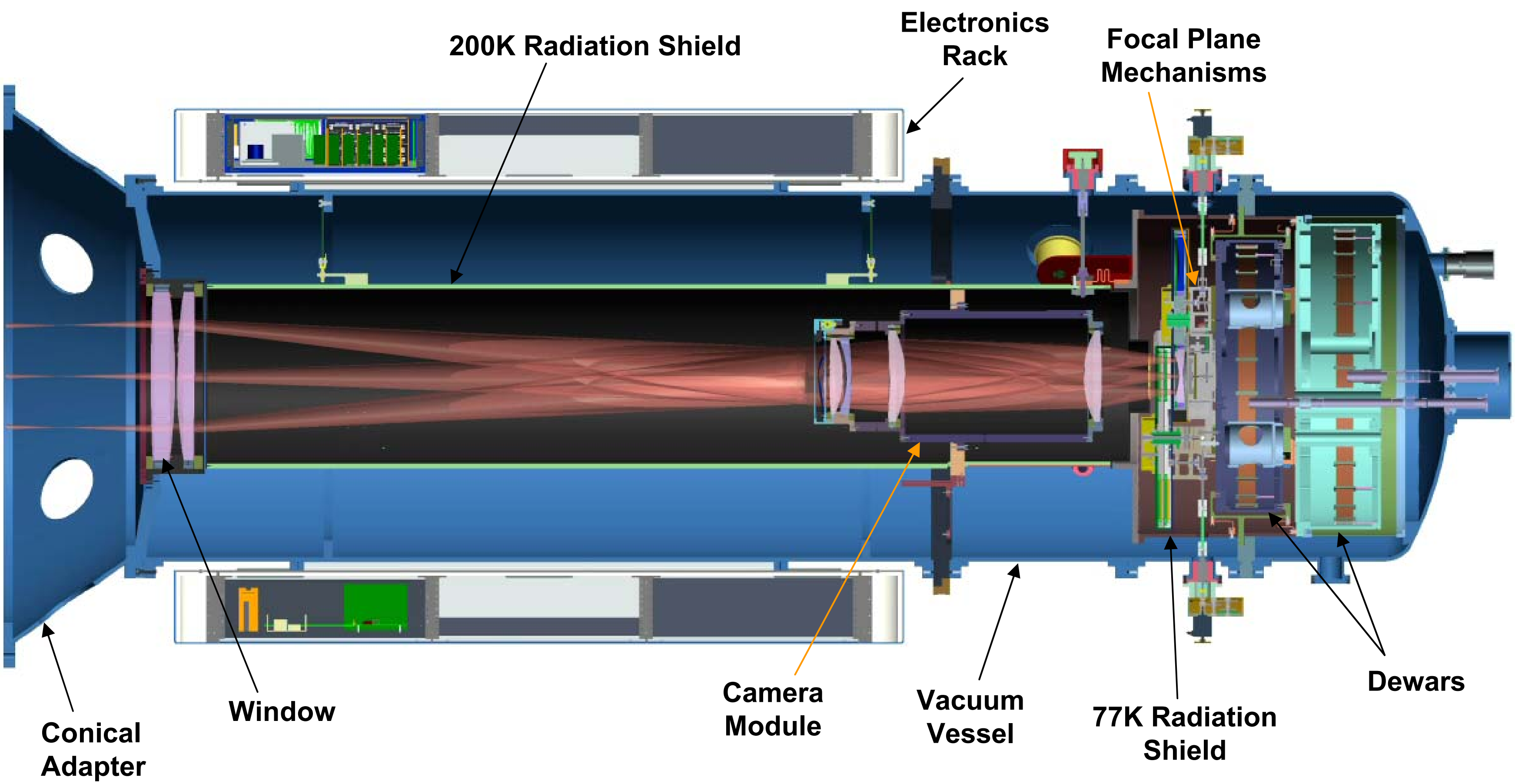
Instrument Configuration



- **Instrument Weight (with LN2) ~2300 lbs**
  - **CG 69 inches from rotator**
- **Cart Weight ~1260 lbs**

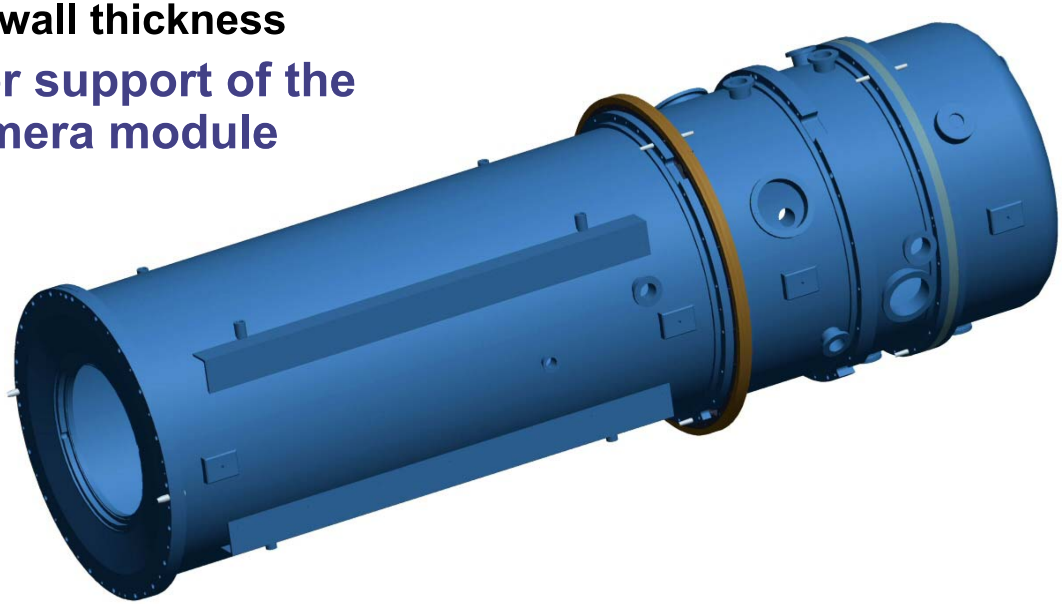
Optomechanical Design

Instrument Overview

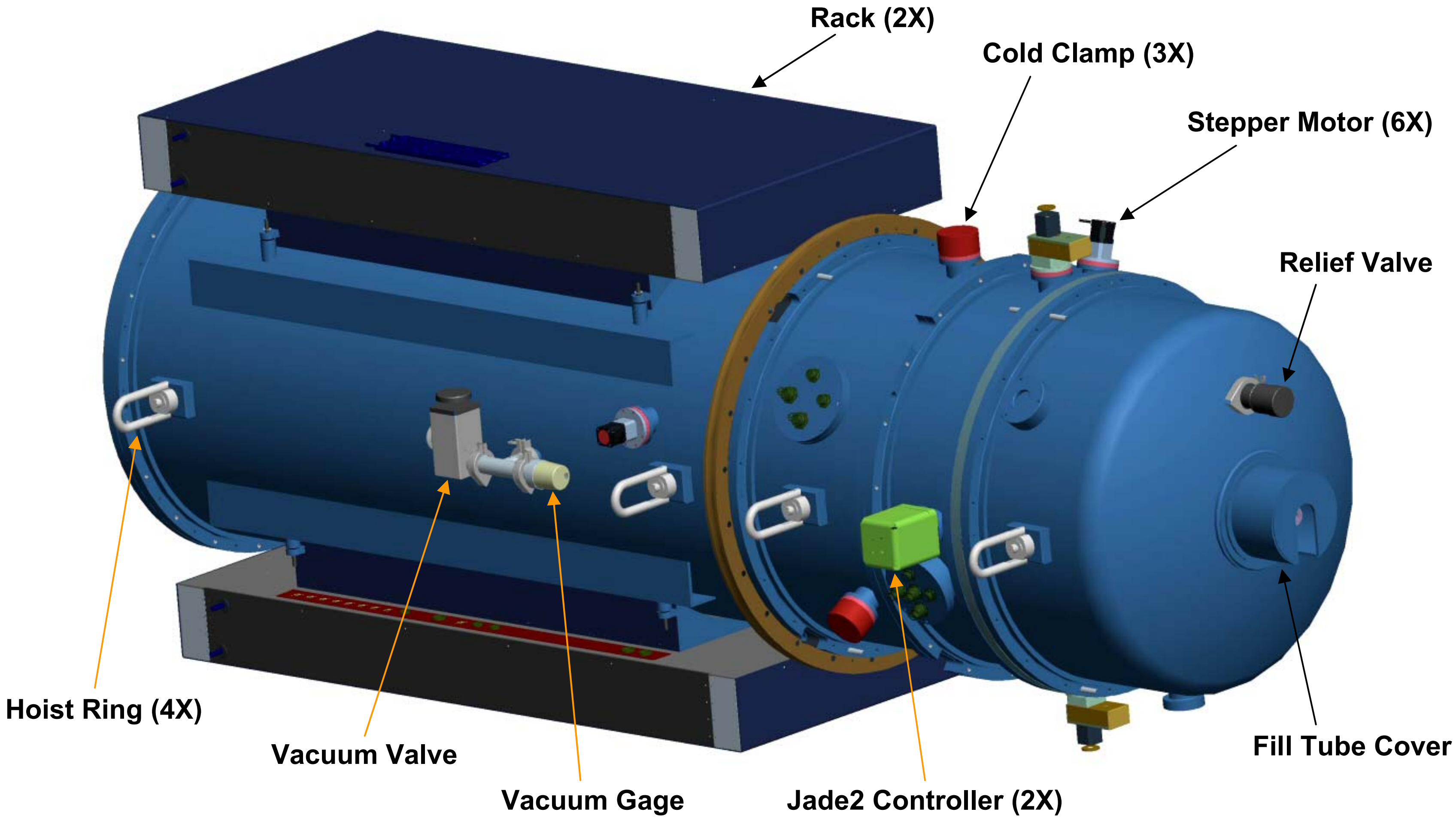


Vessel Design

- Function of the vacuum vessel
  - Facilitates cryogenic operation
  - Mitigates thermal background
  - Is the optical support structure
- Vessel Construction
  - Constructed of 6061-T6 tubular sections
    - 33” diameter, 5/16” wall thickness
  - Stainless Steel rings for support of the detector dewar and camera module

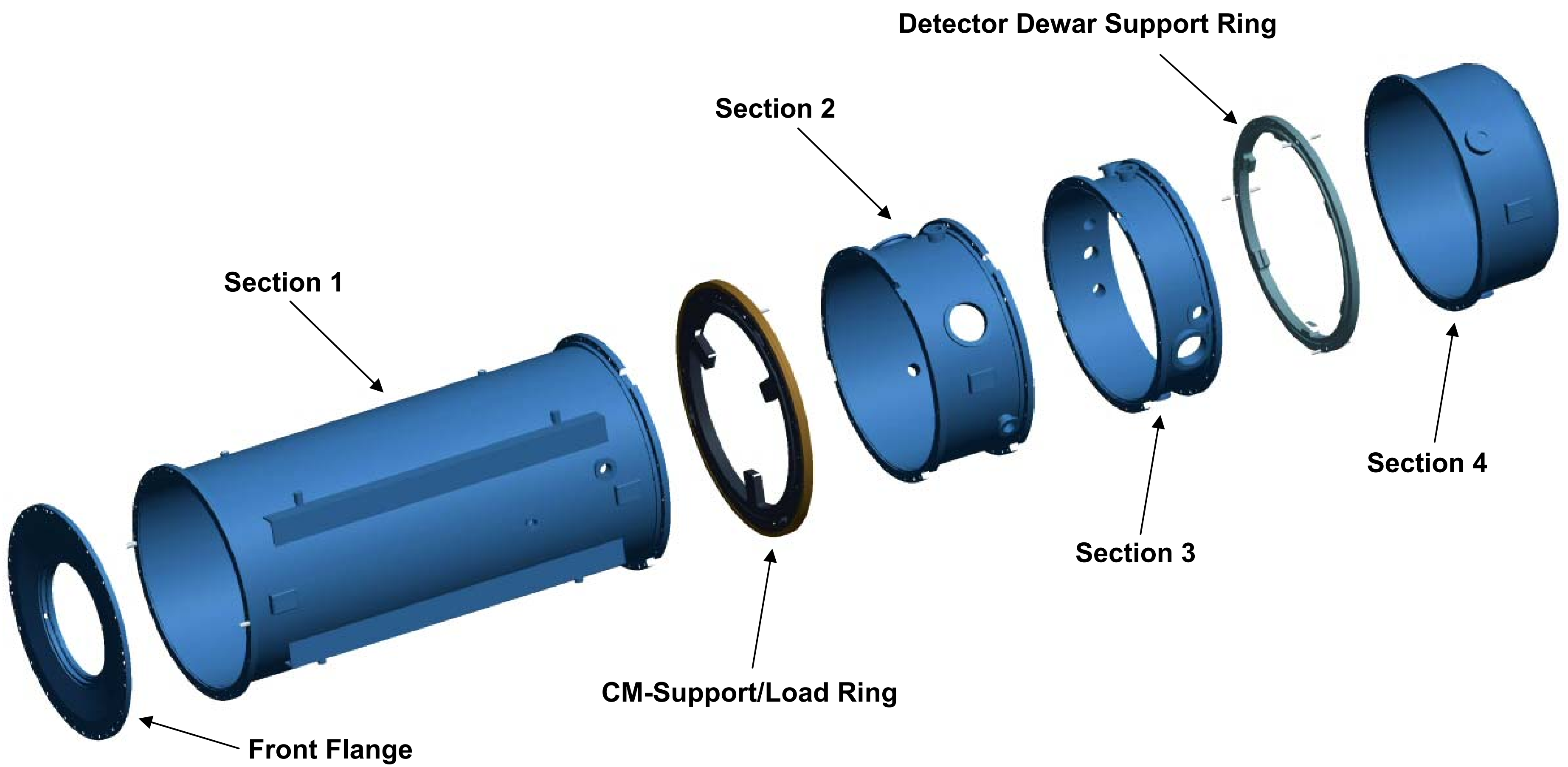


Vessel Details



Optomechanical Design

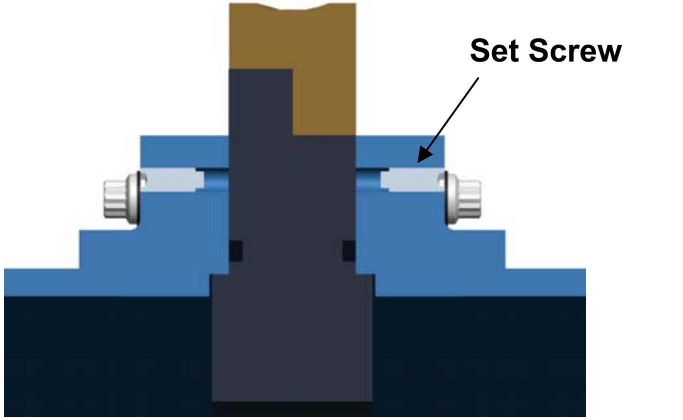
Vessel/Bench Exploded View

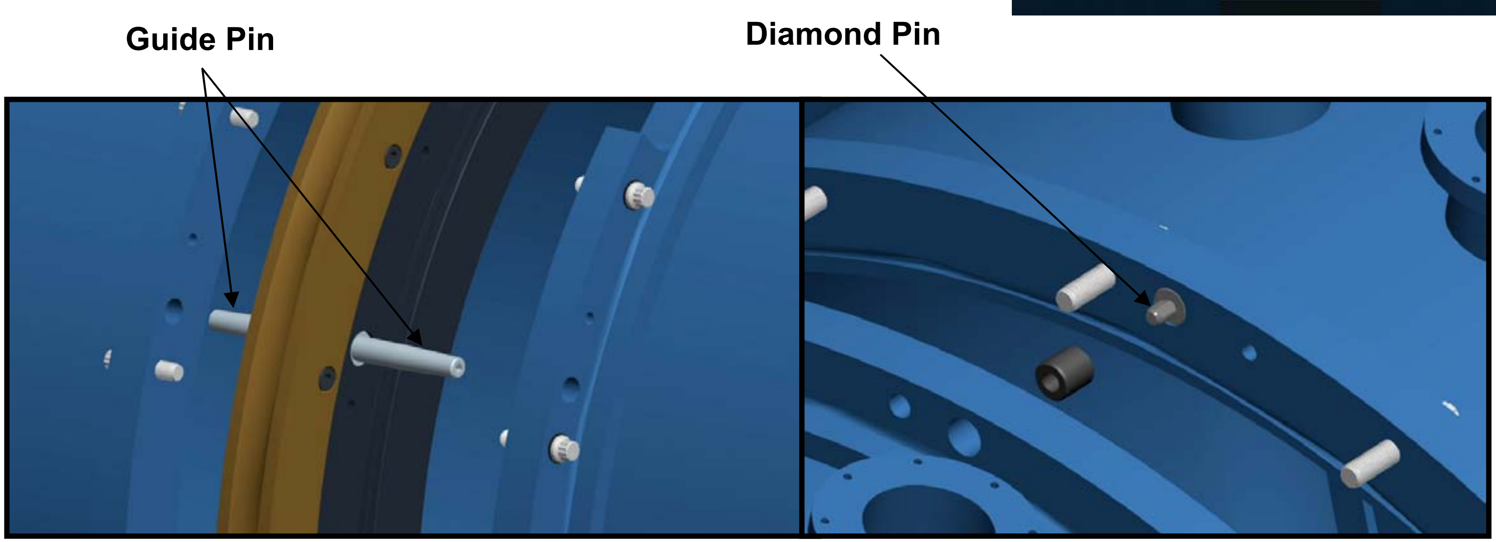


Optomechanical Design

Vessel Section Alignment

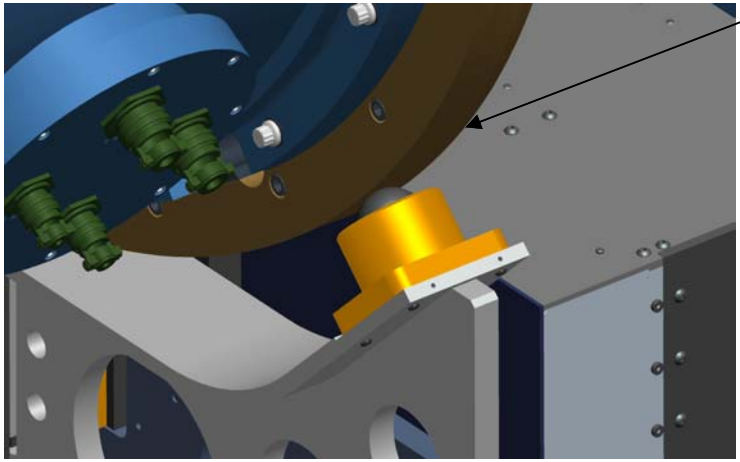
- **Precision shoulder & counter-bore facilitate accurate, repeatable, centration**
- **Diamond pin provides clocking**
- **Guide pins for ease of assembly**

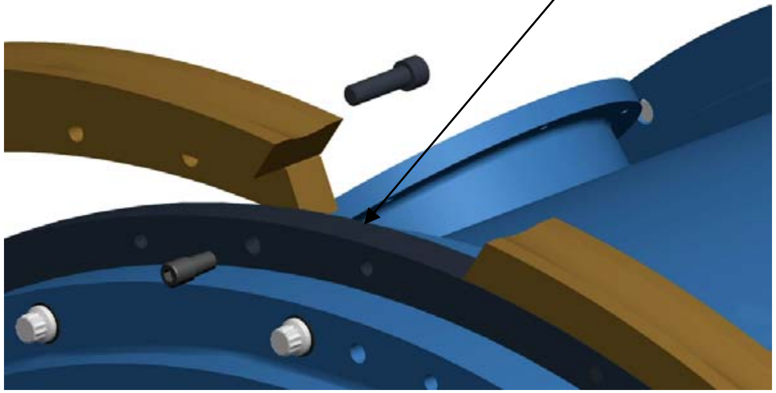


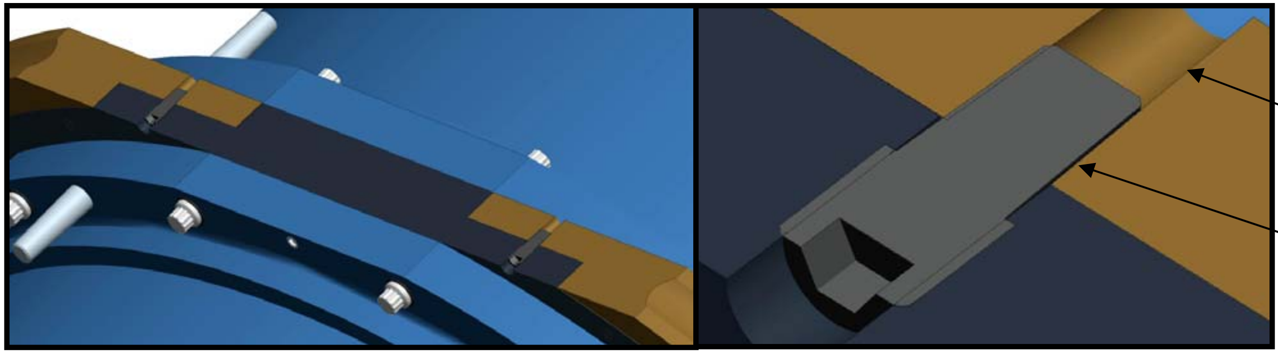


Optomechanical Design

Load Ring Detail



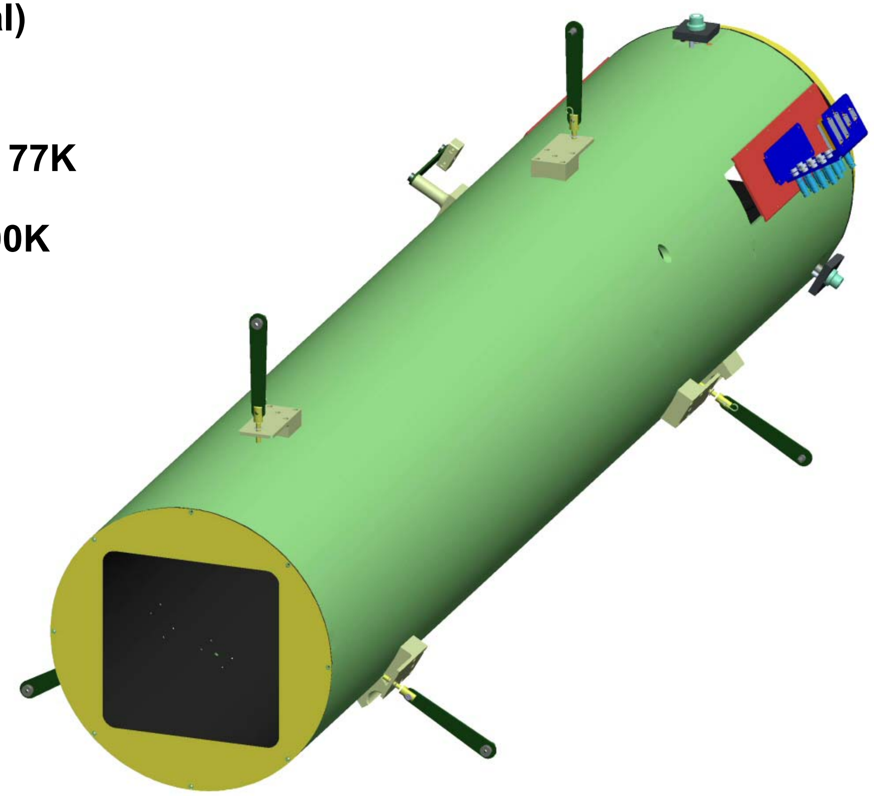




Optomechanical Design

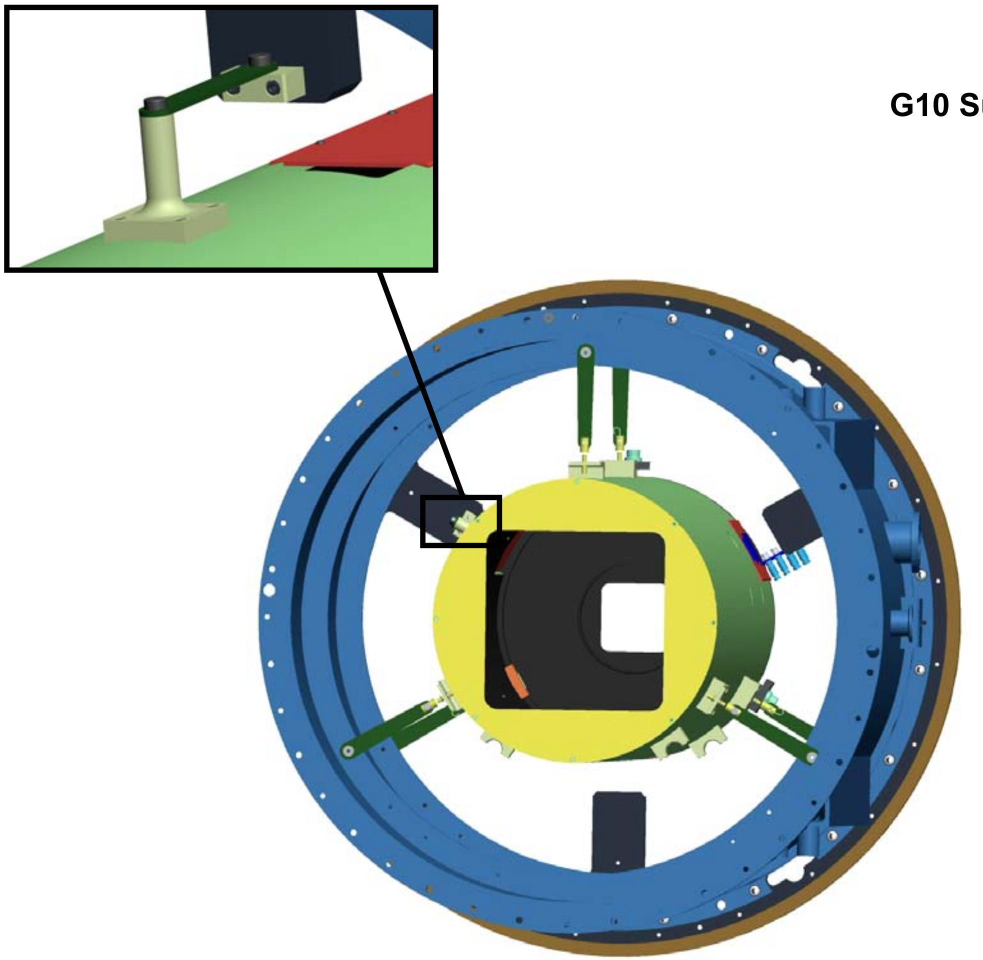
200K Radiation Shield

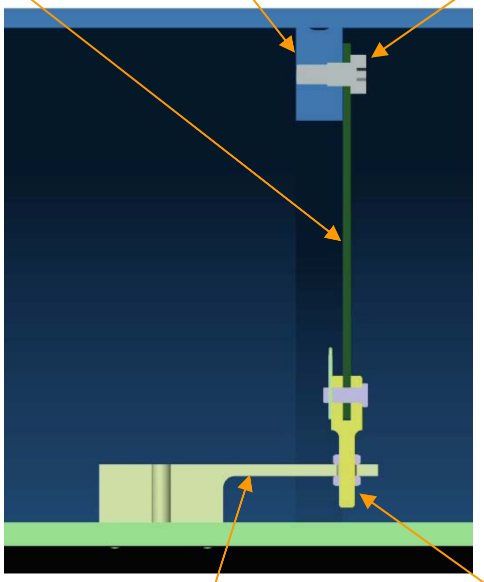
- **Requirements and Considerations**
  - Inner surfaces
    - Temperature < 230K (200K nominal)
    - Black in the near infrared
  - Thermal
    - Minimize heat load to ambient and 77K regime
    - Cold clamp interface to achieve 200K working temperature
- **Features**
  - Inner surfaces painted with Z306
  - MLI for low emissivity outer surface
  - Radiation baffles at each end
  - G10 mounting straps limit heat loss
  - Radial adjustments for centration
  - Cold clamp interface
  - Guide blocks to ease assembly
  - Temperature monitoring



Optomechanical Design

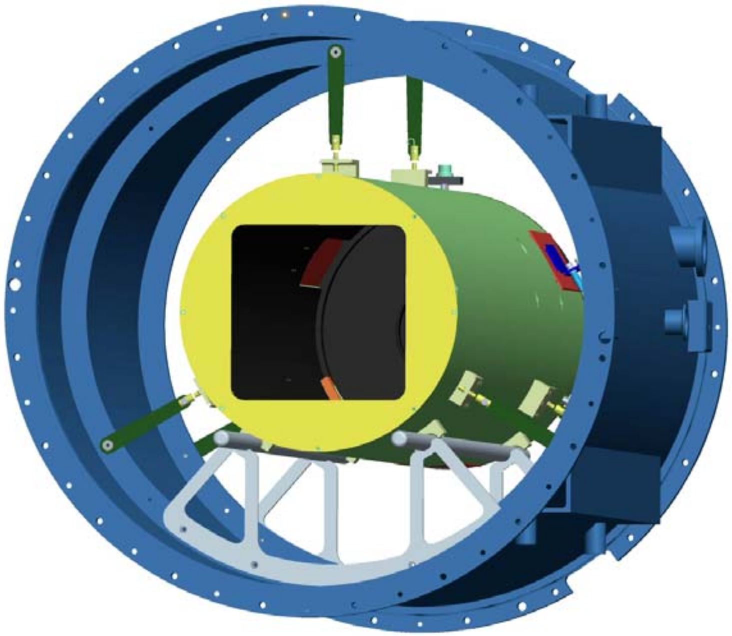
200K Radiation Shield Mounting

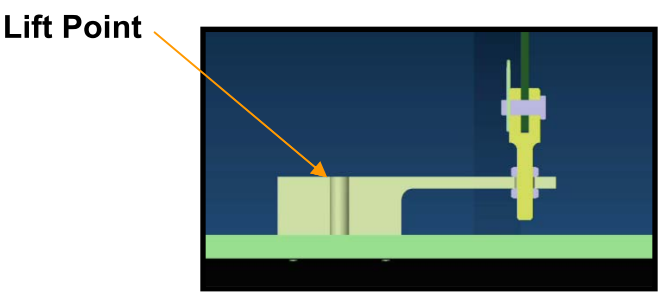


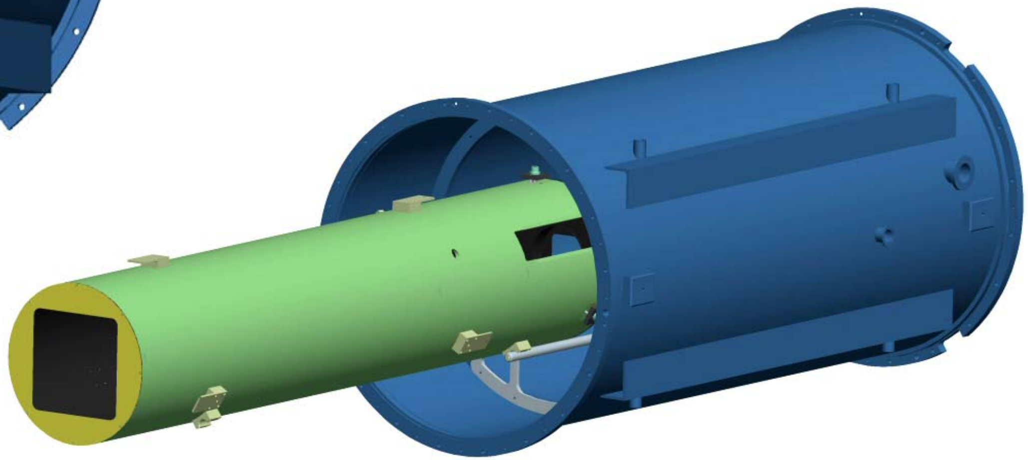


Optomechanical Design

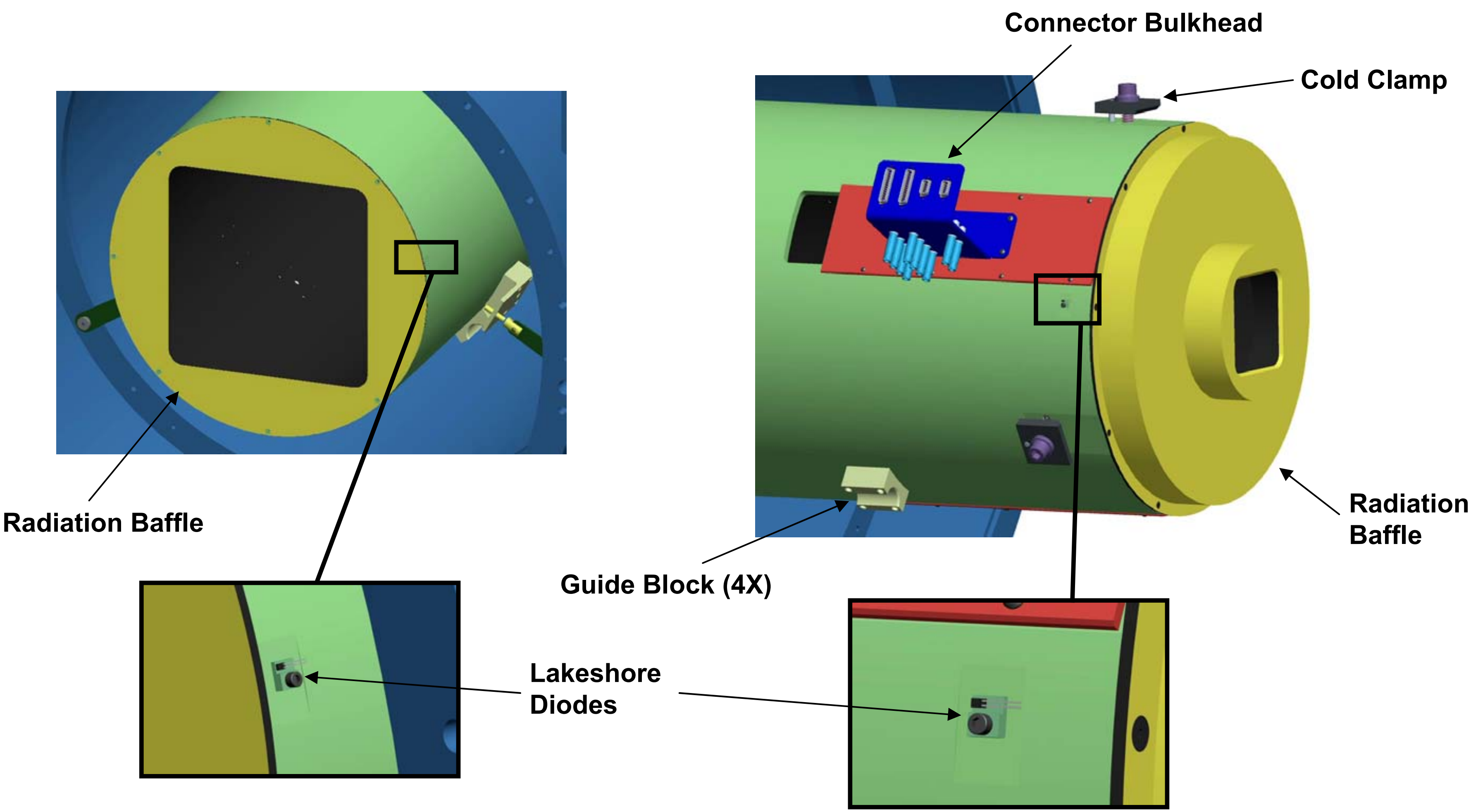
Radiation Shield Assembly





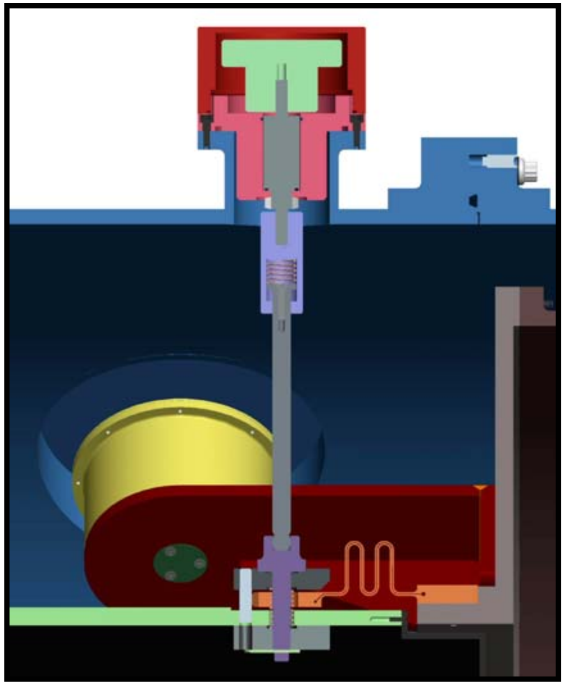


200K Radiation Shield Design Details



Cold Clamp

- **Thermally connect the 200K shield 77K shield**
- **Three cold clamps, 120 degree apart**
  - **Manually operated**
  - **Flow ~ 20 W each**
  - **Two clamps required for steady state operation**
  - **Closing the third clamp accelerates cooldown**
  - **Cold straps are designed for mechanical compliance and proper thermal resistance**



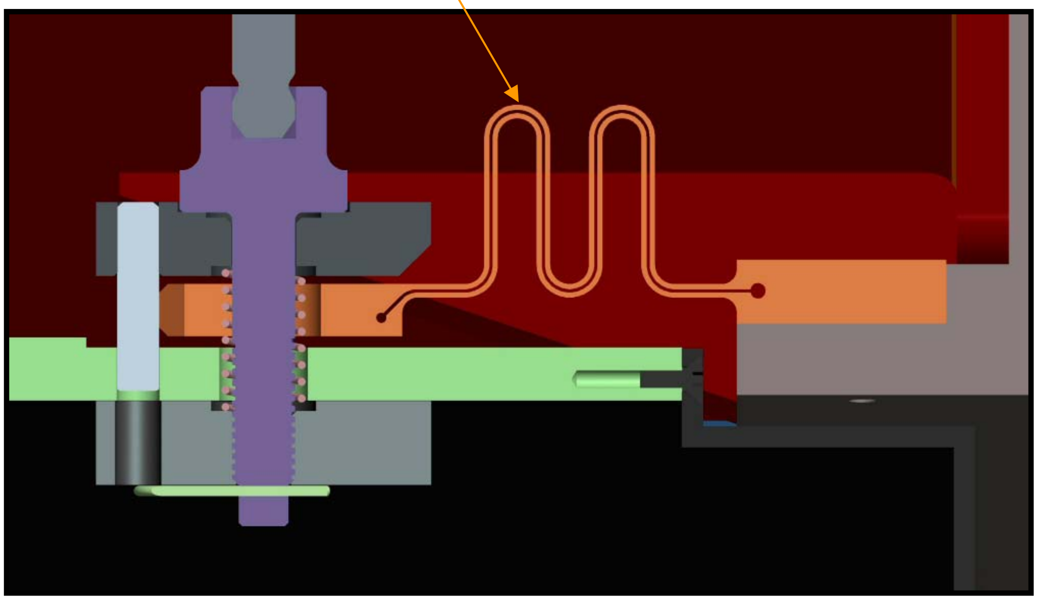
Optomechanical Design

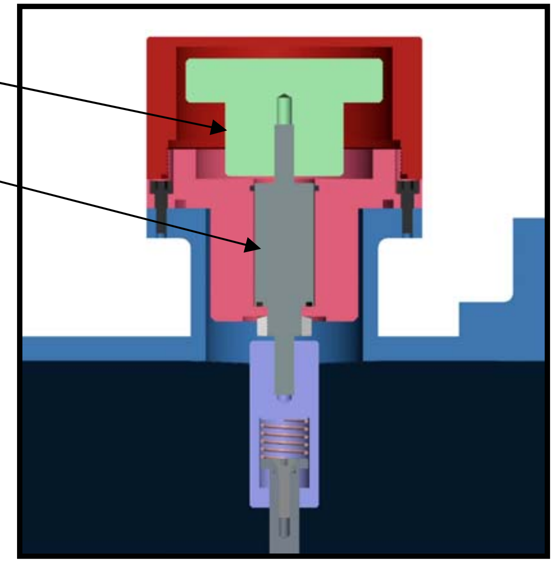
Cold Clamp Details

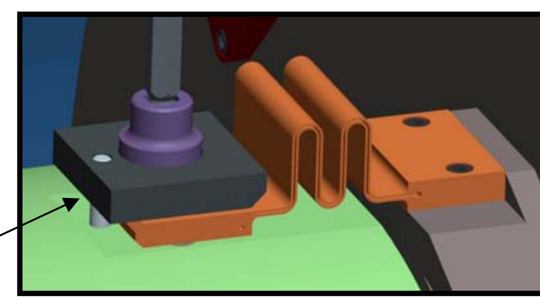
Handle

Ferrofluidic Feedthrough

Cold Strap (Copper)



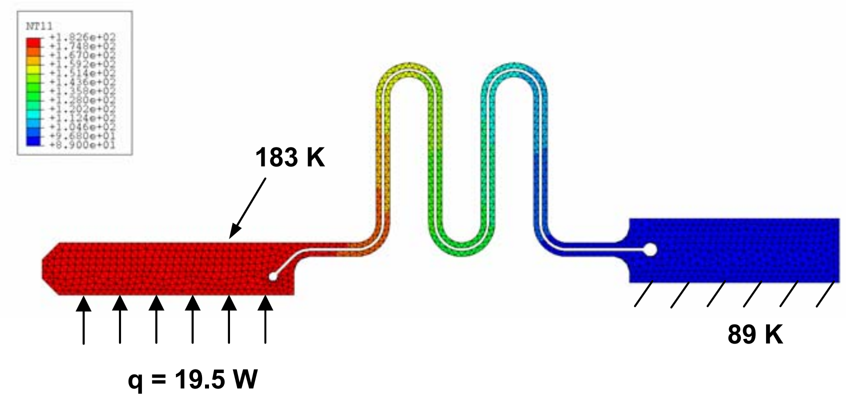




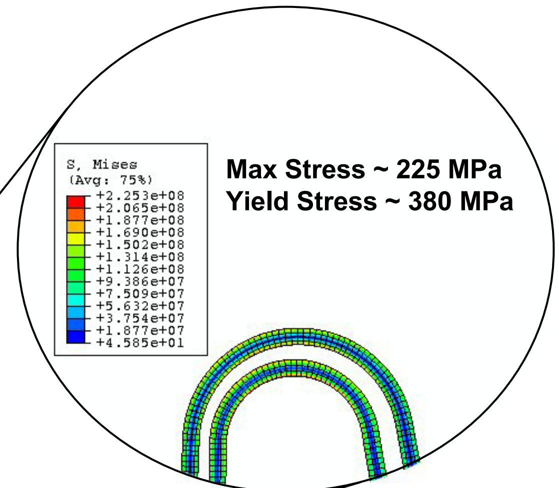
Clamp

Cold Strap FEA

Thermal Temp. Profile

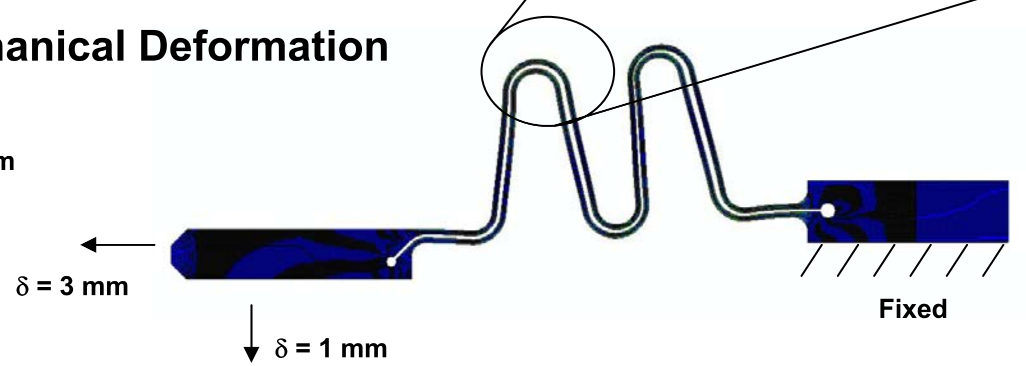


Mechanical Stress



Mechanical Deformation

Spring constant = 42 N/mm



Lens Mounting

- **Requirements**
  - Cell design accommodates differential contraction between glass and metal
  - Lenses must be centered and spaced within optomechanical tolerances when cold

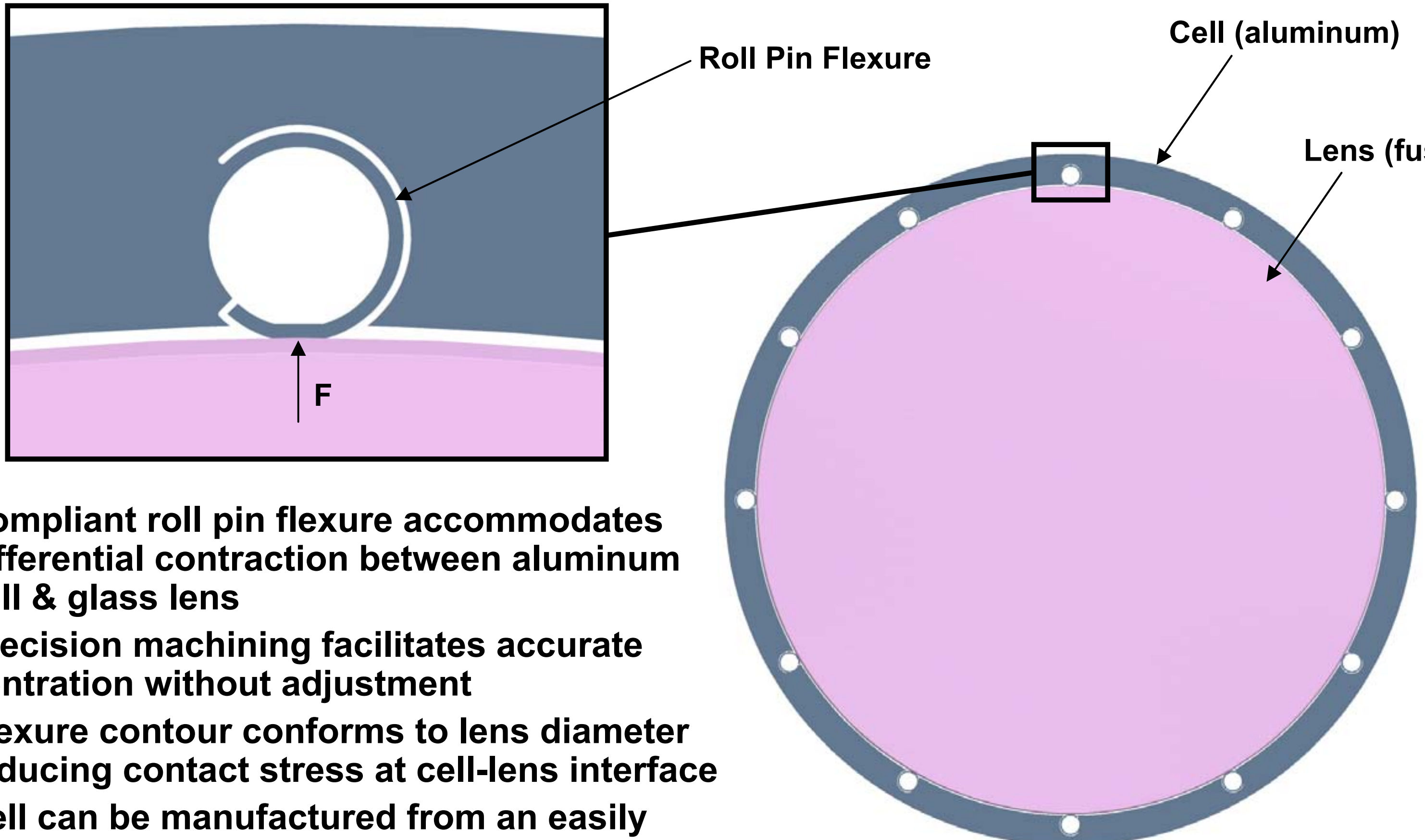
- **Desirements**
  - No adjustments
    - Simplifies assembly
    - Build cells & barrels to as-built lens dimensions
  - Use aluminum for lens cells, mounts and barrels
    - Aluminum is easy to machine and reduces weight/flexure
  - Lenses centered regardless of temperature

Window Lens Details & Tolerances

Lens	Mass (lbs)	Diameter (in)	Tilt (in)	Decenter (in)	Spacing (in)
L1	25. 5	15.00	0.002	0.002	± 0.02
L2	18.0	15.00	0.002	0.002	± 0.003
L3	3.1	6.75	0.001	0.0015	± 0.003
L4	2.3	6.875	0.001	0.0015	± 0.003
L5	6.2	8.125	0.0014	0.002	± 0.003
L6	6.2	8.125	0.0014	0.002	± 0.003
L7	1.5	4.75	0.005	0.005	± 0.02

Optomechanical Design

Roll Pin Flexure Lens Cell

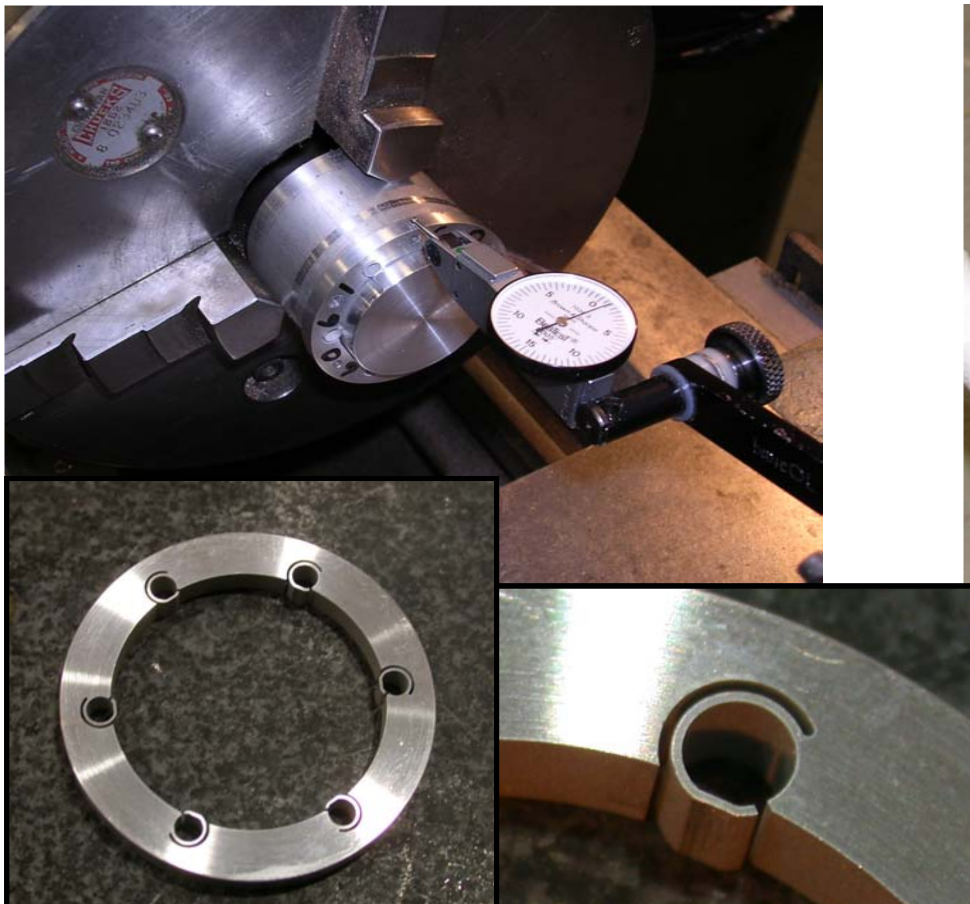


- Compliant roll pin flexure accommodates differential contraction between aluminum cell & glass lens
- Precision machining facilitates accurate centration without adjustment
- Flexure contour conforms to lens diameter reducing contact stress at cell-lens interface
- Cell can be manufactured from an easily machinable material (i.e. aluminum)

Optomechanical Design

Relevant Prototyping Effort

Runout measurement to determine decenter

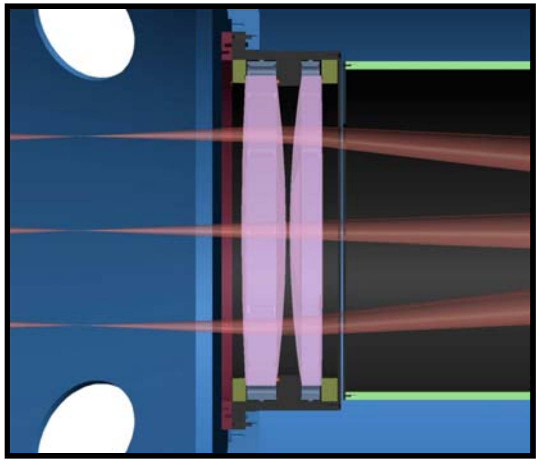


Roll pin flexure cooled in test dewar.

Optomechanical Design

Window Assembly

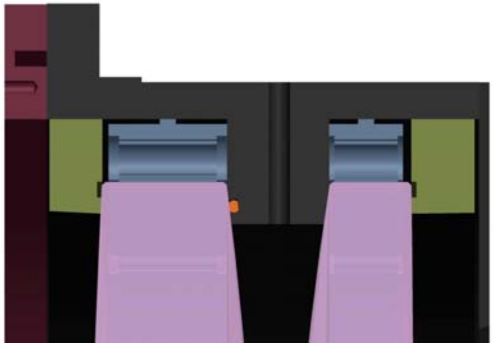
- **Basics**
  - Packages L1-L2
  - All-aluminum mounting, weighs ~ 98 lbs
  - 490 mm diameter, 143 mm long
  - Operates at ambient temperature
  - L1 is the vacuum window

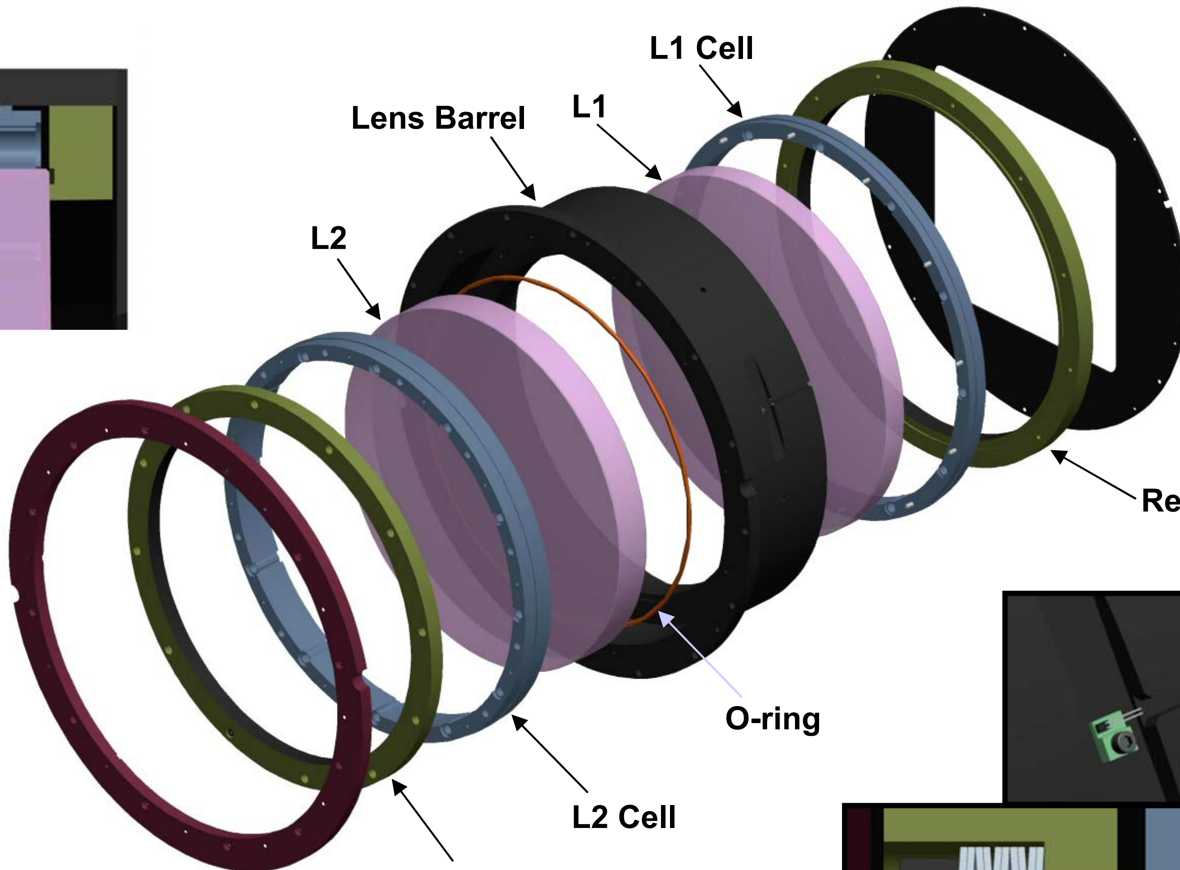


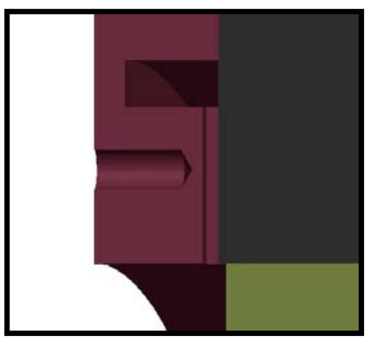
- **Features**
  - Critical scattering surfaces coated with Z306
  - Lens cells and retainers coated with Tufram®
    to reduce friction at interfaces
  - Guide rods and lifting fixture ease assembly
  - Diode for cell temperature monitoring
  - Thermal baffle reduces window heat load
  - Nitrogen purge to prevent frosting

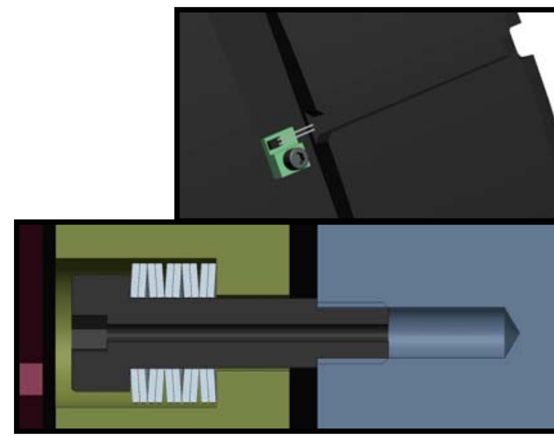
Optomechanical Design

Window Design



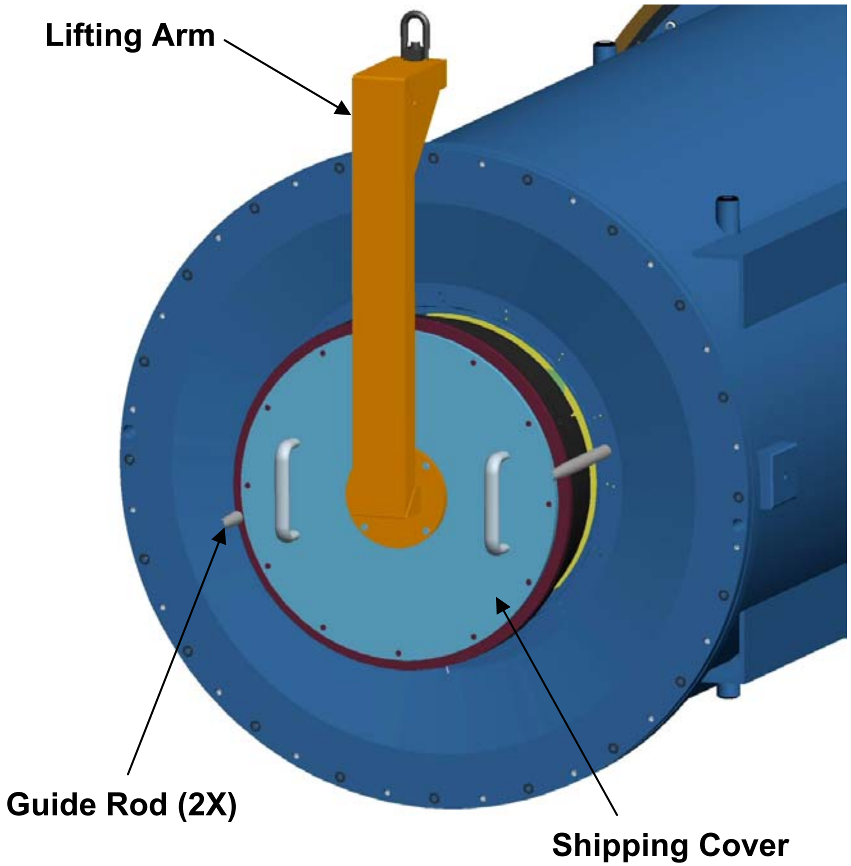


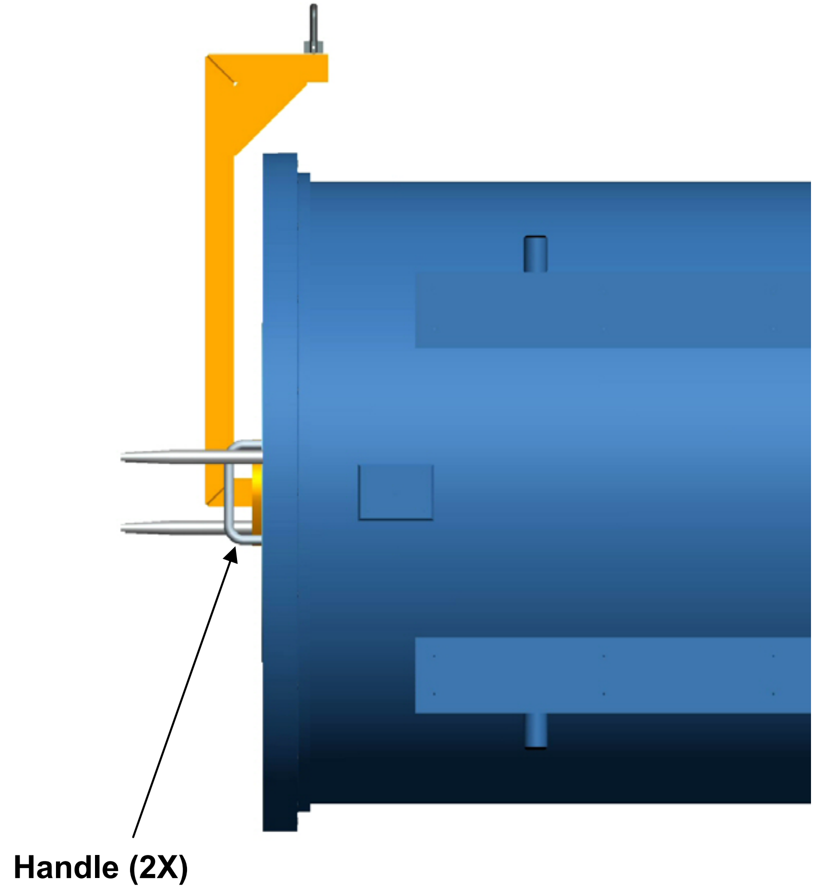




Optomechanical Design

Window Assembly

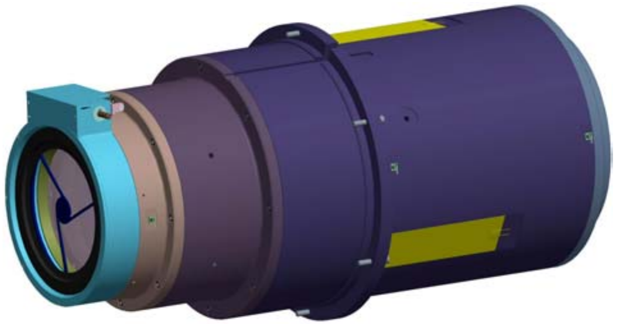




Optomechanical Design

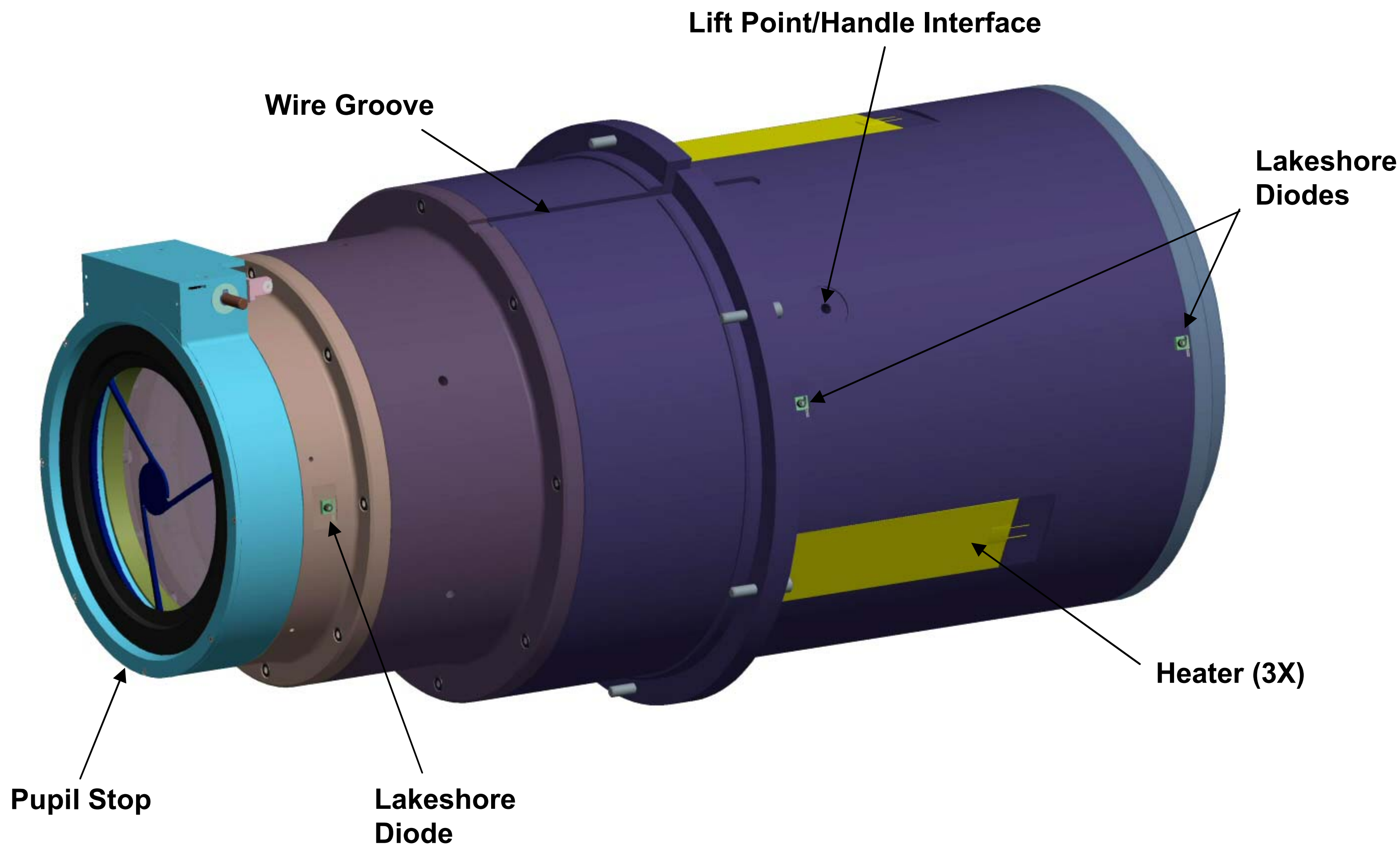
Camera Module

- **Basics**
  - Packages L3-L6
  - All-aluminum mounting, weighs ~ 86 lbs
  - 300 mm diameter, 650 mm long
  - Operates at 200K



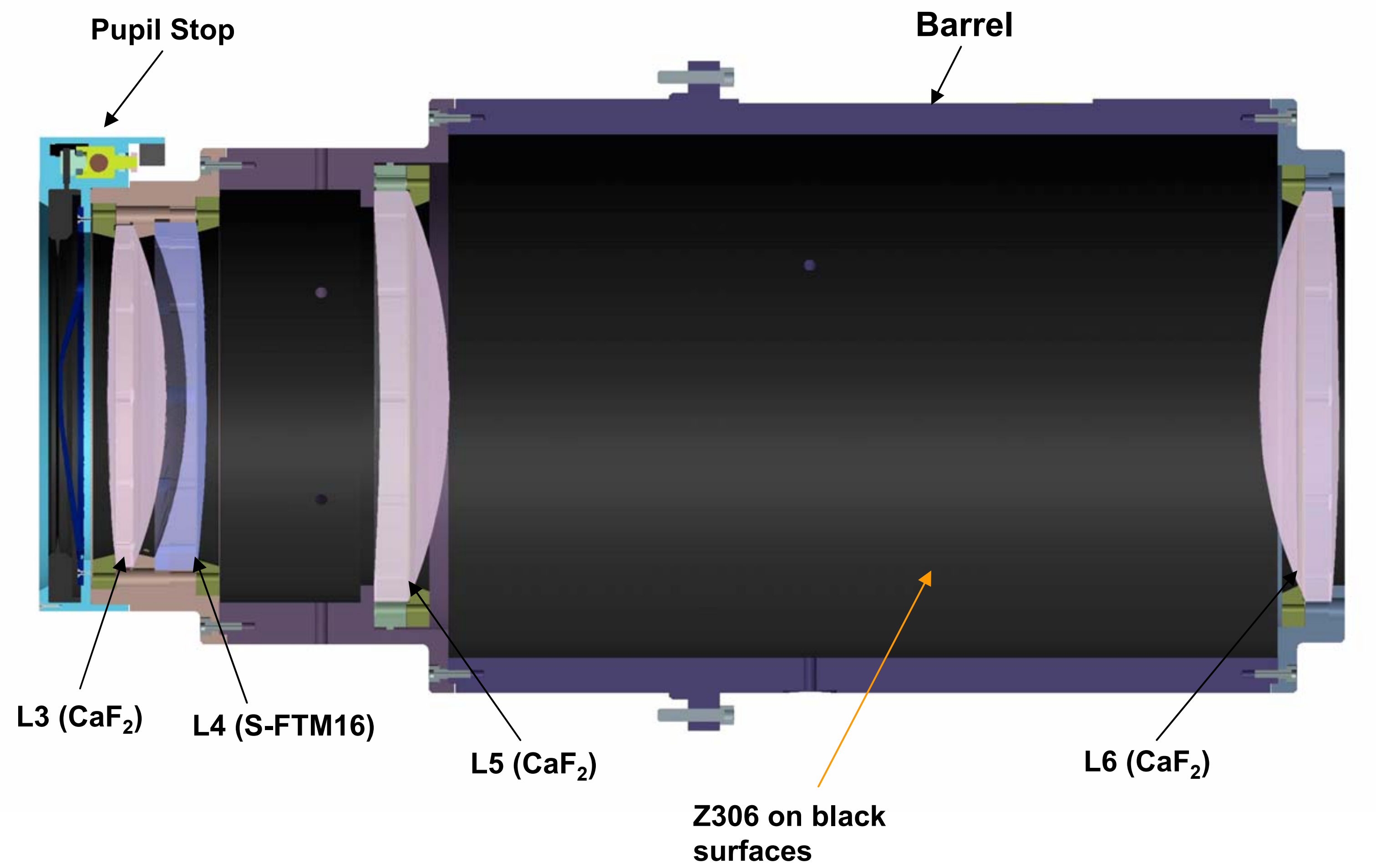
- **Features**
  - Critical scattering surfaces coated with Z306
  - Lens cells and retainers coated with Tufram®
    to reduce friction at interfaces
  - Lakeshore diodes for temperature monitoring
    and control
  - Kapton film heaters for temperature control
  - Adjustable pupil stop

Camera Module Details

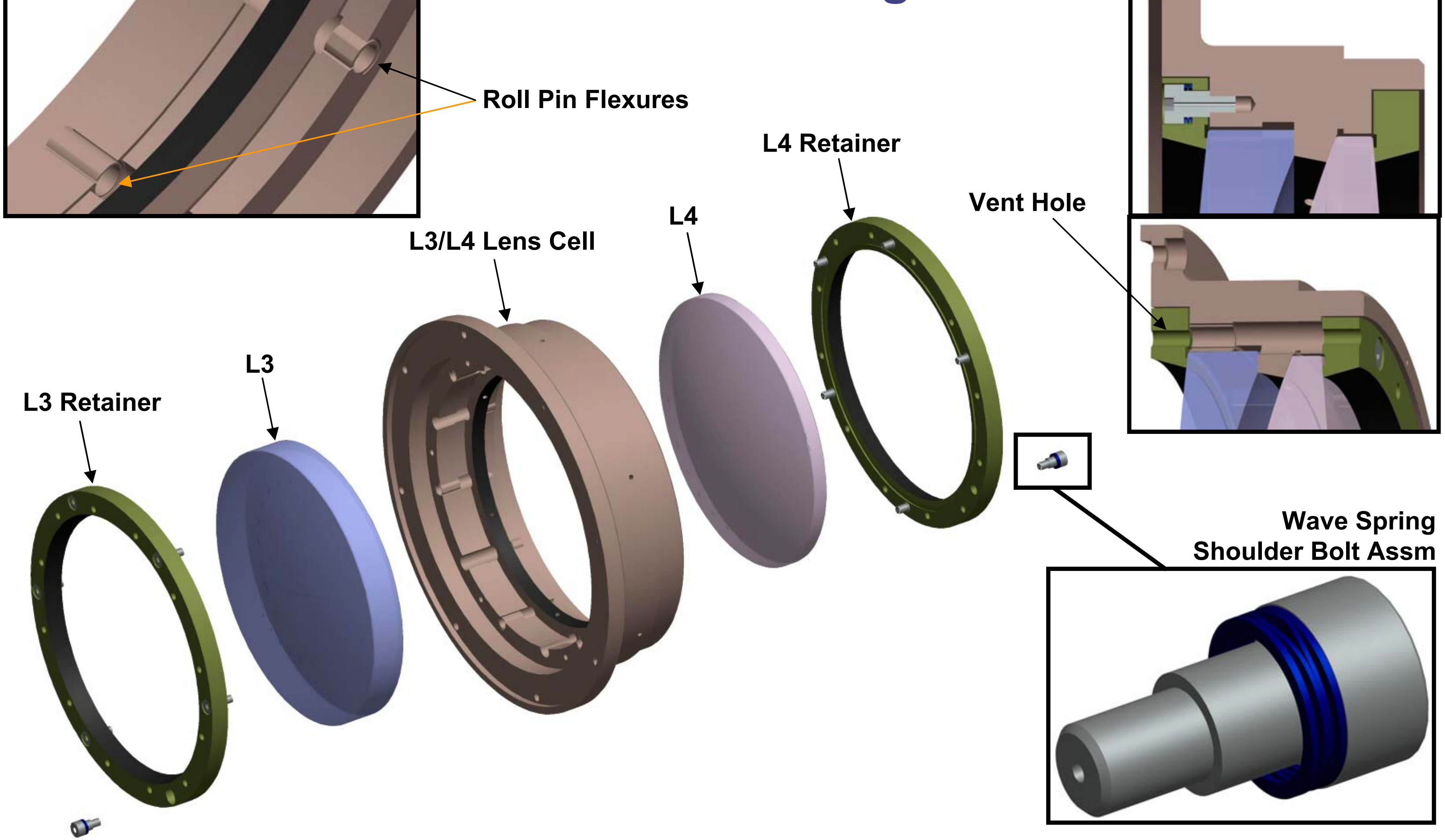


Optomechanical Design

Camera Module Section View

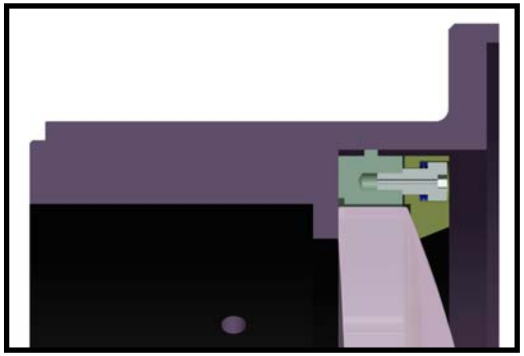


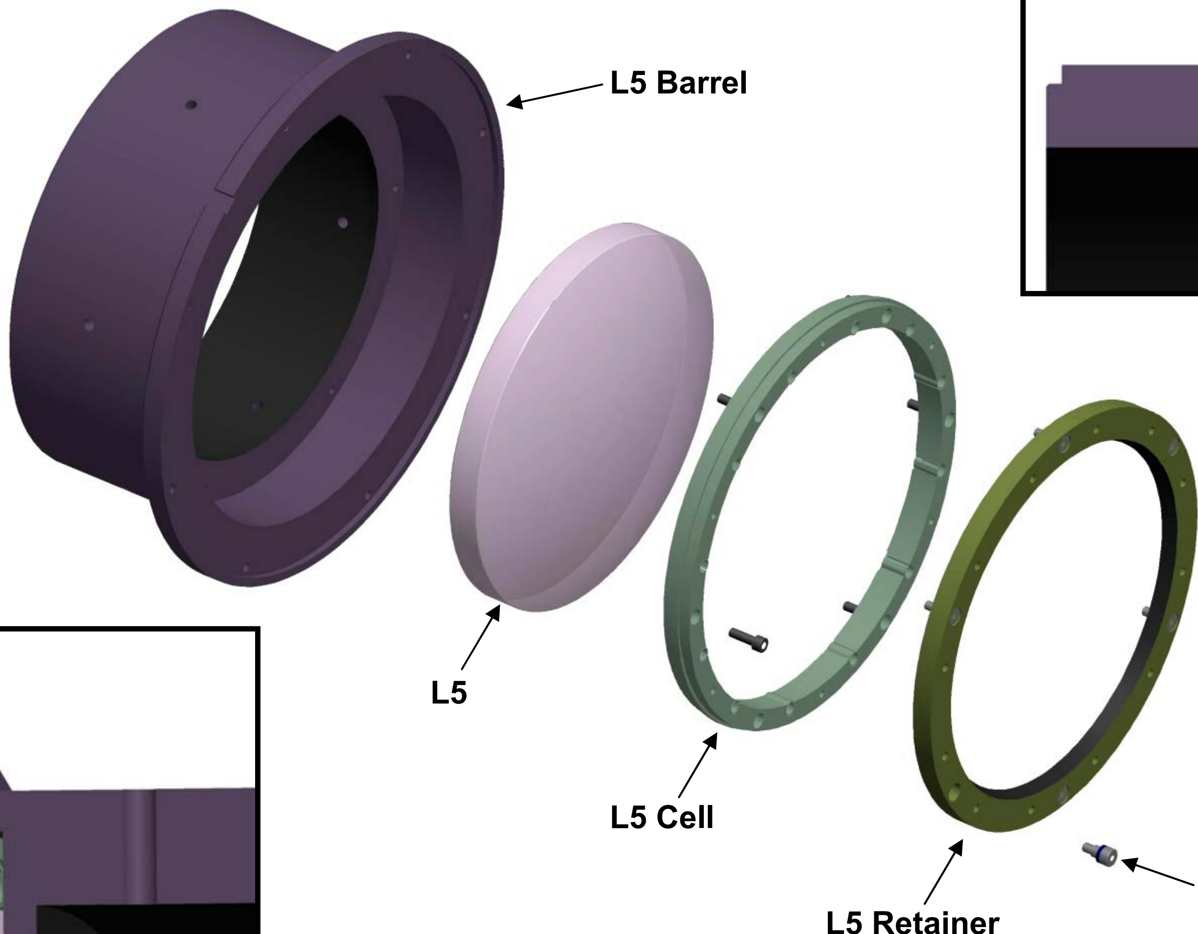
L3/L4 Mounting



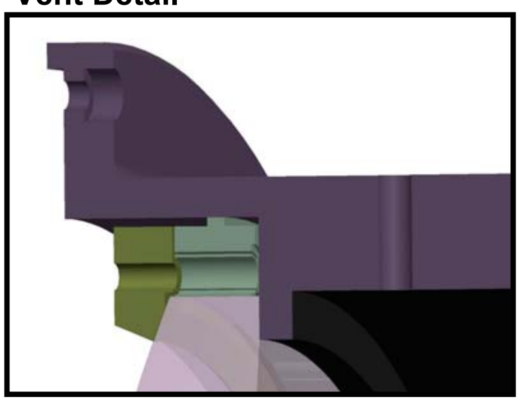
Optomechanical Design

L5 Mounting



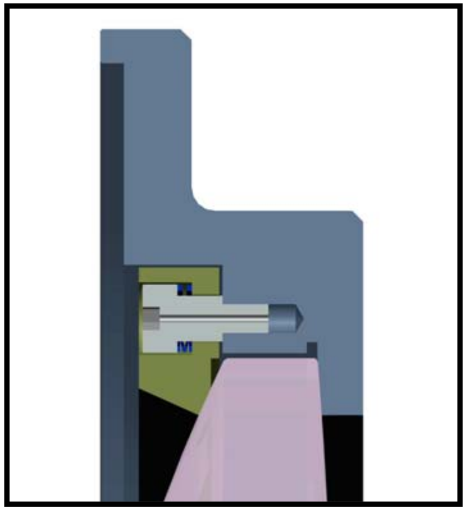


Vent Detail

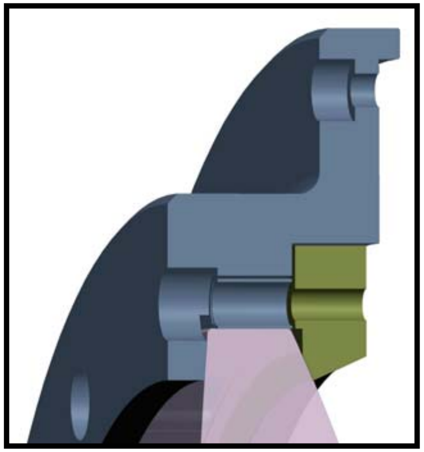


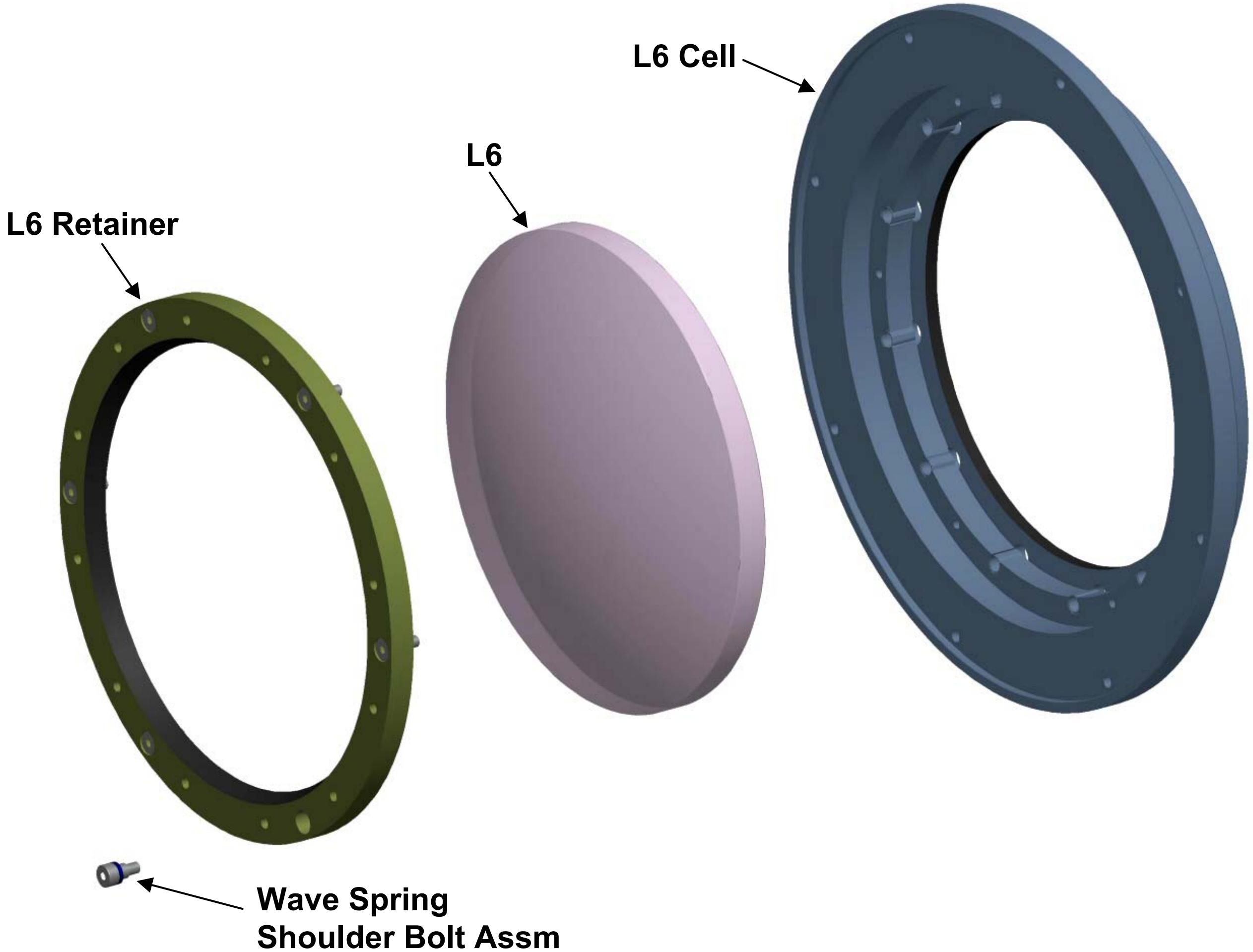
Optomechanical Design

L6 Mounting



Vent Detail



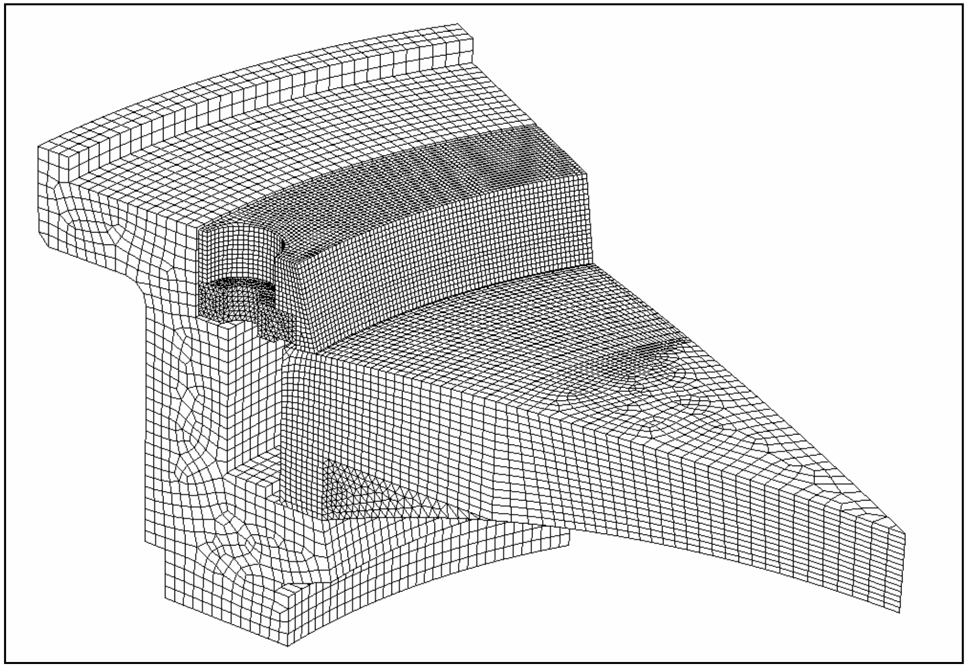


Optomechanical Design

An FEA Model of the L4 Assembly was Created to Evaluate Contact Stresses and Deformation in the most vulnerable Lens

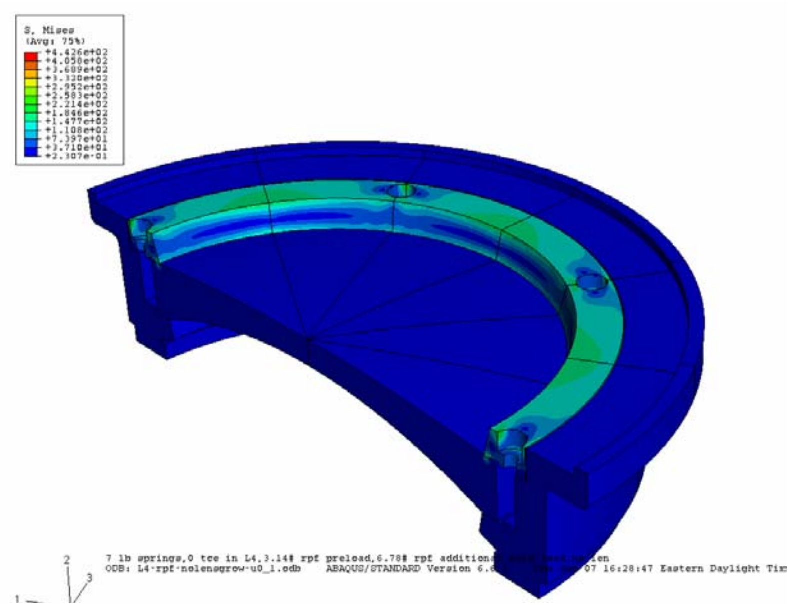
A 30º wedge was modeled using continuum elements and appropriate symmetry BCs. The model applies loads step by step:

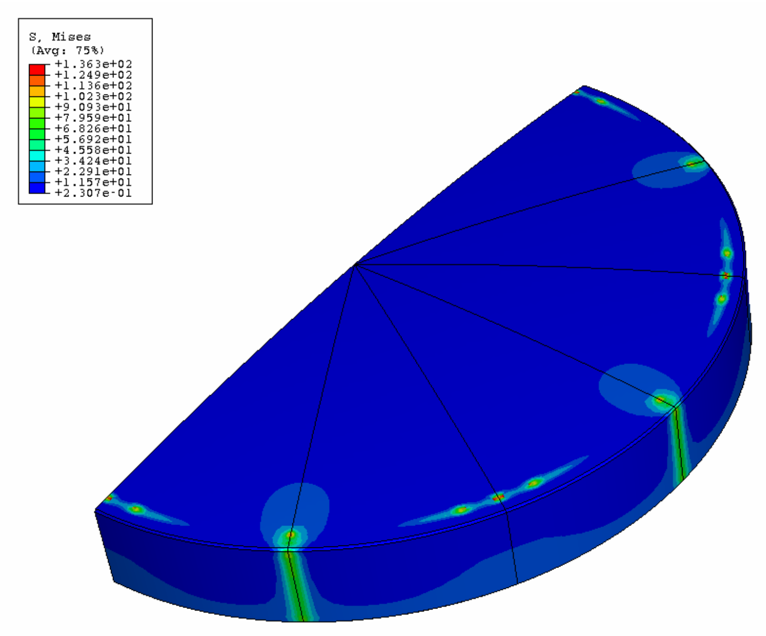
1) Retaining ring fastener spring load.
2) Roll Pin Flexure (RPF) preload.
3) Assembly cool down (coefficient of friction = 0.1)
4) Apply RPF cold load.



Optomechanical Design

Predicted Stresses



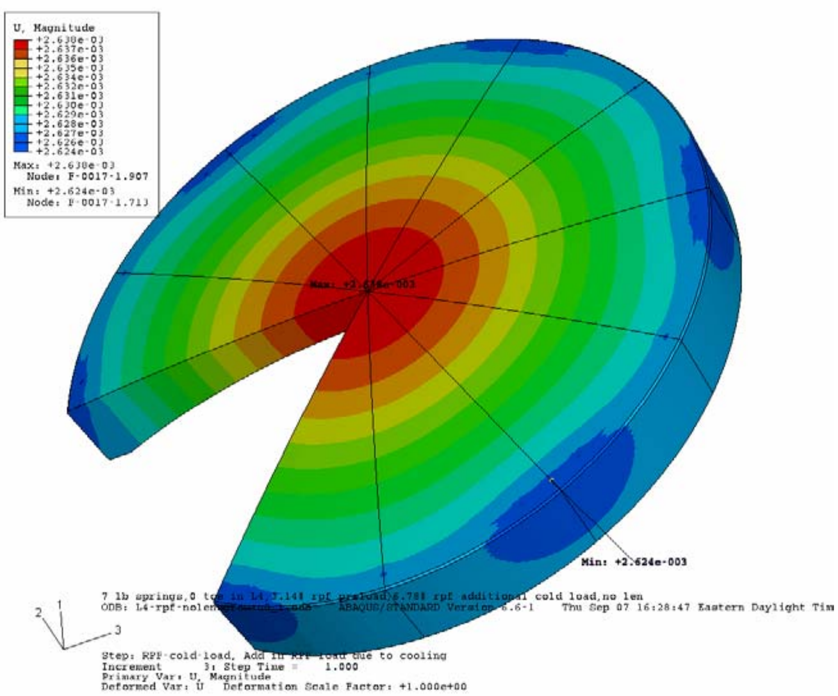


Mises stresses of 440 psi develop in the L4 retaining ring.

Mises stresses of no more than 136 psi are expected to develop in the lens under the influence of the retaining ring fasteners and the RPFs.

Predicted L4 Deflections

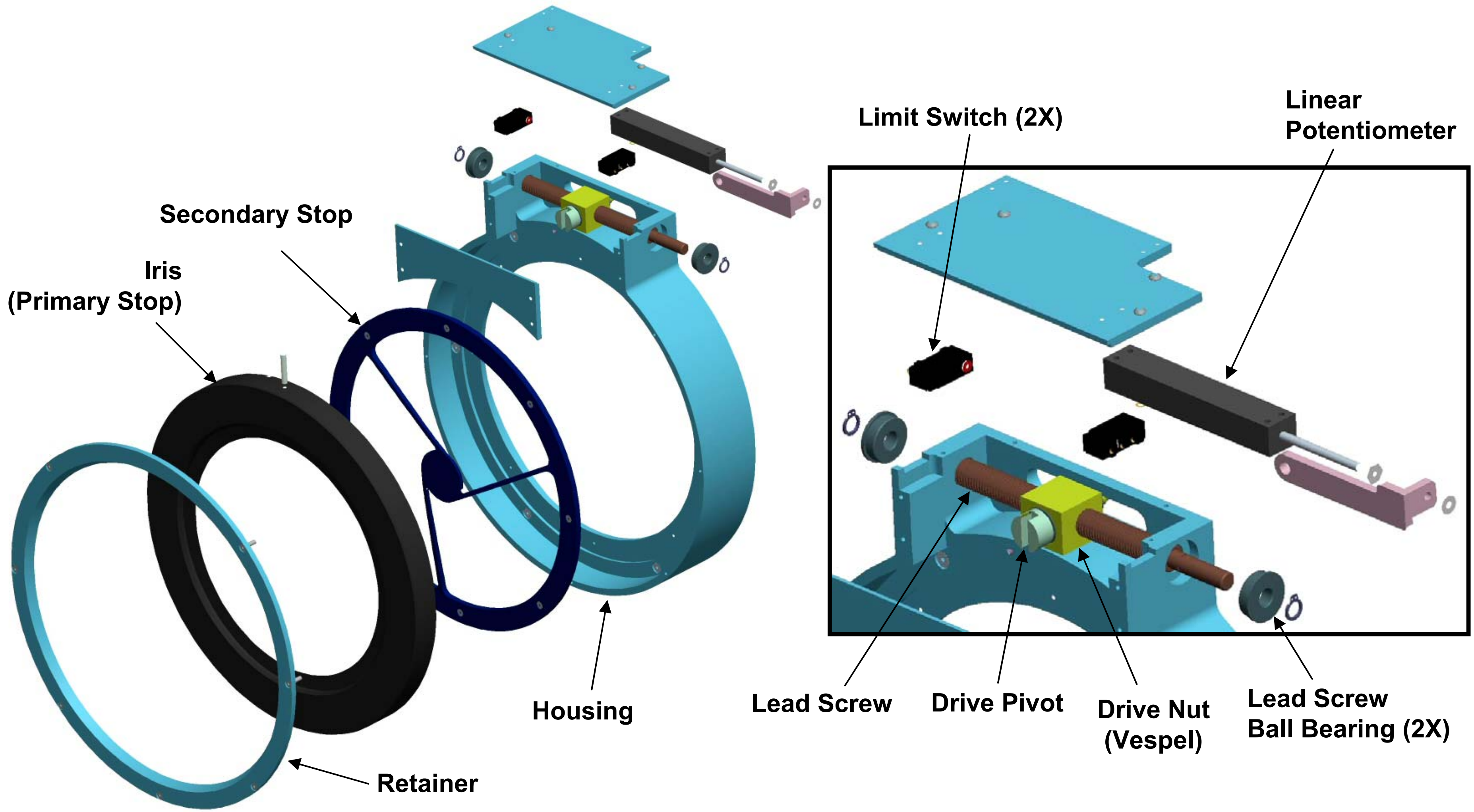
	Model	L4-rpf-nolensgrow-u0_1
	Coeff. of Friction	0.10 (Tufram)
Load	**Description (Effects are Cumulative)**	**L4 Center Deformation (2 direction)**
1	7# per fastener spring load	-3.81e-6 in (0.097 µm)
2	3.14# per RPF radial preload	+2.16e-7 in (0.005 µm)
3	Cool Down Assy (68F→-99.7F)	+2.50e-6 in (0.064 µm)
4	6.78# per RPF radial cold load (additional)	+1.20e-5 in (0.305 µm)



The aluminum RPF considered:
Ø0.310 in
0.75 inches long
t=0.020 inches
K=1572 #/in

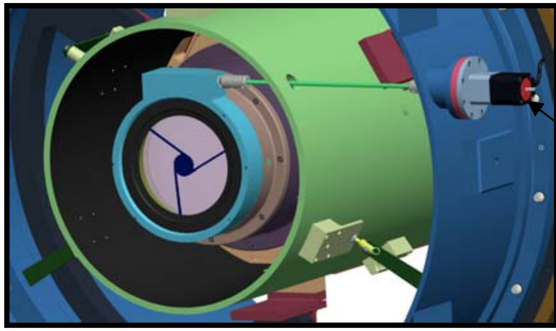
Optomechanical Design

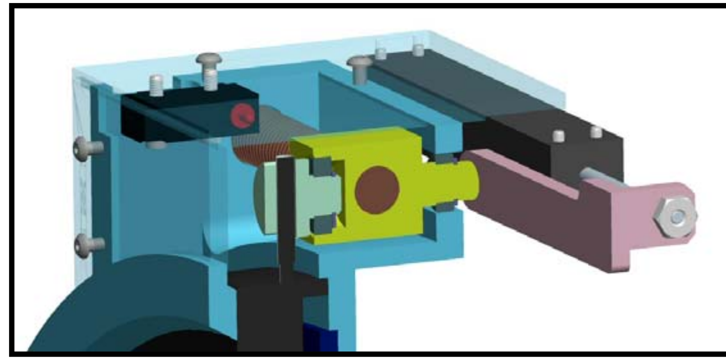
Pupil Stop Assembly Details

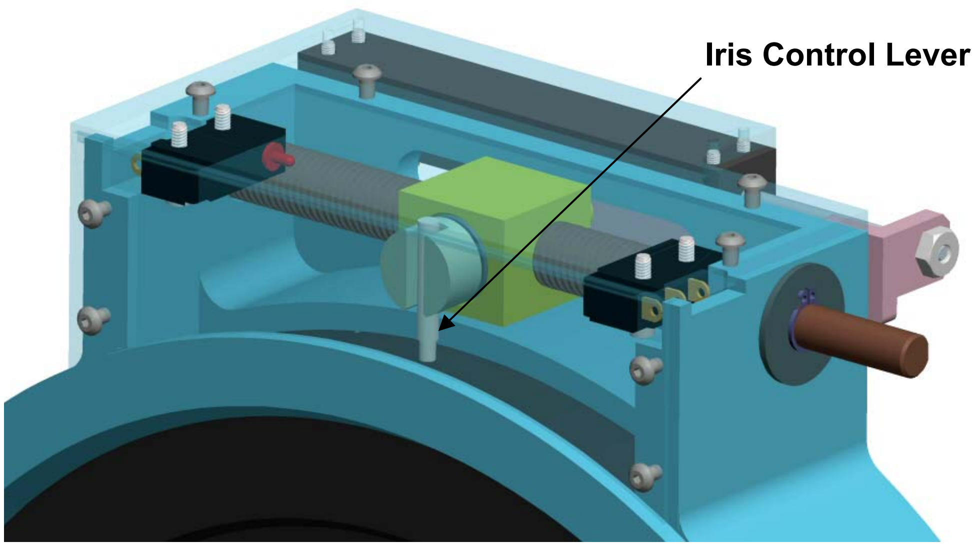


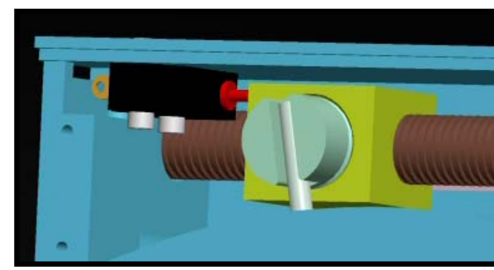
Optomechanical Design

Iris Drive Mechanism Details



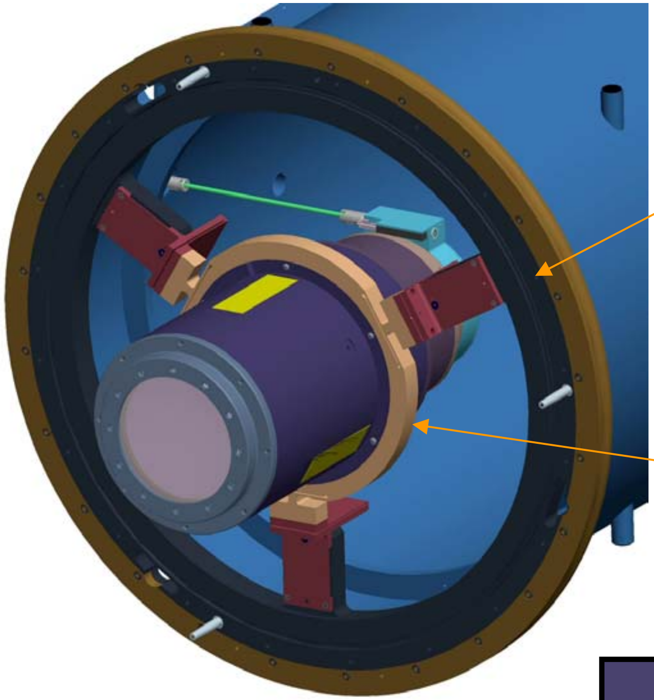






Optomechanical Design

Camera Module Mount

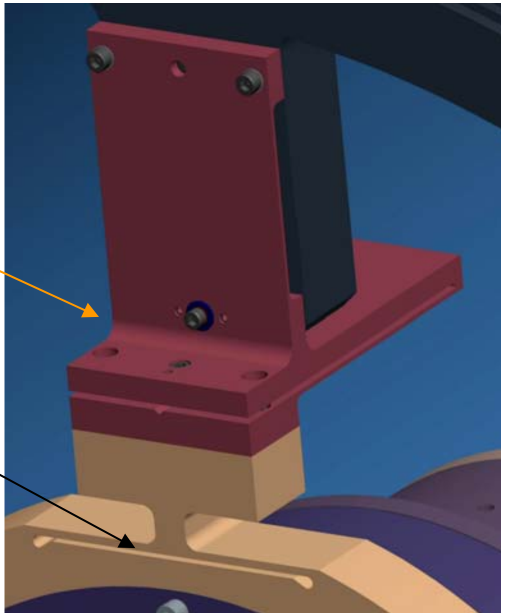


Support Ring
(Stainless Steel)

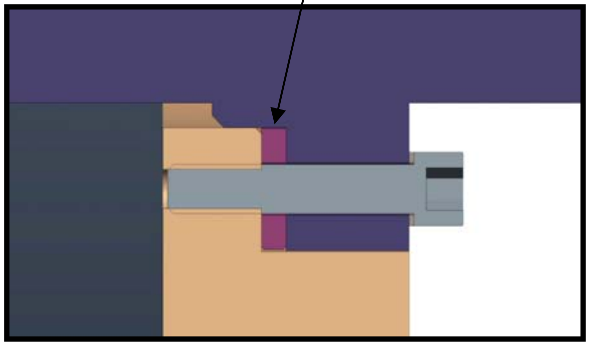
Mounting Ring
(Aluminum)

Adjustment Flexure
(Titanium)

Radial Flexure



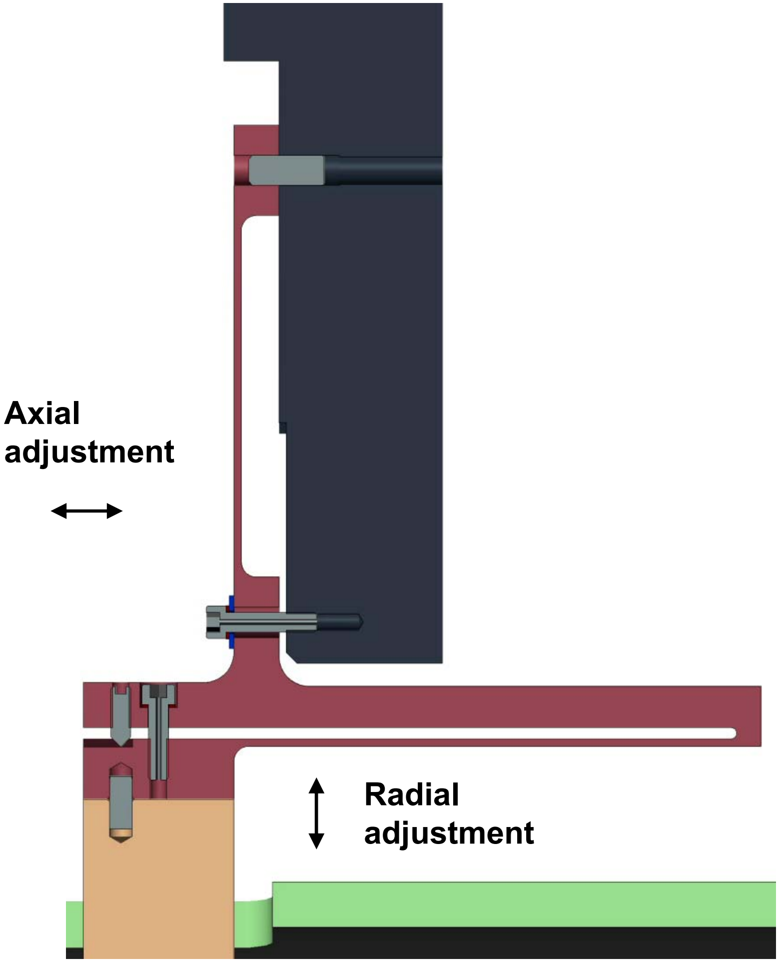
Shim

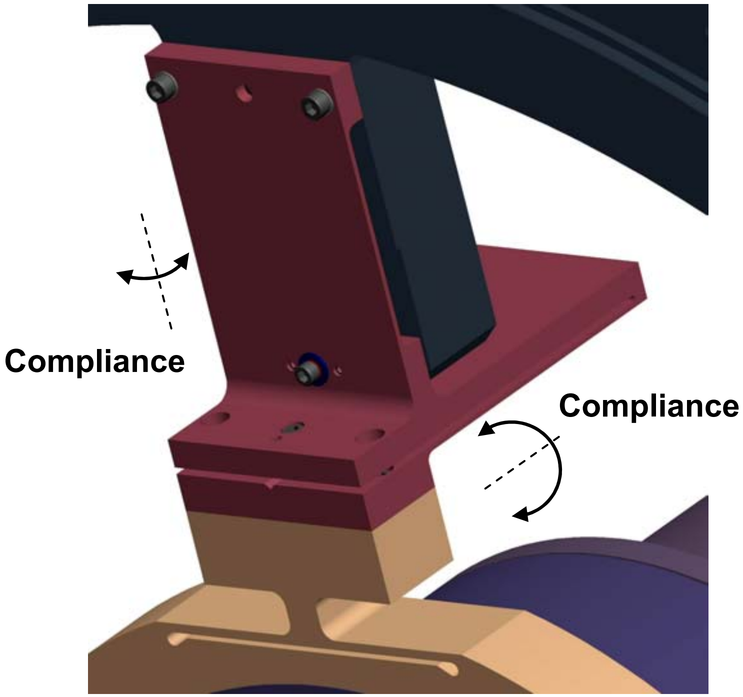


Optomechanical Design

Camera Module Adjustment

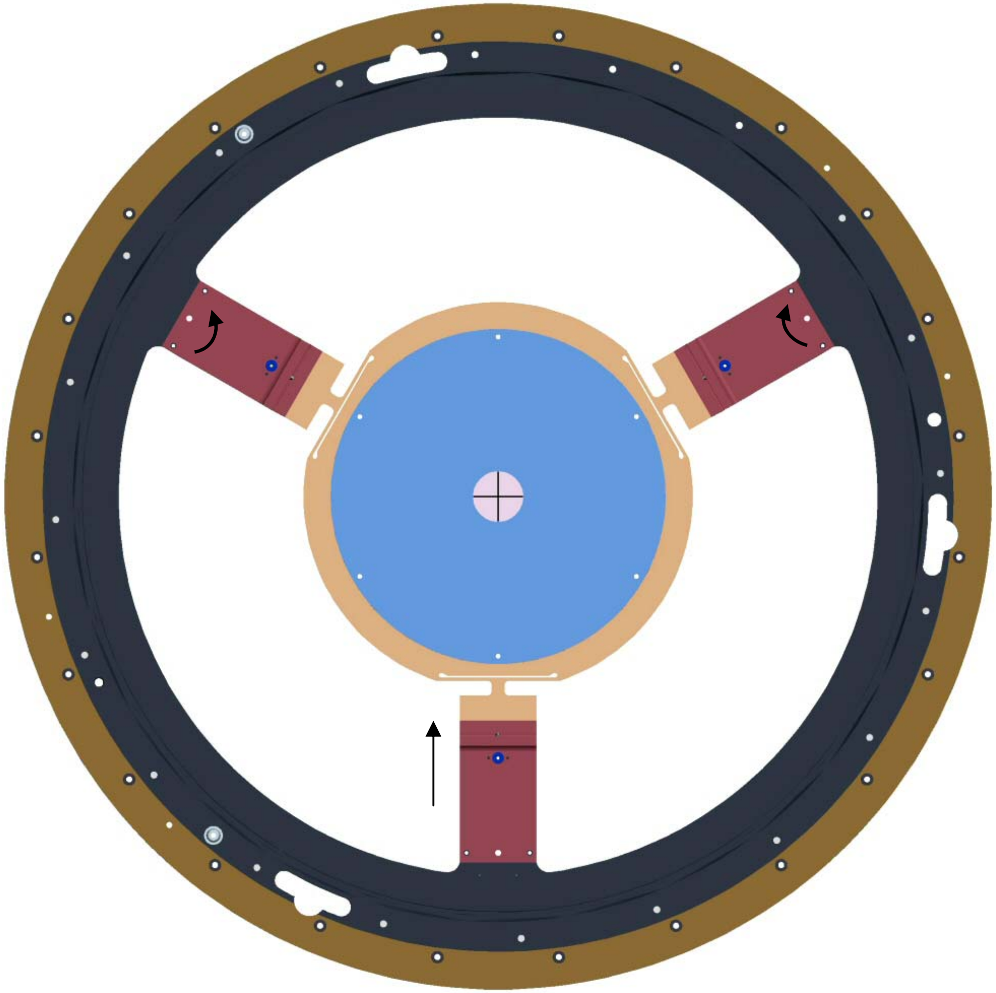
- **Titanium flexure facilitates tip, tilt, piston, and radial adjustment**
- **Heat load minimized by low conductivity and long thermal path**





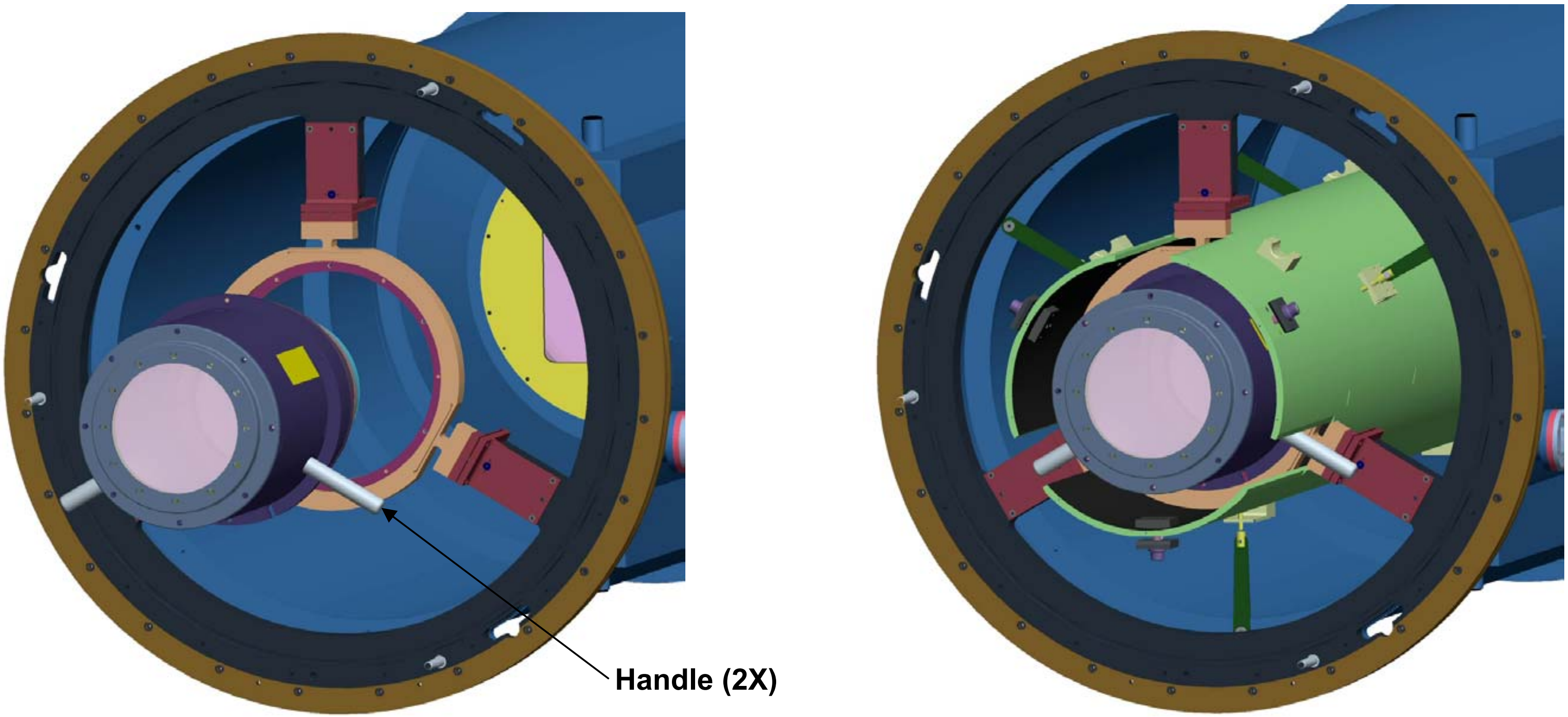
Optomechanical Design

Camera Module Adjustment



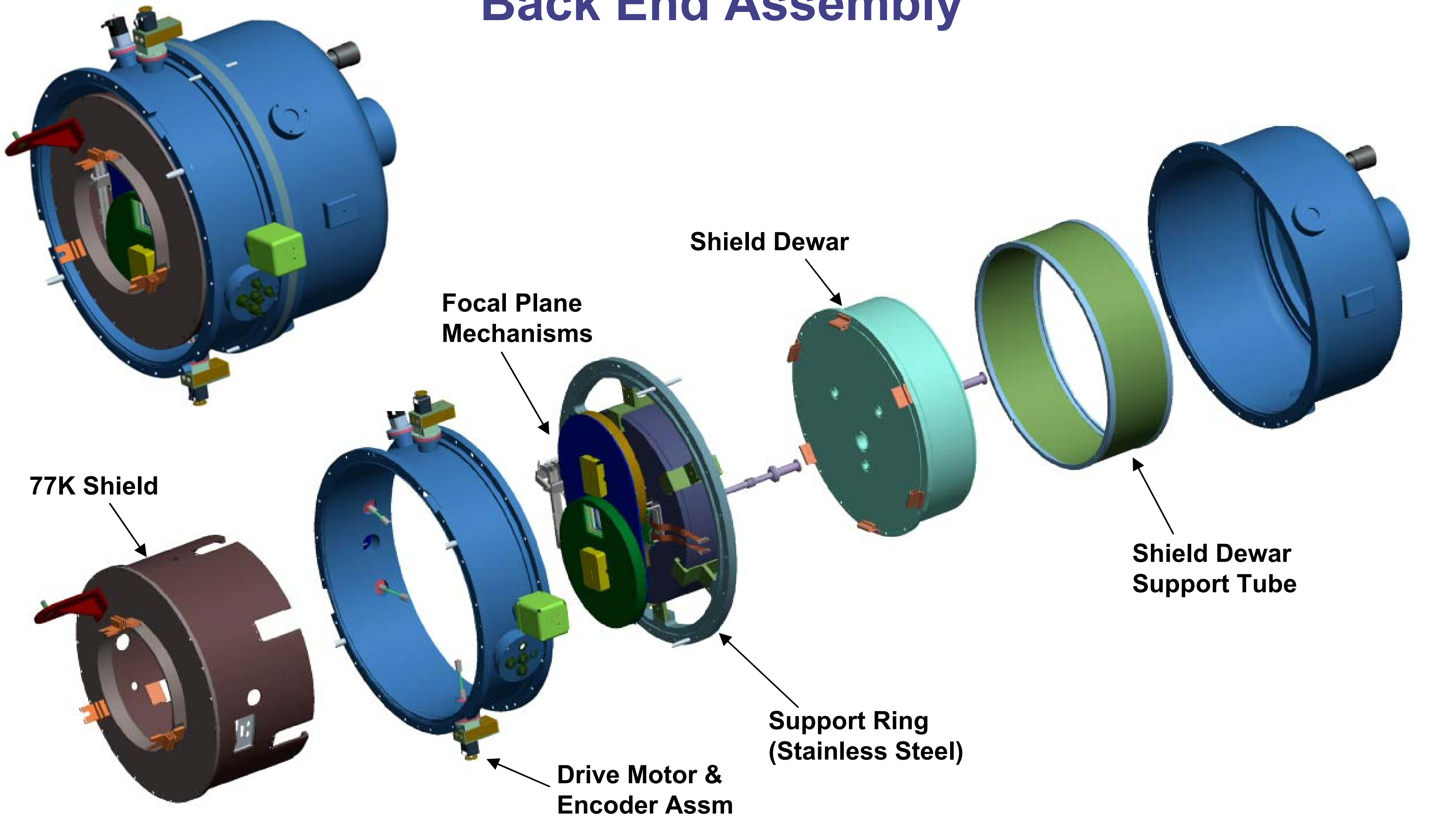
Optomechanical Design

Camera Module Assembly

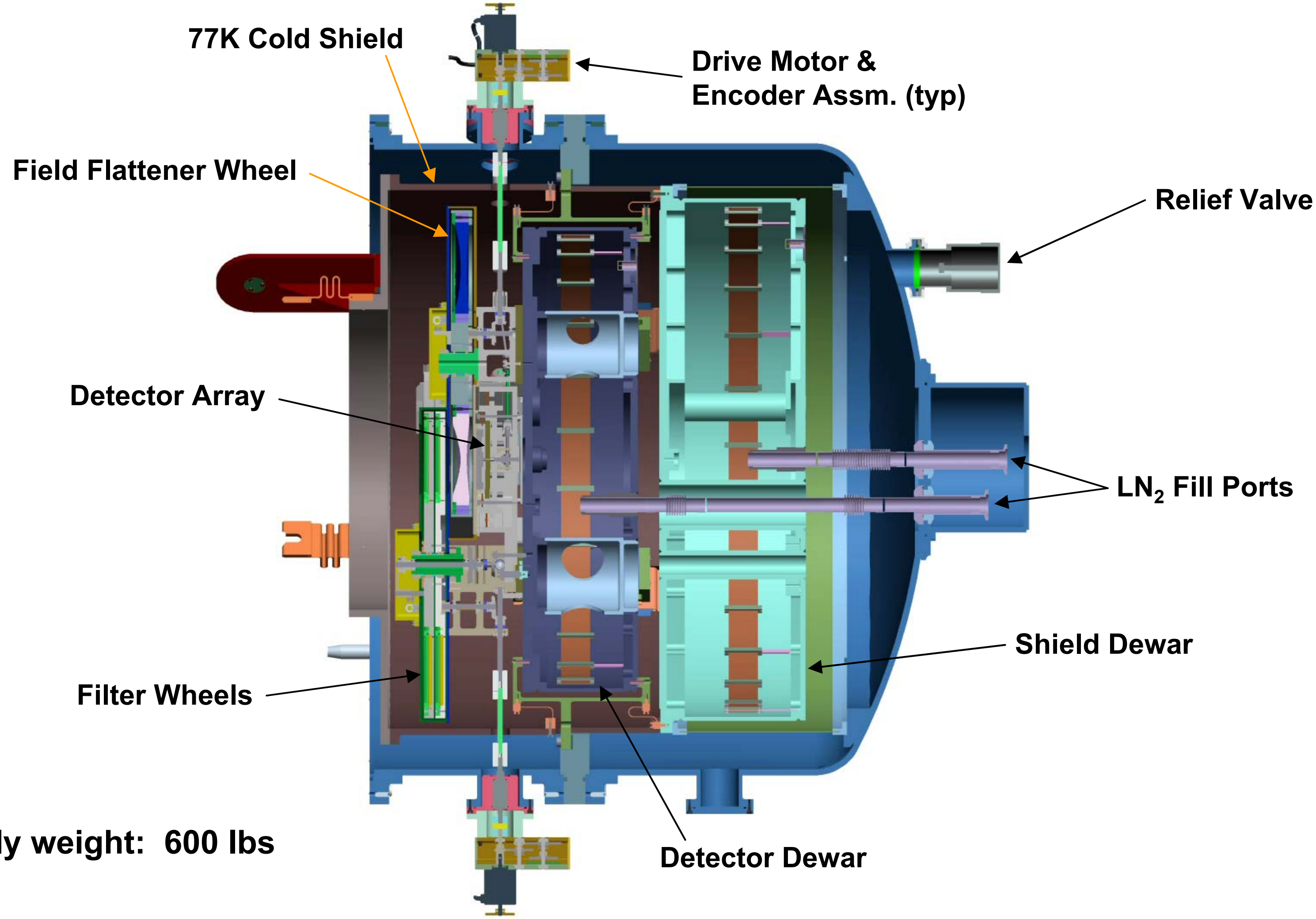


Optomechanical Design

Back End Assembly



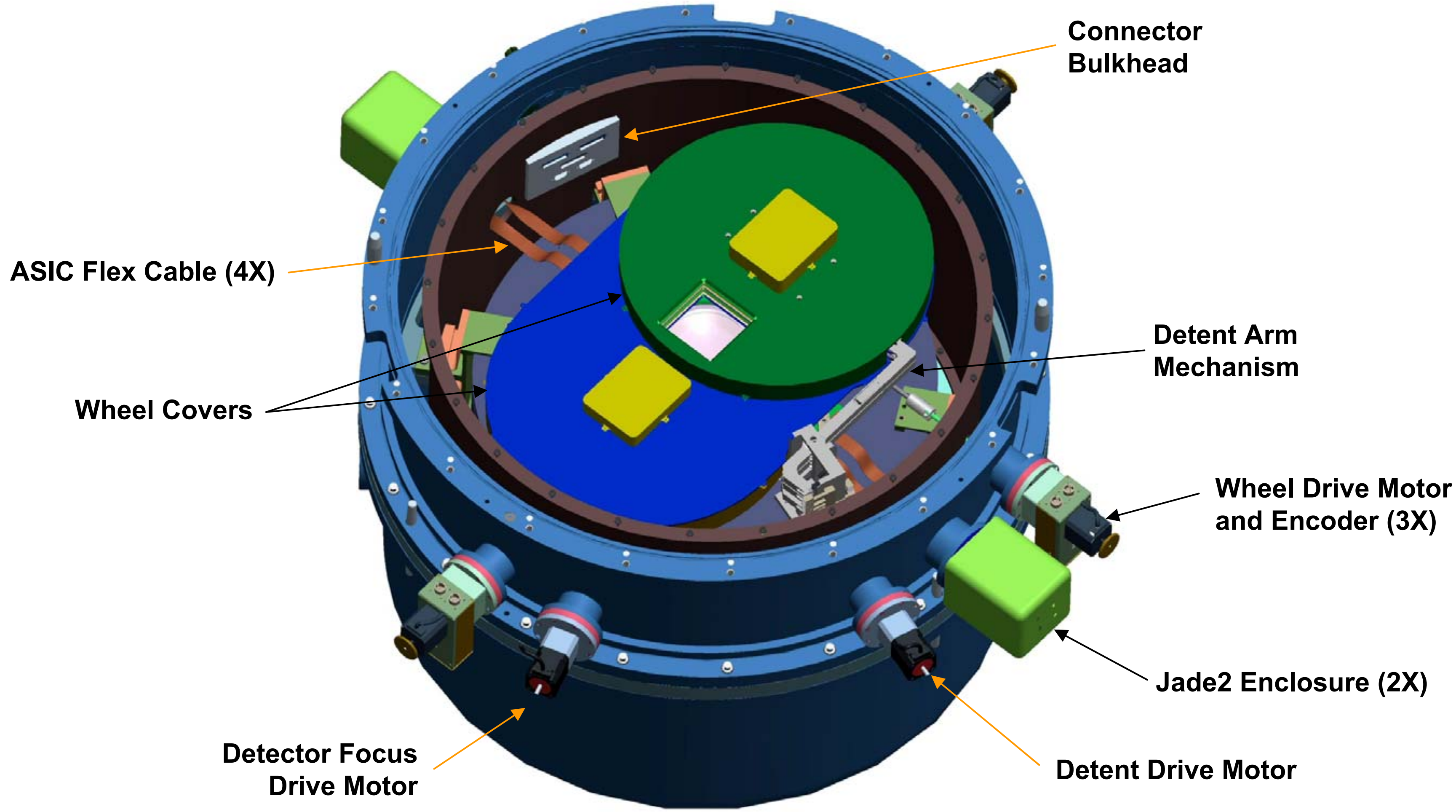
Back End Assembly Section



Assembly weight: 600 lbs

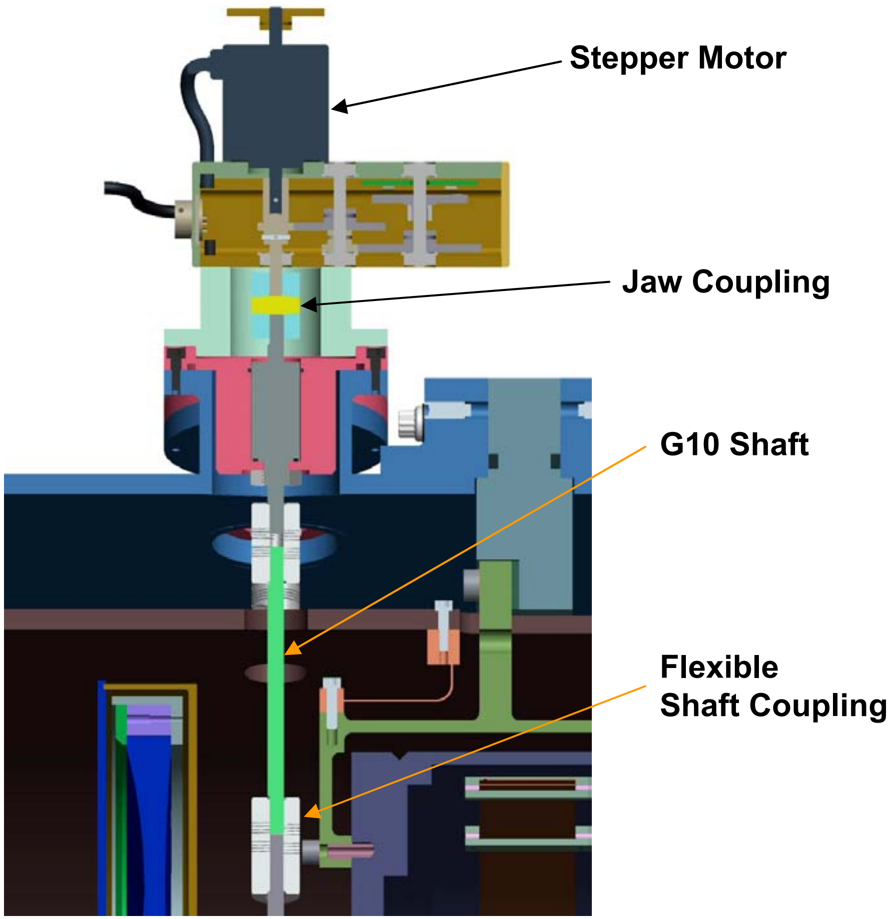
Optomechanical Design

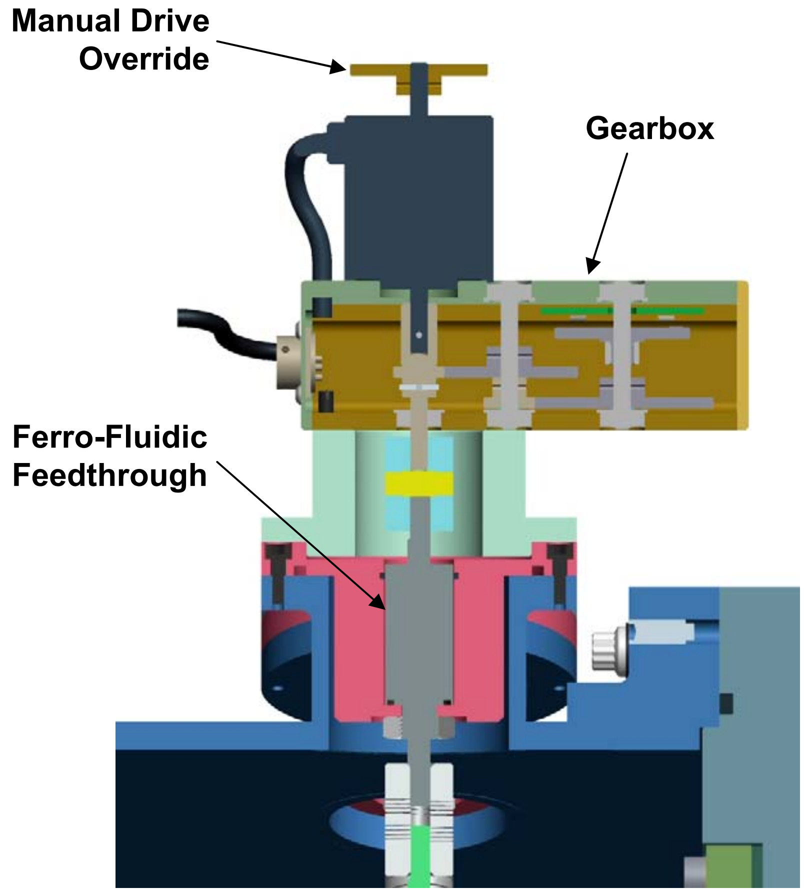
Back End Details



Optomechanical Design

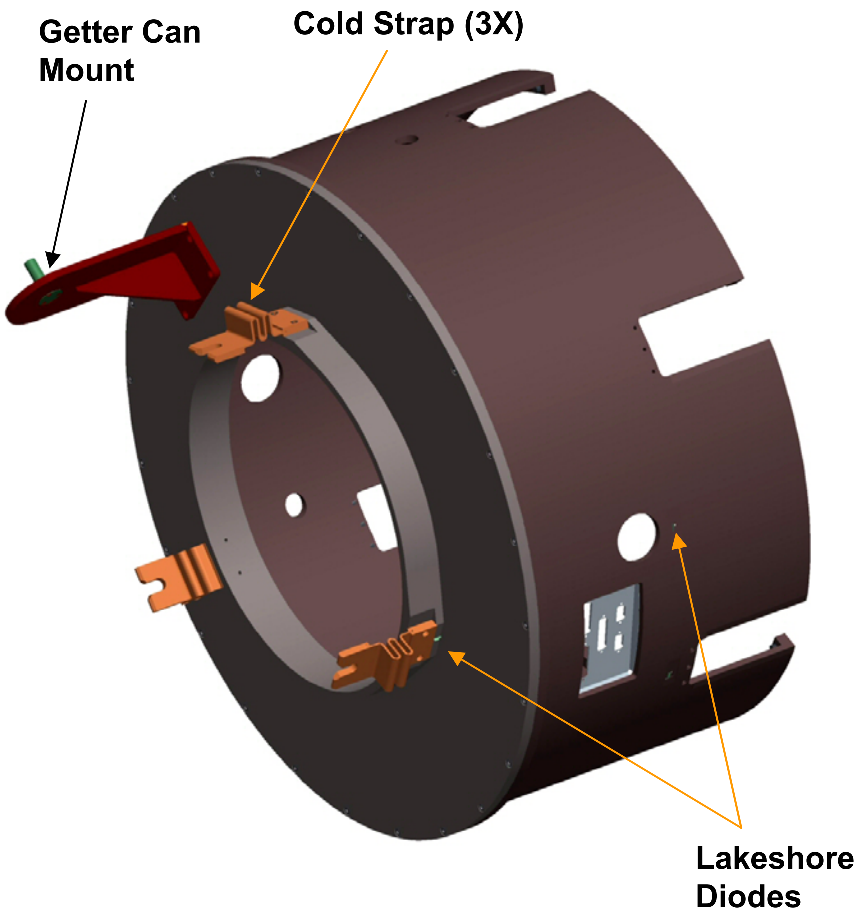
Motor Feedthrough Assembly

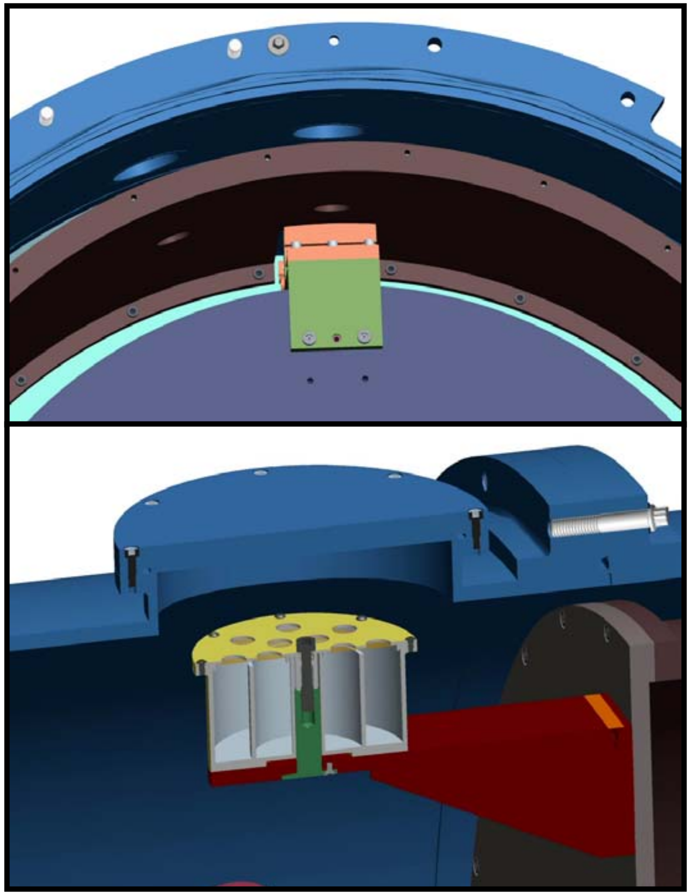




Optomechanical Design

77K Shield Details

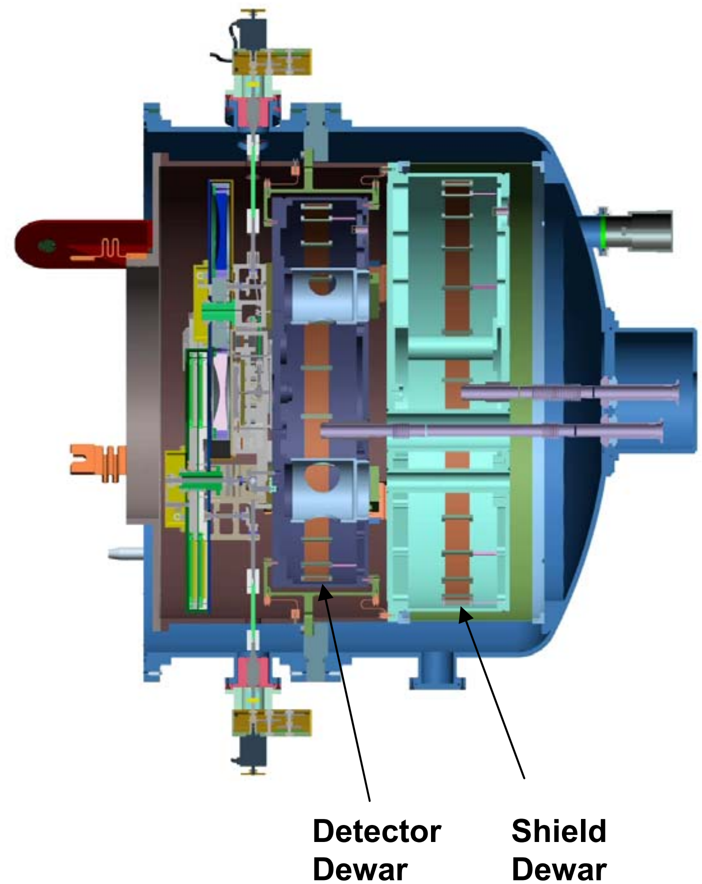




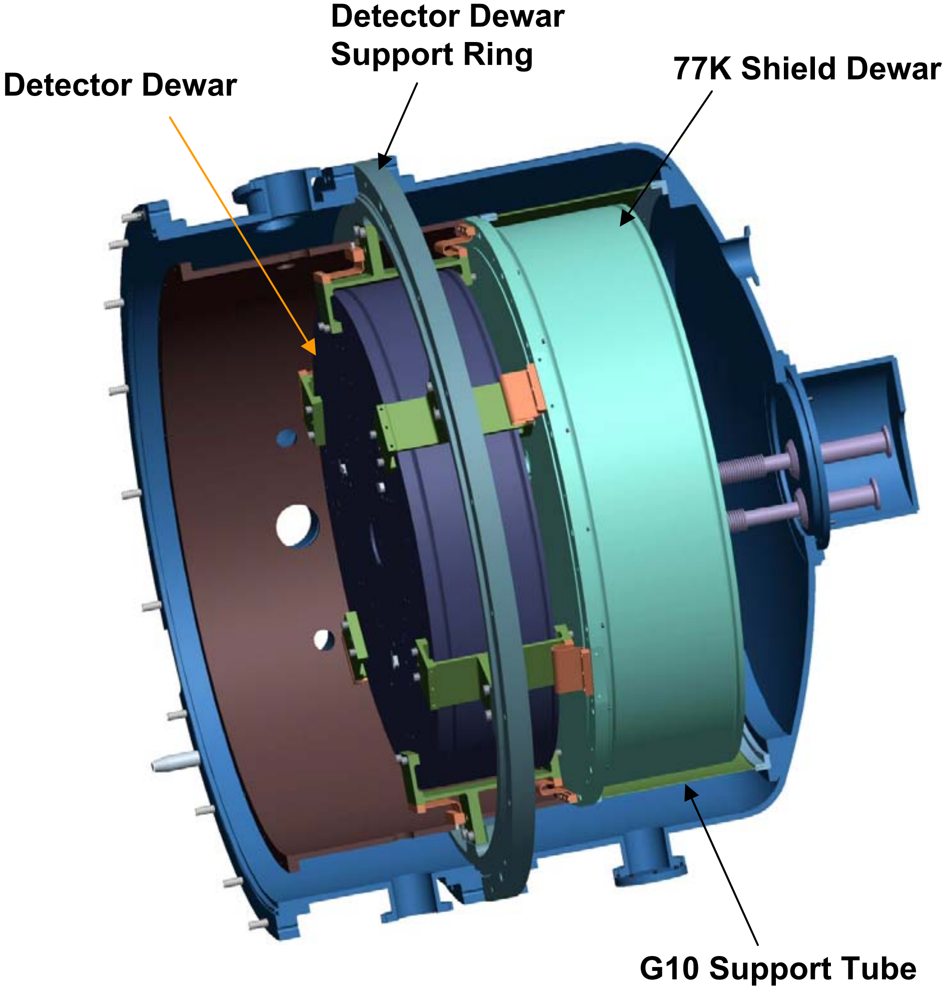
Optomechanical Design

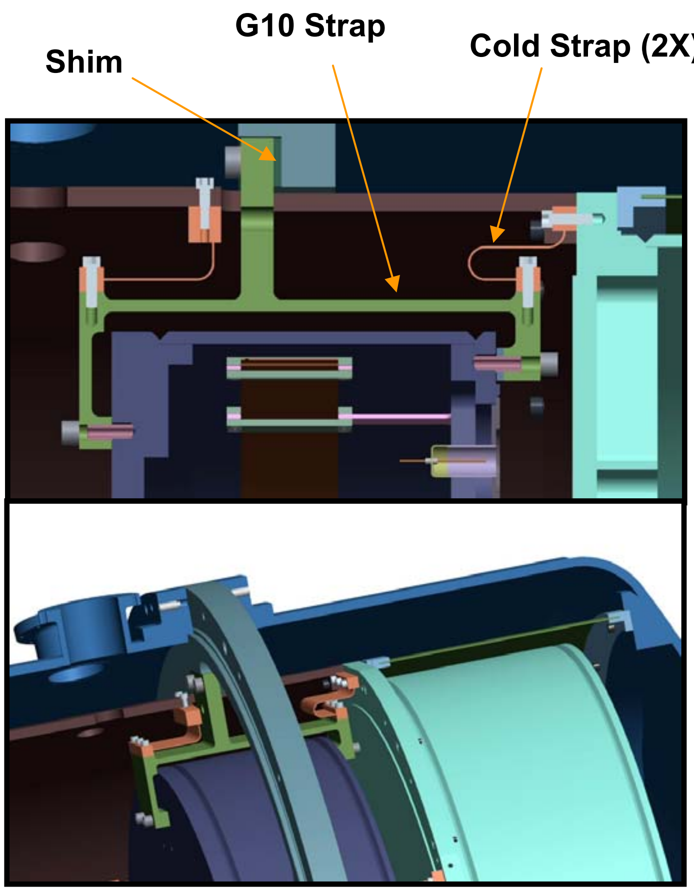
Dewars

- **Detector Dewar**
  - **14 liter usable volume**
  - **6061-T6 aluminum**
  - **615 mm diameter, 150 mm long**
  - **Capacitance sensor for level monitoring**
  - **Manually filled**
  - **Hold time ~ 2-3 weeks**
- **Shield Dewar**
  - **30 liter usable volume**
  - **6061-T6 aluminum**
  - **690 mm diameter, 190 mm long**
  - **Capacitance sensor for level monitoring**
  - **Auto-filled**
  - **Hold time ~ 24 hrs**

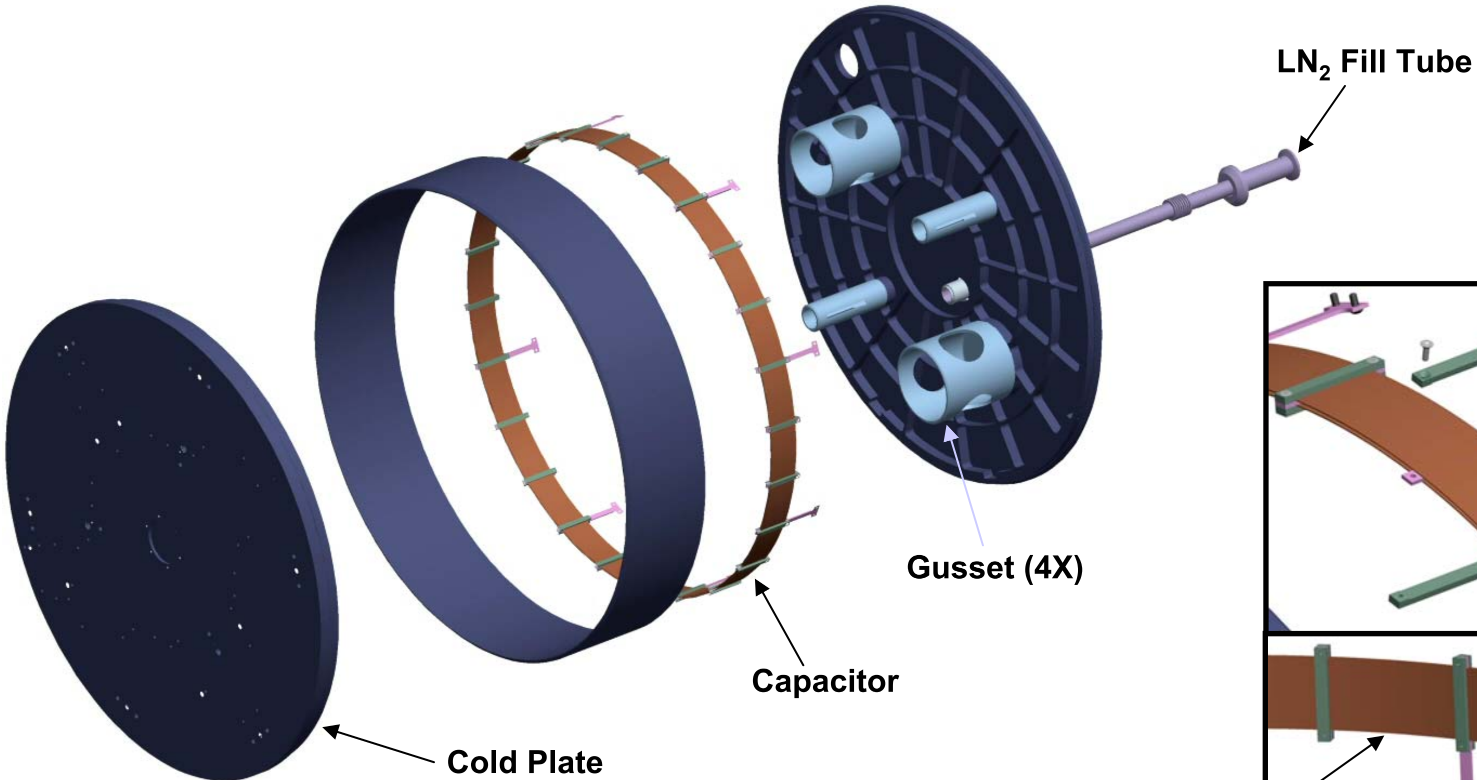


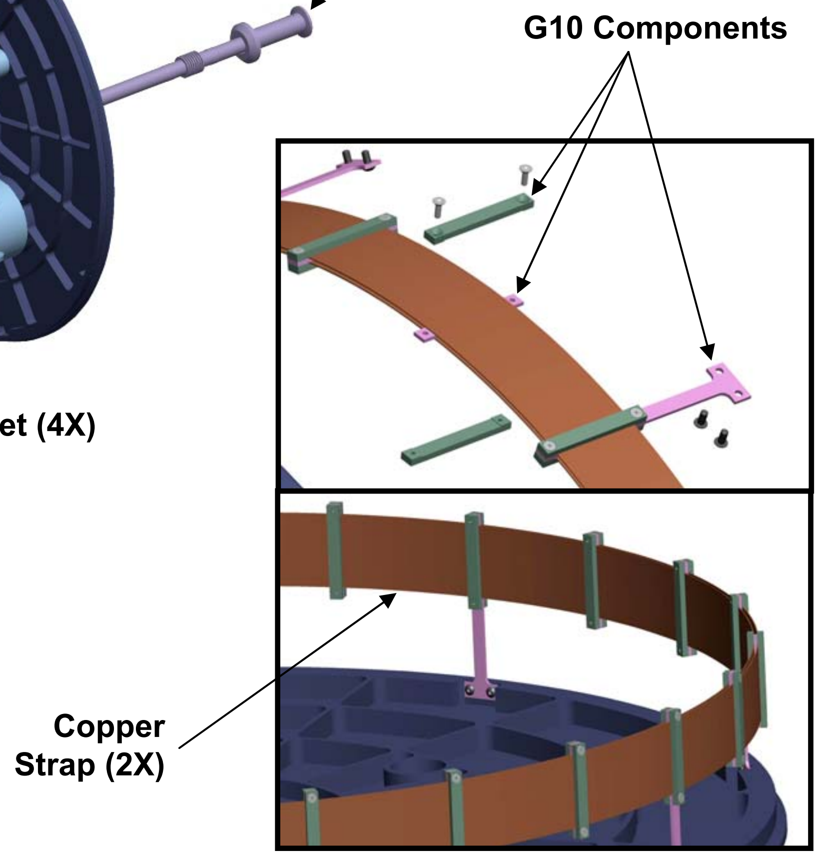
Dewar Mounting





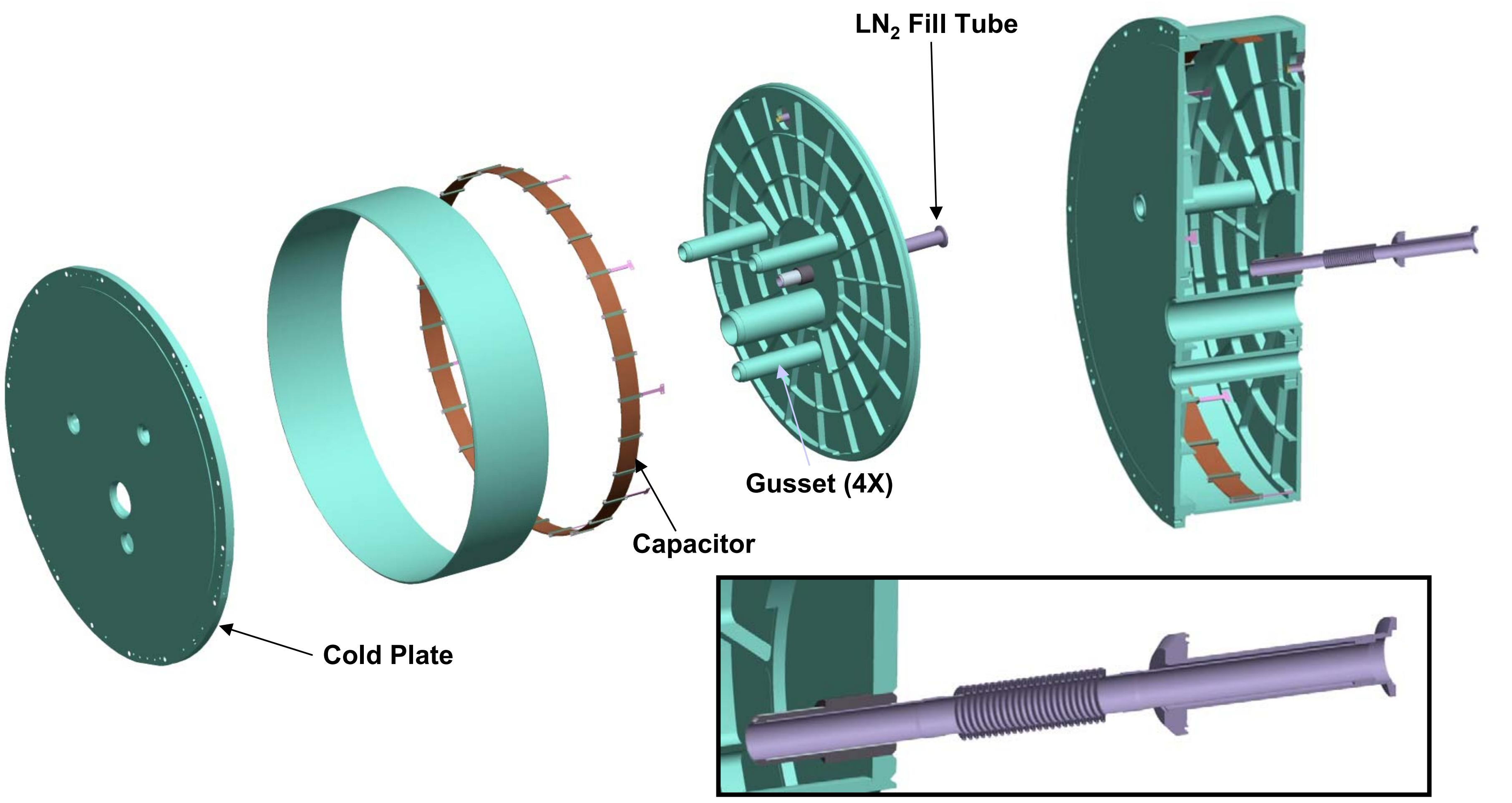
Detector Dewar Design Details





Optomechanical Design

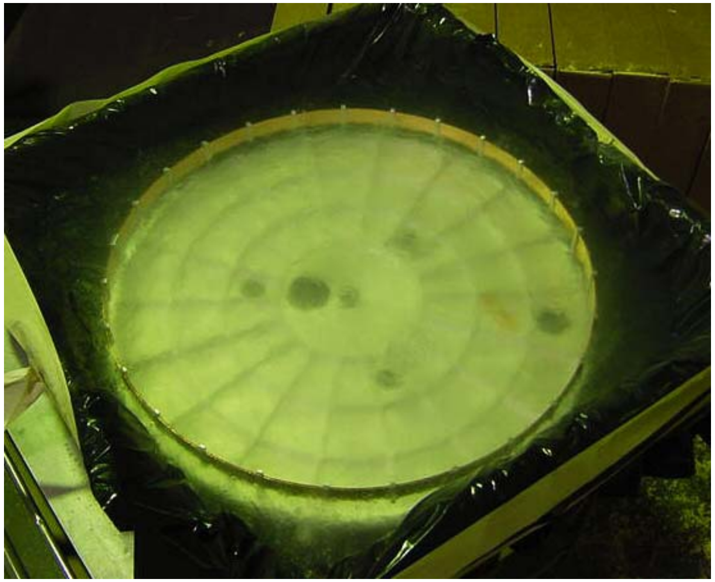
Shield Dewar Assembly



Dewar Capacitor Images

Assembled Capacitor

Survival Test

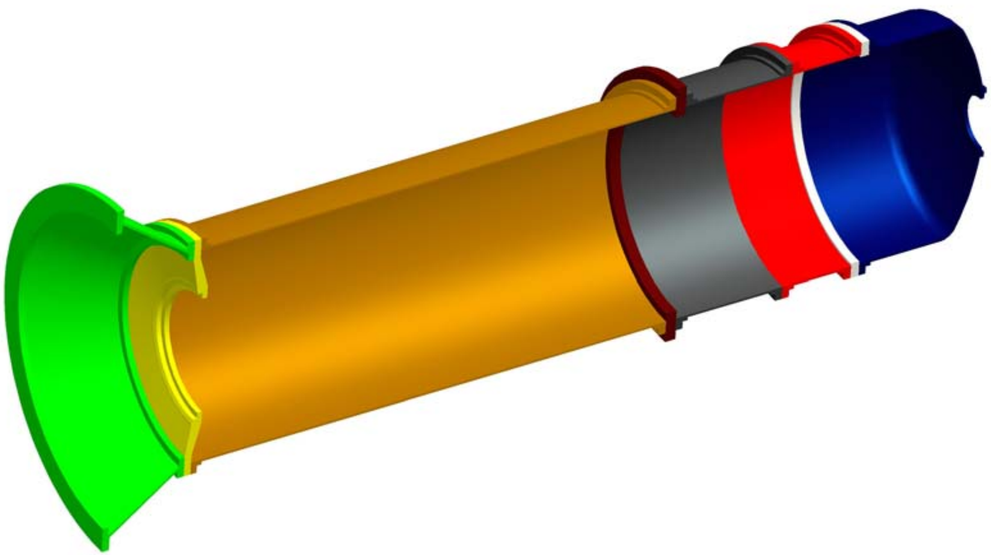


Instrument Flexure

- **Goals**
  - Determine the motion of the detector under a 1g load for a 15 deg. rotation of the rotator
    - In-plane motion leads to smearing
    - Out-of-plane motion leads to defocus
- **Modeling strategy**
  - Model vessel flexure
  - Model dewar sag
  - Superimpose results to calculate image shift and defocus

Vessel Flexure Model

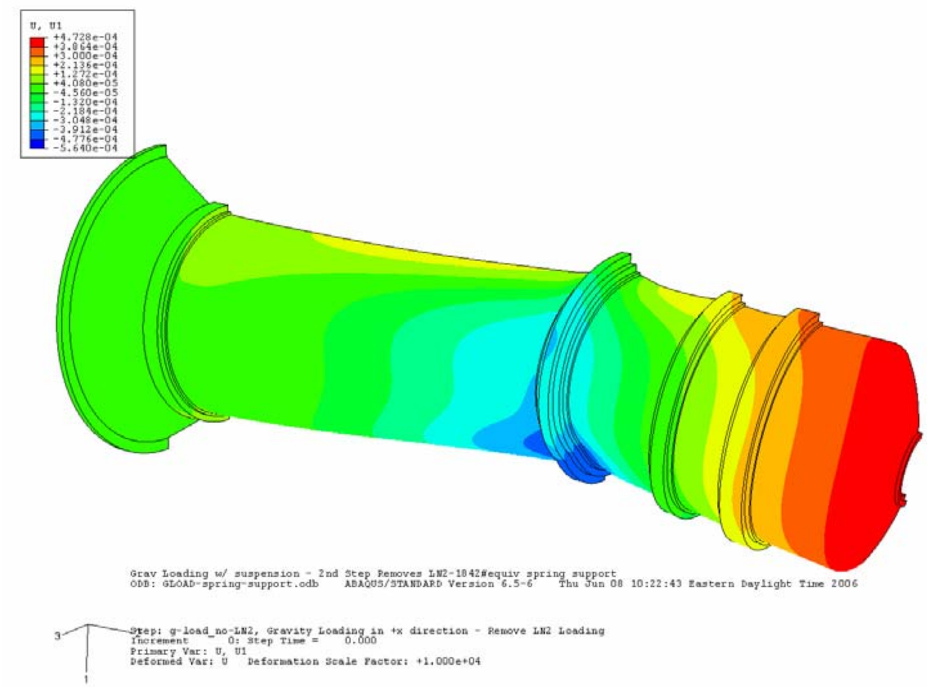
- Half-symmetric model
- Vessel divided into eight segments
- Density of each section adjusted to represent internal components
  - CG of simplified model matches quite well to actual model
- 1842 lb astatic vertical load applied to load ring
- 1g load applied to entire vessel
- Fixed boundary condition at the conical adapter



Optomechanical Design

Vessel Flexure Results

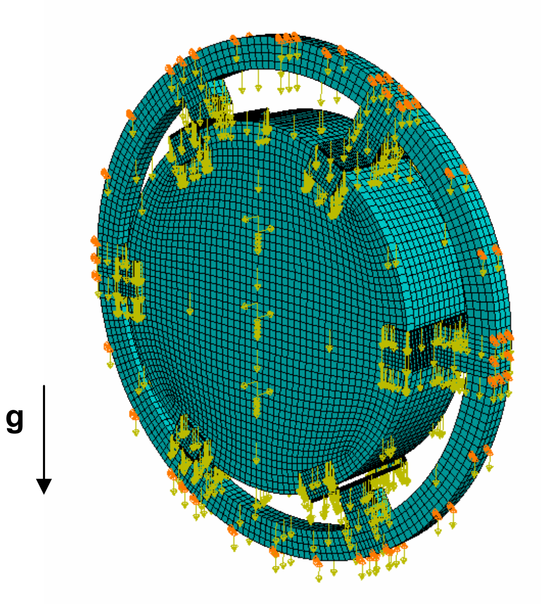
- **1g sag of detector dewar support ring**
  - **Full dewar: 13.5 μm**
  - **Empty dewar: 4 μm**



Dewar Flexure Model

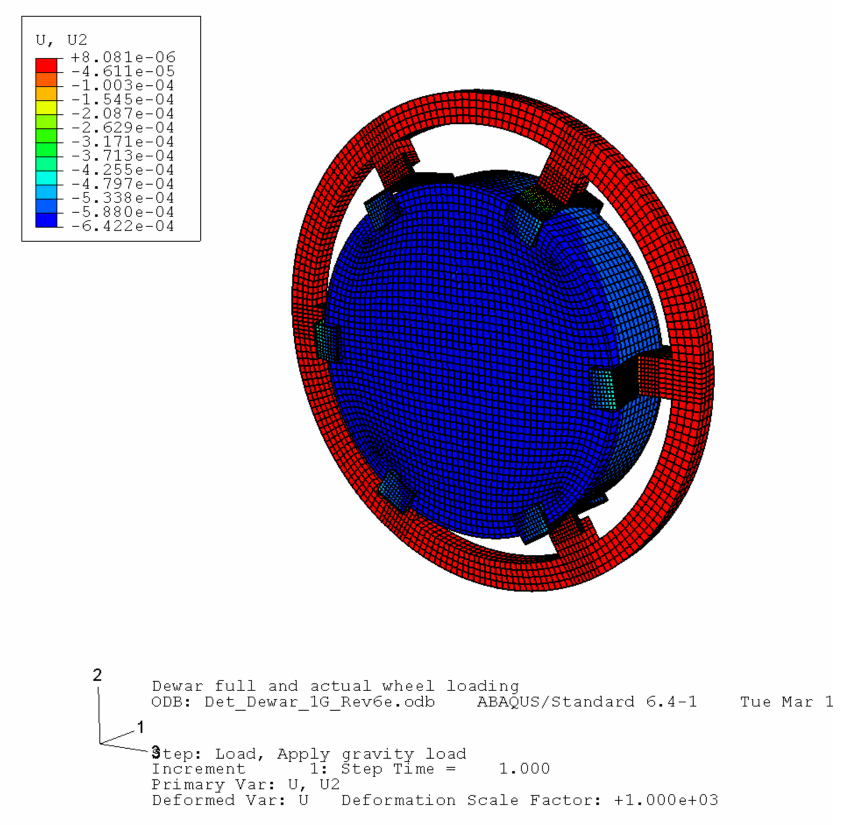
- **Gravity Loading**
  - **Dewar: 55 lbs**
  - **LN2: 25.8 lbs**
  - **Detector: 7.6 lbs**
  - **Filter wheel: 15.5 lbs**
  - **Flattener wheel: 9.5 lbs**
  - **Detent assembly: 2.3 lbs**
  - **Total 115.7 lbs**

- **Moment Loading**
  - **Filter wheel: 62.2 in·lbs**
  - **Flattener wheel: 26.13 in·lbs**
  - **Detector: 10.8 in·lbs**
  - **Detent assembly: 5.6 in·lbs**



1g Dewar Flexure Results

- **Full Dewar**
  - **Decenter: 16 μm**
  - **Tilt: 0.7 arcsec (0.3 μm top-to-bottom across the detector)**
- **Empty Dewar**
  - **Decenter: 13 μm**
  - **Tilt: 1.0 arcsec (0.4 μm top-to-bottom across the detector)**



Flexure Results Summary

- **1g sag of detector**
  - **Full dewars: 29.5 μm**
  - **Empty dewars: 17 μm**

- **Image motion over a 15 deg rotation**
  - **Full dewars: 7.7 μm (< 1/2 pixel)**
  - **Empty dewars: 4.4 μm (< 1/3 pixel)**

- **Defocus is well within the ± 30 μm diffraction limited DOF**

Optomechanical Summary/Status

- Final design is complete with maybe a few exceptions
- Blueprints are complete for most subsystems
  - Final review is still needed on most drawings
    - Vacuum vessel drawings are being expedited since they are on the critical path
- Fabrication has started but not in earnest
  - Dewars are being built now
  - Three vendors identified for fabricating the vacuum vessel
    - Stadco, Major Tool, and Precision Cryogenics

FourStar

Thermal Design And Analysis

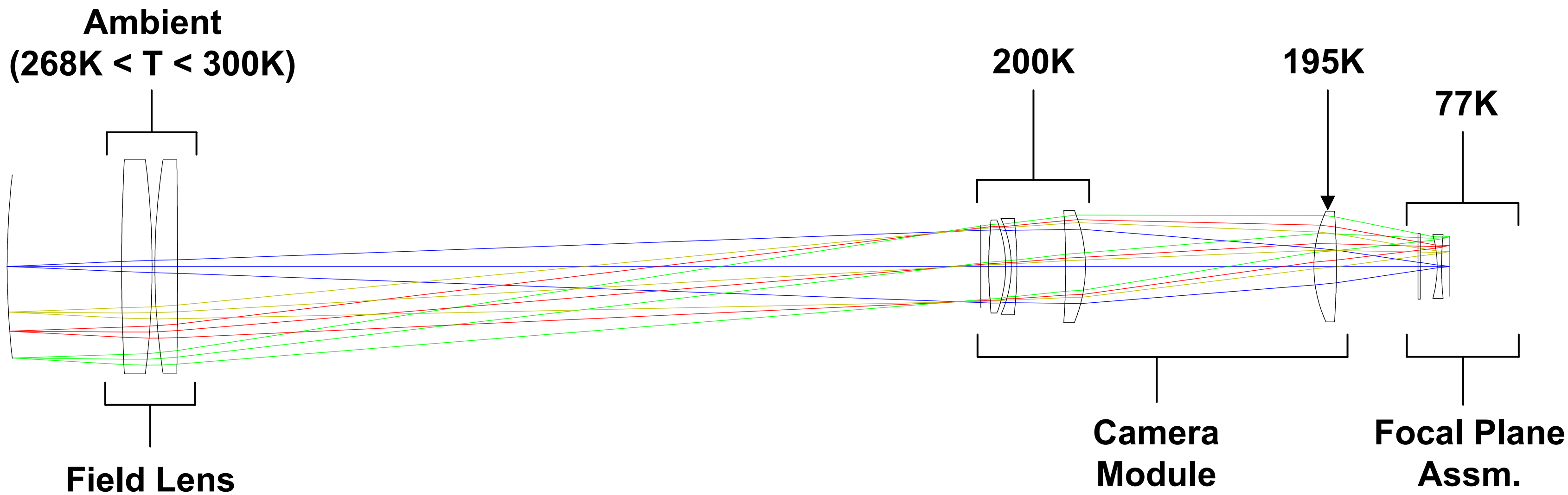
Stephen Smee
smee@jhu.edu
(410) 516-7097

21 September 2006

JOHNS HOPKINS UNIVERSITY

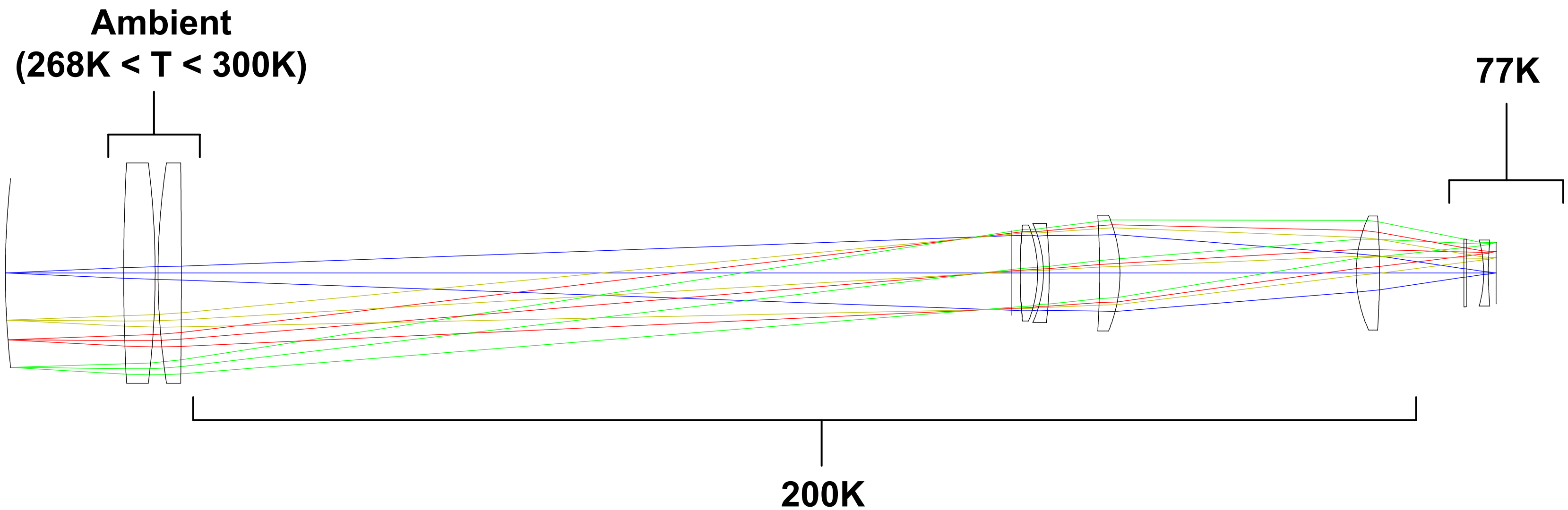
Objectives

- Determine system temperatures
- Estimate system heat load
- Estimate cooldown time
- Determine window temperature and thermal gradients



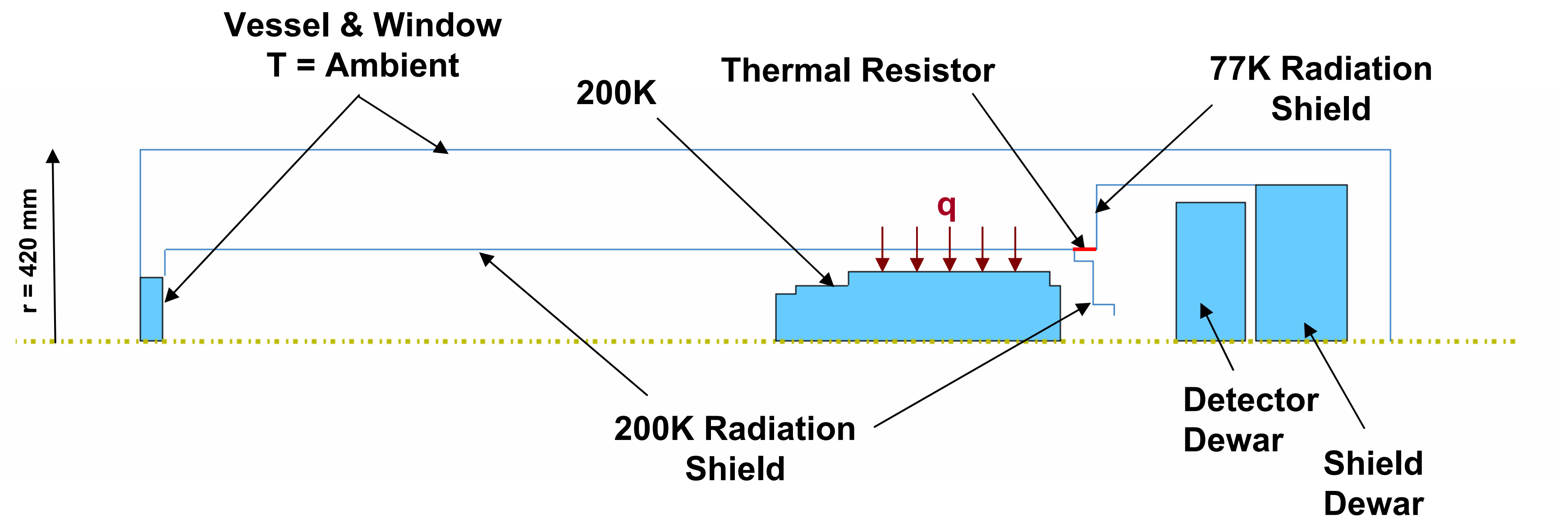
Thermal Regimes

- Three thermal regimes: Ambient, 200K, and 77K
- 200K and 77K regimes cooled by LN_2



Thermal Management Strategy

- **Two dewars**
  - One to cool the radiation shields (autofilled)
  - One to cool the focal plane mechanisms (manual fill)
- **Use thermal resistor to achieve 200K shield temperature**
  - Subcool slightly to facilitate camera module temperature control



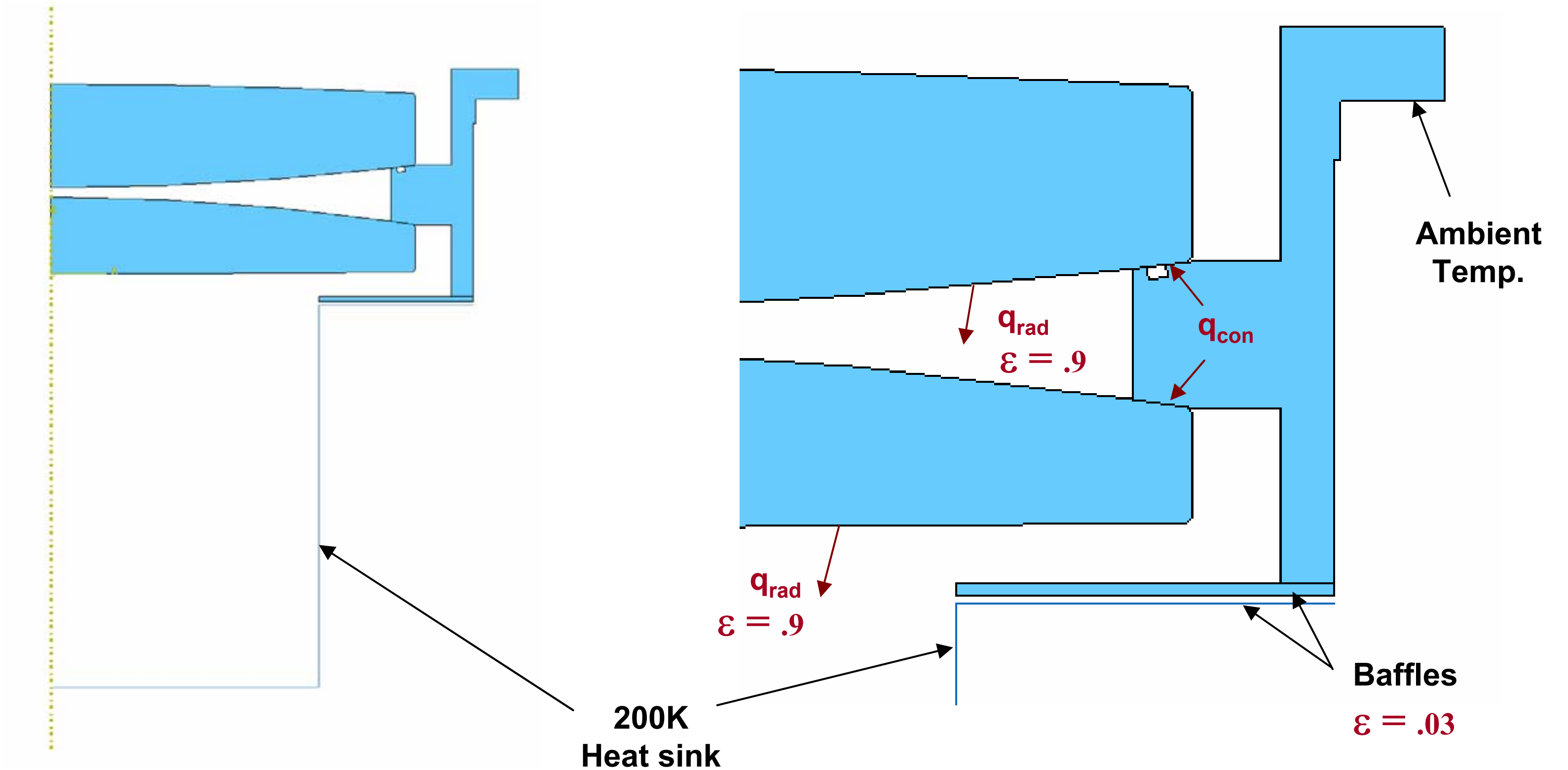
Thermal Modeling Strategy

- **Develop accurate analytical and FEA submodels for key assemblies**
  - Window, Camera Module, flexures, etc.
- **Evaluate submodels**
  - Temperature profiles, thermal resistance, etc.
- **Use results from submodels to create simplified, compact models for system level analysis**
- **Feed results from submodels and system model back into the thermal/mechanical design**

Thermal Analysis

Window Thermal Analysis

- **Objectives:**
  - Determine lens radial temperature profile
  - Determine heat load

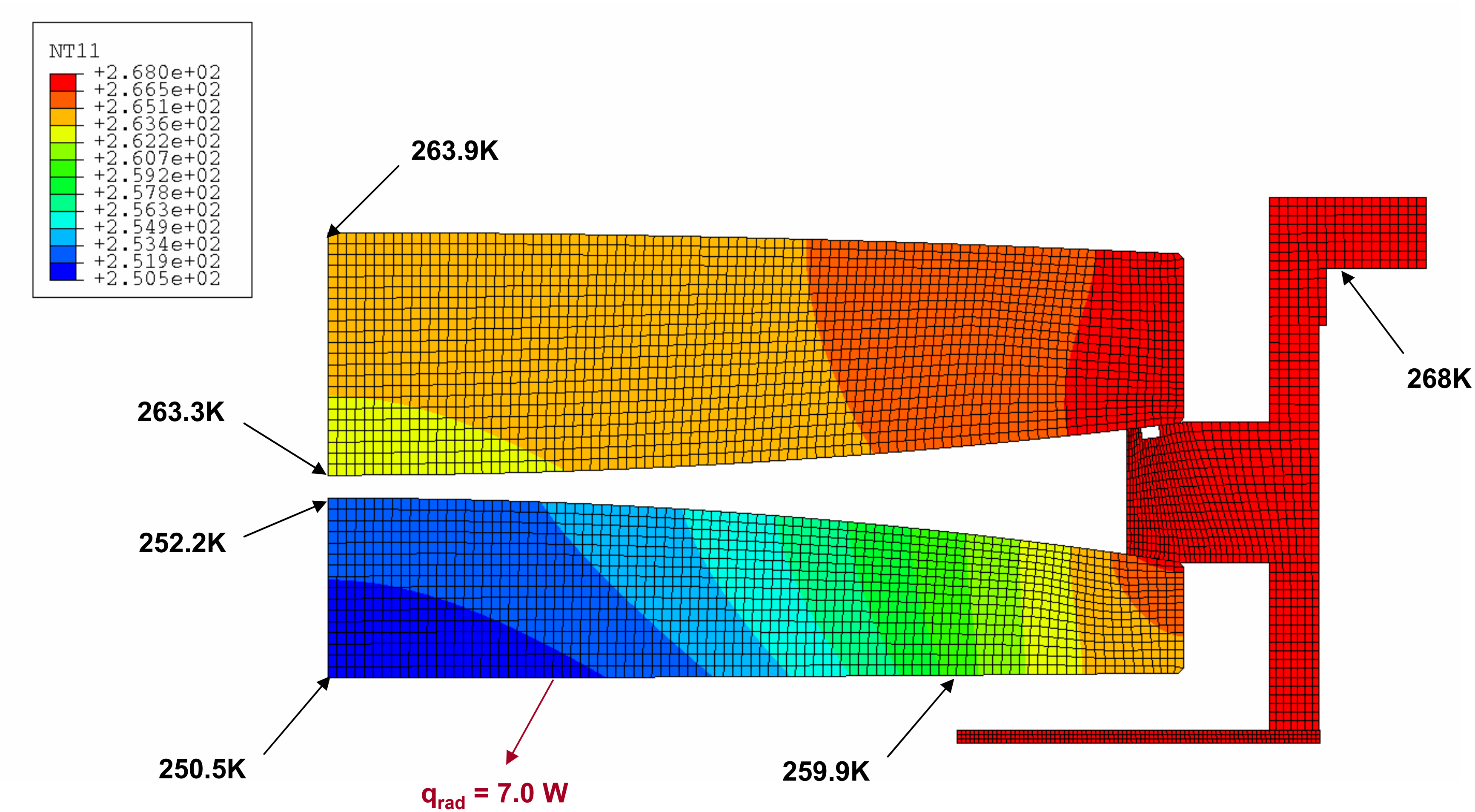


Window Model Details

- **Axisymmetric model**
  - **Baffle diameter scaled to area of square opening**
- **Steady State, coupled conduction/radiation model**
- **Conduction to lenses only considered at the lens-seat interfaces**
- **Scale**
  - **L1: 15” diameter, 2.13” thick**
  - **L2: 15” diameter, 1.58” thick**
- **Materials**
  - **Lenses: Fused Silica, k = 1.38 W/mK**
  - **Barrel and Cell Material: 6061-T6, k = 165 W/mK**
- **Ambient temperature range: 268K < T < 300K, 285K (nominal)**
- **Lenses assumed to be black, ε = 0.9**
- **ε = 0.03 assumed for low emissivity surfaces**
- **FEA Software: ABAQUS**

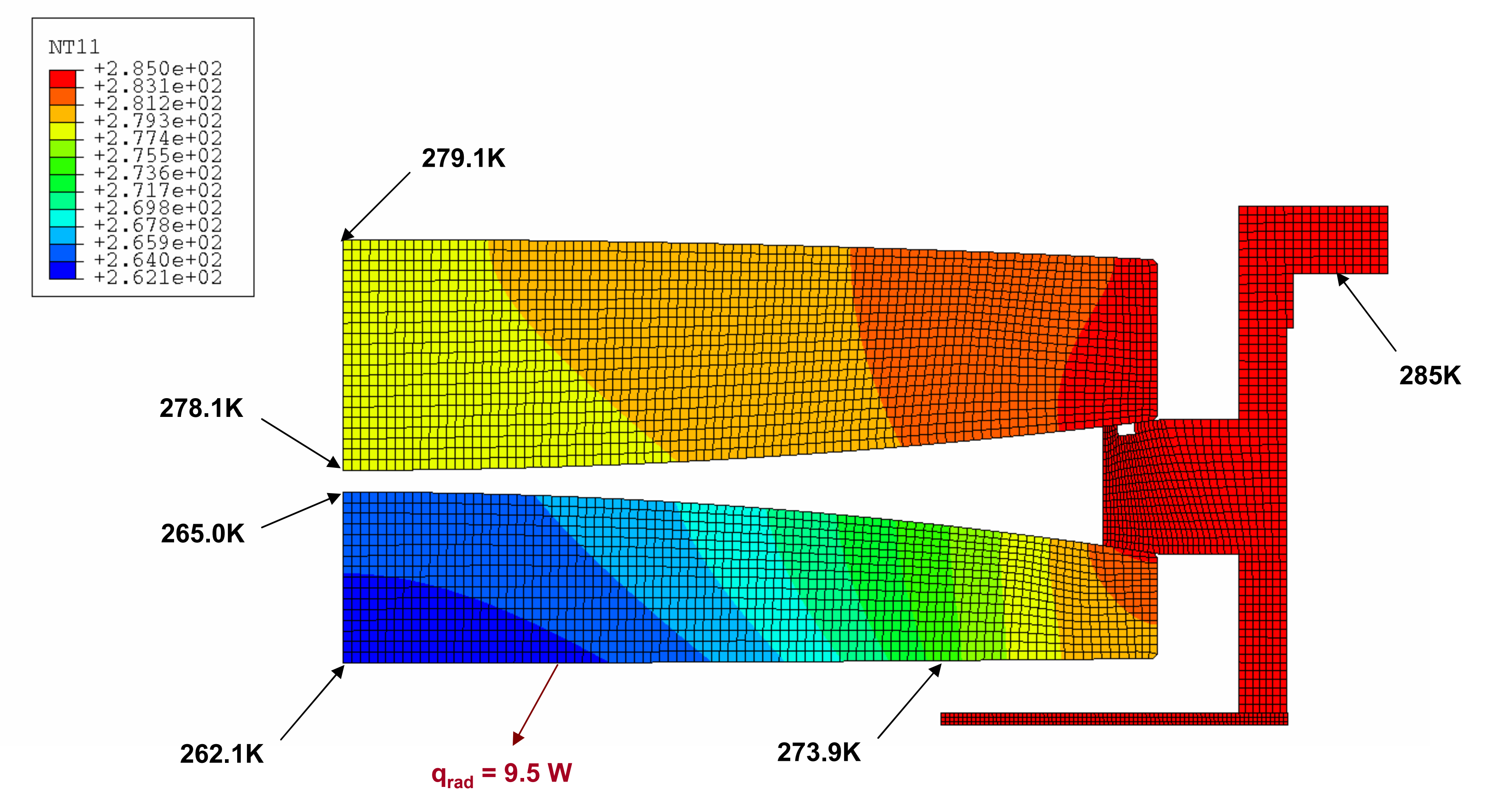
Thermal Analysis

Temperature Profiles: 268K ambient (lower limit)

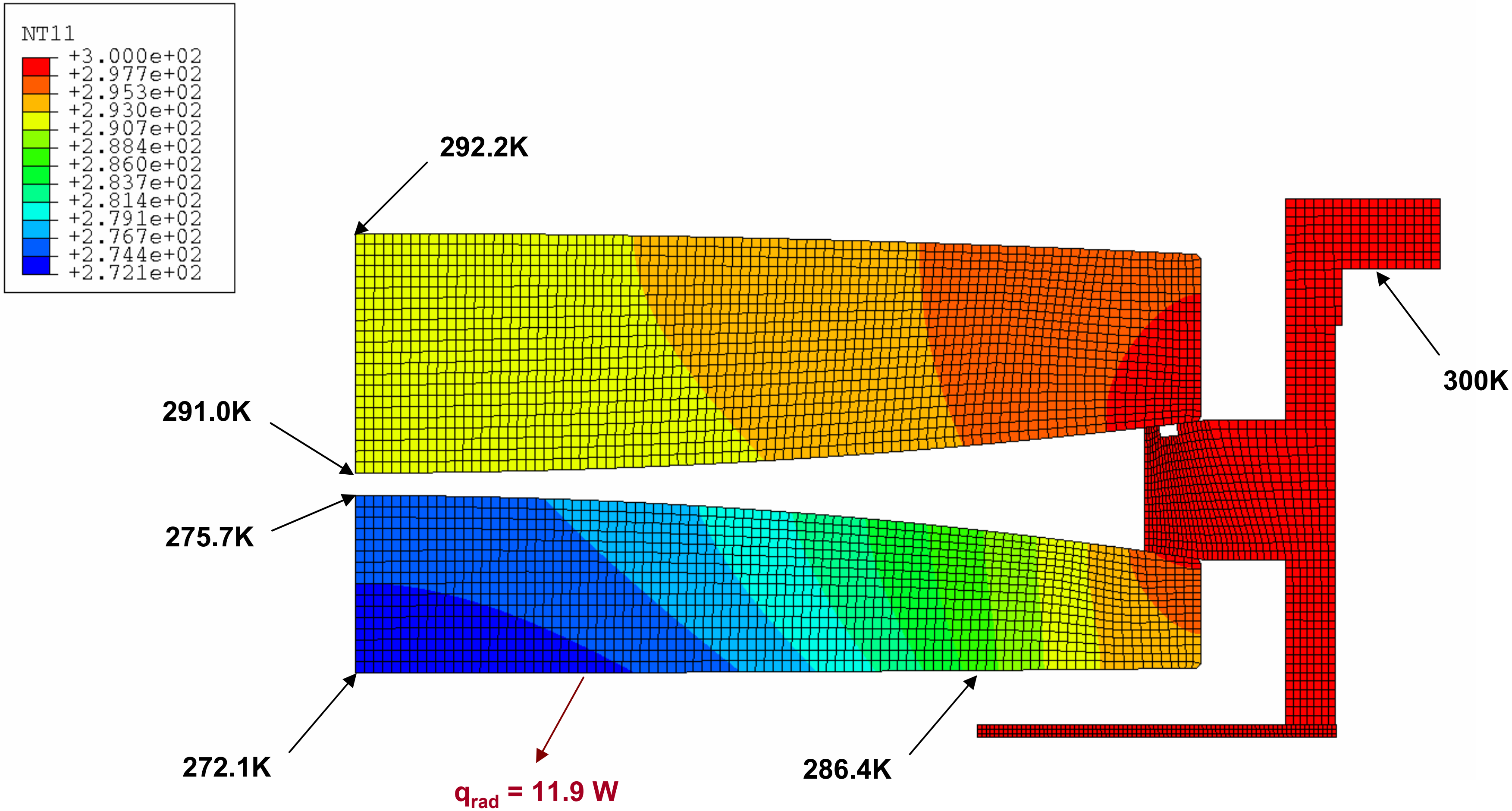


Thermal Analysis

Temperature Profiles: 285K ambient (nominal case)

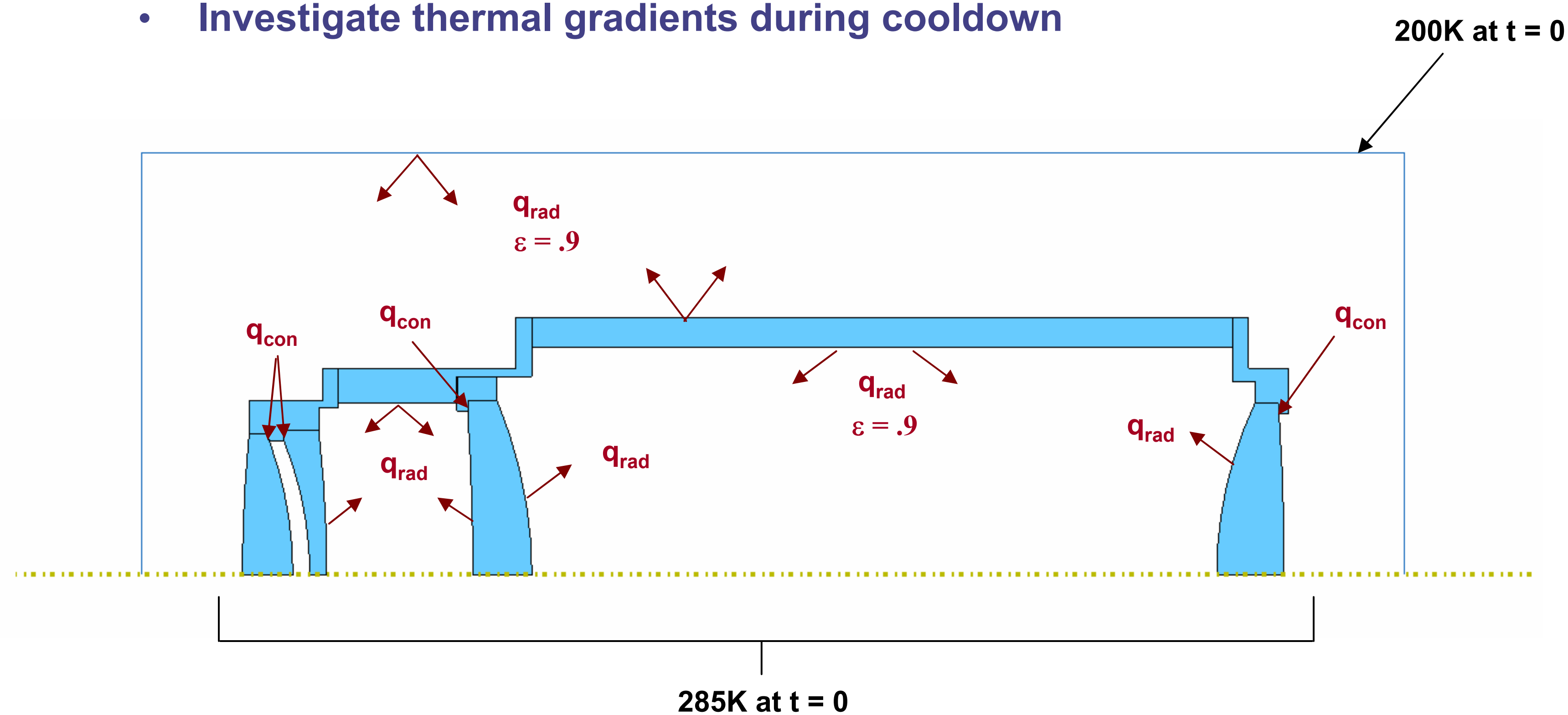


Temperature Profiles: 300K ambient (upper limit)



Camera Module Analysis

- **Objectives:**
  - **Determine cooldown time for the camera module**
  - **Develop compact model for system analysis**
  - **Investigate thermal gradients during cooldown**

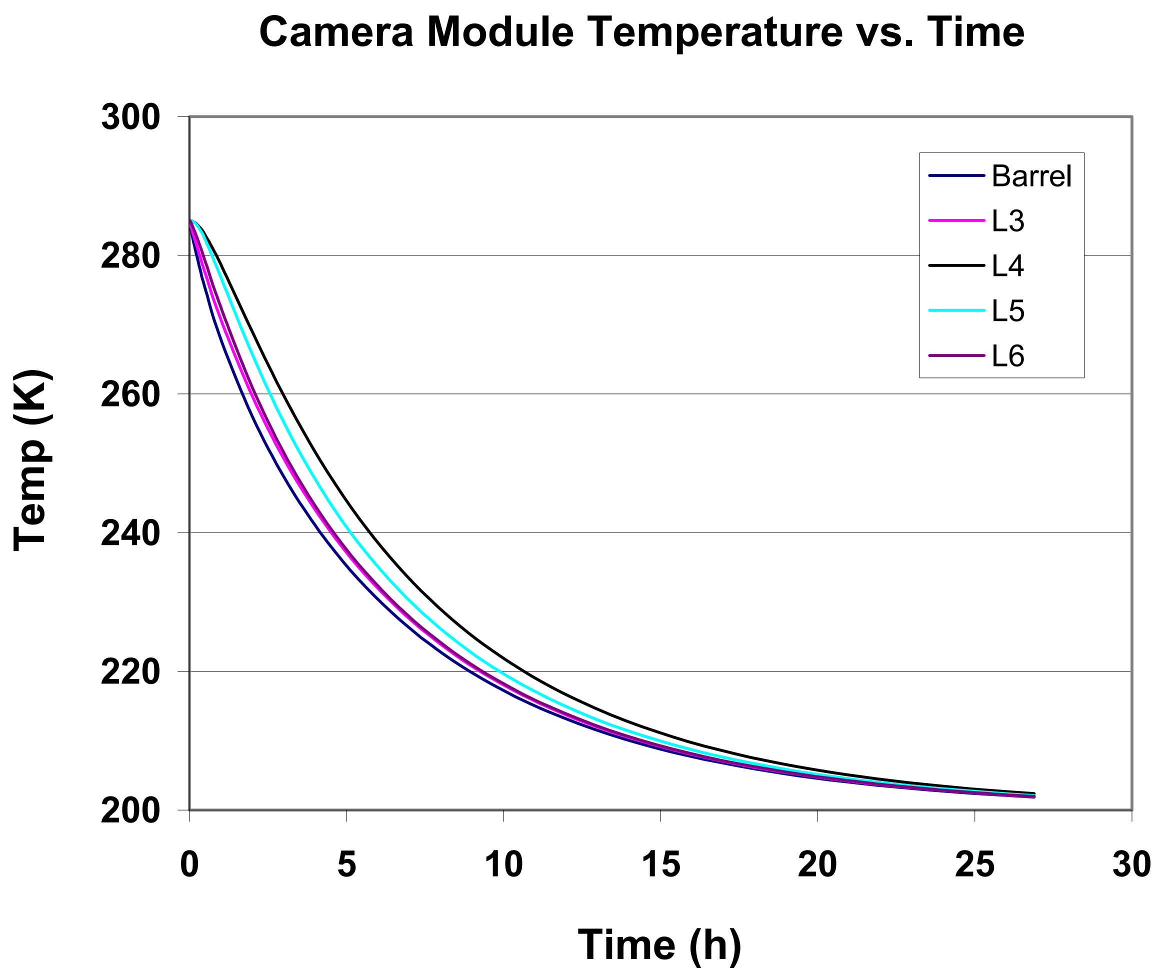


Thermal Analysis

Camera Module Model Details

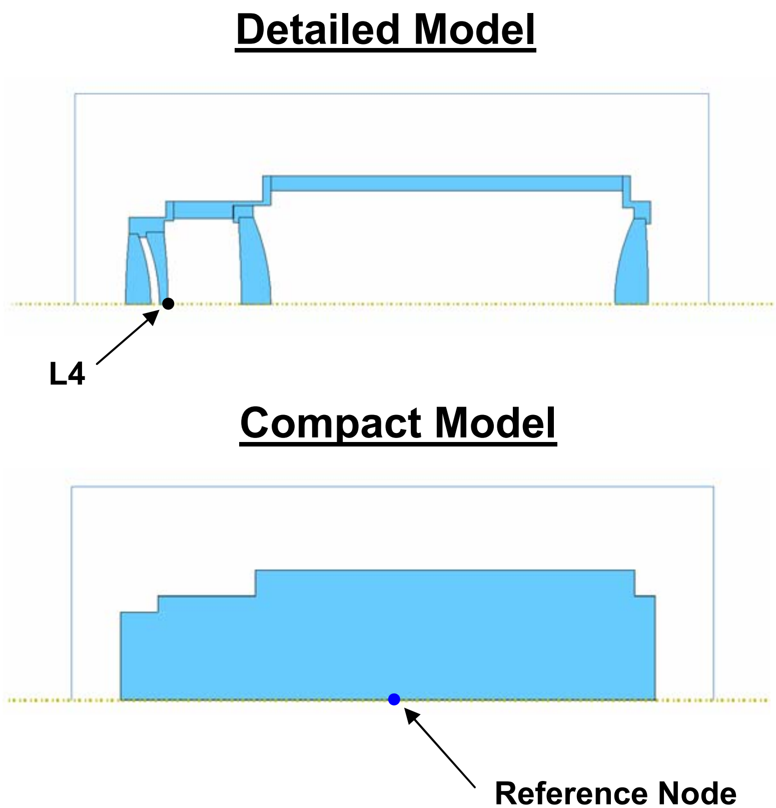
- Axisymmetric model
- Transient, coupled conduction/radiation model
- Materials
  - Lenses
    - CaF_2: k = 9.7 W/mK, Cp(T)
    - S-FTM16: k = 0.947 W/mK, Cp(T)
  - Lens mounts
    - 6061-T6, k = 136 W/mK, Cp(T)
- All radiating surfaces assumed black, $\varepsilon = 0.9$
- Initial conditions:
  - Vessel temp = 200K
  - Camera Module = 285K
- FEA Software: ABAQUS

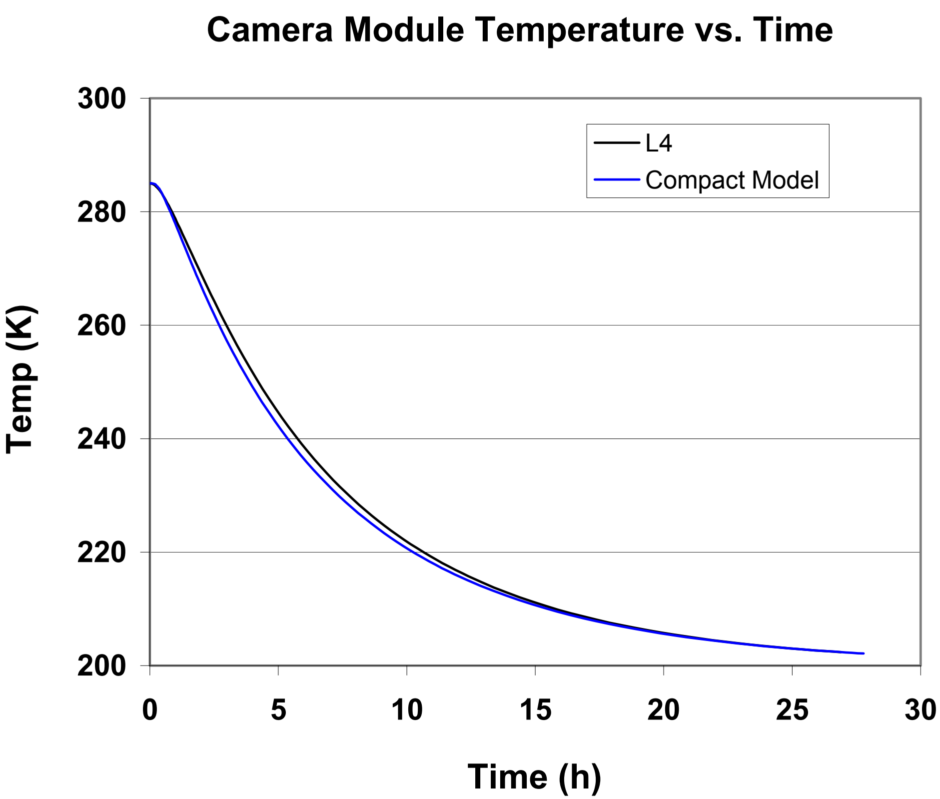
Camera Module Transient Results



Thermal Analysis

Camera Module Compact Model

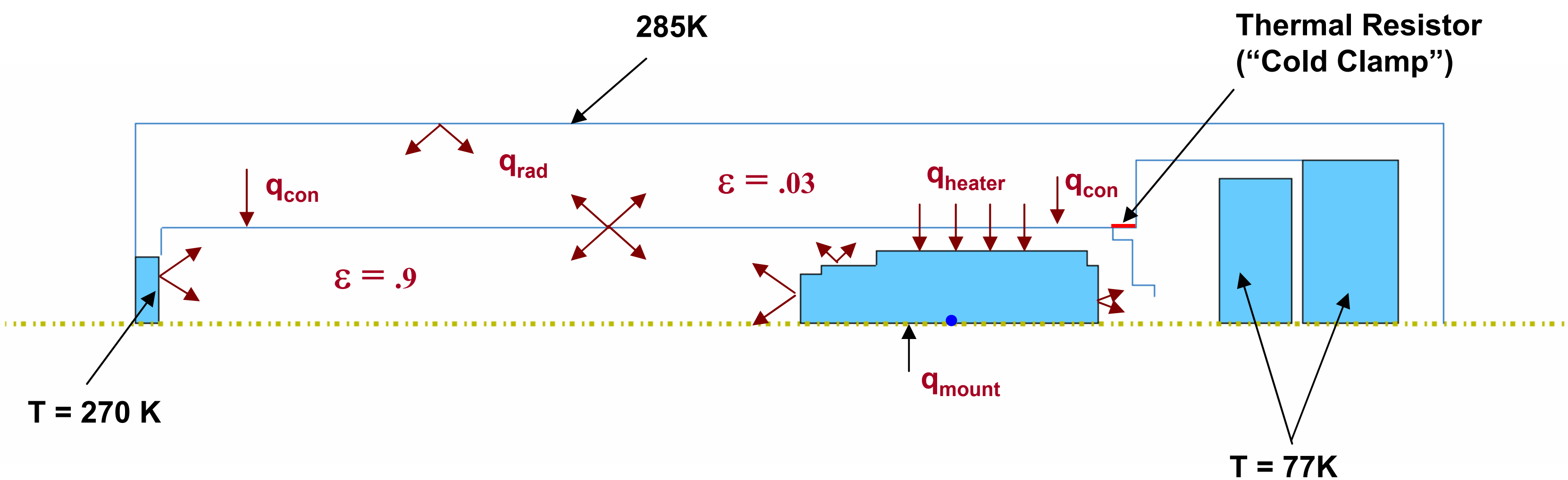




Thermal Analysis

System Level Model

- **Determine:**
  - Cooldown time
  - Steady state heat load for 268K, 285K, and 300K ambient
  - Required heat input to camera module



System Level FEA Model Details

- **Axisymmetric model**
  - **Baffle diameters scaled to area of square opening**
- **Transient, coupled conduction/radiation model**
- **Simple conductive paths calculated analytically; not included in (FEA model)**
- **Radiating surfaces**
  - **ε = 0.9 assumed for black surfaces**
  - **ε = 0.03 assumed for low emissivity surfaces**
- **Vacuum vessel**
  - **Held at ambient temperature**
  - **Low emissivity inner surface**
- **Window**
  - **Represented by compact model with constant temperature as determined by FEA submodel**

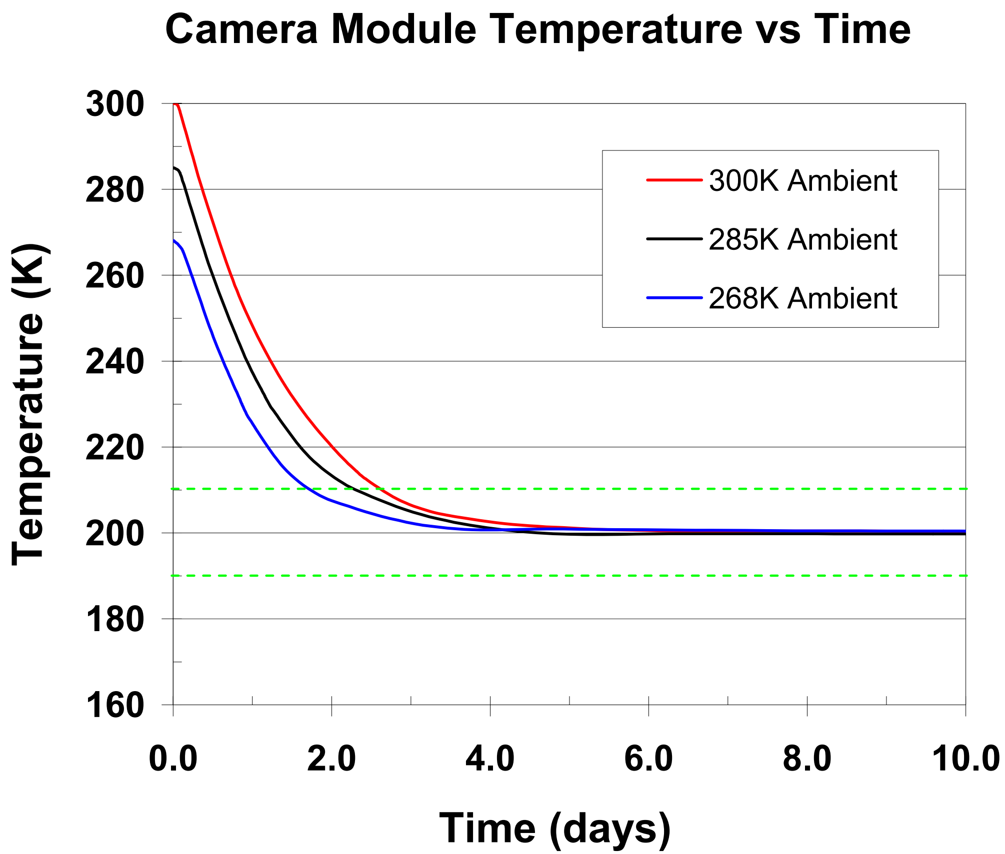
Thermal Analysis

System Level FEA Model Details Cont.

- **Radiation shields**
  - **10 mm thick, 6061-T6**
  - **Low emissivity outer surfaces, black inner surfaces**
- **Camera Module**
  - **Compact model used to simplify computation**
  - **Cooled by radiation only; black surfaces assumed**
  - **Heat flux applied to achieve 200K operating temperature**
    - **Approximately 4W comes from the mounts**
- **Thermal resistor i.e. the “Cold Clamps”**
  - **Heat flow through the resistor adjusted to achieve camera module operating temperature (200K)**

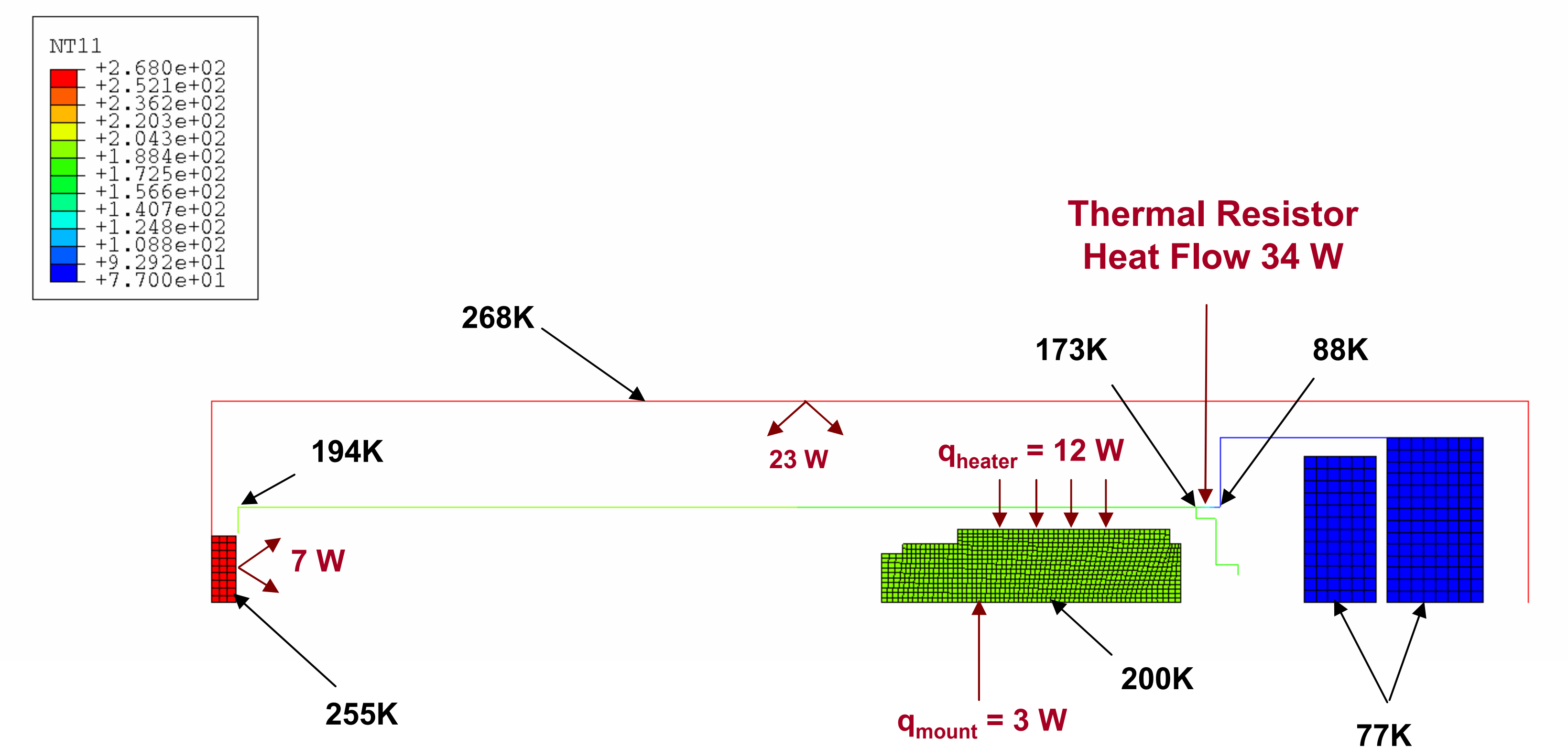
Thermal Analysis

Cooldown Results

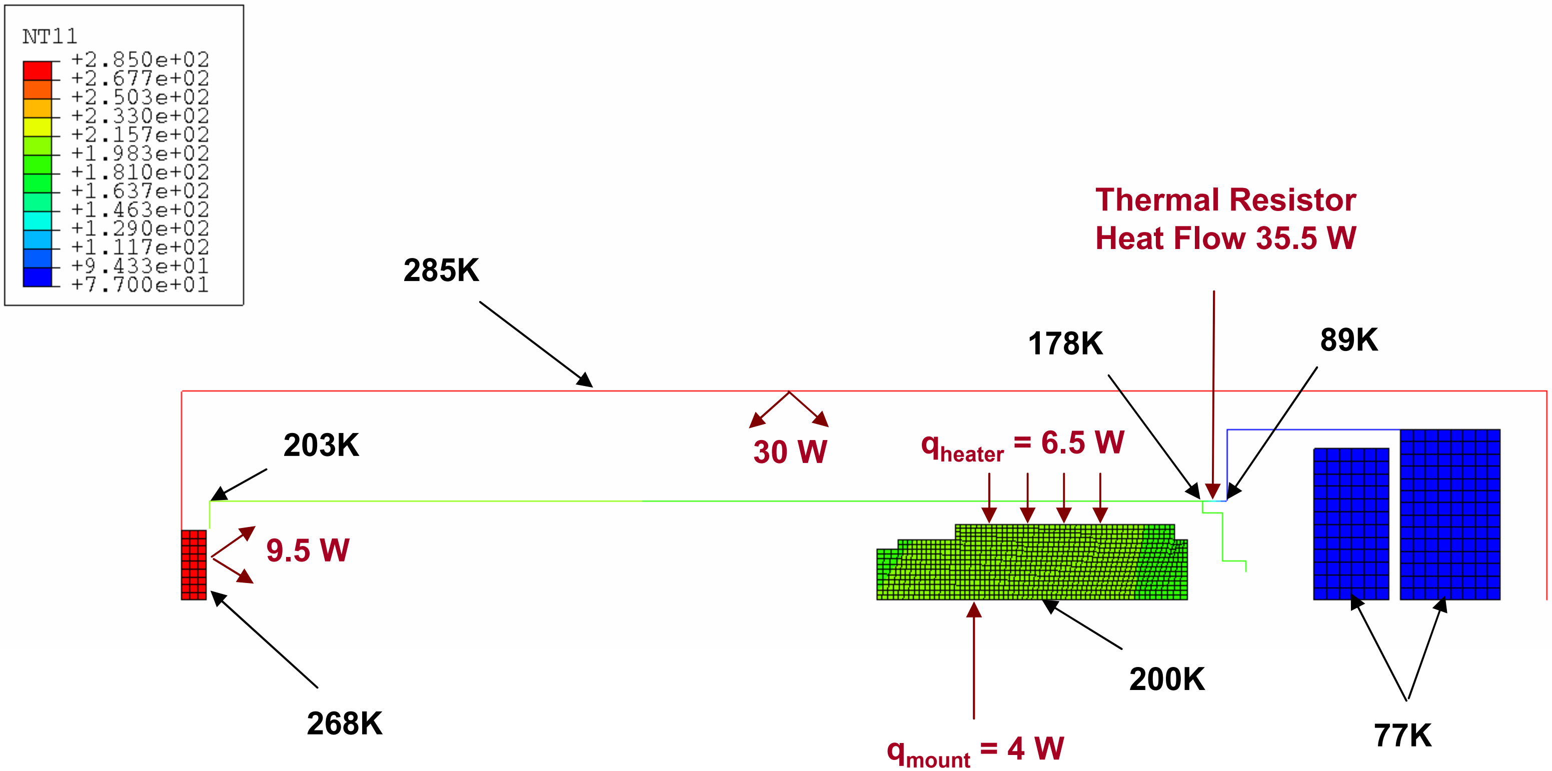


Thermal Analysis

Steady State Thermal Profile: 268K Ambient

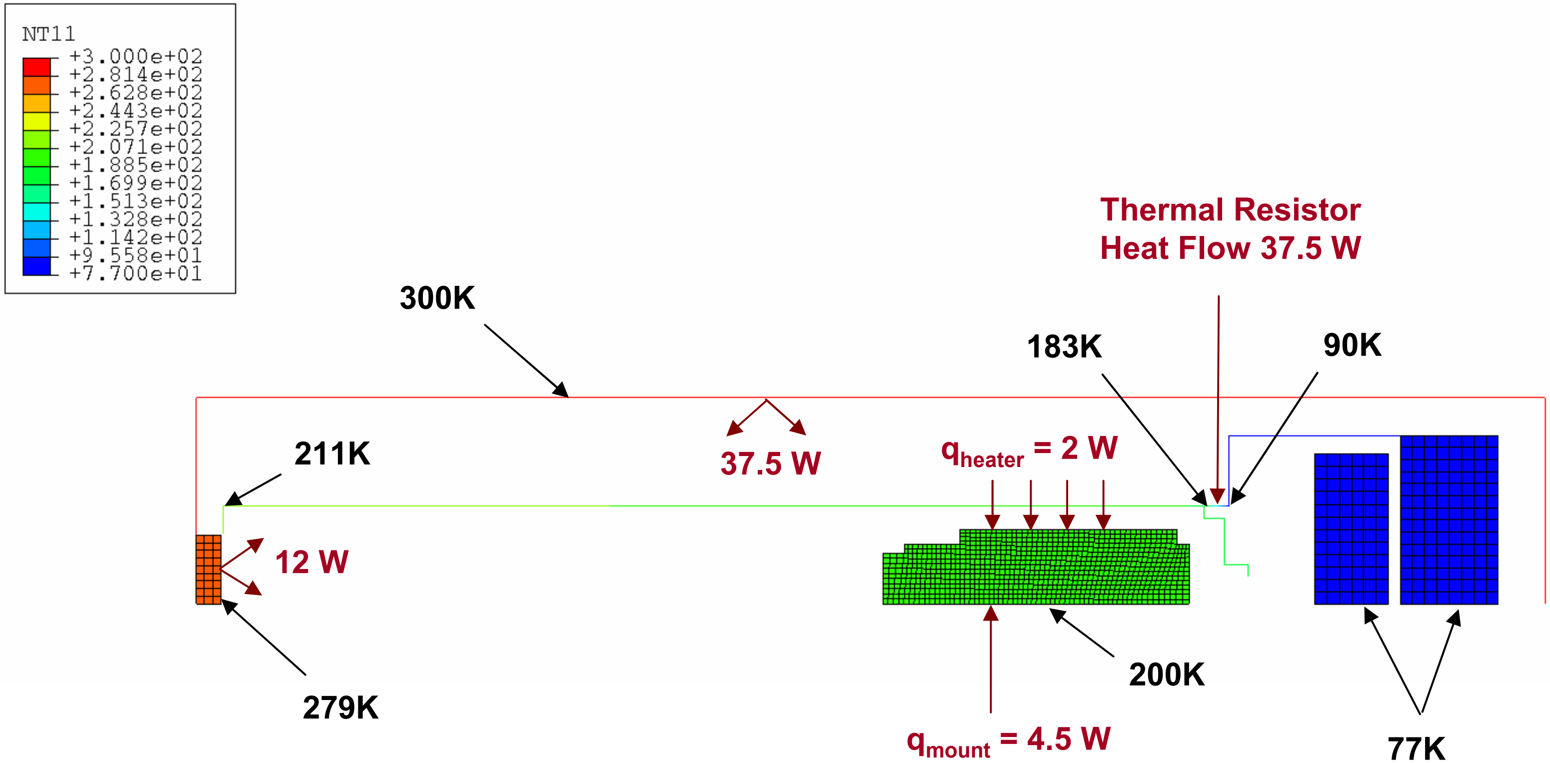


Steady State Thermal Profile: 285K Ambient



Thermal Analysis

Steady State Thermal Profile: 300K Ambient



Thermal Analysis

Heat Load Summary

	Heat Load (W)		
	268K Ambient	285K Ambient	300K Ambient
Vessel Wall Radiation	23.2	30.2	37.6
Window Radiation	7.0	9.5	11.9
Shield Dewar Mounting	1.5	1.6	1.7
Detector Dewar Mounts	3.0	3.4	3.7
Camera Module Mounts	3.1	3.9	4.6
Camera Module Heat Input	12.1	6.7	1.8
Misc.	0.2	0.2	0.3
Total Heat Load	50.1	55.5	61.6
LN_2 Burn Rate (liters/hour)	1.1	1.23	1.37

Thermal Analysis

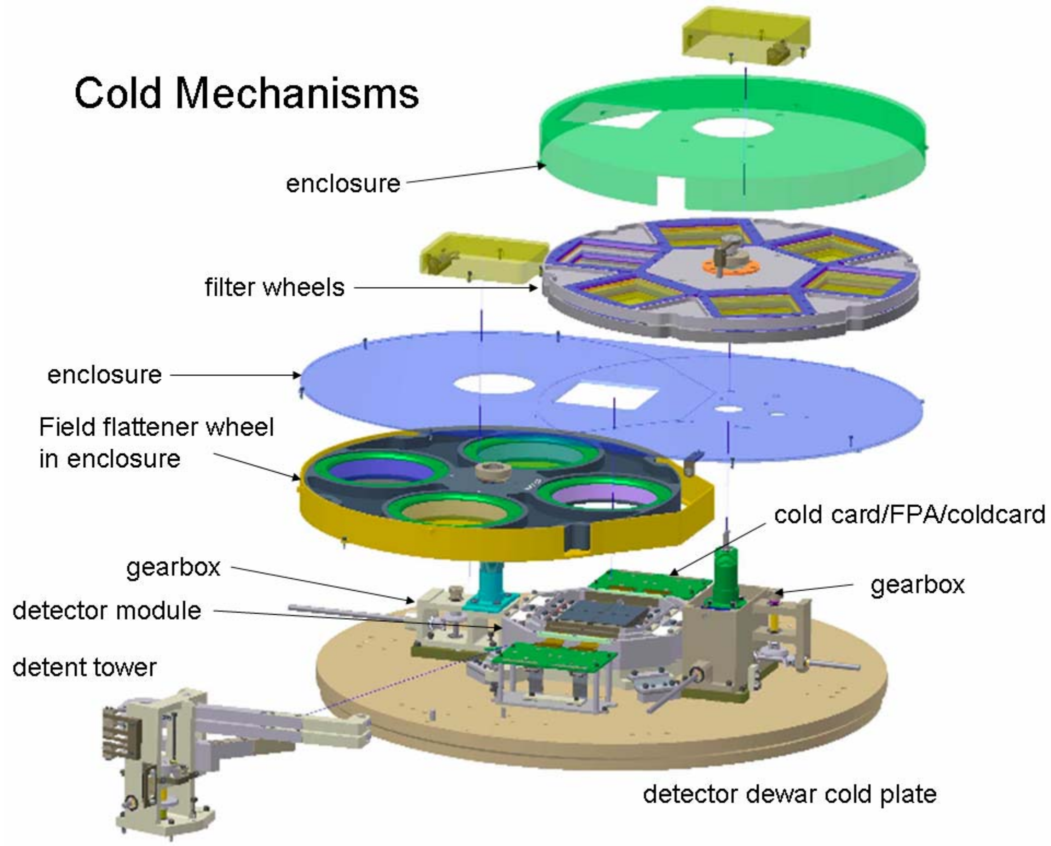
Conclusions

- **Heat load over the anticipated operating temperature range is between approximately 50 W and 62 W**
  - **LN_2 usage will be about 1.25 liters/hr**
- **Cooldown time will be approximately 2 to 3 days**
- **System temperature are in line with expectation**
  - **Thermal gradients are high in L2 but do not pose a problem optically**
  - **Temperature gradients in L3 – L6 are < 1K**
- **A thermal resistor that flows approximately 37 W between the 77K and 200K radiation shields is necessary.**

TAB 6

6. Dewar Mechanisms

There are six principal internal mechanisms of FourStar which we describe below. Five such mechanisms are operated at 77K and one at 200K.



Detector Module

The overall size of the camera and the possible stack-up of tolerances led us to adopt a conservative approach to aligning the plane of the detectors orthogonal to the optical axis. The procedure will be discussed later, but suffice it to say that it led to the design of the detector module. In addition, because of the speed of the beam onto the detectors (F/3.6) we wanted to be able to test their relative tip-tilts and pistons without having to remove and replace them (perhaps) several times. The procedure for achieving both detector co-planarity and detector orthogonality to the optical axis depends on using available adjustments in the detector module in concert with a specially designed optical alignment fixture/lens set known as "FakeStar". Each FPA is kinematically mounted on its own Molybdenum block, and the assembly of blocks is kinematically Mounted on the cold work surface of the detector dewar. The FPAs can be moved in focus while the instrument is cold. Although we do not plan to manipulate the focus at the telescope it provides an additional optical degree of freedom for empirical compensation of the design if required.

Field Flattener and Filter Wheels

To achieve maximal image quality, higher throughput, and suppress ghosting off the detector surface we adopted separate field flattener lenses for each passband. This led to a wheel just forward of the focal plane that holds three optimized field flattener lenses. A fourth position, used solely for optical alignment purposes holds a FakeStar test optic.

To accommodate an adequate filter capacity we decided on two filter wheels, with accommodations for five 94mm square filters and one open position each. Although FourStar is not designed for either spectroscopic or narrow-band applications, calculations indicate that narrow-band filters (~ 2%) can be used if they are designed long in central wavelength and if the cold pupil is stopped down to a 25% flux loss. Intermediate-band filters (~ 6%) may be used without stopping down the pupil.

The filter wheels and field flattener wheels are enclosed in a light baffle. This should eliminate any thermal leaks from feedthroughs or past the pupil stop, but in addition it helps to cool the filters and lenses and to keep them clean.

Internal space constraints and other concerns regarding maintainability and electrical accessibility led to a design whereby the wheel positions are externally encoded. This is accomplished by providing each wheel with a custom built absolute encoder. The external encoder mechanism is geared in such a way that one rotation of the encoder corresponds to one rotation of the internal wheel (1:1). This has some important advantages, among them is that a computer is not necessary to see what position a wheel is in. Of course this method depends upon being able to reconnect the internal gear train shafts in a unique way after disassembling the dewar; this is inherent in the coupling design. The absolute encoding scheme is backed up by an internal home position for each wheel; these are micro switches activated by the wheels themselves. The in/out locations for the detent tower arms are sensed by micro switches - two per function for redundancy. All the encoding and switch information is sent to the Motor Controller and integrated into the overall camera control system. An important capability of the filter wheels mechanisms is that they may be positioned by hand if necessary with no ambiguity in position in the event of a total failure of the control electronics, i.e. complete manual override.

Detent Tower

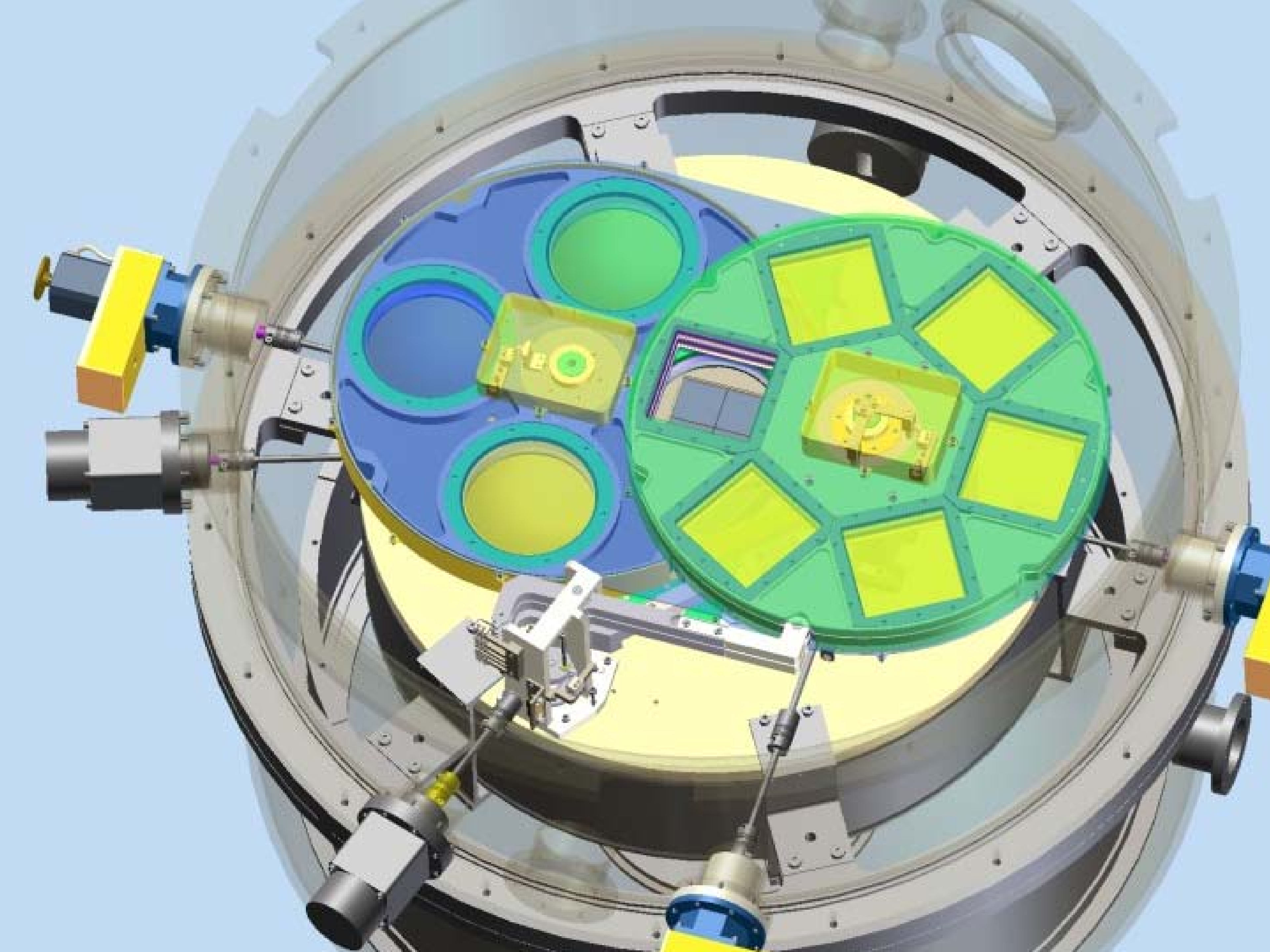
To assure photometric and image stability we wanted each of the wheel mechanisms to be locked into position with a highly reproducible mechanical detent system. In order to reduce torque requirements on the wheel motors, we decided to load and unload the force on the detent via a spring mechanism each time a filter position was changed.

Pupil Mechanism

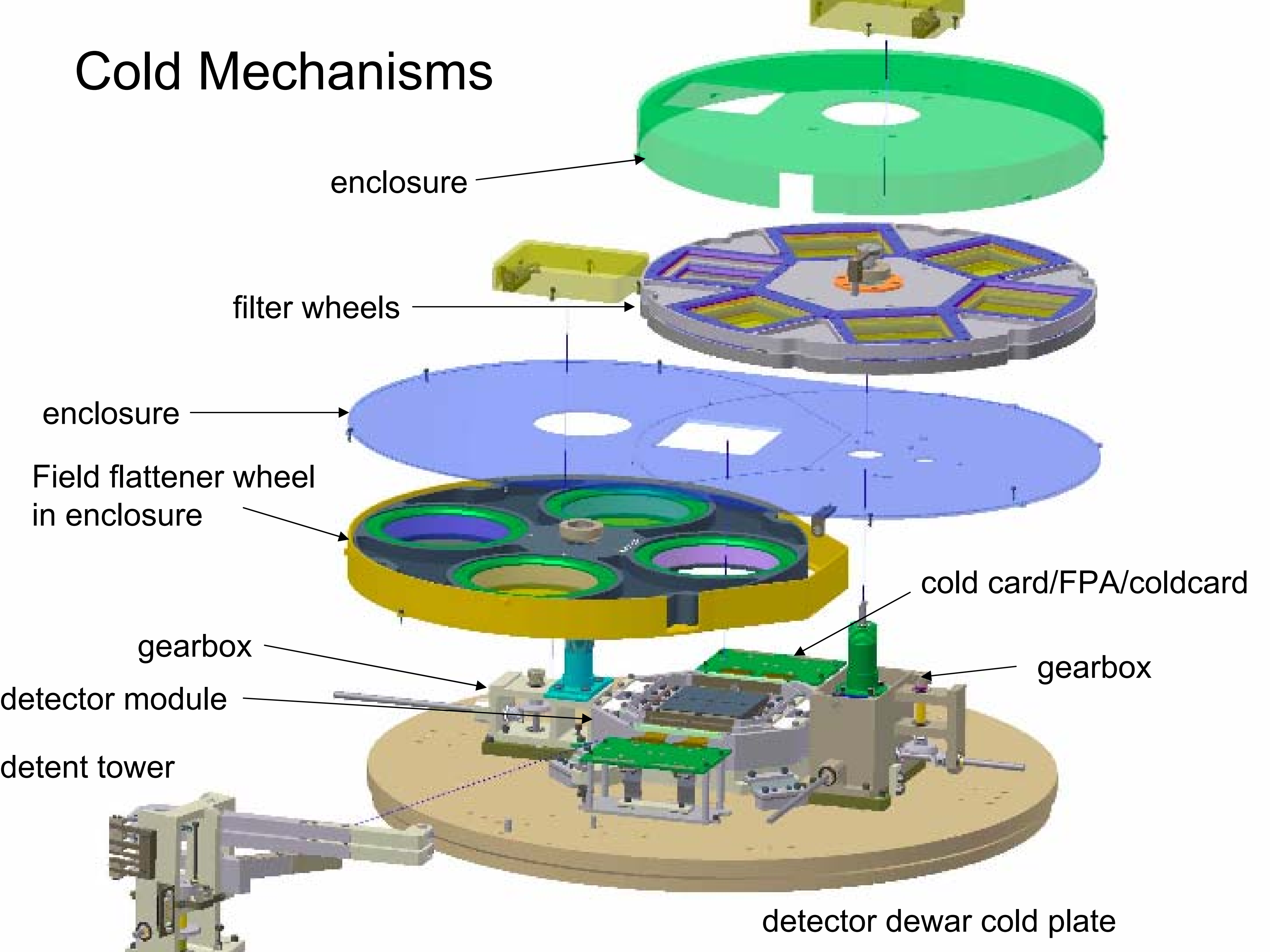
The pupil mechanism is operated at 200K and is adjustable with an external stepper motor, an absolute encoder, and limit switches. It is an iris diaphragm which has a fixed opening for the Ks bandpass, and is wide open for J and H. The reasoning behind this will be clear from the optical design, i.e., the different focal lengths of the entrance window/fabry lens(es) causes the J band focus to fall about 50 mm from the Ks-band focus, where wwe want the pupil stop to be placed.

Cold Mechanisms

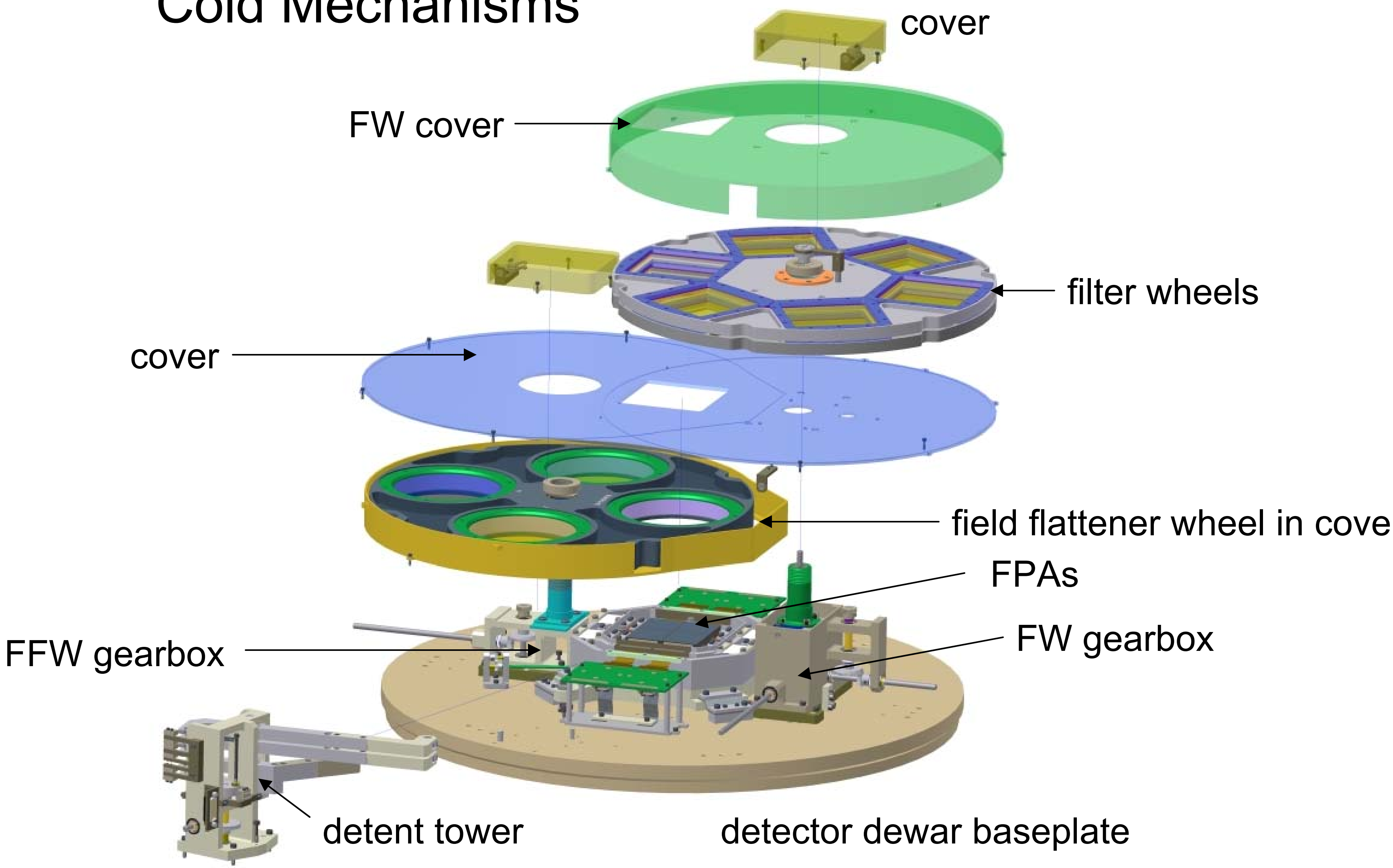
- Two filter wheels (total 10 passbands) leaves room for splitting the bands into two or three, or using narrow-band filters
- Field flattener wheel (4 positions - JHKs, alignment optic)
- Detent arm mechanism to lock wheels
- Detector module focus, including cold focusing
- Pupil iris opening
- Detent mechanisms which can apply force when needed; locations are determined by mechanical means, not counters or sensors
- Detents in/out encoded by microswitches
- External absolute position encoders for wheels; redundant with internal home position microswitches (reason: tight space constraints and ease of repair)
- Detector module allows safe alignment of detectors and cold “FakeStar” testing
- Six external stepper motors (conservative)

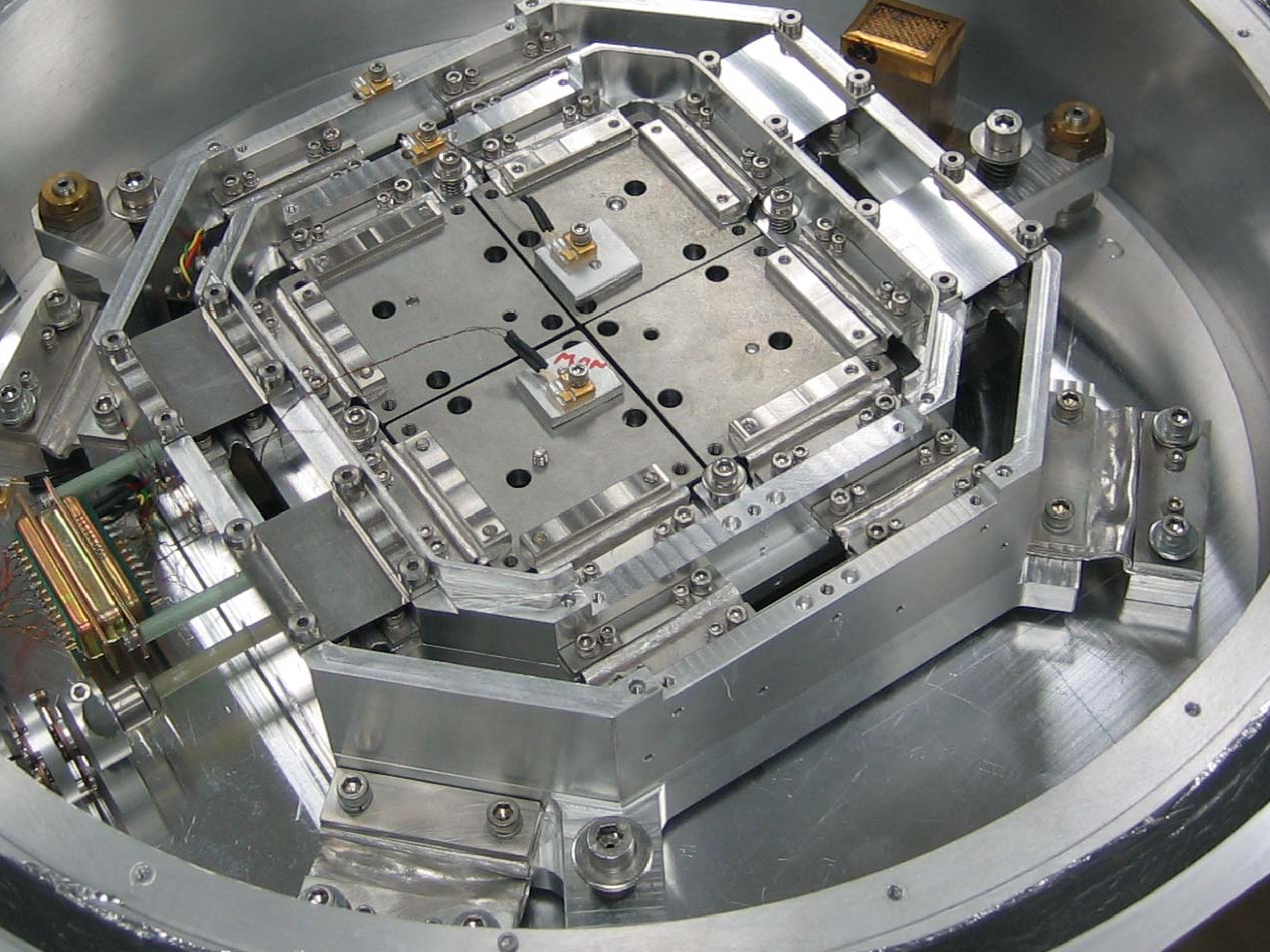


Cold Mechanisms

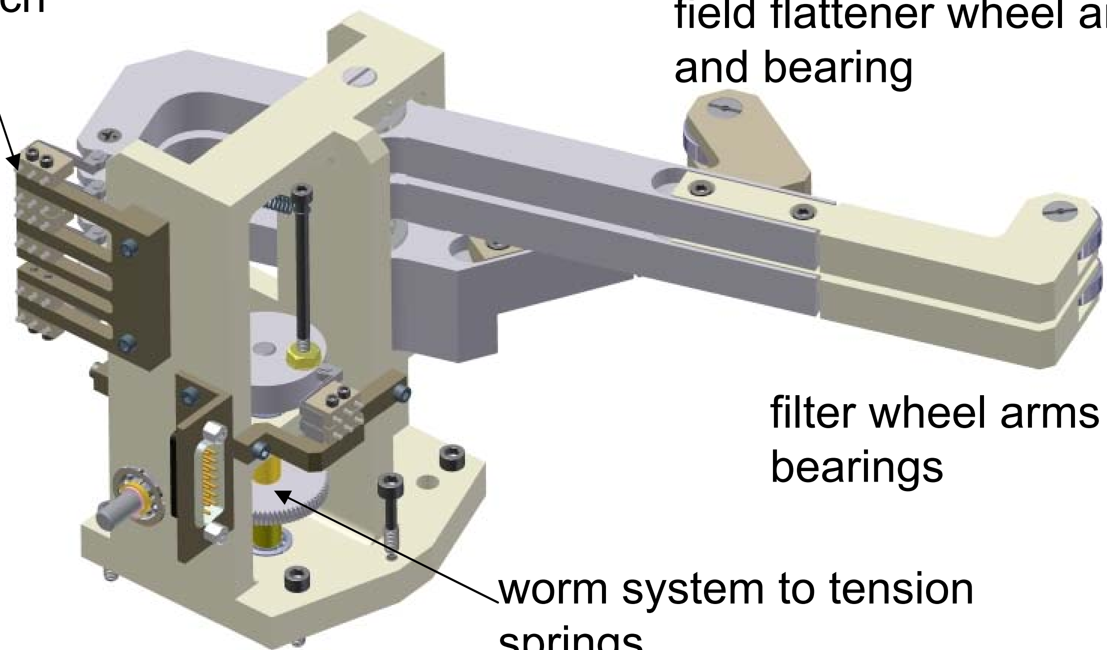


Cold Mechanisms

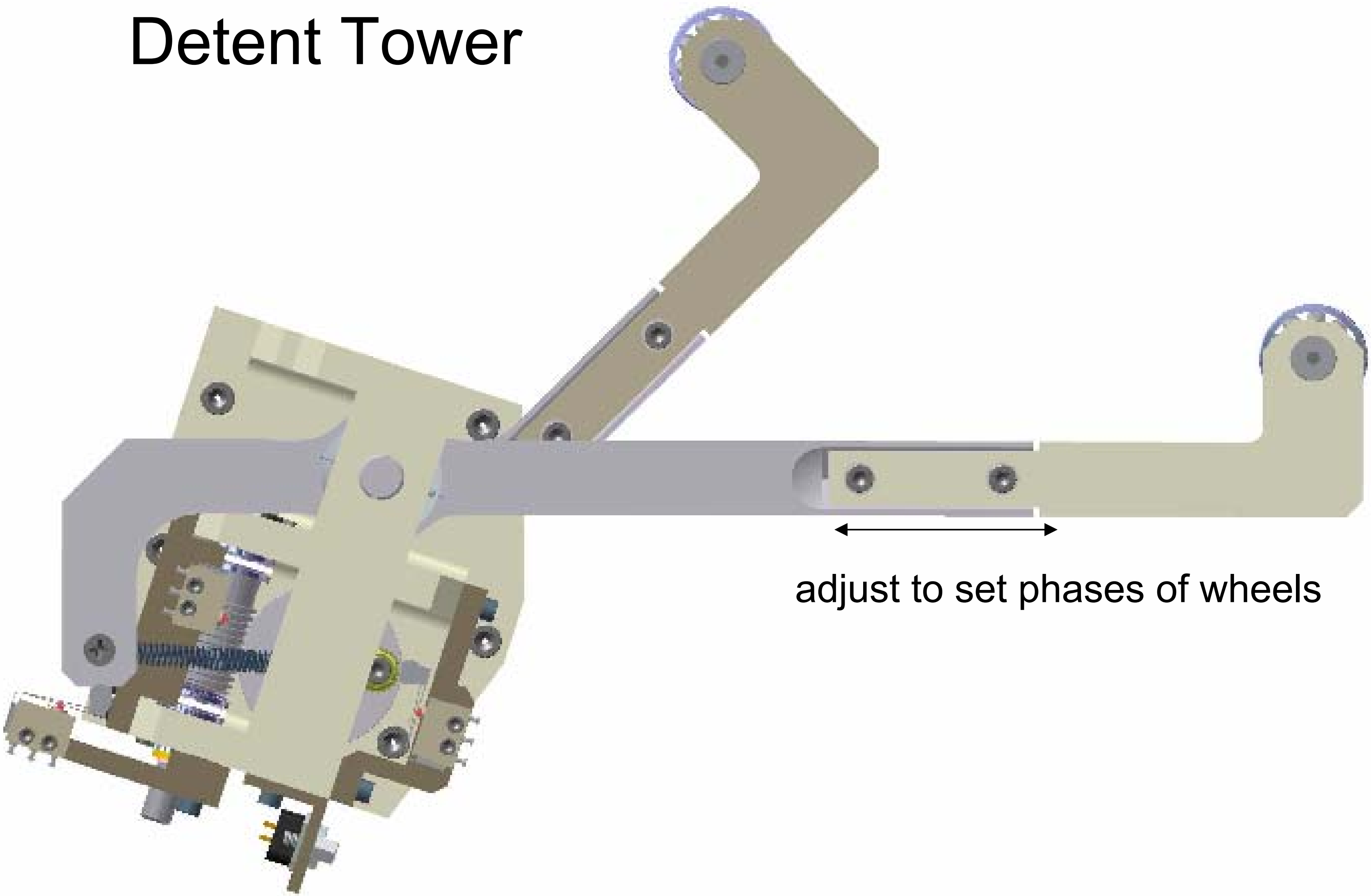




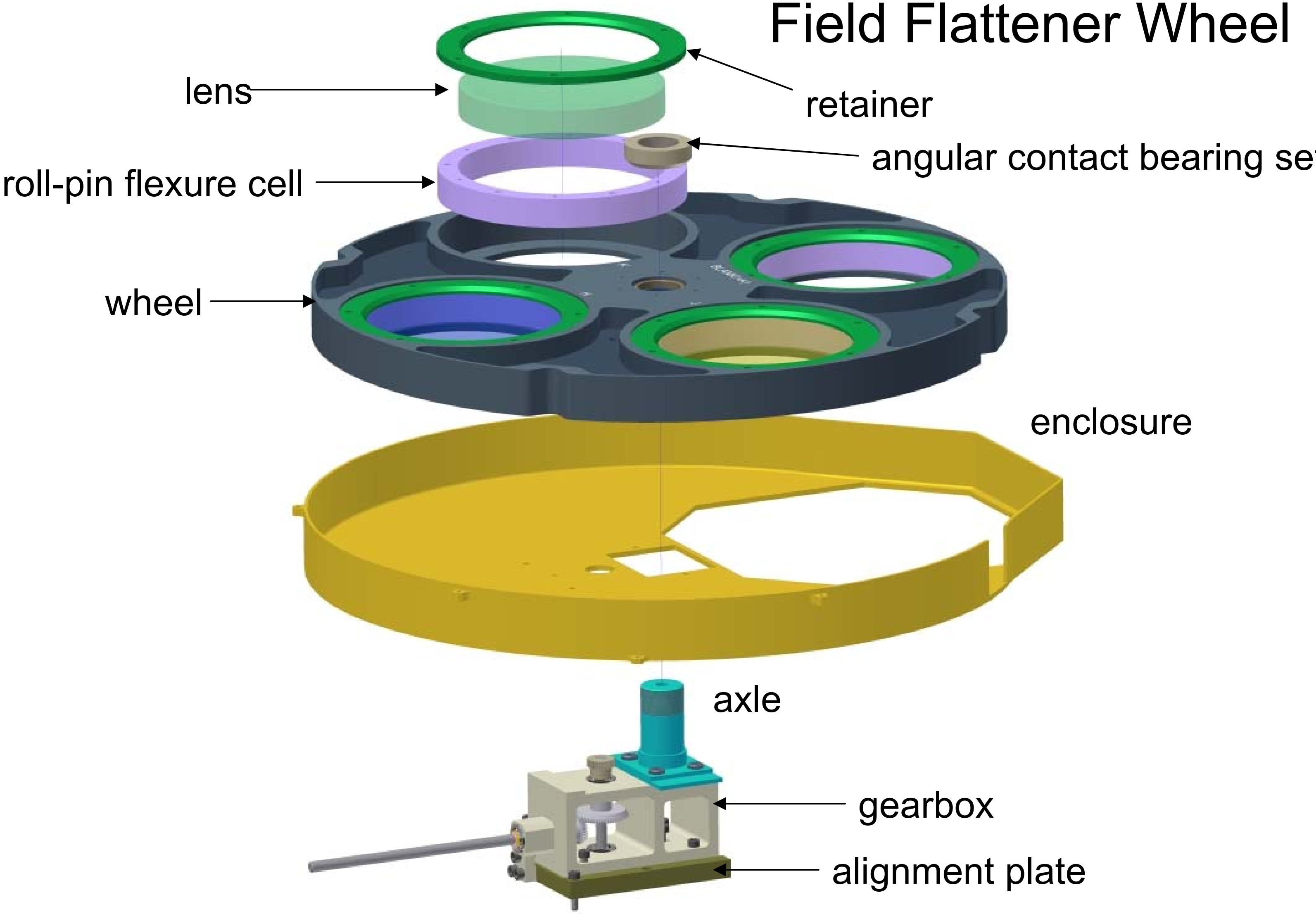
Detent Tower



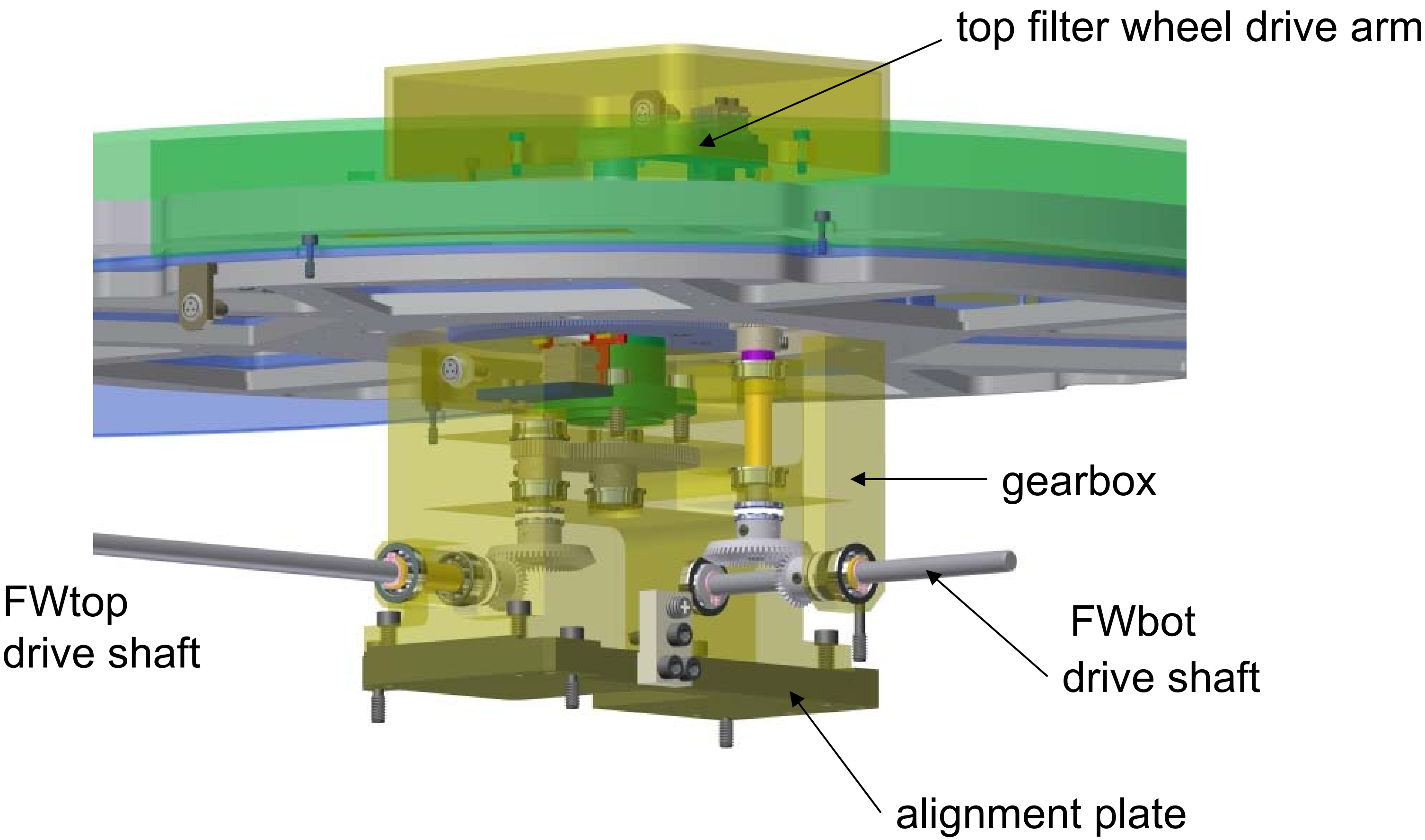
Detent Tower



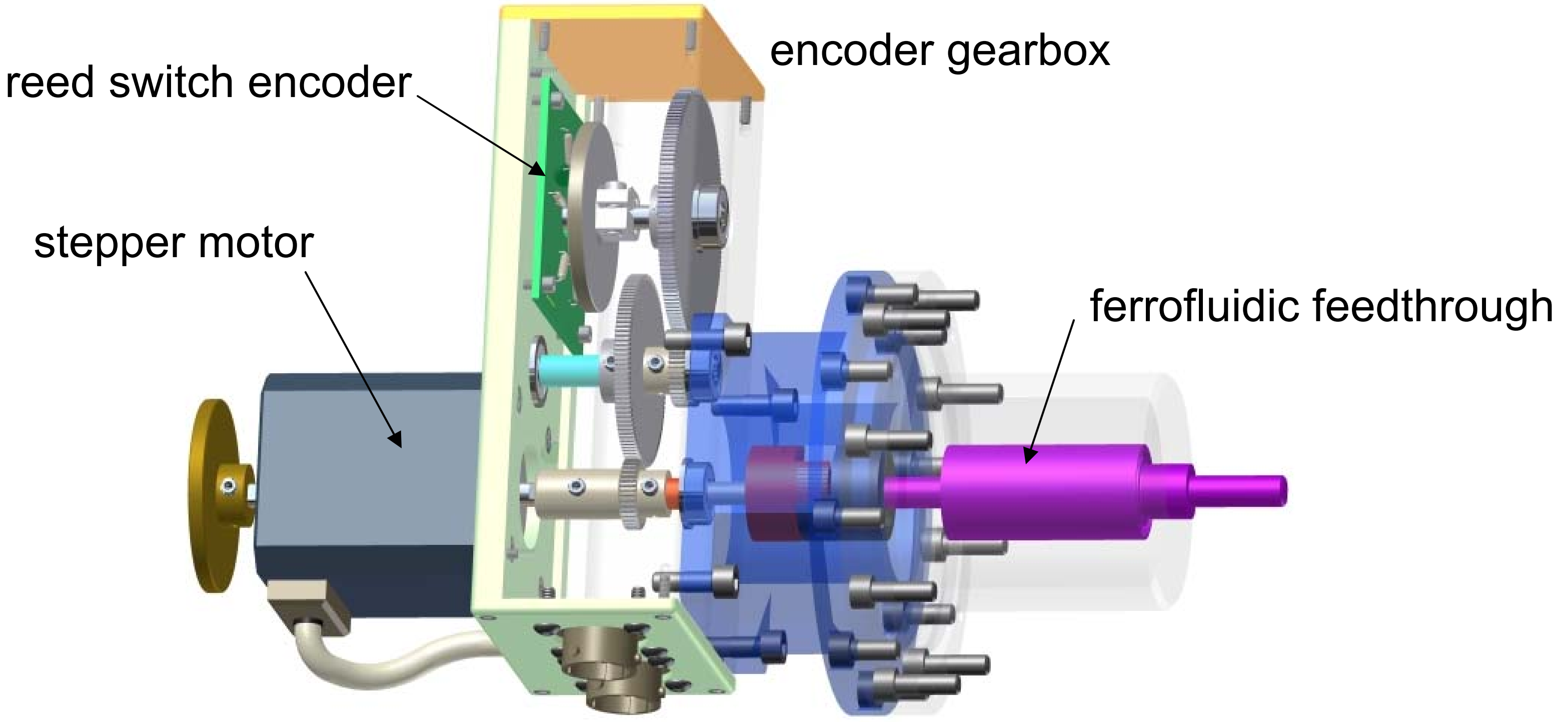
Field Flattener Wheel



Filter Wheels Gearbox



Motor/Encoder gearbox



TAB 7

7. Rockwell HAWAII-2 RG Detectors and Sidecar ASIC Electronics

The decision to use the Rockwell HAWAII2-RG detectors was made at the very beginning of the project. Likewise, when we learned that Rockwell Science Center RWSC) was developing integrated electronics (the Sidecar ASIC) to run alongside the detector and digitize the signals, we did not see any advantage to developing our own. The ASICs promise to be of higher performance from a noise perspective, to be more robust in the sense that they would be out of harm's way in an observatory, and that they would be cheaper: we estimate a factor of two. The prospect of having 128 channels of amplification and A/D conversion provided on four small boards seemed preferable to our own custom engineered solution. The ASIC’s and associated support electronics, documentation, and software support package will be delivered before the end of 2006 and at that time we will proceed to test the arrays.

We received our bare multiplexer and engineering-grade detectors in 2005. The delivery date for our science-grade detectors has been delayed several times, but this has not yet affected the project schedule. In the interim Rockwell decided to start a program to remove CdZnTe substrate material from HAWAII2-RG to enhance quantum efficiency, and asked us to accept these. Because substrate removed detectors are sensitive into the visible, we checked our filter curves for shortwave blocking and were satisfied that blue leaks would not be a problem. In summary, FourStar will be implemented with four substrate removed HAWAII2-RG detectors.

One channel (one detector) of the electrical system consists of seven components: a HAWAII2-RG detector array; a 140-pin Hirose connector cable; one Sidecar ASIC mounted on the Cold Card; a 30-lead Hirose connector cable to a hermetic connector; a custom-designed Micro-D hermetic connector laser-welded into a vacuum interface plate; a short jumper cable; and a JADE2 Card. The JADE2 card is interfaced to the control computer with USB 2.0. All control information and data from the ASIC/HAWAII2-RG system use the USB 2.0 link. In the ASIC/HAWAII2-RG received all their operating power via USB.

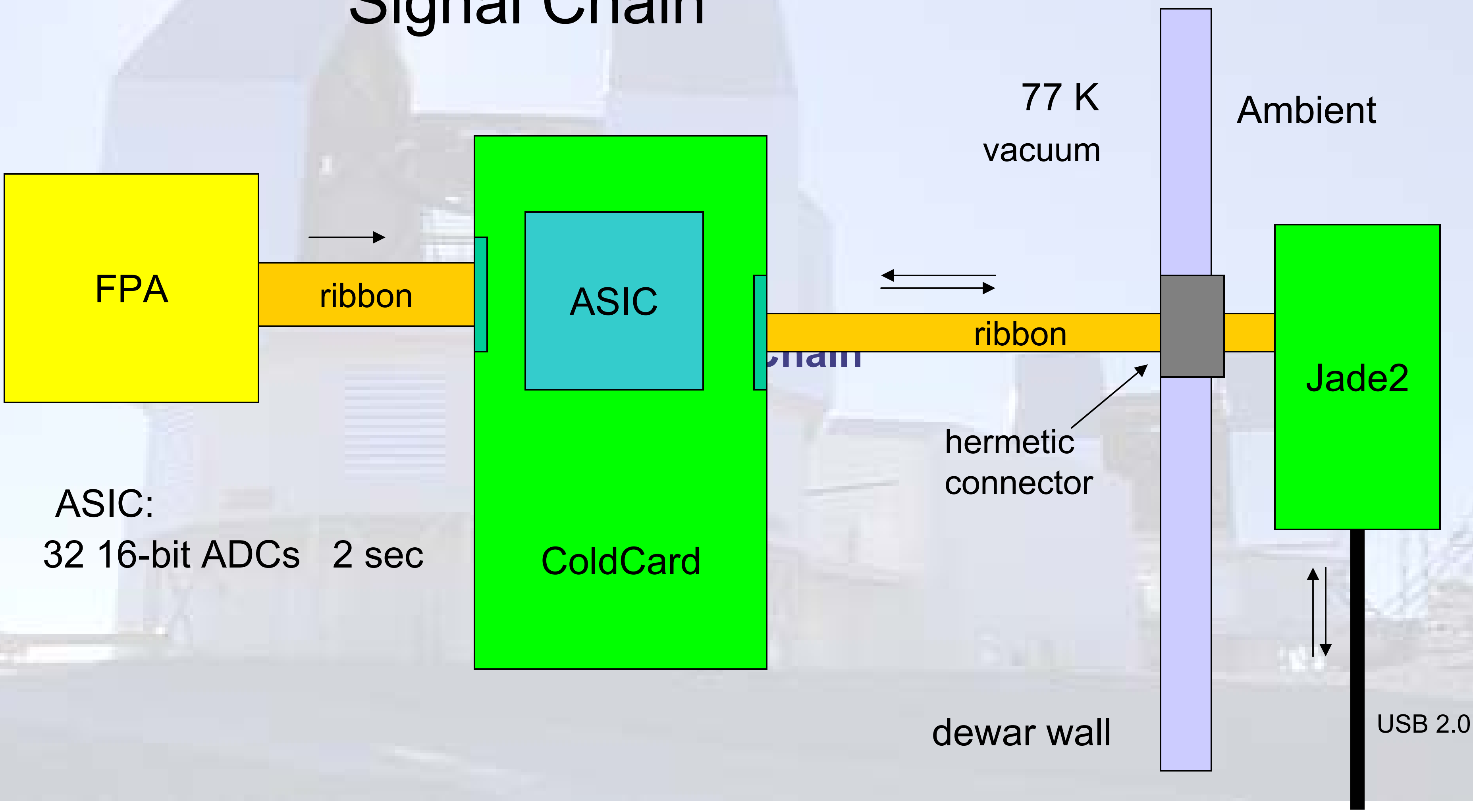
The mounting of two ASICs to serve two detectors butted together presents a problem because the center-to-center spacings for the chips (ASIC vs. HAWAII2-RG) are not commensurate. The ASICs require slightly more room, and thus a specially-designed board to hold two ASICs was developed. As a strategic partner and as part of a contract, Rockwell agreed to apply their expertise and design this board for us, as well as the cable(s) needed to connect it to the ambient world.

The ASICs operate at 77K, so our mount incorporates a design from GL-Scientific that clamps the ASIC to a circuit card, while also clamping a heatsink to the ASIC. The thermal energy dissipated in one ASIC running at full speed is about 100 mW, which we want shunted into the dewar so as not to heat the detector. Each signal cable that runs between ambient and its cold card has been designed to deliver no more than 70 mW, while maintaining an impedance for the five power supply lines of 1 ohm each and for the two ground planes of 2.6 ohms each. The impedance criteria were specified by Rockwell while Carnegie specified the desireable thermal loads. There was no difficulty in satisfying the two opposing criteria. The thermal load through the cable could easily be reduced by shunting some of it into the radiation shield.

In order to test the detector electronics, cool down procedures, and so forth, we have assembled a test dewar (mostly out of surplus IR Labs dewars). The test dewar will hold the Detector Module and gives us the ability test one array and with its entire associated signal chain.

FourStar

Signal Chain

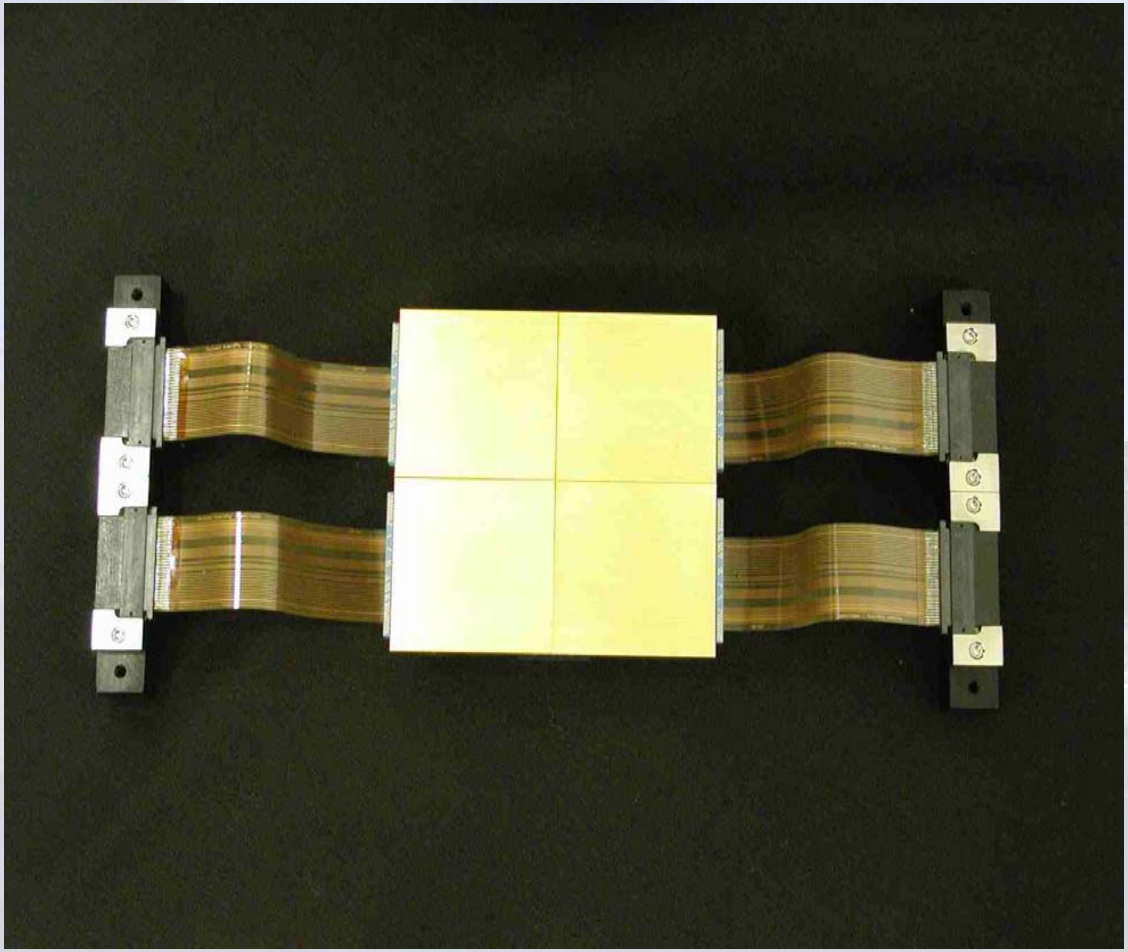


Signal Chain (per detector)

1. 2048x2048 array
2. 4.5-inch long 140-pin cable; Hirose connector. These connect underside of array socket to “cold card”.
3. ASIC “cold card” - holds two ASICs. Thermally clamped to cold work surface.
4. 15-inch 37-pin cable; Hirose at one end, micro-D at the other. This runs from cold card to the dewar hermetic connector. Shunting of thermal energy to the radiation shield is possible here.
5. Hermetic 37-pin micro-D connector welded into plate.
6. Micro-D to Hirose connector flat cable.
7. Jade2 card in housing.
8. Commands up to ASIC, and data from FPA via USB 2.0.

FourStar

4K x 4K Mosaic



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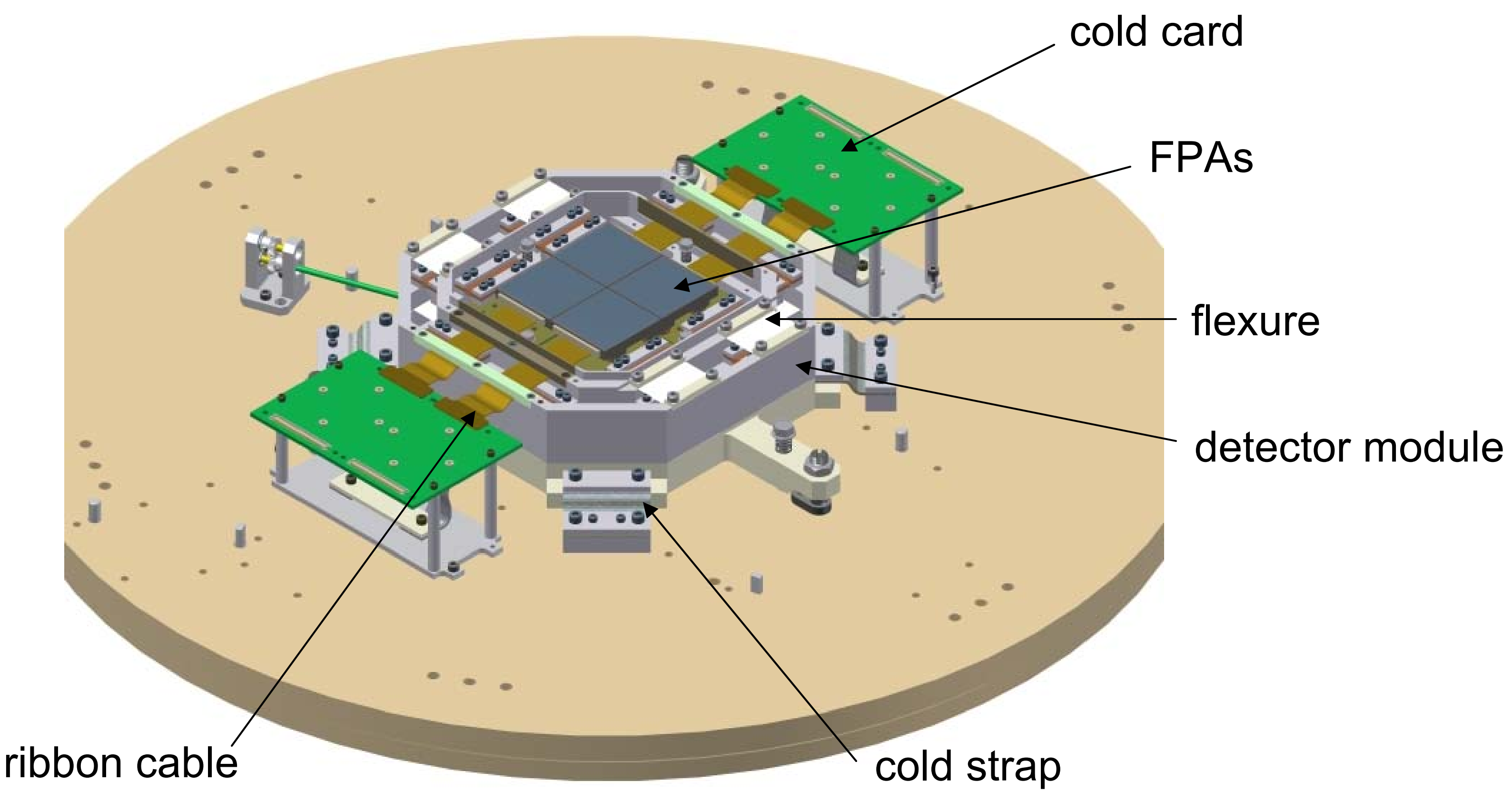
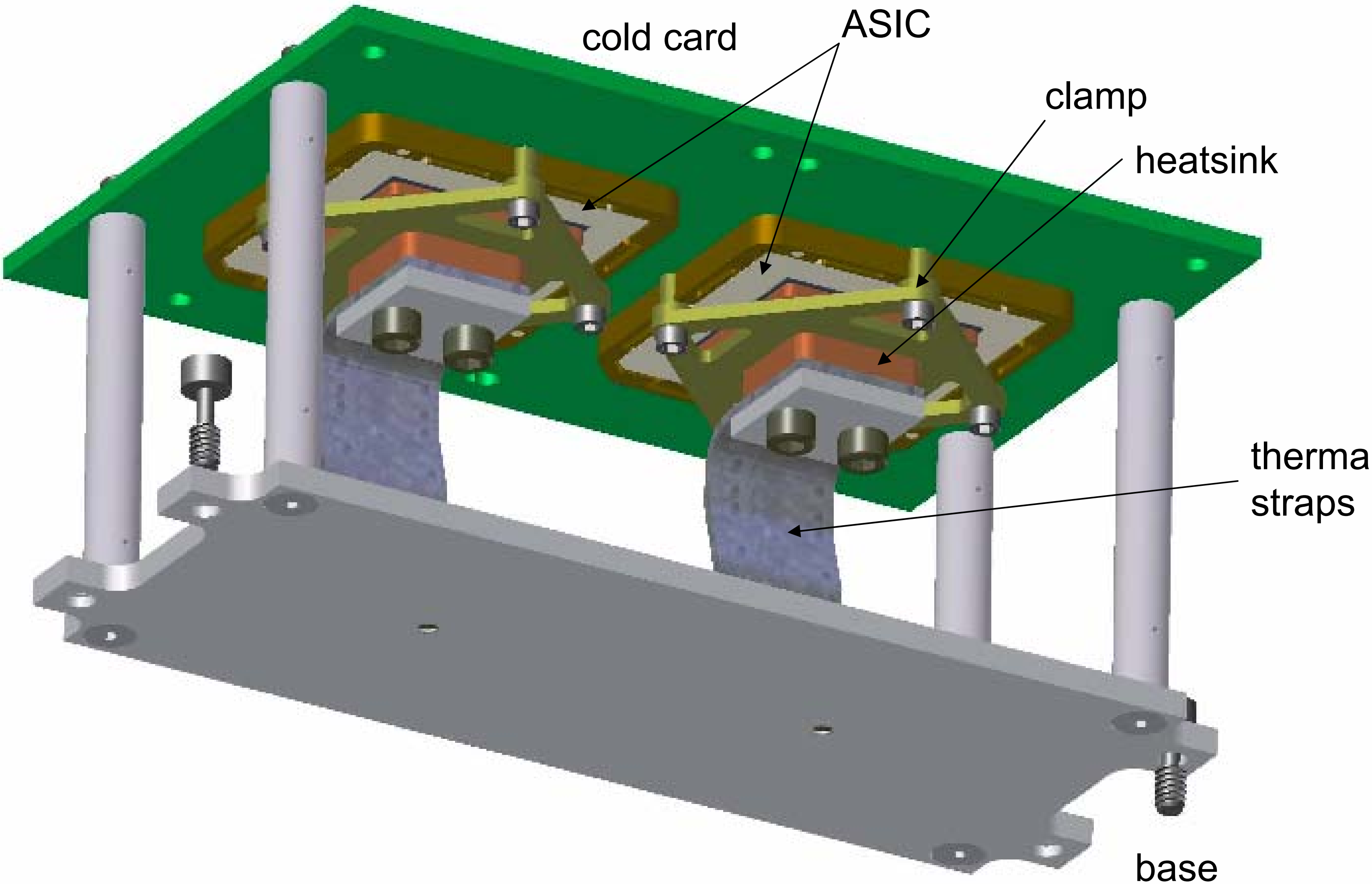
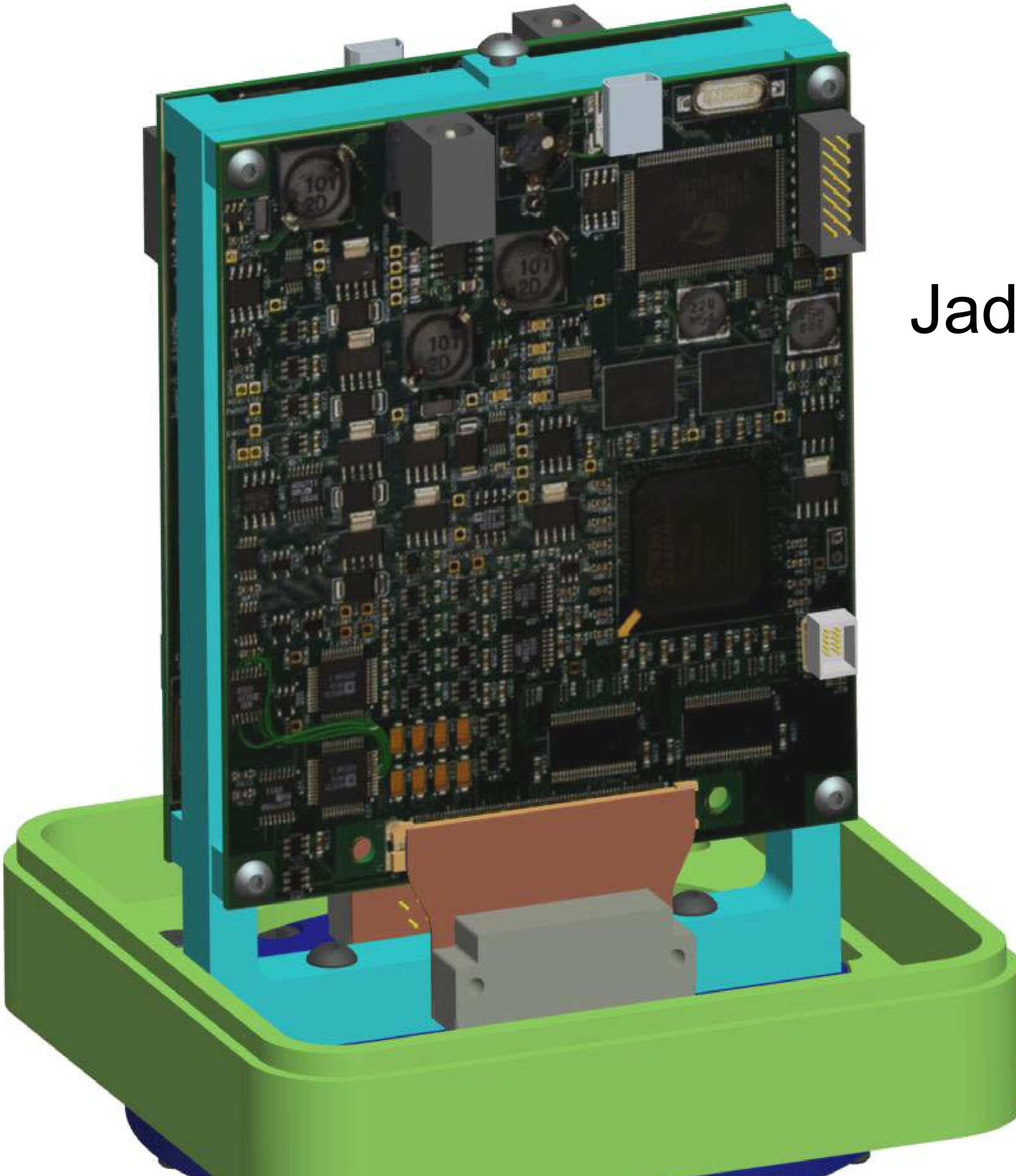
Detector Module, FPAs, and Cold Cards



Cold Card with 2 ASICs





Jade2 Cards

Detector and Electronics Status

- 4 Science-grade arrays due by 10/31/2006

readnoise	15 electrons rms
dark	< 0.1 electrons/sec
QE	90% at K, possibly 80% at J

  Very small number of dead pixels
- Mechanical design much superior to HAWAII-1
  - ASIC socket now settled and tested.
  - Thermal clamp design by GL-Scientific.
- We need a Cold card with ASIC spacing equal to detector spacing; RWSC signed up to this.
- All cards and cables to be provided by RWSC by 11/15/2006:
  This is through a separate contract which includes software support to read the arrays - contract signed, work has started.
- Testing will be started with bare MUX and engineering-grade array in test dewar.

Cooldown Procedures

All the following will be certified before any optics or the detectors are placed within the instrument.

1. The radiation shield (shroud) dewar is cooled while the temperature of the camera module is controlled to overshoot the (final) 200K target by about 10K.
2. This is accomplished via a “metacontroller” program which sets a running target for the Lakeshore controller to attempt to keep up with.
3. The metacontroller program is operated from a gui in the control room.
4. A second metacontroller is simultaneously being used to control the temperature of the inside of the detector module. Once the radiation shield dewar has reached about 240K, filling of the detector dewar can begin. (This number of 240K will be experimentally determined.)

Cooldown Procedures (cont'd)

5. As the detector dewar is filled, the detector module will be brought down in temperature at a rate that will not endanger the FPAs. We believe this rate to be 0.15K/min or less. If this requires a careful sequence of filling steps, we will have determined that beforehand.
6. The camera module heaters/metacontroller will be set to warm up those optics to 200K so that both subsystems are ready for operation at about the same time from start.
7. To warm up the system we expect to allow both dewars to run out of lN2 while helping them along with the heaters/metacontrollers.

TAB 8

8. Control System - Architecture & Hardware

The control system divides into two parts - those functions concerned with controlling the array clocking and readout, and those concerned with monitoring and controlling the (non-array) camera subsystems.

Much of the array control system is actually provided by the many functions that can be invoked by instructing the ASIC. RWSC will provide a Microsoft COM interface that will allow us to communicate with the ASIC and take images. Following Rockwell's lead, PC's running Windows XP will be used control the ASIC and field imaging data from the arrays.

The camera control and monitoring functions include temperature control and monitoring, motion control for the mechanisms, monitoring the dewar pressure, and monitoring and controlling LN2 levels for the dewar.

Our Motor Control unit is based around the a Nyden-Mycom MAC300, a programmable stepper motor controller. We have considerable experience with this controller and have successfully used it on three other infrared cameras at the Observatory. The stepper motors are all 5-phase steppers. We think that the overall development of the FourStar motion control system will be straightforward as we have practical knowledge of the selected components at all levels: hardware, software and firmware.

The internal temperatures are monitored and controlled by two model Lakeshore 340 temperature controller/monitors each configured to accept up to 10 cryogenic sensors. In addition to the cryogenic temperature sensors, FourStar also utilize eight themistors for non-cryogenic monitoring of the external vacuum vessel temperature and the electronic racks. A microcontroller-based process controller has been designed to control and monitor critical dewar functions. This unit will monitor a Pfeiffer vacuum gauge, the set of eight thermistors, and the LN2 level sensors (described above). The vacuum monitoring is vital for cool down procedures and long-term operational safety. The thermistors are needed to compute the length variations of the dewar due to thermal expansion/contraction in real time for telescope focus compensation. The resulting predicted telescope focus offsets will be sent to the telescope control system and updated every few minutes. The LN2 level sensors are used in a control loop to actuate an LN2 solenoid valve to auto fill the dewar as necessary.

The instrument cool down and warm up procedures are special operational cases. All the optics and the detectors must be protected from rapid temperature changes, and for this we have developed "meta-controllers", programs running on the camera control computer that continuously updates target points of the Lakeshore controller which also implement their own PID loops. Once the instrument has stabilized at its operating temperature the detector servo loop is turned off and only the camera module is controlled. Three MINCO heaters are attached to the body of the camera module and these provide the small amount of thermal energy needed to keep the lenses at 200 +/- 5 K design operating temperature.

Four Star Data System Overview

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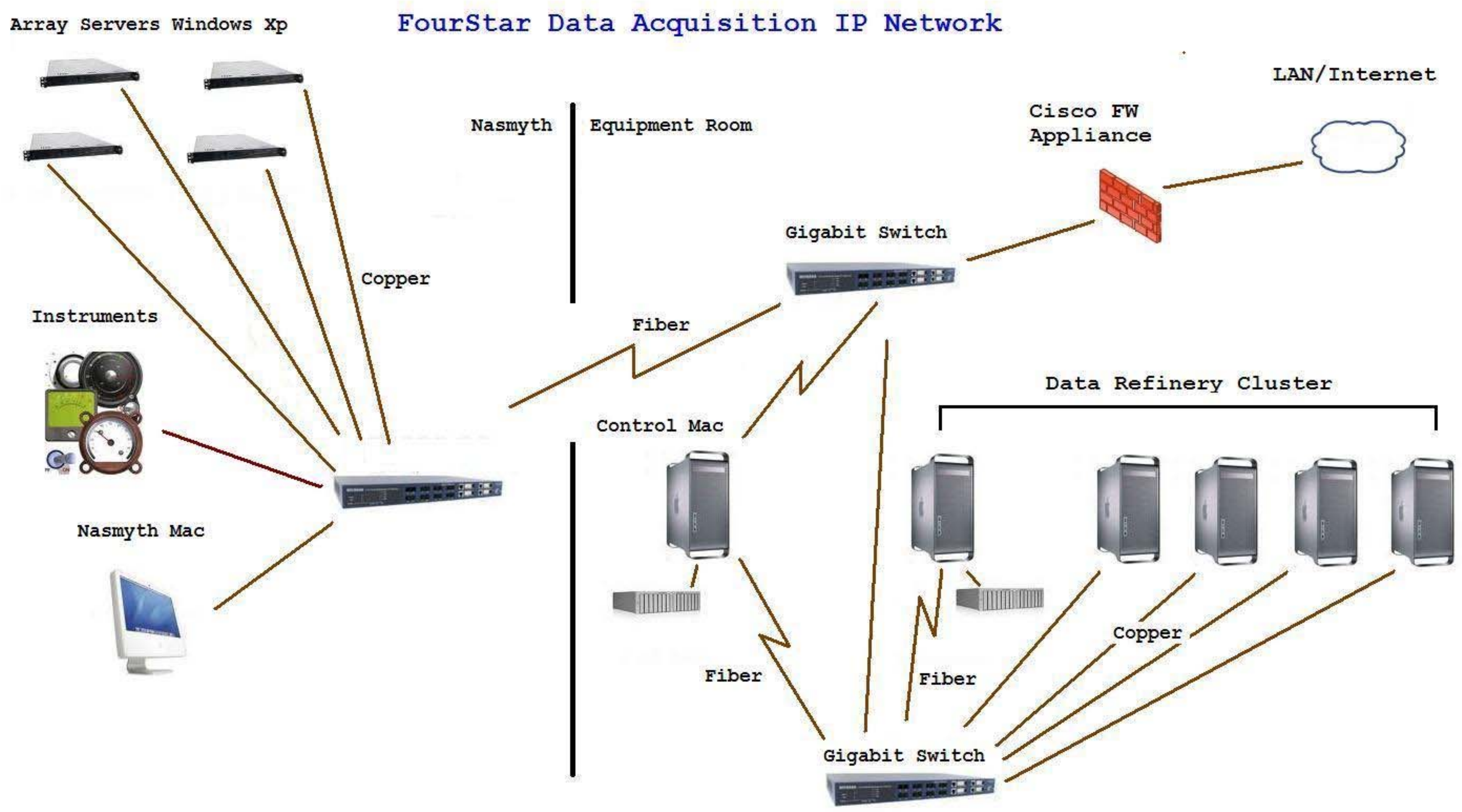
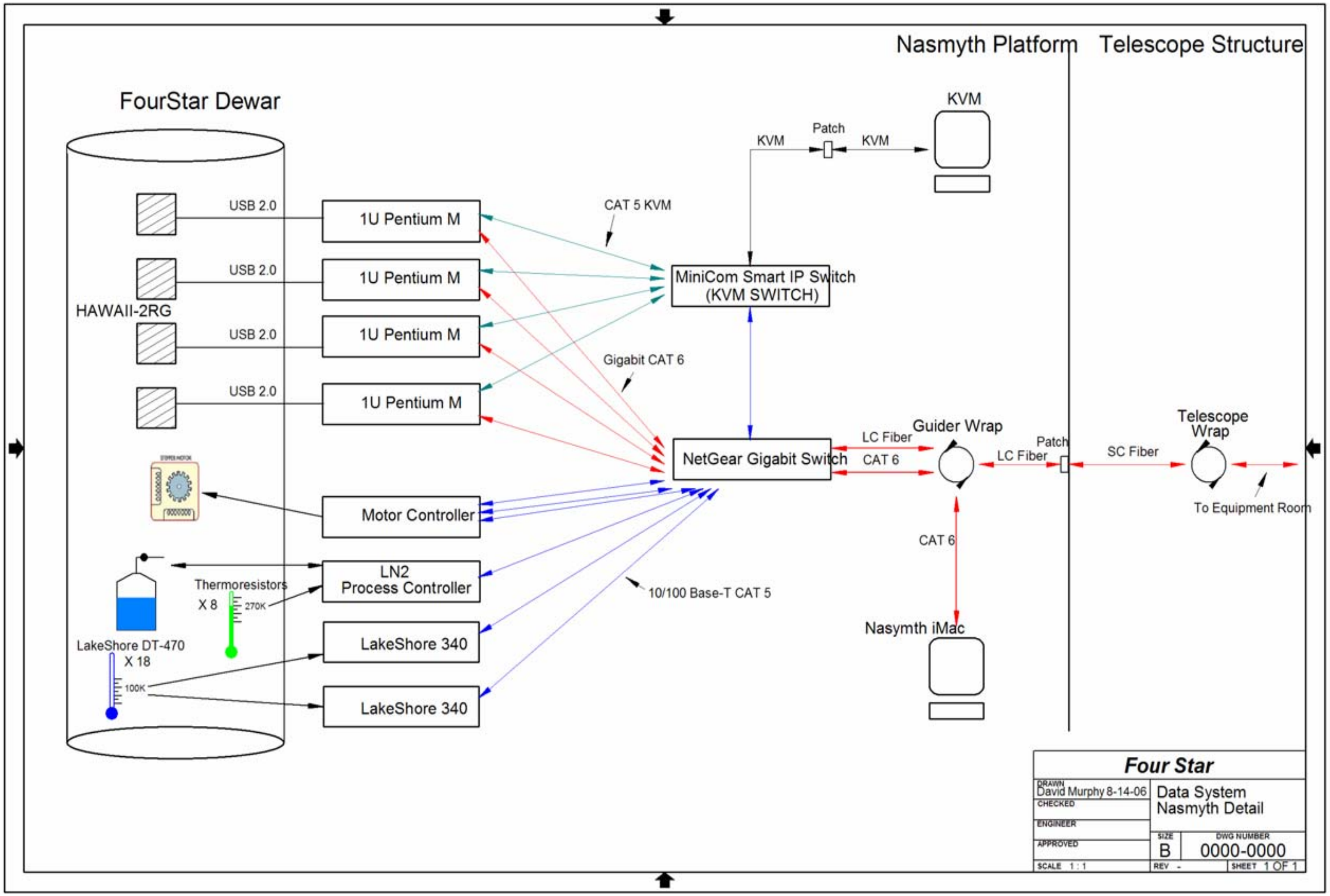
Main Data System Design Goals

- Read and control HAWAII-2RG arrays effectively
- Performance: Allow continuous acquisition of DC “pictures” every 3 sec. -> sustained data rates of 85 Megabytes/s (Mb/s)
- Provide an effective and friendly user interface and tool set to control and monitor FourStar
- Provide effective online tools for “quick look” reduction to monitor data flow and quality
- Provide a full and final data reduction pipeline at the telescope (but not real-time): Pipeline aka. Data Refinery
- Reliability, ease of implementation, ease of maintenance, modular, adherence to popular standards, robust, expandable
- Facilitate effective operation of instrument at telescope or offline (lab, Nasmyth local control). Untethered operation.
- Security: For data. Protection from external attacks or tampering. Isolation: “Good fences make good neighbors” (Frost, 1915).

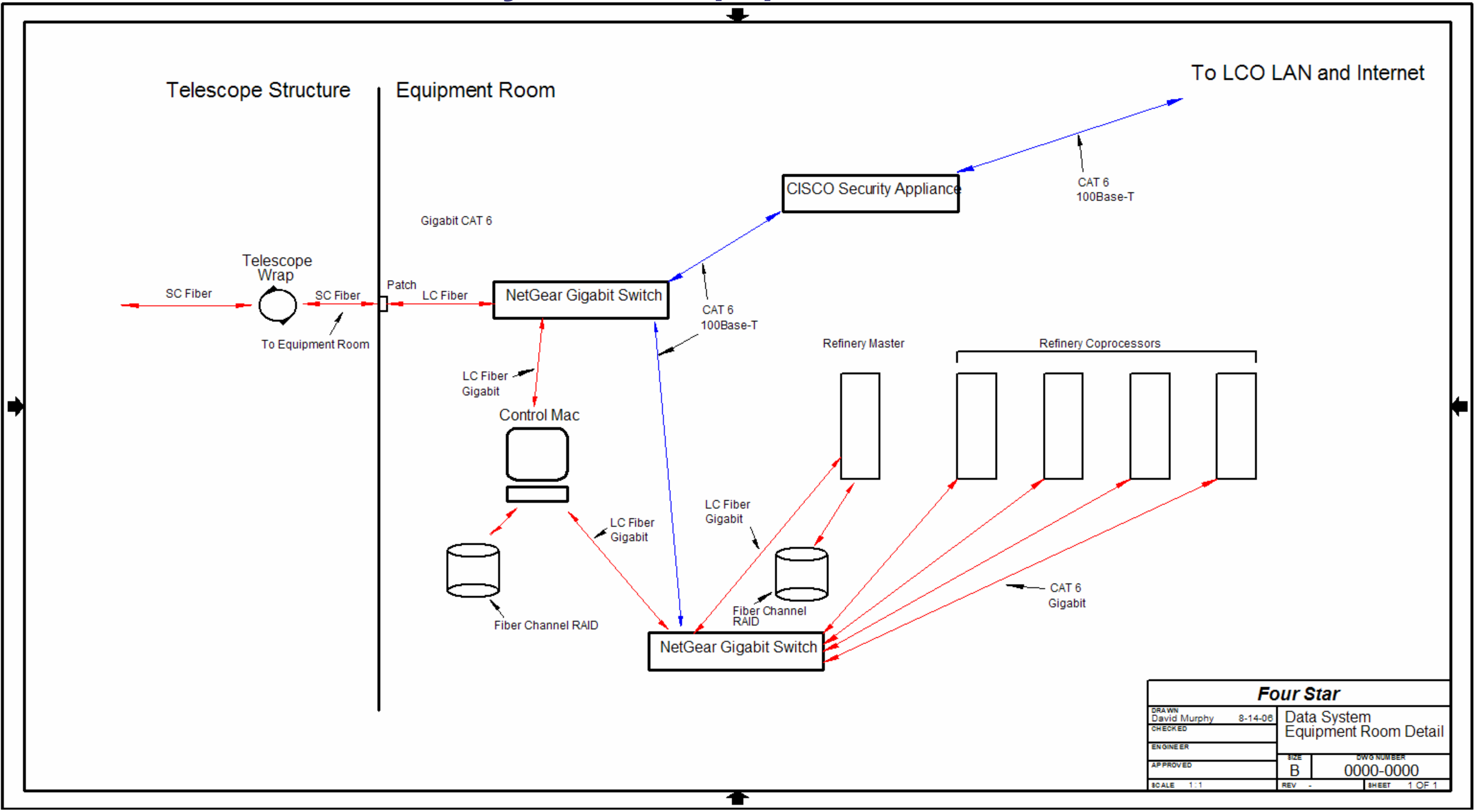
Four Star Data System



Data System – Nasmyth Detail



Data System – Equipment Room Detail



Design Features Adopted to Meet Goals

- Adherence to Rockwell developed/recommended methods: ASIC/USB Interface, COM Software interface, Windows XP, One PC per array: Conservative results oriented approach which will not tax human resources
- Gigabit Ethernet, fast computers, fast disks (multiple Firewire 800). Judicious Fiber/Copper cabling and switching topology. High performance work stations as required provided with ample quantities of processors, memory, and fast, large disks
- Native MacOS GUI’s for all control, acquisition, and monitoring tasks (and possibly for Pipeline control)
- Online display and monitoring or real time data by the DAS, semi-automated Pipeline “light” for quick sky subtracted stacks

Design Features Adopted to Meet Goals (cont.)

- Data reduction pipeline online, at the telescope. Capable of providing finished and final data product to the observer
- Cluster of five dedicated “Data Refinery” computers
- Mac OS, Ethernet, IP protocol, FireWire, USB. Facilitates rapid “system integration” – avoid custom configuration headaches, avoid hardware design, driver development, forced adoption of obsolete hardware/software (aka. Linux) . Standard network appliances, universal cabling/connectors, universal software/knowledge interfaces
- Primary communications medium: Internet Protocol (IP). All instruments are IP devices (at a certain level). IP Democracy.
- Universal adoption of IP and rack localization on dewar allows any computer to control the instrument. Specifically untethered operation supported with Nasmyth Mac.

Design Features Adopted to Meet Goals (cont.)

- For Security, isolation, protection, independence, performance, ease of maintenance: FourStar has its own private physical and logical network encapsulated within a broadcast domain behind a Cisco Internet Firewall Appliance.
- Predominant use of Macs, locally locked down OS configurations, non-routable IP space will further enhance security and isolation.
- All applications will be designed and proven not to require external access to Internet.
- Instrument can be fully operated with no access to Internet or even the Control/Equipment room (with some restrictions)

Relevant Data Rates to Consider

- Design can handle a sustained data acquisition throughput of 10.7 megabytes/s. This is a double correlated read of the array with a one second integration time performed continuously. Worst case.
- Physical network bandwidth required: 86 megabits/s
- Copper Gigabit anecdotally can support about 300 Megabits/s. Fiber close to 1000 Megabits. Real-world Ethernet efficiencies are factors of 3-10 less than this.
- Most critical data paths will use Fiber Gigabit to guarantee data rates. Fiber is also needed in the system to handle long cable runs and provide electrical isolation. Fiber eliminates uncertainties of Copper Gigabit performance.
- Two FireWire RAID or Fiber Channel RAID (a SCSI standard) disks will be employed to stream two copies of raw data archive. Simple FireWire RAID volumes will probably be adequate for our needs. Independent drive controllers can be used if more load balancing is needed.
- Care must be exercised by application software. Disk access to raw image data must be planned as to so as to prioritize and avoid multiple accesses which can sap critical bandwidth (tokens ?).

Four Star Data System

Data Capacities and Mass Storage

- Worst case scenarios might generate 300 gigabytes of data per night. More typical will be 100 gigabytes per night.
- In reality 3-5 X this capacity needed to also store intermediate data products and multiple nights of data.
- 1-2 Terabyte FireWire and/or RAID drives with 50-100 megabytes/s sustained capacities are available now at reasonable cost
- Mass storage media not decided. Blue Ray is a candidate with 100-200 GB capacity on multilayer disks.
- Optical media may be too slow – portable hard drives a possibility (several hours to write 100GB on Blue Ray at best)

Maintenance and Support at LCO

- Older data systems: Focus on hardware maintenance, debugging, repair, knowledge, calibration, noise suppression, environmental problems, etc.
- FourStar: Focus will be on network administration, software support, system administration

FourStar

Electrical System

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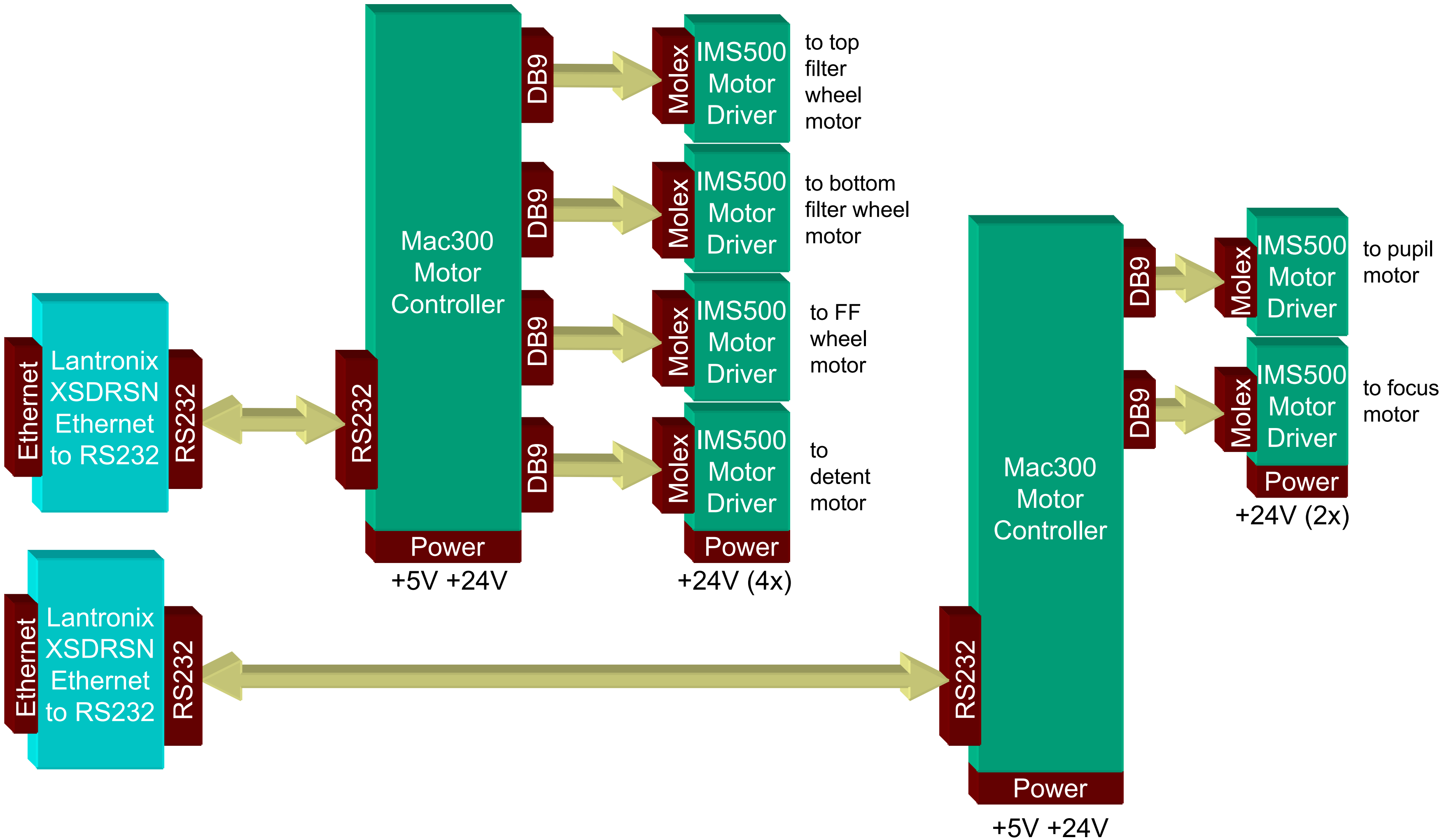
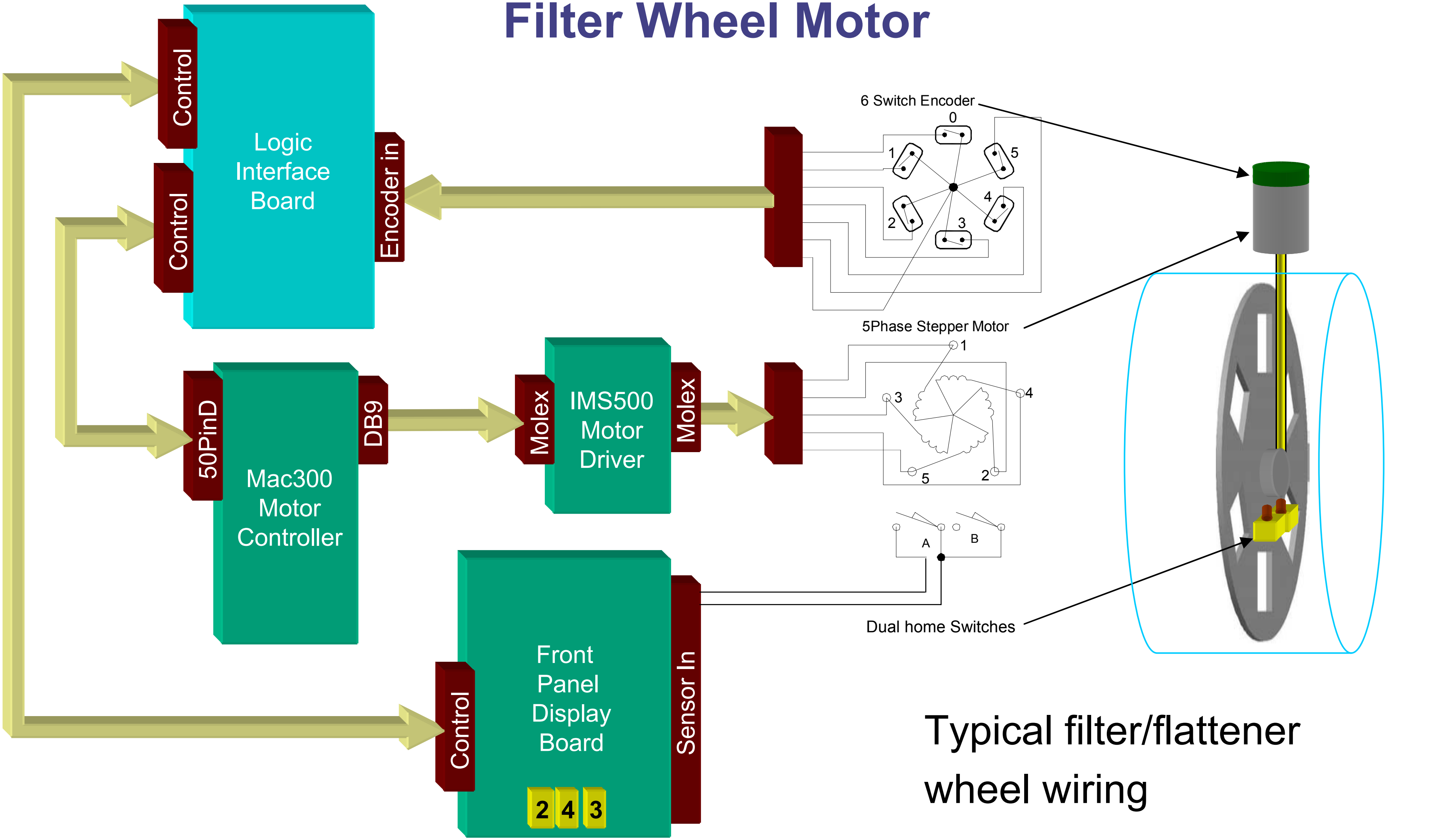
Motor Control Chassis



Four Star Data System

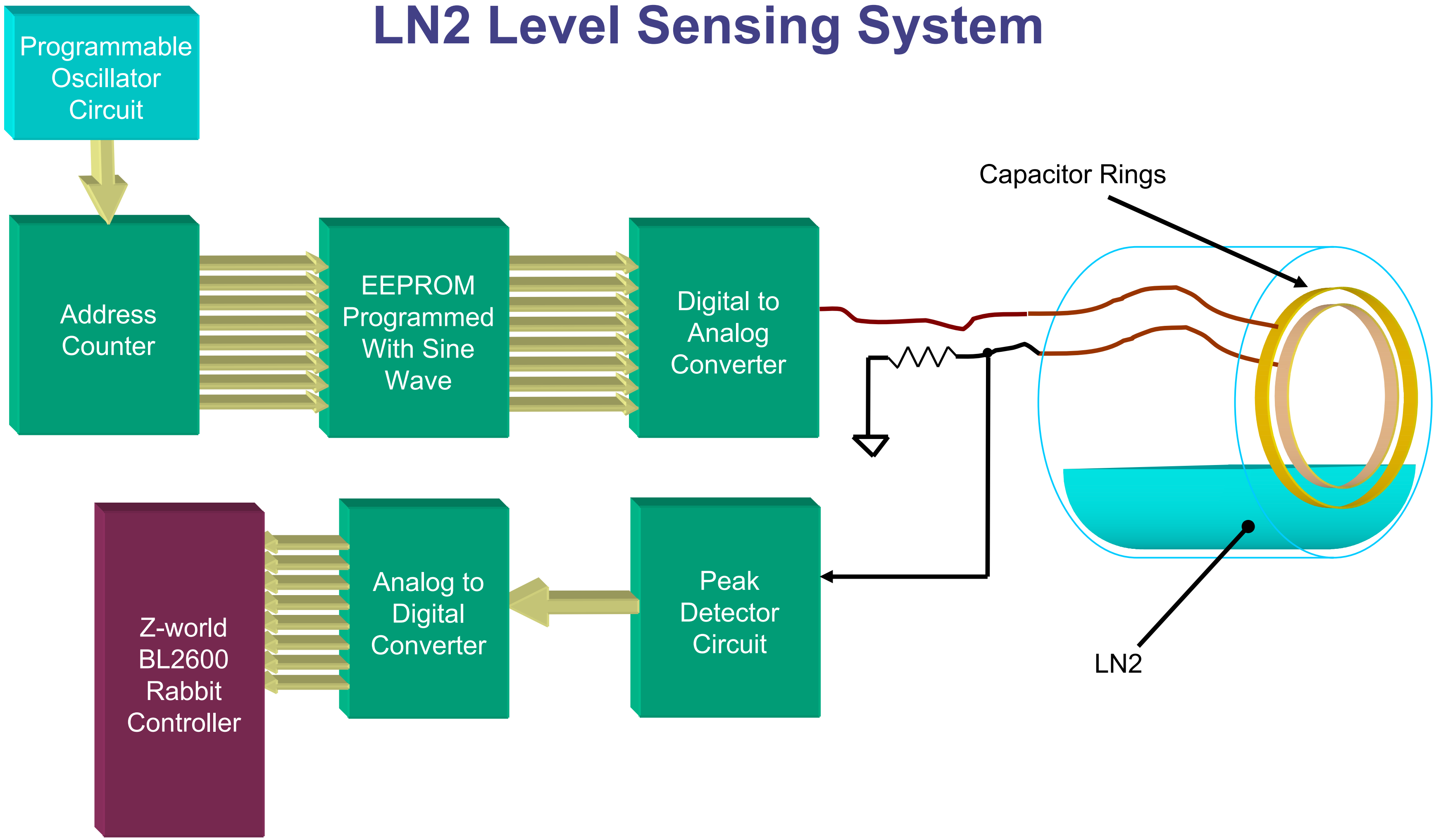
Filter Wheel Motor



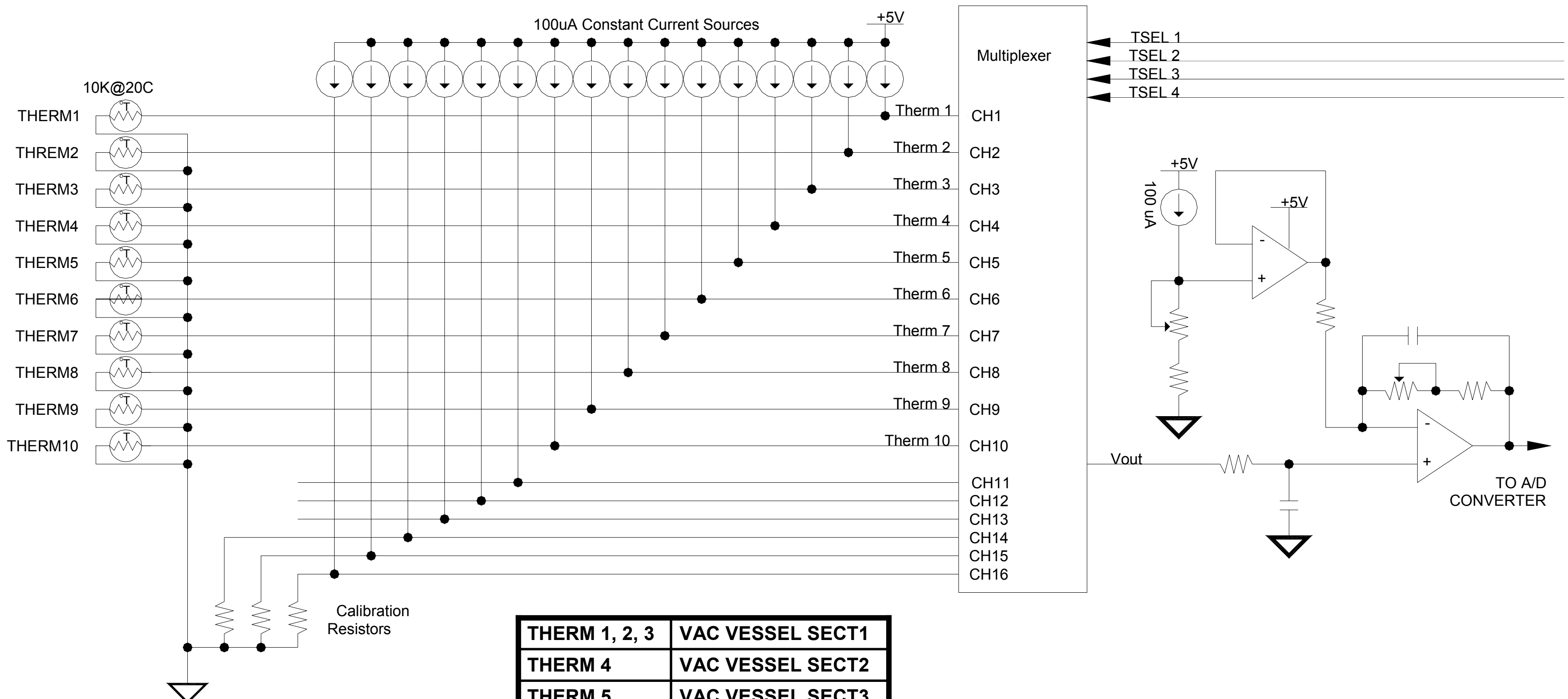
Typical filter/flattener wheel wiring

Four Star Data System

LN2 Level Sensing System

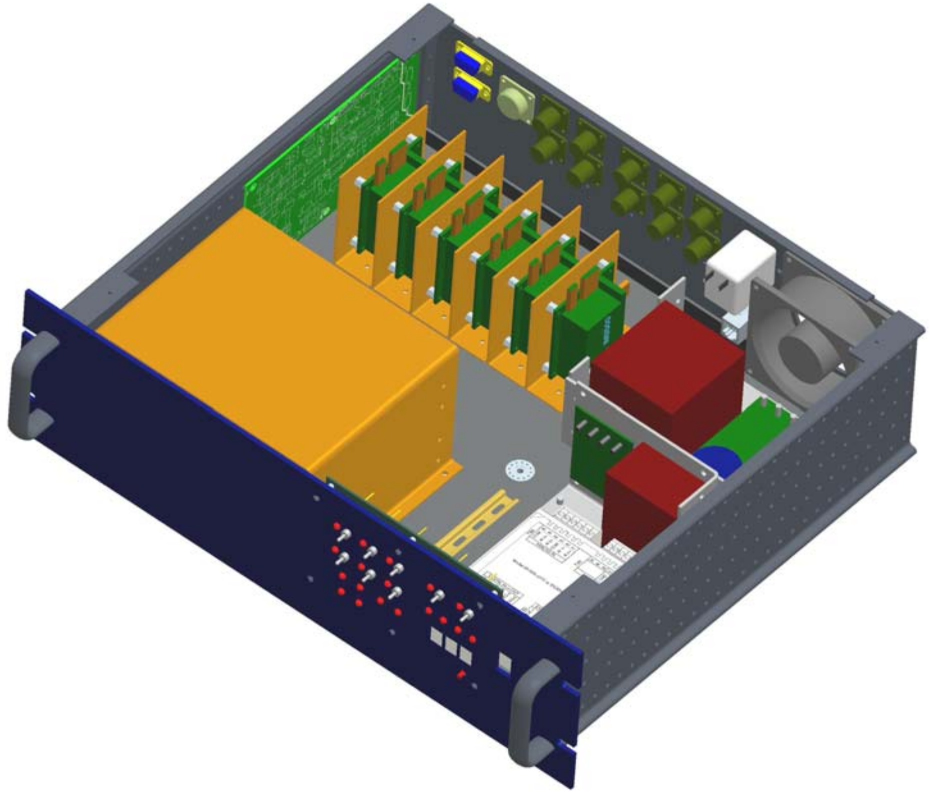


Thermistor Readout System

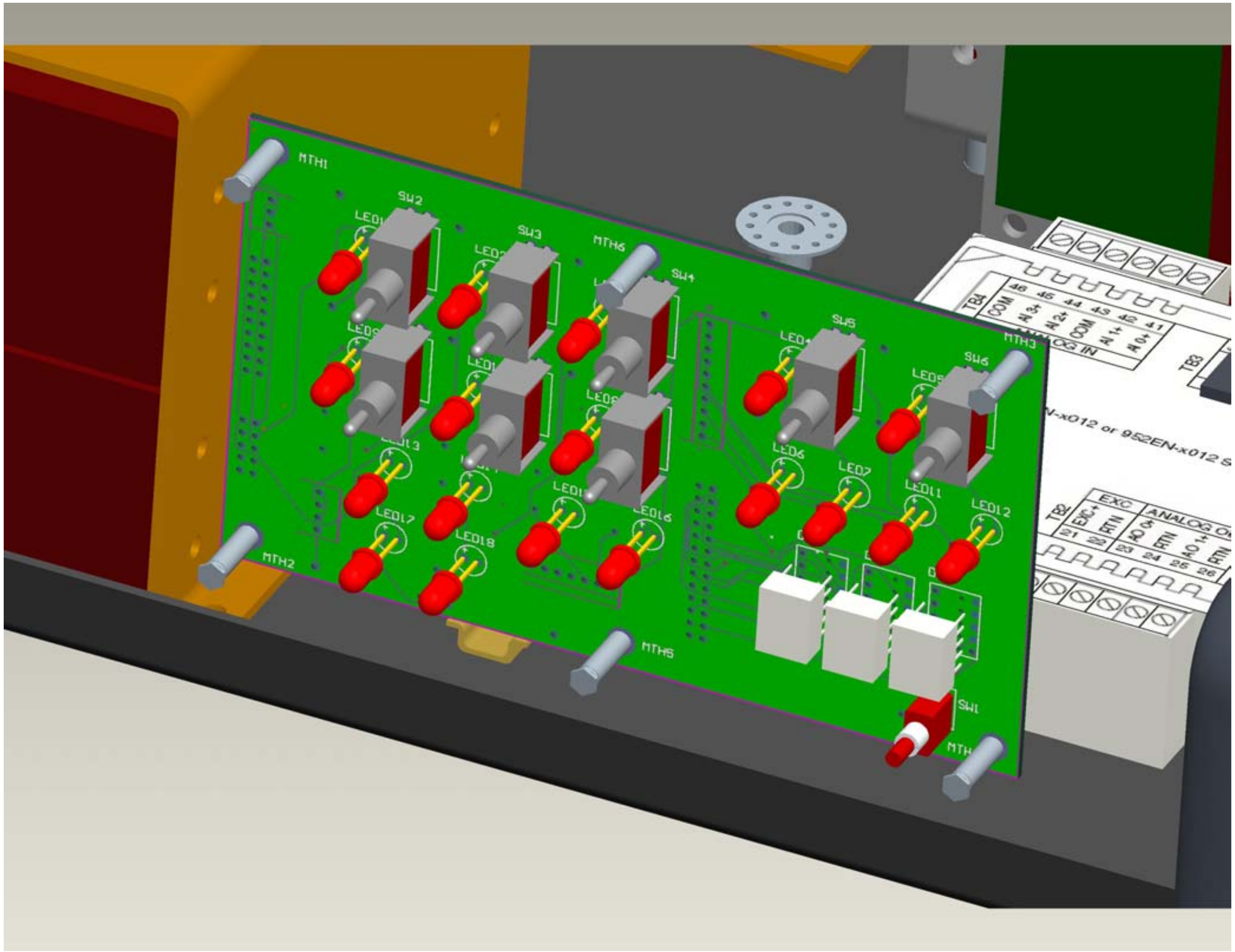


THERM 1, 2, 3	**VAC VESSEL SECT1**
THERM 4	**VAC VESSEL SECT2**
THERM 5	**VAC VESSEL SECT3**
THERM 6	**VAC VESSEL SECT4**
THERM 7, 8	**RACK1**
THERM 9, 10	**RACK2**

Motor Controller Perspective



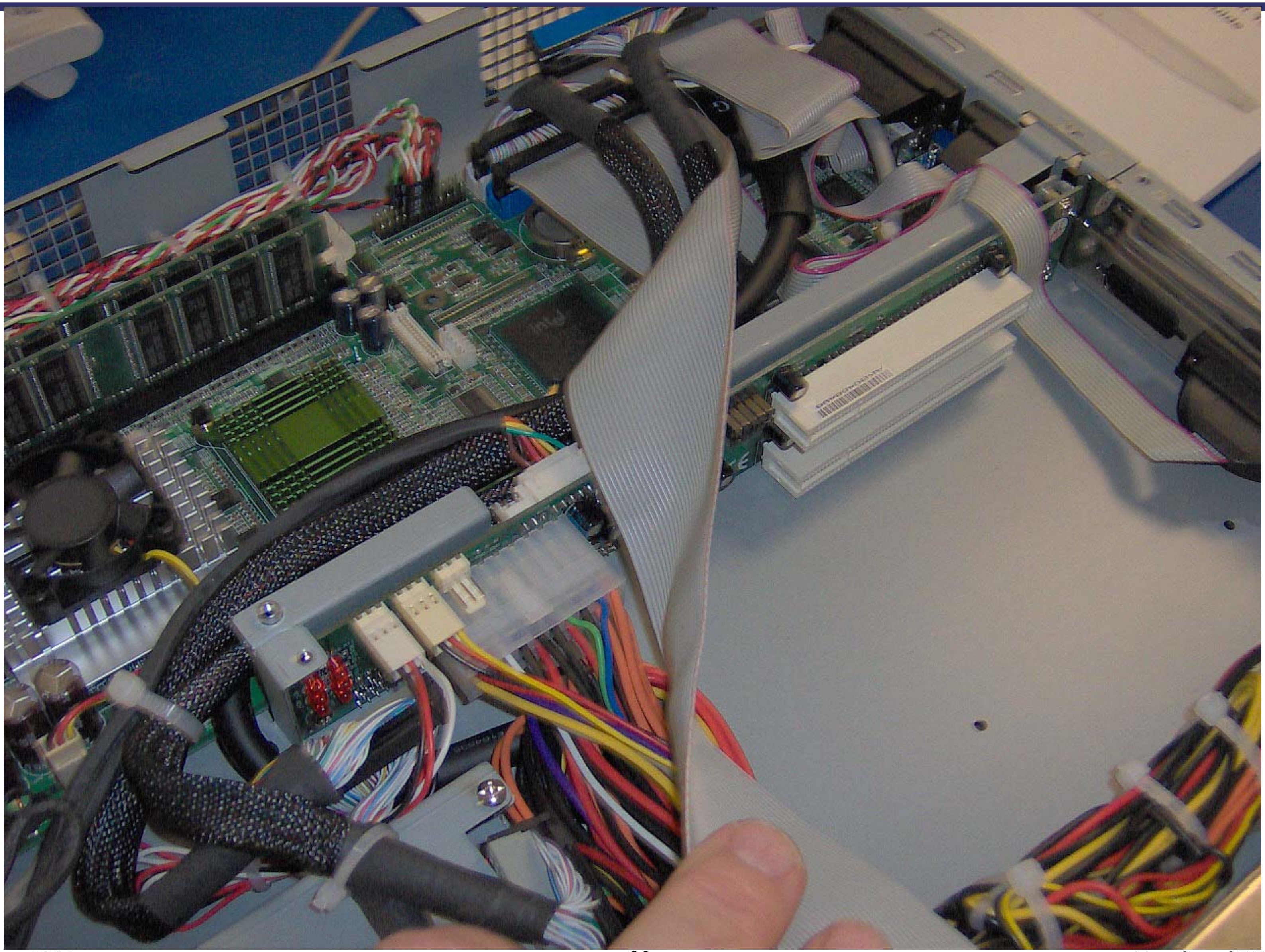
Motor Controller Logic Interface Board Detail



Array Servers

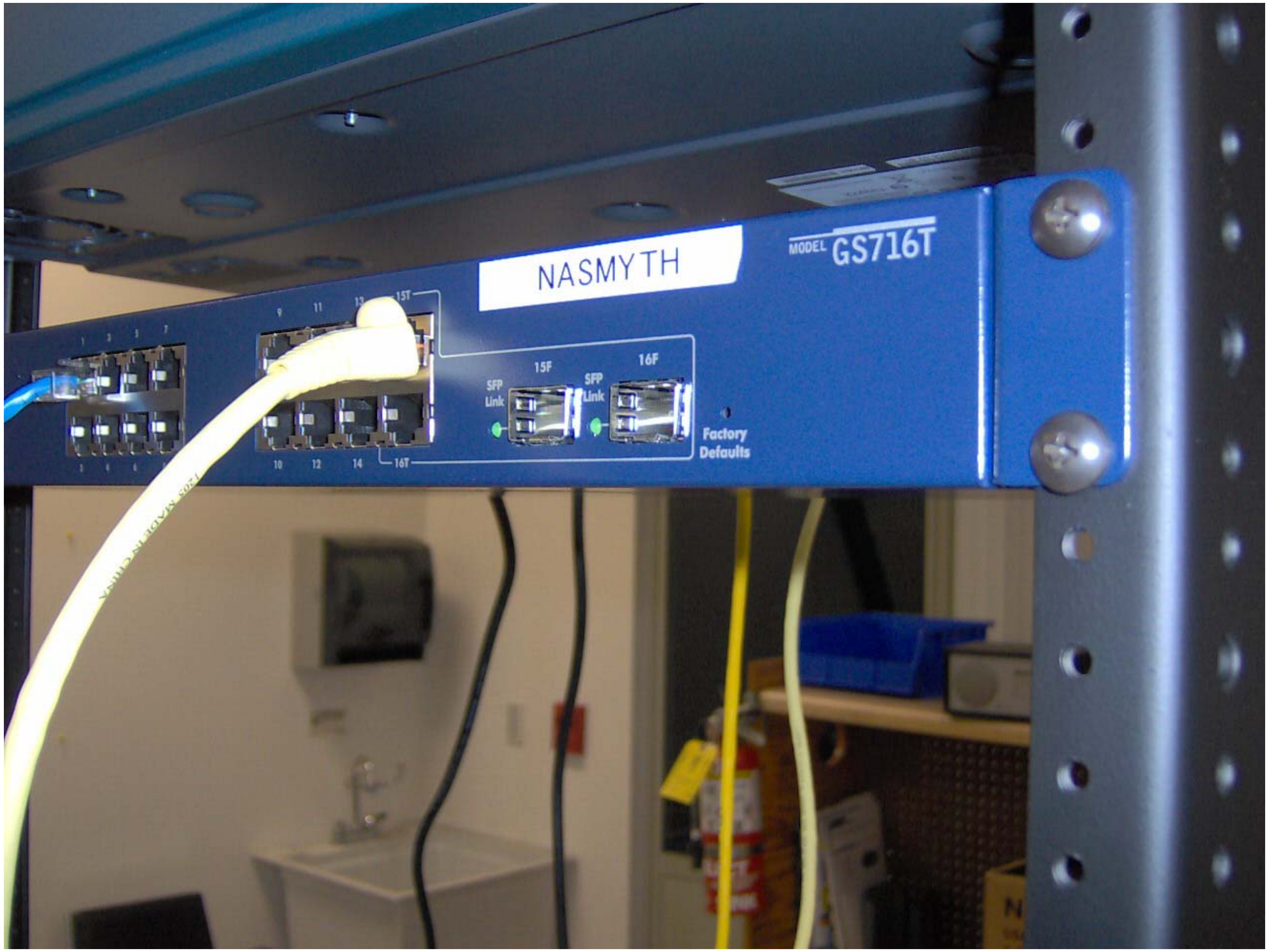
Array Servers X 4
BSI RMS-6113 PICMG SBC Based 1U Computers
Pentium-M 2 GHz Based – 50 Watts Power Disp.
2 PCI Expansion Slots
2GM Memory, DVD-R/W, 40GB HD, 1000BaseT, WinXP Pro

Four Star Data System



Four Star Data System

NetGear Fiber "Backbone" Breakout



LakeShore Model 340 Temperature Controller

- 10 cryogenic sensor inputs
- Two auto tuning control loops: 100W and 1W
- Fully computer interfaced
- Autonomous operation
- Configurable display
- Used with “metacontroller” so that control can be done from telescope control room with more adaptable interface and graphical display

FourStar

Electronics Rack

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29 November 2005

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Design Requirements/Considerations

- **Mount racks to 4Star body**
  - Greatly reduces cable wrap
- **Size**
  - Minimize height/depth to clear cart during rotation
- **Heat removal**
  - Limit ambient dissipation to 30 Watts total
- **Environment**
  - Temperature range: -5 °C to +20 °C
  - Moisture – benign
  - Vibration – benign
- **Serviceability**
  - Ease of removal (racks & components)
  - Ease of access to front panel displays

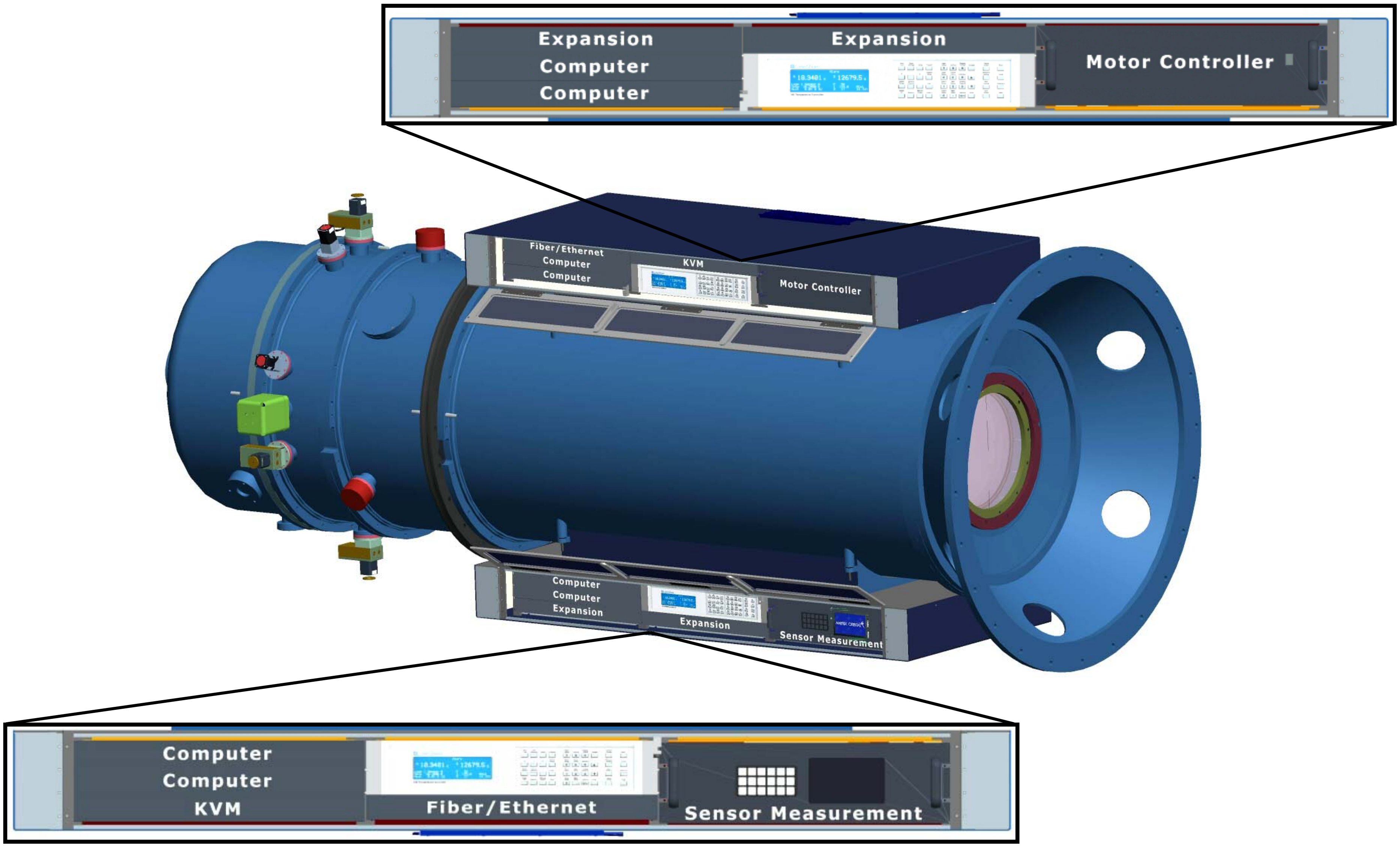
Rack Contents

- Computers
  - Four total - one per Hawaii 2RG array
- Instrument temperature controllers/monitors
  - Two LakeShore 340s (one control channel & eight monitor channels)
- Motor controller chassis
  - Six control axes
  - Limit switch and position feedback
- Sensor chassis
  - LN_2 level/autofill
  - Pressure
  - Environmental temperature
- Communication
  - Fiber ethernet switch
  - KVM switch
  - Ethernet-to-serial converters
  - Power supplies

Cable Wrap

- 110 V AC
- Gigabit copper
- Fiber for communication
- Water/glycol for heat removal (1.5 GPM per rack)
- 24 V DC for LN_2 autofill

Four Star Data System

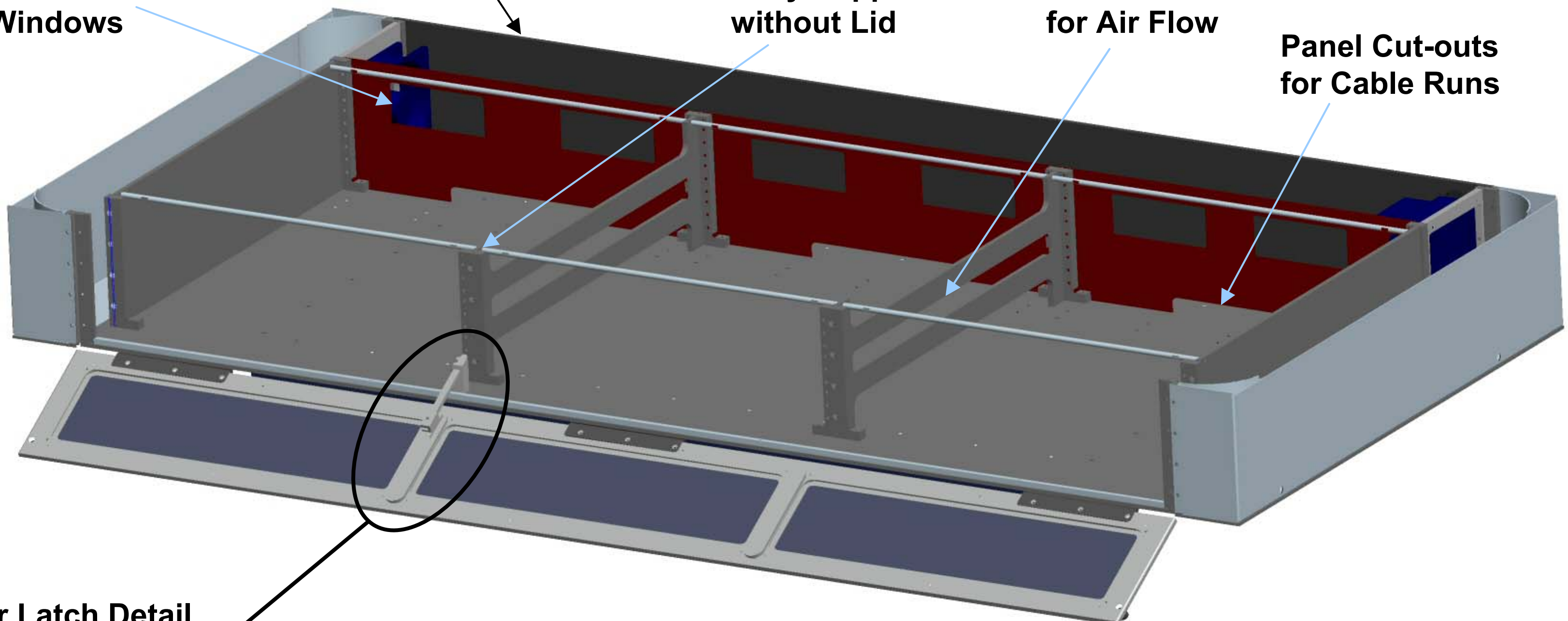


Design Features

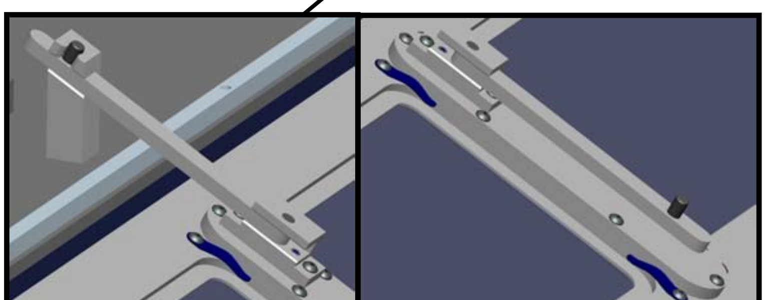
- 3-wide x 3U tall 19” bays (front panel accessible)
- Heat removal system
  - Water/glycol heat exchanger and cold plate
- DIN rail mounting of power and communication modules
  - AC plugs
  - DC supplies
  - XPress DR ethernet-to-serial converters
- Computers closest to Detectors
  - Reduces cable length
- Assembly & Service simplified:
  - Captured bolts
  - Hinged front door with integral sliding “dark” panel
  - DIN rail components for ease of repair
- Connector bulkhead to ease rack removal/installation

Four Star Data System

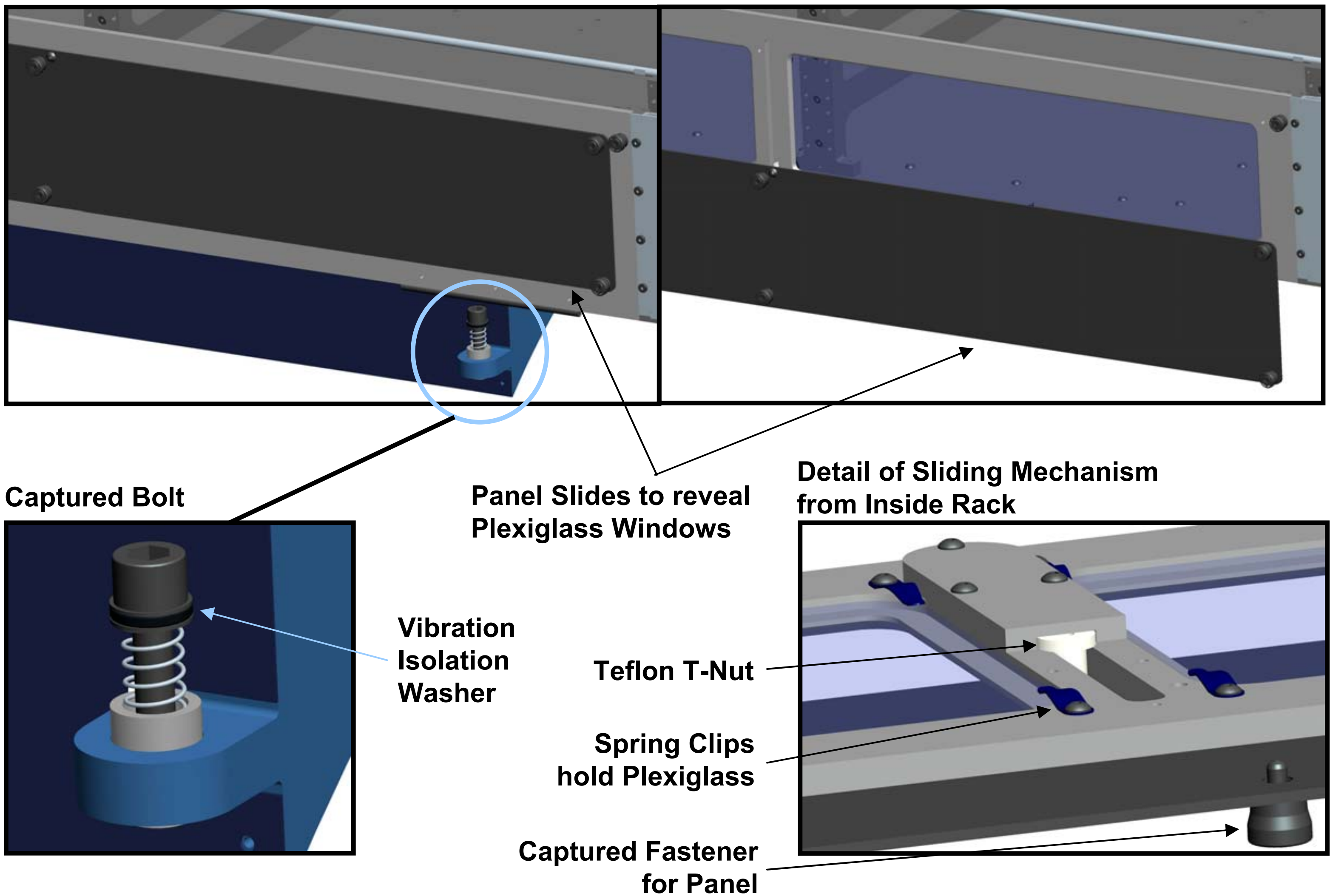
Isometric View with Lid Assembly Suppressed



Door Latch Detail



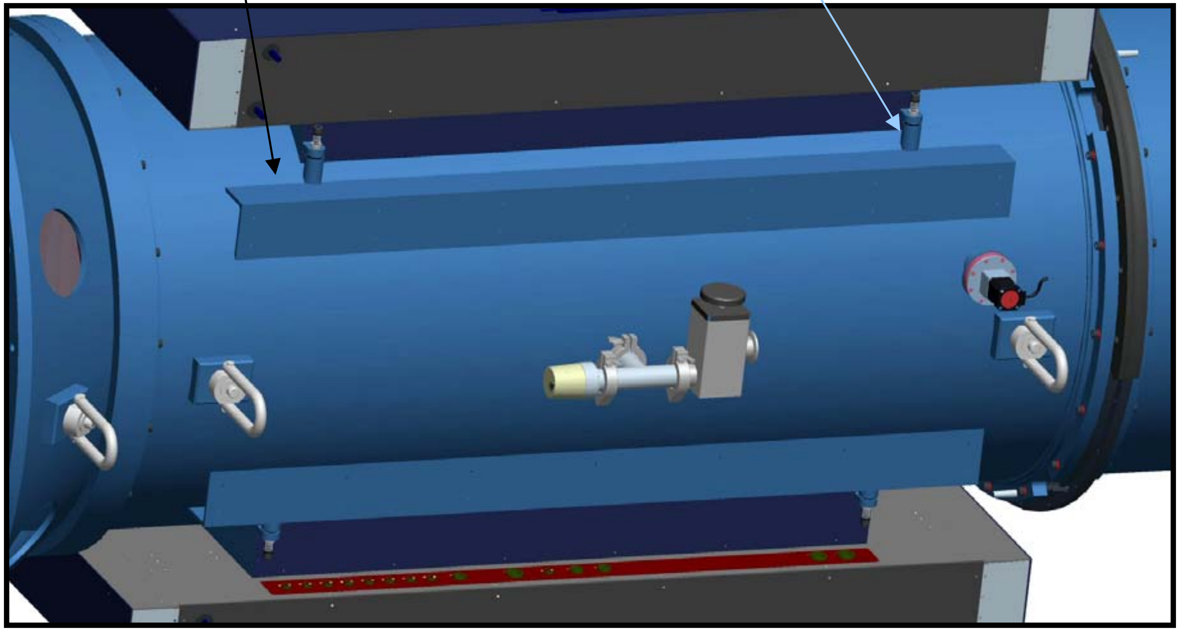
Four Star Data System

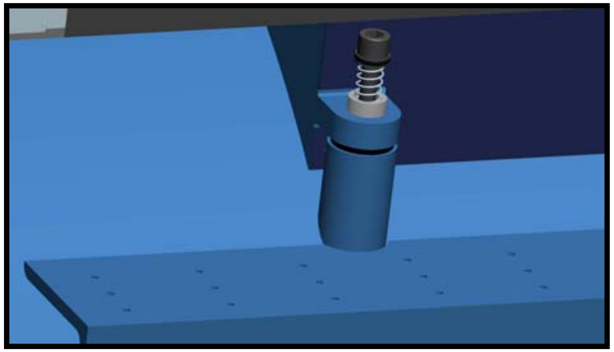


Four Star Data System

Strain Relief/Cable Management

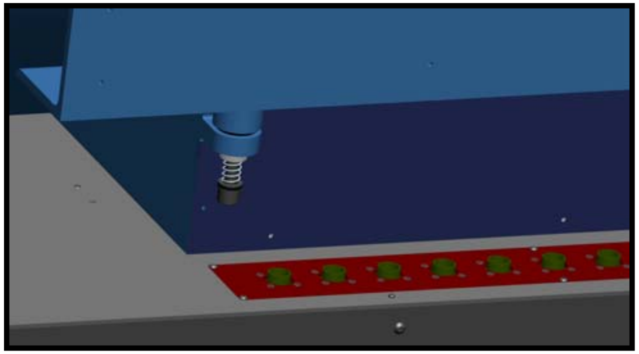
Rack Mount Post



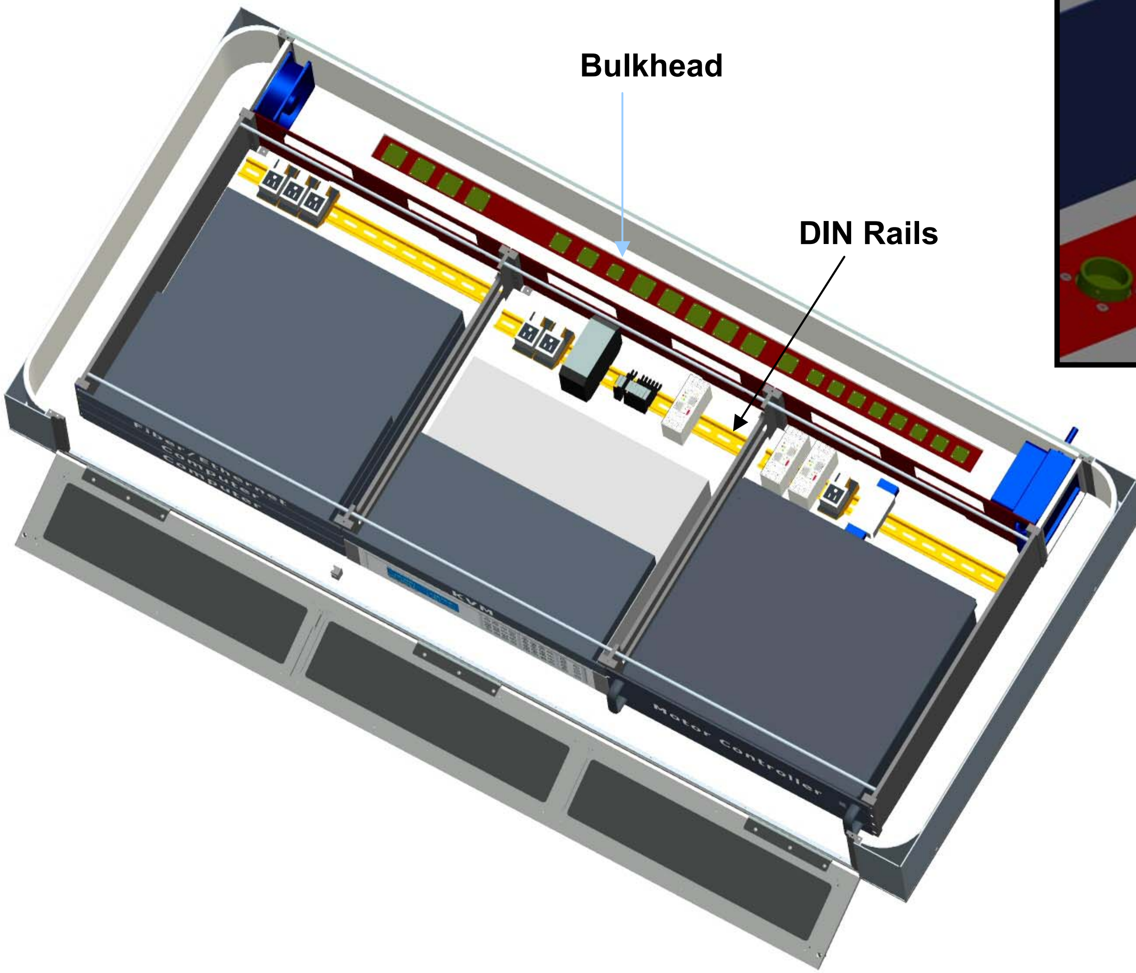


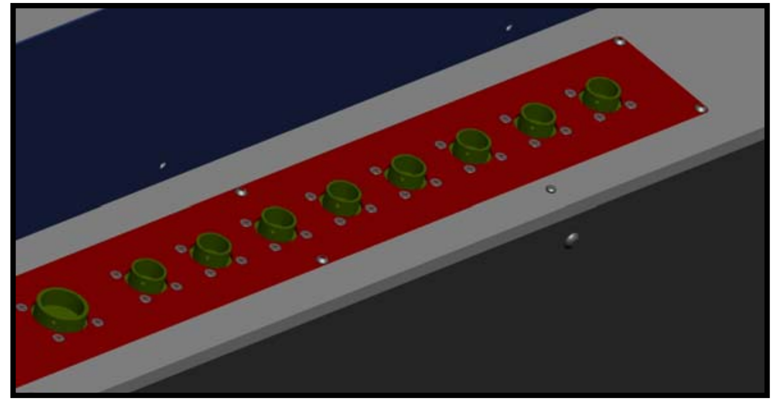
Vibration Isolation on Rack Mount

Bullhead about 6” from Cable Tray



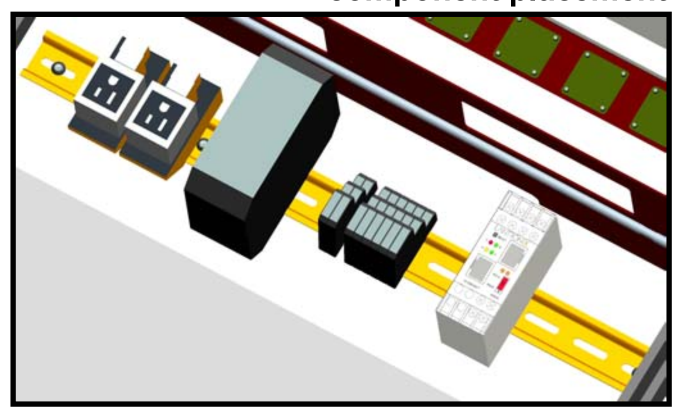
Four Star Data System





Bulkhead shown from under Rack

DIN Rail mounted for easy component placement



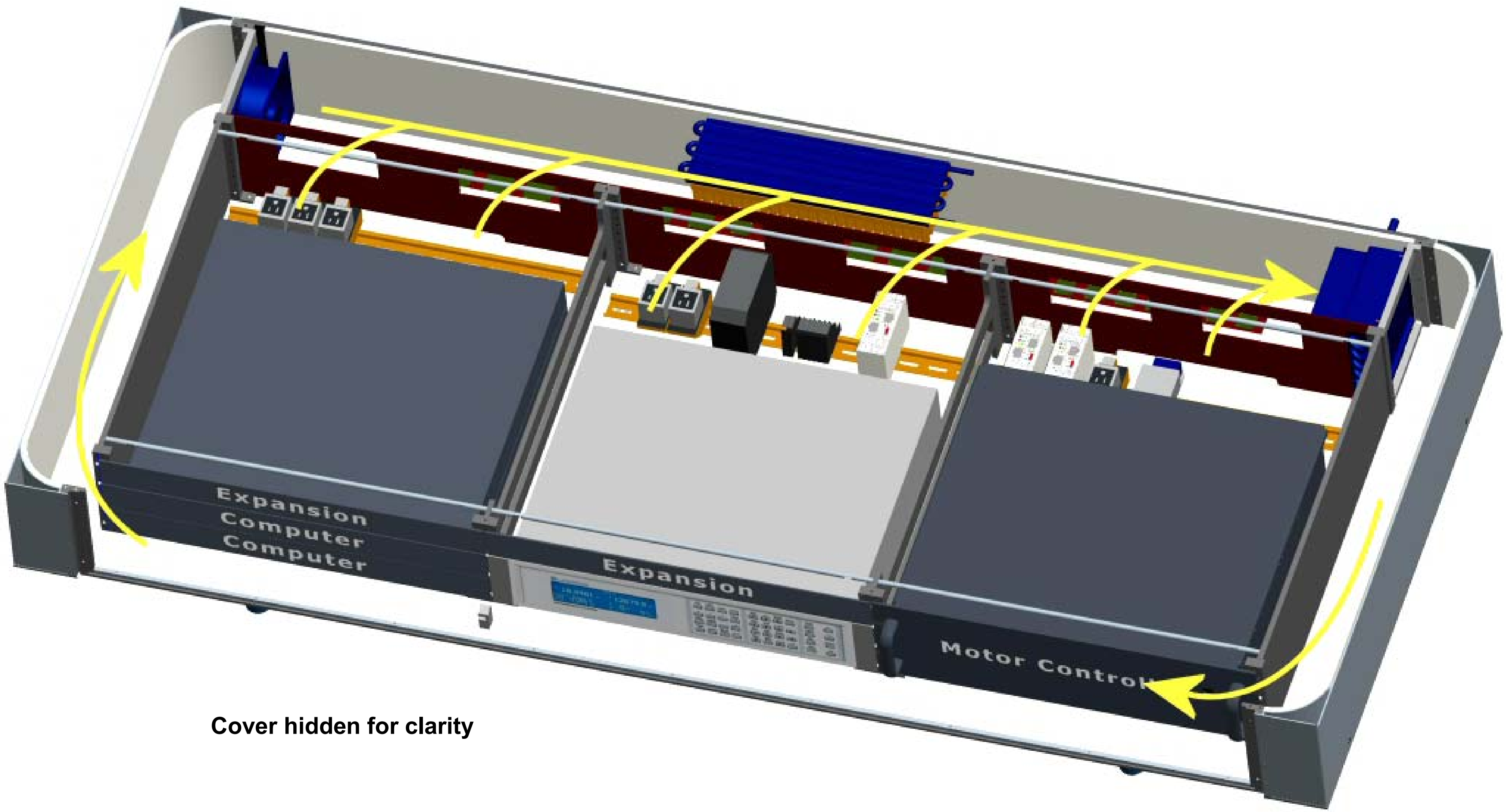
Thermal Design Features

- Cooling via Lytron heat exchanger & cold plate using EGW
- Heat sink attached to cold plate for added forced convection heat transfer
- Additional 100 cfm fan to ensure proper air flow
- Aluminum lid cooled by cold plate for reduced convection heat loss to ambient
- Stagnant air flow beneath rack to limit conduction & convection to instrument
- ¼” Volara closed-cell insulation (k = 0.036 W/mK)

Rack Heat Load

- **Top Rack**
  - Two 1U Computers (51 W each)
  - Lakeshore 340 Temperature Controller (50 W)
  - Stepper Controller (60 W)
  - KVM Switch (12 W)
  - Three XPress DRs (ethernet to serial, 3 W each)
  - Two Cooling Fans (20 W each)
  - *Total Power Dissipation ~ 258 W*
- **Bottom Rack**
  - Two 1U Computers (51 W each)
  - Lakeshore 340 Temperature Controller (50 W)
  - Fiber Ethernet Switch (32 W)
  - KVM Switch (12 W)
  - Sensor Measurement Enclosure (16 W)
  - One XPress DRs (ethernet to serial, 3 W each)
  - Two Cooling Fans (20 W each)
  - *Total Power Dissipation ~ 254 W*

Expected Thermal Paths



Cover hidden for clarity

Expected Thermal Results Per Rack

- **Heat Exchanger: ~125 W**
- **Cold Plate/Aluminum Lid: ~118 W**
- **Ambient: ~13 W**
- **Instrument (between rack & instrument): < 1 W**
- **Comments:**
  - Heat Loss is a function of Rack Orientation
  - Analysis uses worst case orientation parameters
  - Heat Sink was not included in calculations

Control Functions and Hardware

Functions	Hardware
Internal temperatures (16 + 2 spare)	Lakeshore 340(2)
Control of camera module temperature	Lakeshore 340
Control of detector and camera module temperatures during cooldown/warmup	Lakeshore 340
Wheels in/out	microswitches
Detents in/out	microswitches
Iris opening and limits	linear pot/switches
Detector focus and limits	linear pot/switches
lN2 levels	capacitive sensor
Dewar vacuum	Pfeiffer gauge
Vessel temperatures	thermistors
Motors	Mycom steppers (6)
Controllers	Mycom MAC-300 (2)

TAB 9

9. Control System - Software

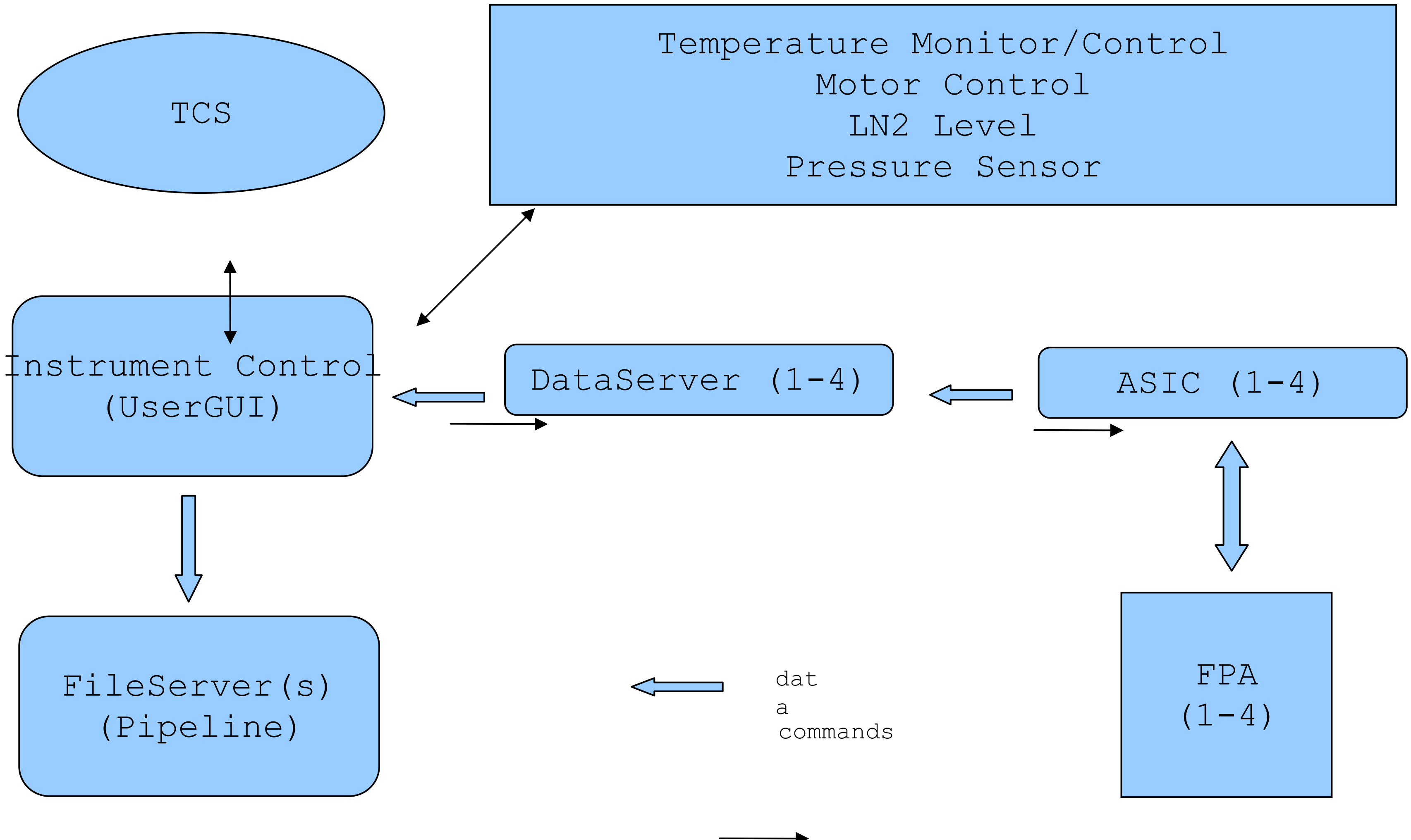
We will begin the ASIC/FPA readout software coding once we have a bare MUX and ASIC working together in our lab test dewar. We have seen a sample of the code that RWSC has developed to read out their lab HAWAII-2RG devices via their ASIC, but lacking an ASIC and the necessary support electronics, we are not yet at the point where we can test so much as our bare MUX. The delivery date for all four science-grade FPAs is October 31, 2006, and likewise for the ASICs and ancillary electronics which Rockwell is under contract to build for us. Given our good relationship with the people at Rockwell, we are certain that we will be able to avail ourselves of the software development tools they have, and are confident that reading out our devices will be straightforward.

The software control system for the (non-array) subsystems of the camera are being developed from very similar programs that have been used at Las Campanas for years. Code for the motor controller, temperature monitoring and control, telescope interface, and quick-look data inspection will all be recycled from working versions. The code that has yet to be written is that which talks to the Rabbit controller, i.e., the Z-world unit that monitors dewar vacuum, lN2 levels, and thermistor readings.

Software

- Instrument Control
- Data `Acquisition`
- Array Control (ASIC)

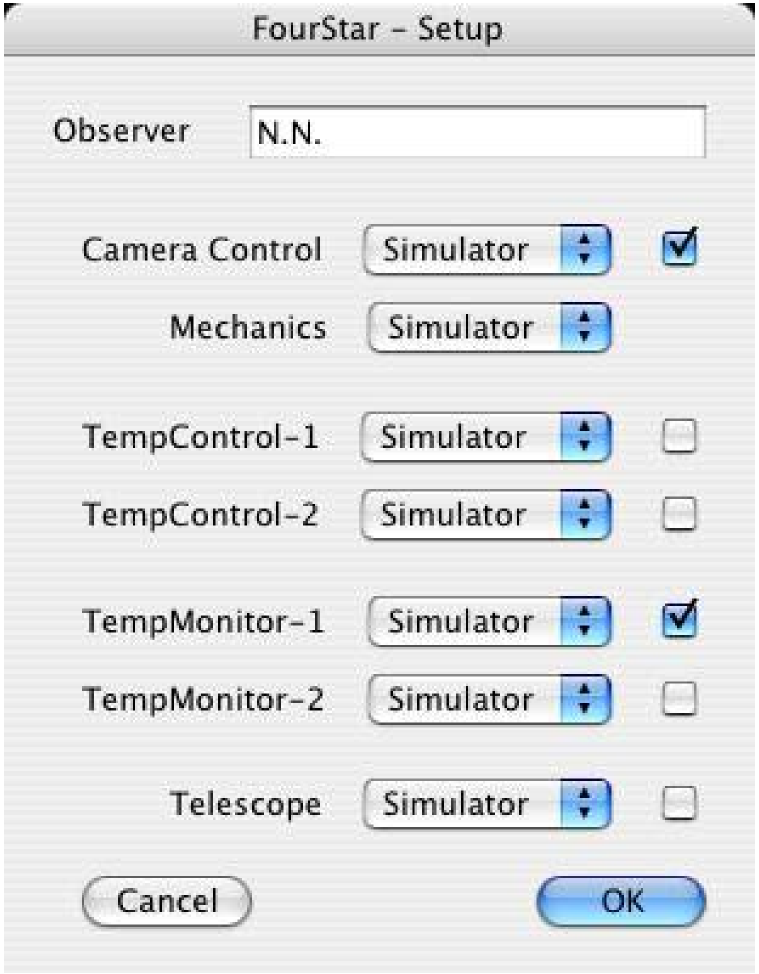
Layout



Temperature Monitor/Control
Motor Control
LN2 Level
Pressure Sensor
TCS
Instrument Control
(UserGUI)
DataServer (1-4)
ASIC (1-4)
FileServer(s)
(Pipeline)
FPA
(1-4)
dat
a
commands

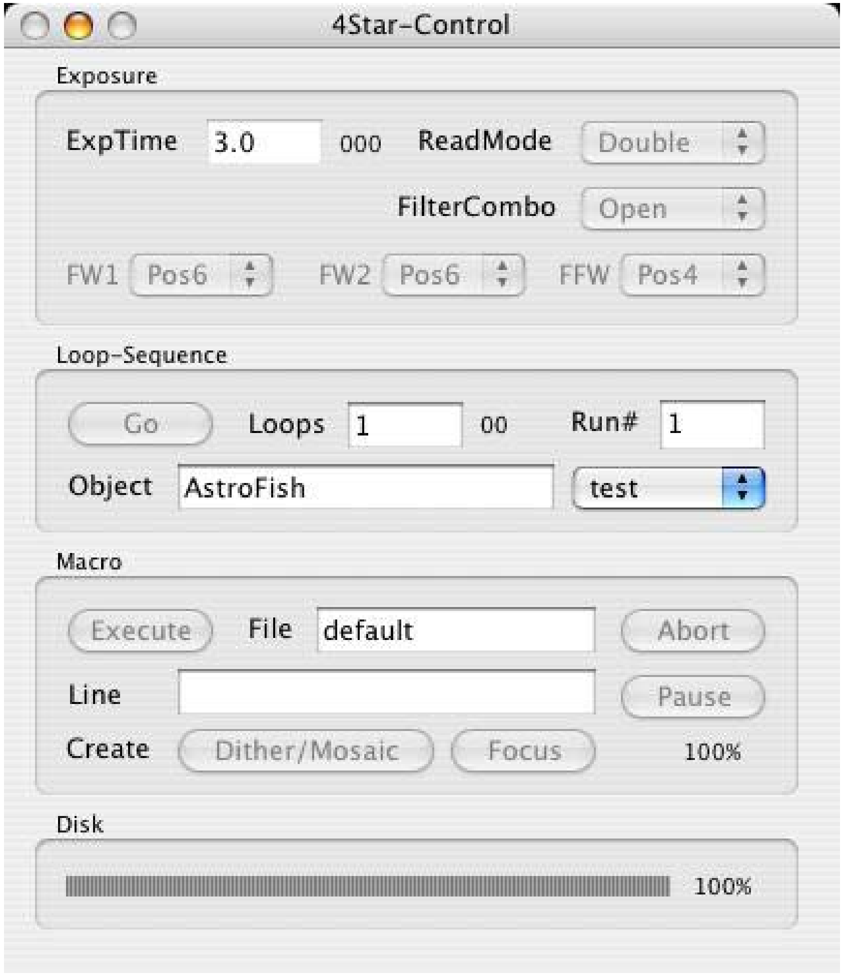
Philosophy

- Modularity
- Full Simulator Mode



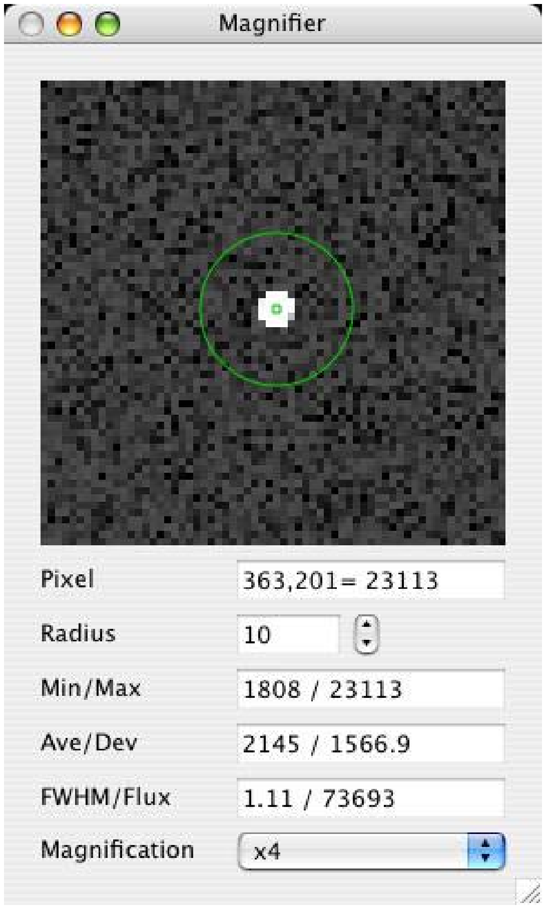
Main User Interface

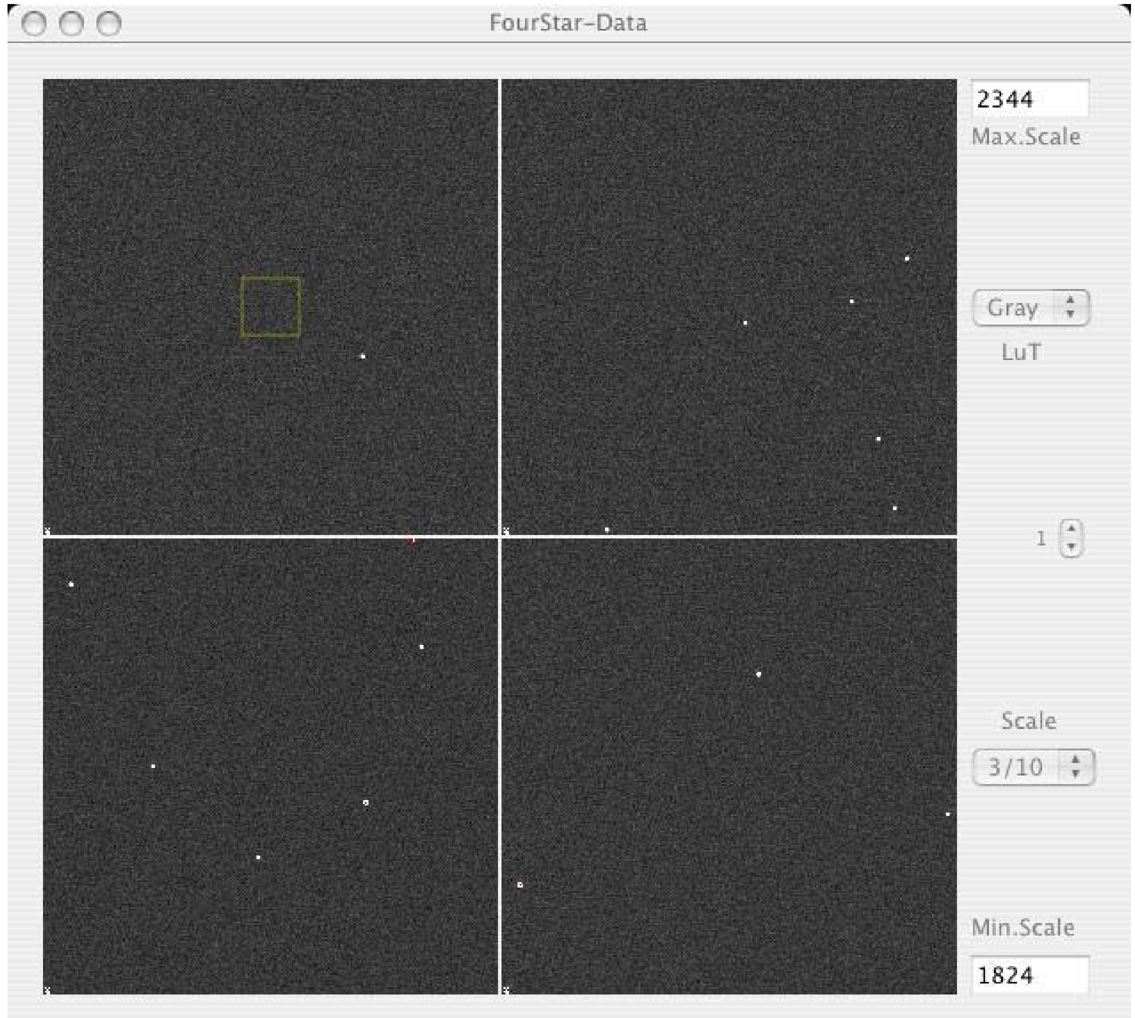
- Exposure Settings
- Filter/Pupil Combo
- Loops
- Macros



Software

Quick Look Data Display





Observing Macros

- Dithering-, Mosaic-, Focus- Macros
- Created from a predefined list (Dice-5)
- Simple ASCII scripts
- Custom Macros

Environment / Sensors

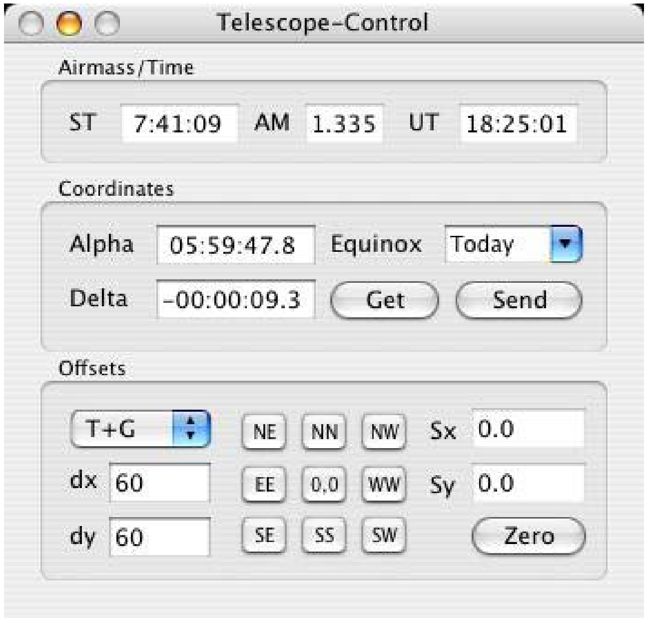
- LN2 Control
  - Sensors (2)
  - Solenoids (2?)
  - Auto-Fill Settings

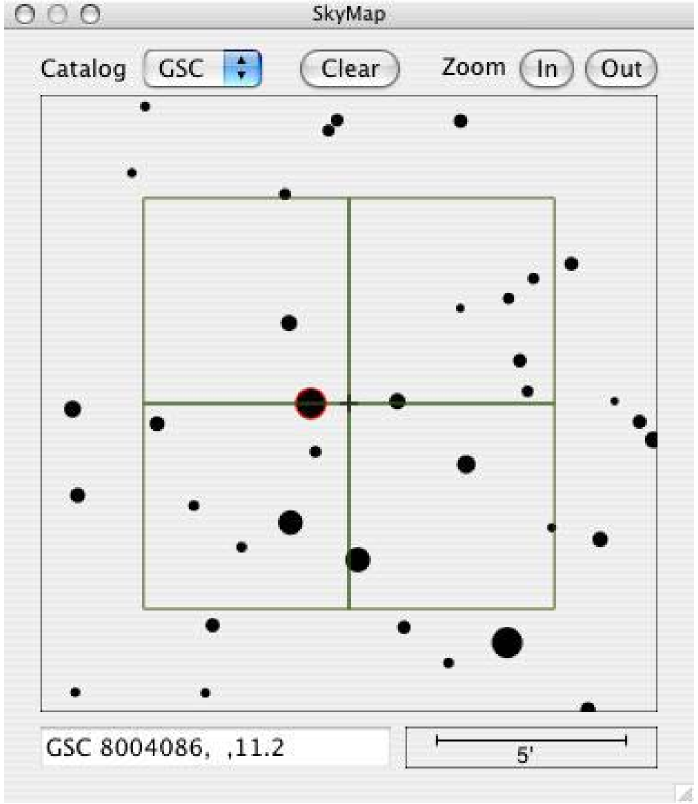
TODO

- Environment Temperature(s)
  - Auto-Focus

- Dewar Pressure
  - Alarm Settings

Telescope Control



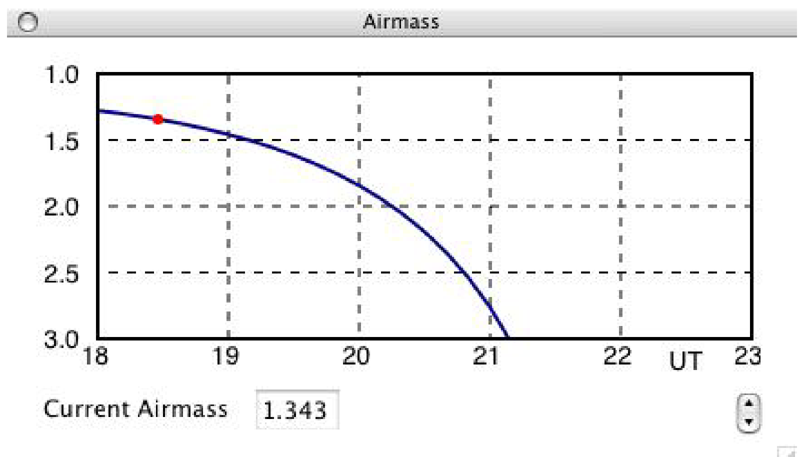


Object Lists

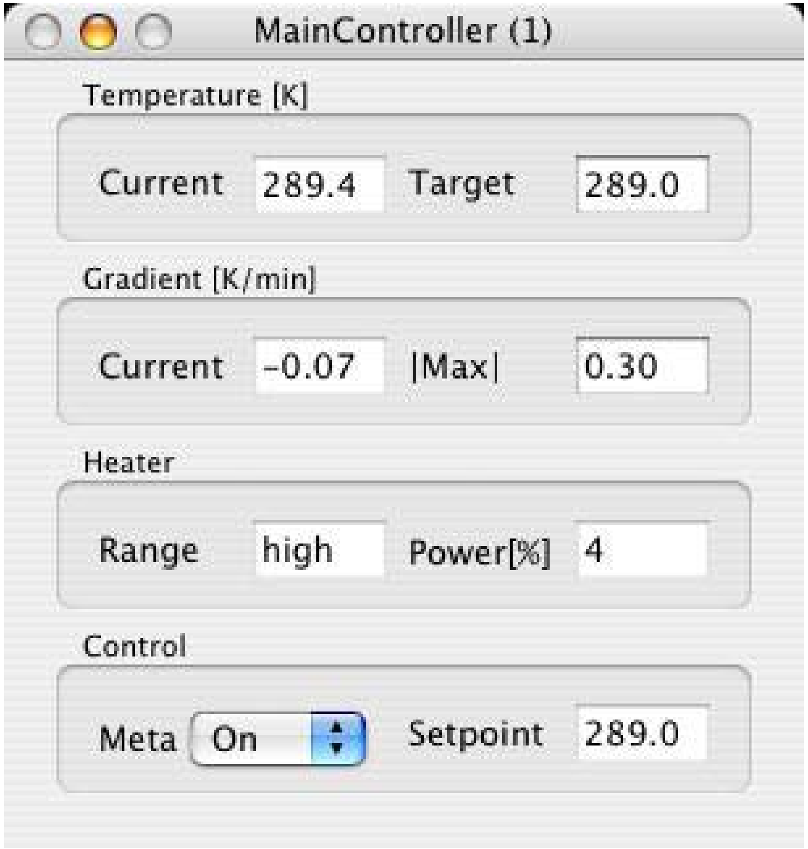
/Users/birk/FourStar/default.objects

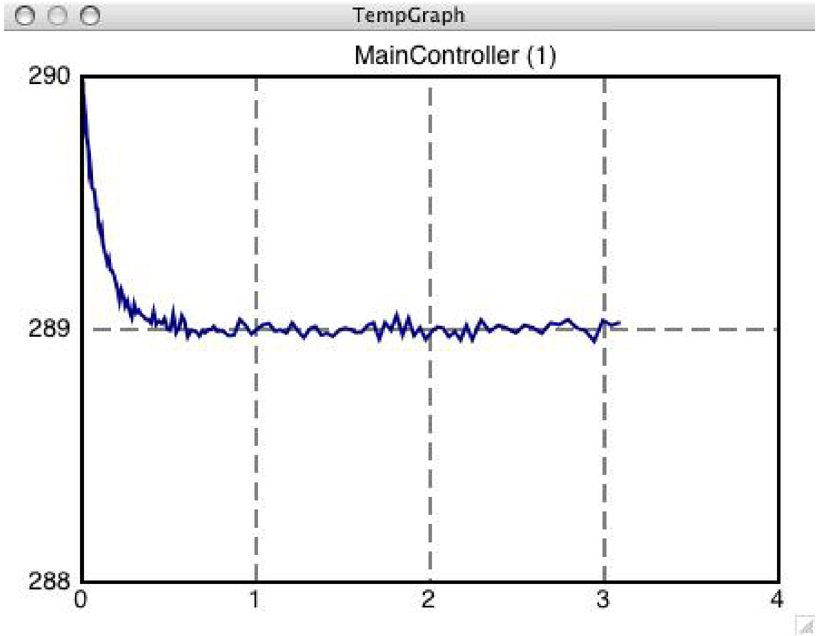
Name	Alpha	Delta	Equ.	Mag.	Comment
M7	17:53:54.0	-34:49:00.0	2000.000	3.30	open cluster
HR 6714	18:00:36.0	02:56:00.0	2000.000	4.00	54.6, 0.16
HR 6752	18:05:30.0	02:30:00.0	2000.000	4.10	16.6, 1.70
HR 6927	18:21:06.0	72:44:00.0	2000.000	13.70	10.2, 1.50
HR 7001	18:36:54.0	38:46:00.0	2000.000	20.10	89.7, 1.50
HR 7056	18:44:48.0	37:36:00.0	2000.000	4.30	43.2, 1.28
HR 7069	18:47:00.0	18:11:00.0	2000.000	4.40	18.8, 0.93

Edit Add Remove SendTo

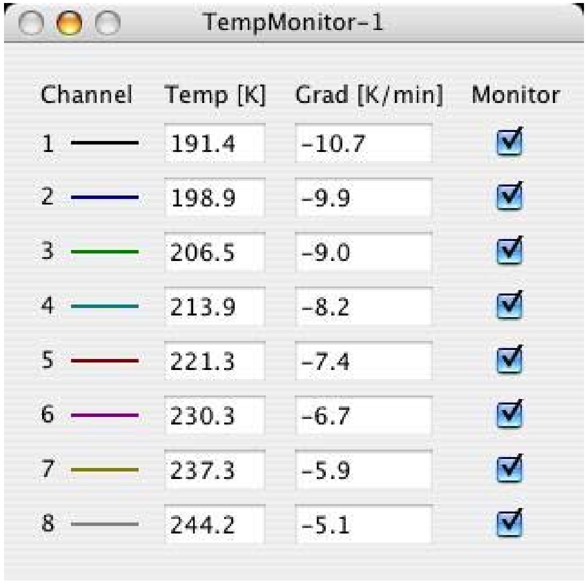


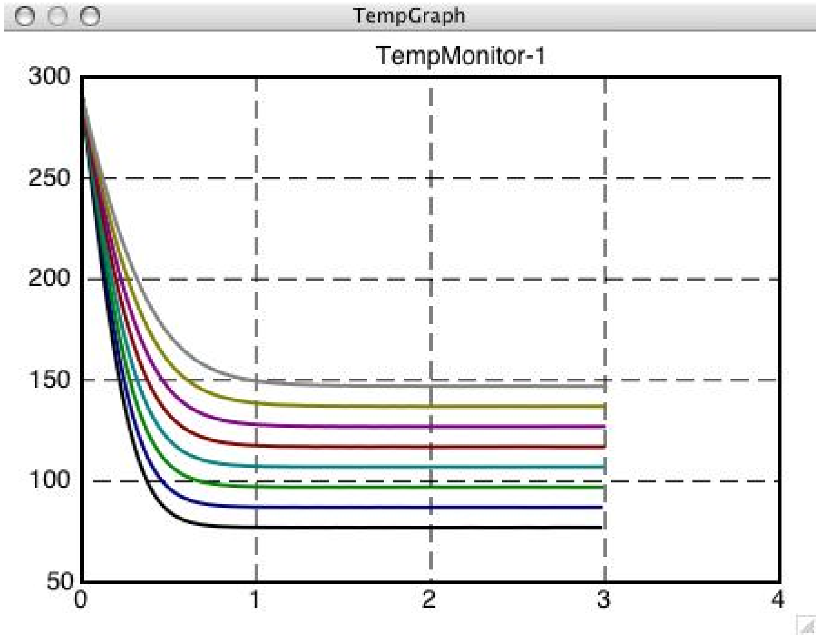
Temperature Control





Temperature Monitor





Data-Server

- One for each FPA
- Real time I/O with ASIC
- Low Level Array Tests
- Data Simulator

ASIC

- Application Specific Integrated Circuit
- USB interface to Data-Server
- Rockwell supplied driver
- Rockwell supplied example code

TAB 10

10. Instrument Handling and Telescope Mounting

There will be two instrument carts. Cart 1 carries the front of the instrument, and acts as the mounting system when the instrument is in use on the telescope. As Cart 1 is part of the instrument, it has been carefully engineered to handle the load without over constraint, and to allow the instrument to rotate as the guider turns. The function of Cart 2 is to allow work on the back-end of the instrument, which houses the wheels, detectors and LN2 dewars. Thus subassemblies, such as the focal plane mechanisms, or cool down and warm up procedures for the detector module, can be tested without having to cool the entire instrument. The two carts can be brought together in the lab to allow testing of the assembled instrument: optical alignment warm or cold, cold mechanism full-scale temperature monitoring, control tests, and detector tests.

FourStar

Instrument Cart (Cart 1)

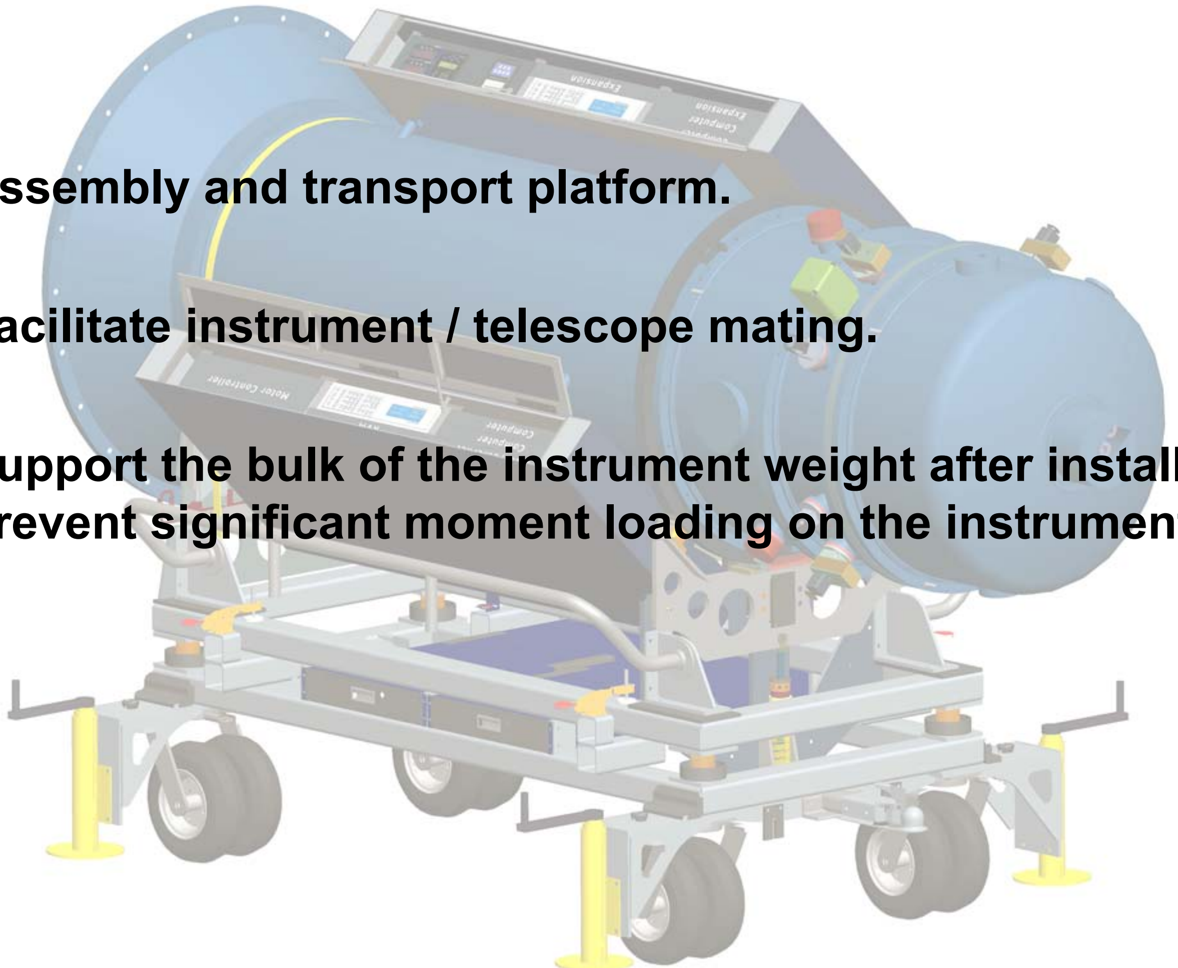
Randy Hammond
rph@pha.jhu.edu
(410) 516-8390

22 September 2006

JOHNS HOPKINS UNIVERSITY

Instrument Cart

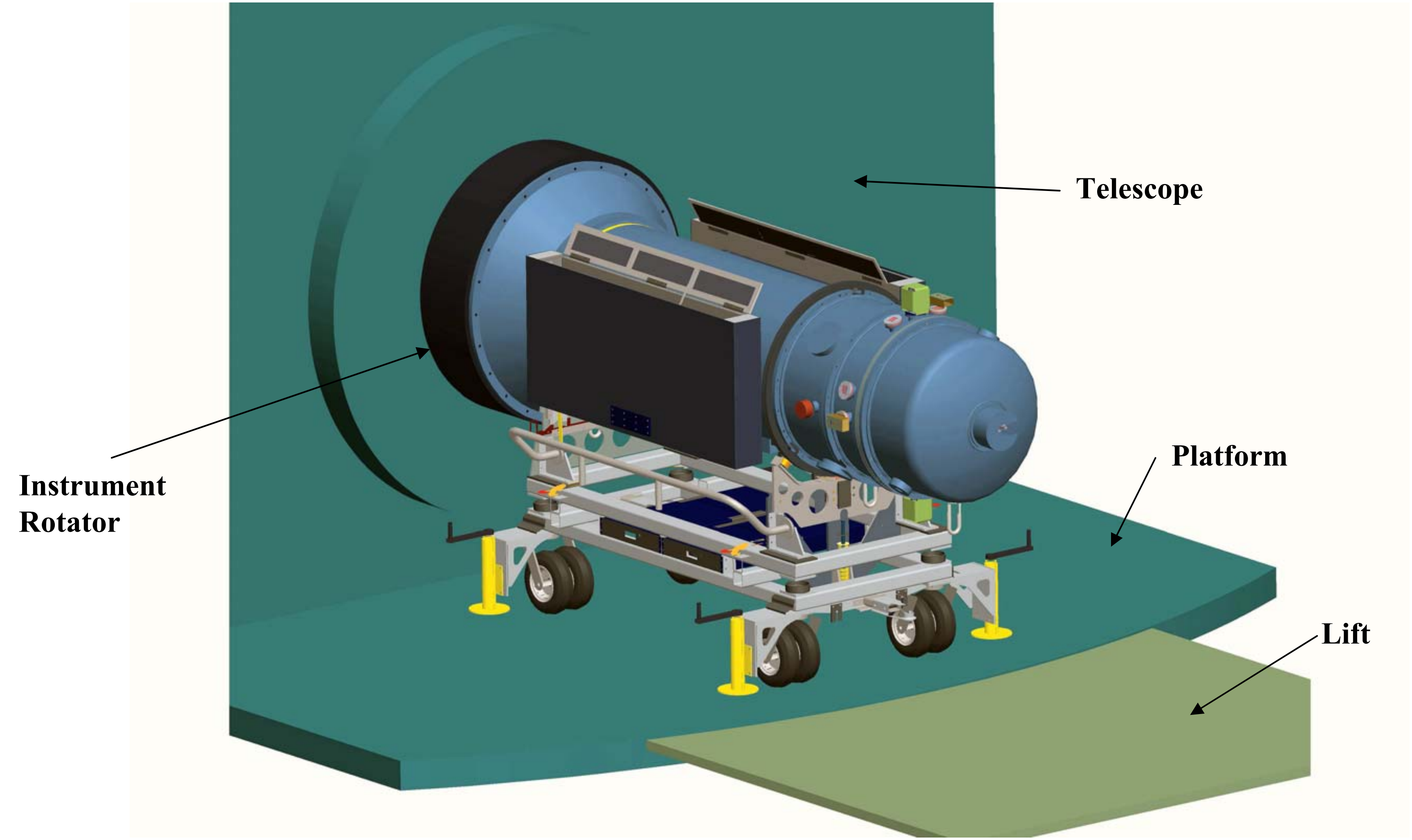
The instrument cart serves the following primary purposes:



- **Assembly and transport platform.**
- **Facilitate instrument / telescope mating.**
- **Support the bulk of the instrument weight after installation to prevent significant moment loading on the instrument rotator.**

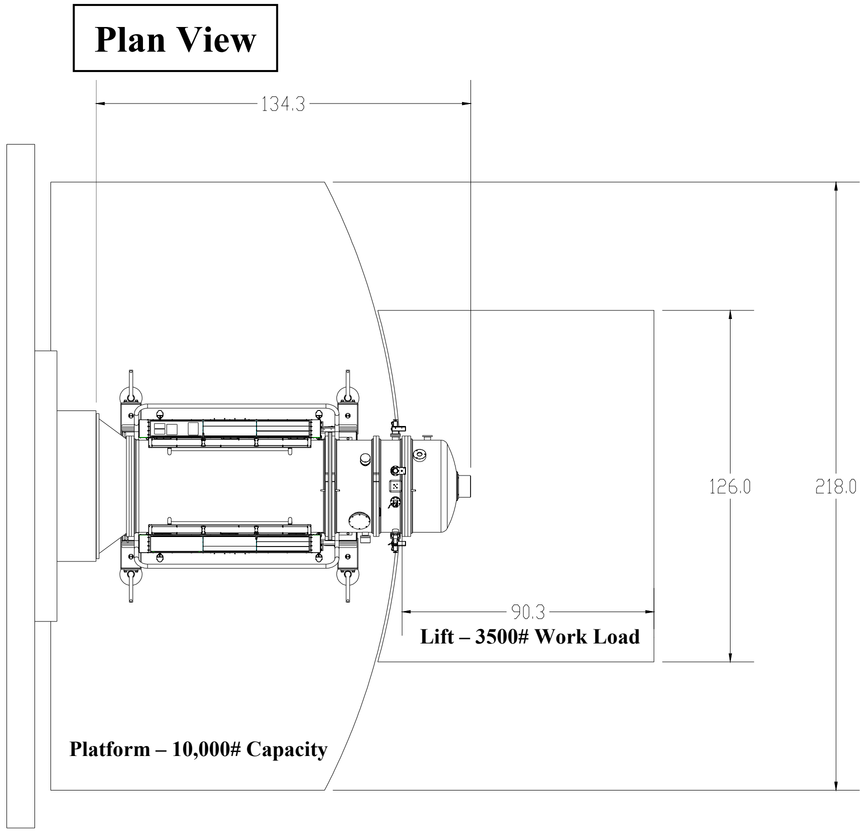
Instrument Cart

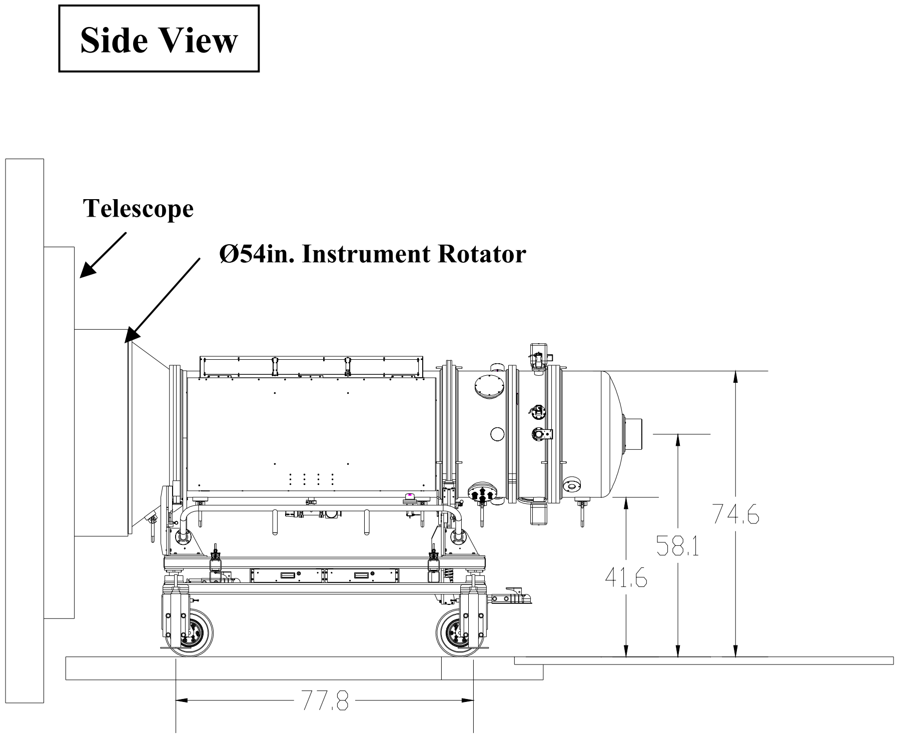
Perspective View – Mounted Instrument



Instrument Cart

Overall Dimensions



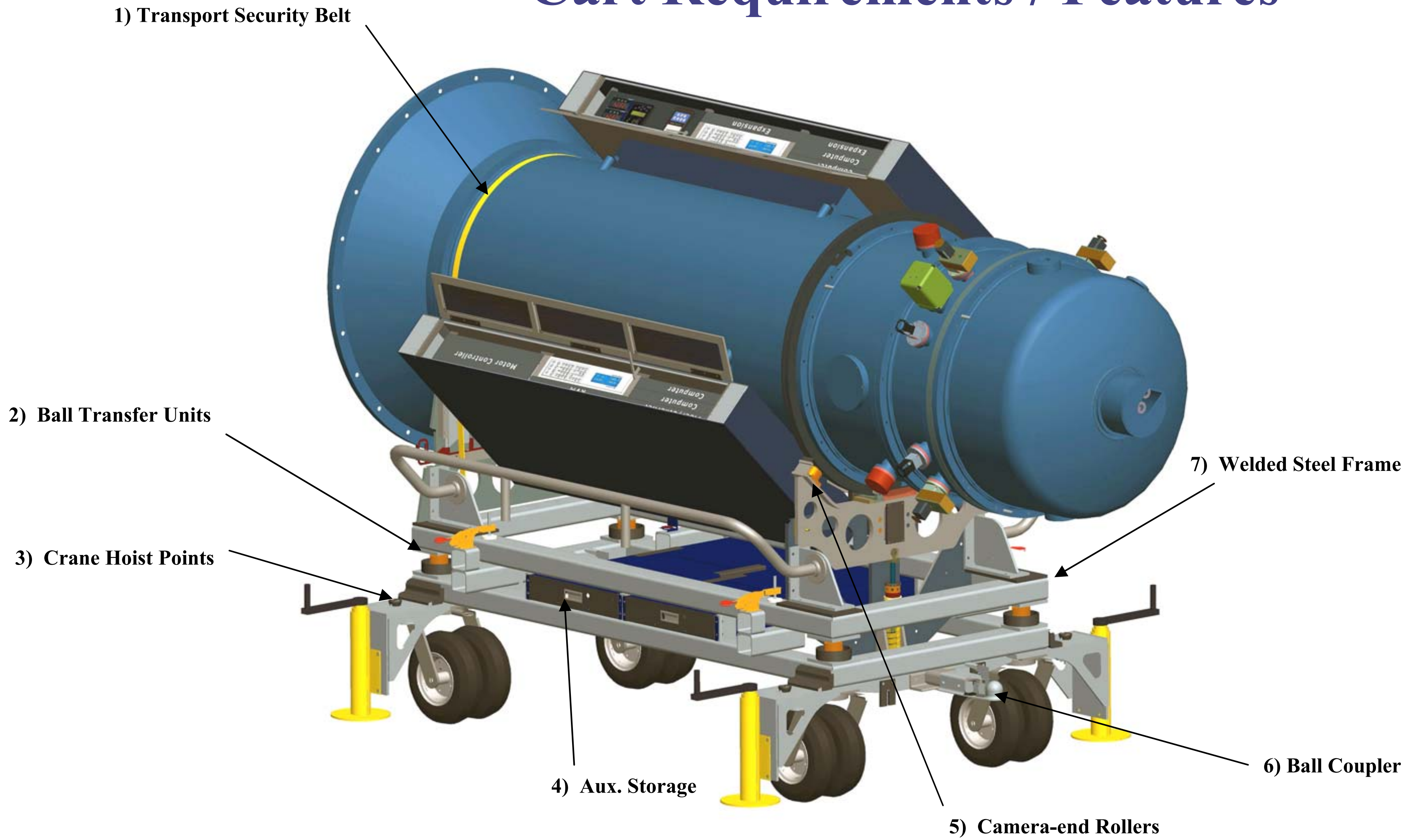


(Rotator CL at 58.5 in. height. Instrument shown prior to lift and mount.)

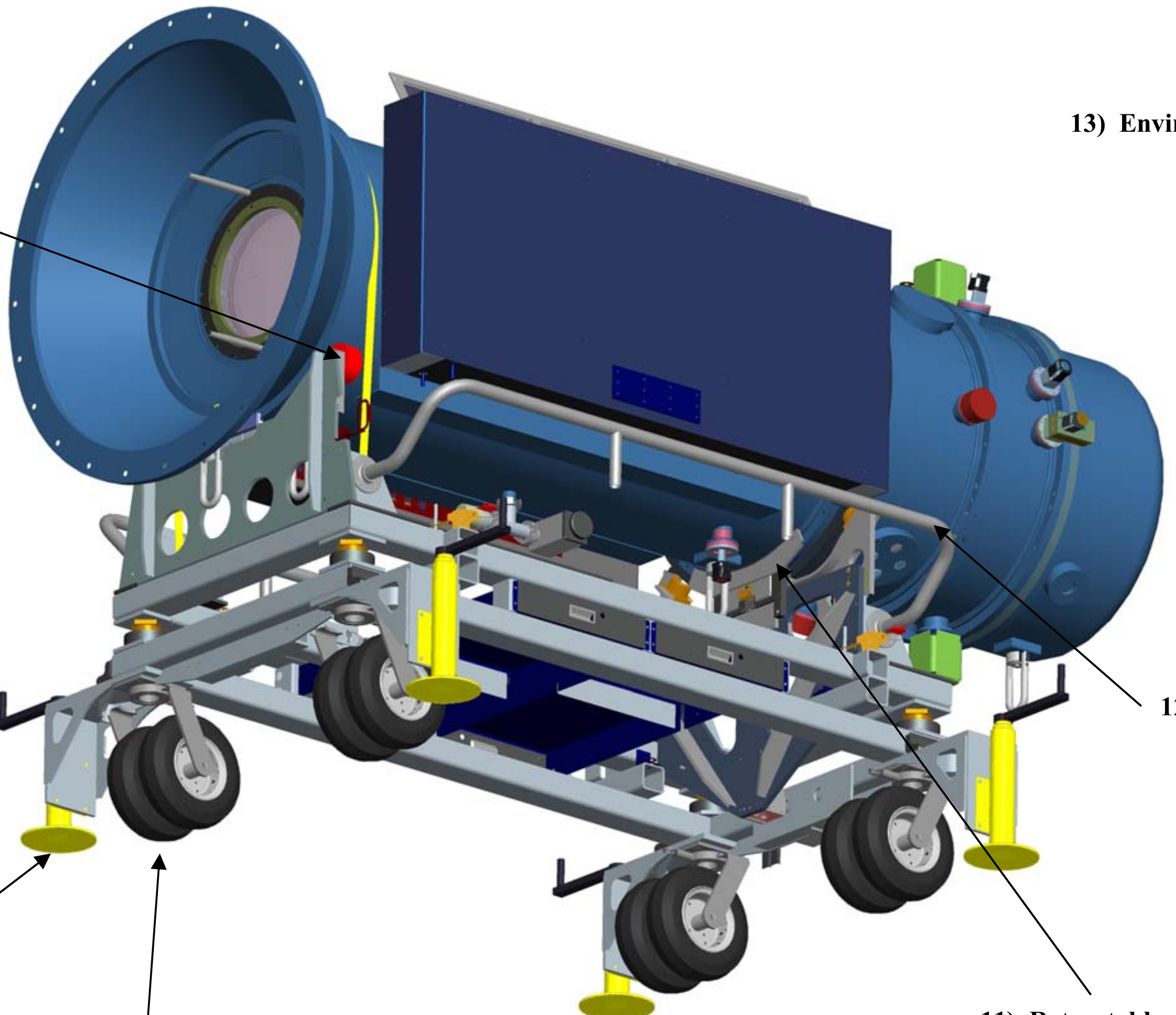
The current cart design weighs 1260#.

Instrument Cart

Cart Requirements / Features



Cart Requirements / Features



13) Environment to -6 °C

8) Retractable Telescope-end Rollers

12) Substantial Handles

9) Jack Points

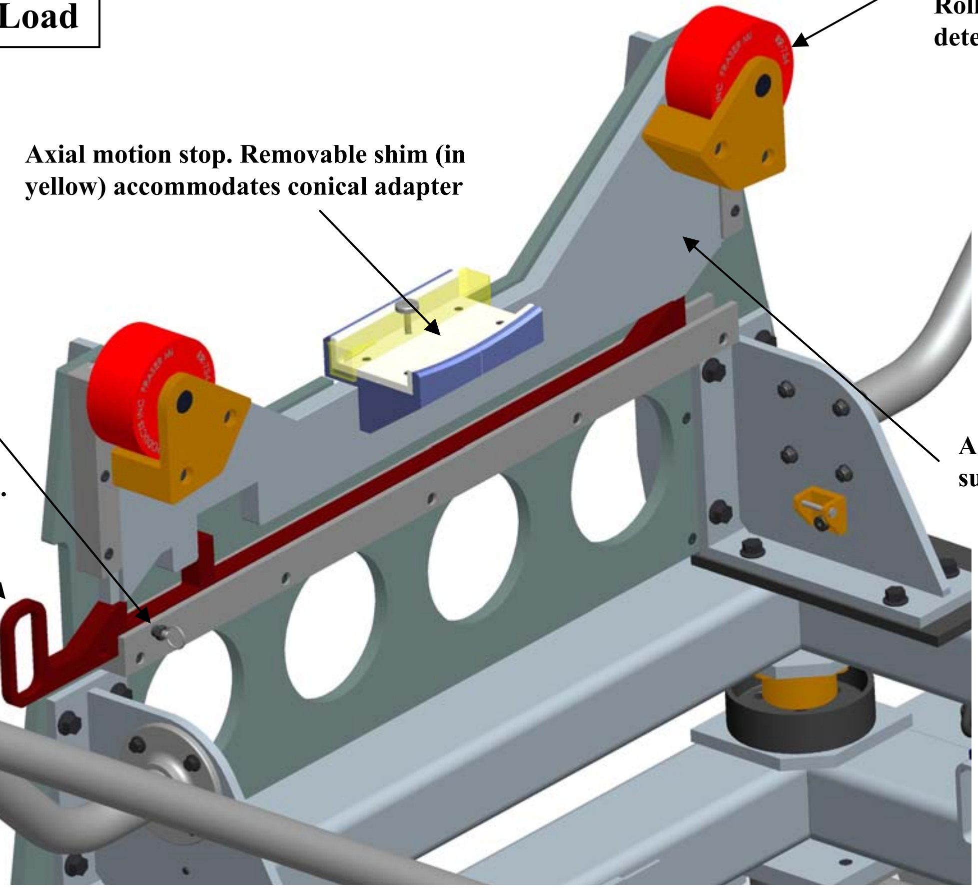
10) Four Swivel Casters

11) Retractable Assembly Cradle

Instrument Cart

Telescope-end Retractable Rollers

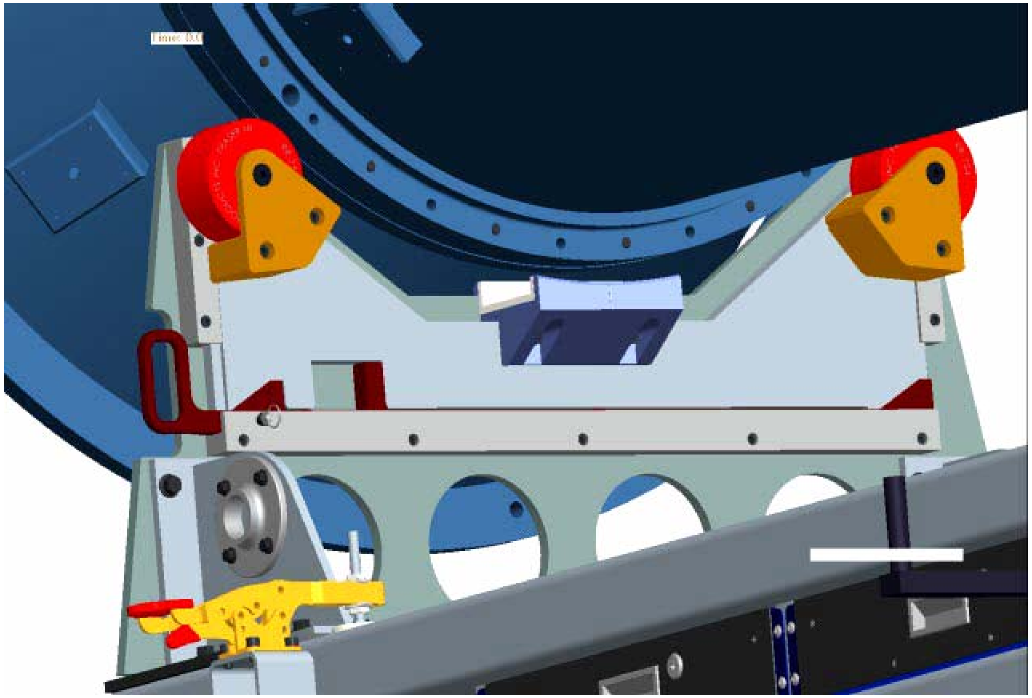
518# Max. Supported Vertical Load



Instrument Cart

Telescope-end Retractable Rollers

Disengage → Engage Operation



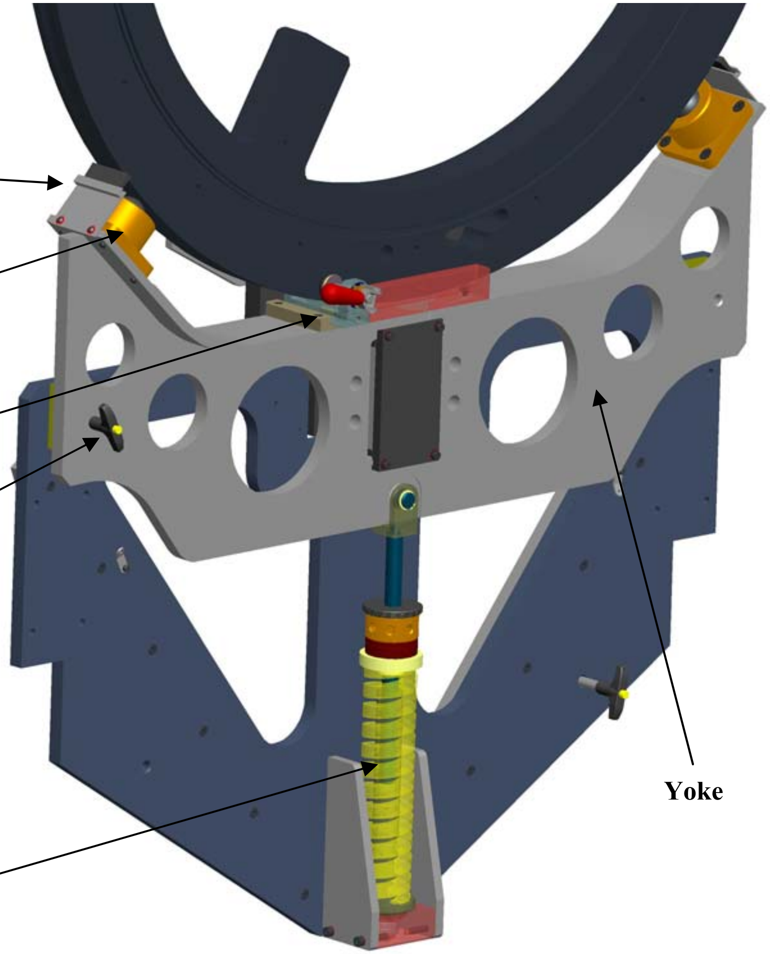
Rollers retracted upon mating of instrument and telescope.

Instrument Cart

Camera-end Rollers

1896# Max. Supported Vertical Load

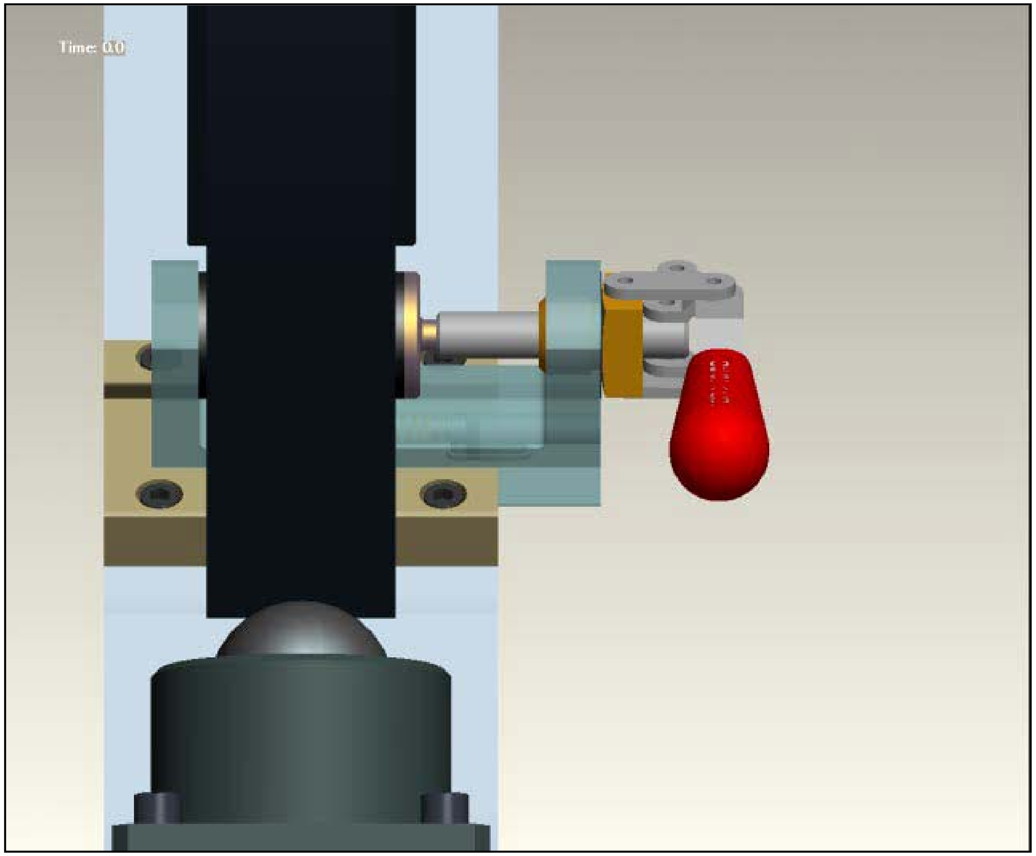
For simplicity and compactness, a spring-suspended system is proposed instead of a counterbalanced, true astatic suspension. (With the current spring, a 0.01 load ring out-of-roundness results in less than 7# of load variation.)



Instrument Cart

Camera-end Rollers

Brake Engage → Disengage Operation

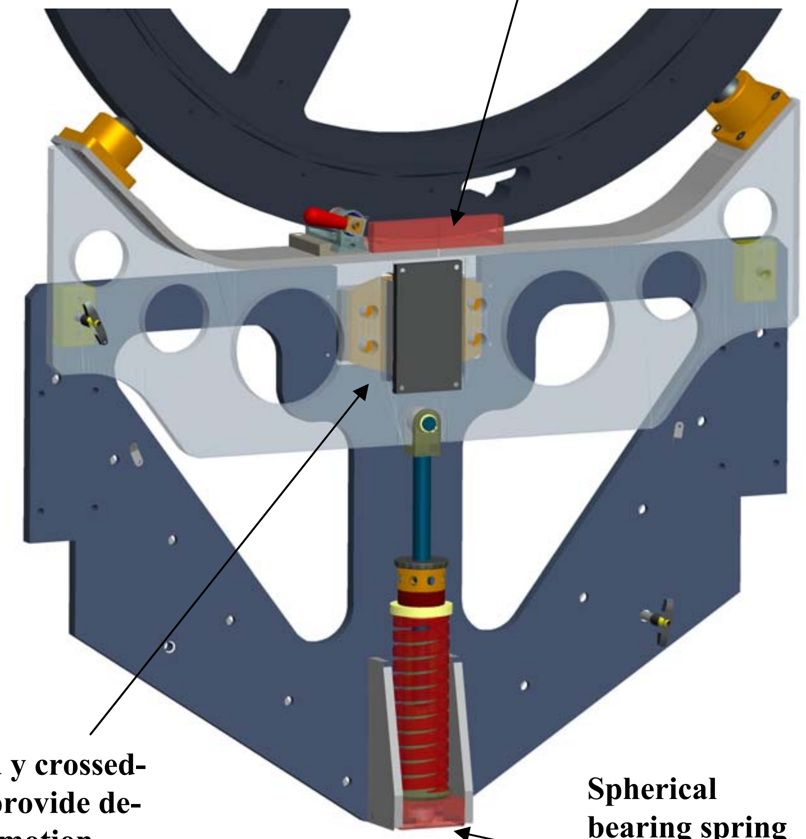


A microswitch could be included in the brake mechanism to lock out the instrument rotator upon brake engagement.

Yoke Suspension

Crossed-Roller Stage Suspension

- Two stacked crossed-roller stages are used to entirely decouple the vertical and horizontal motions of the yoke.
- Binding should be impossible. The stages are extremely stiff.
- A pivot is added to the spring mount to accommodate the motion.
- Stops are currently set at +/- 0.1 inch in both axes.
- Off-the-shelf crossed-roller stages (American Linear Manufacturers) are specified.

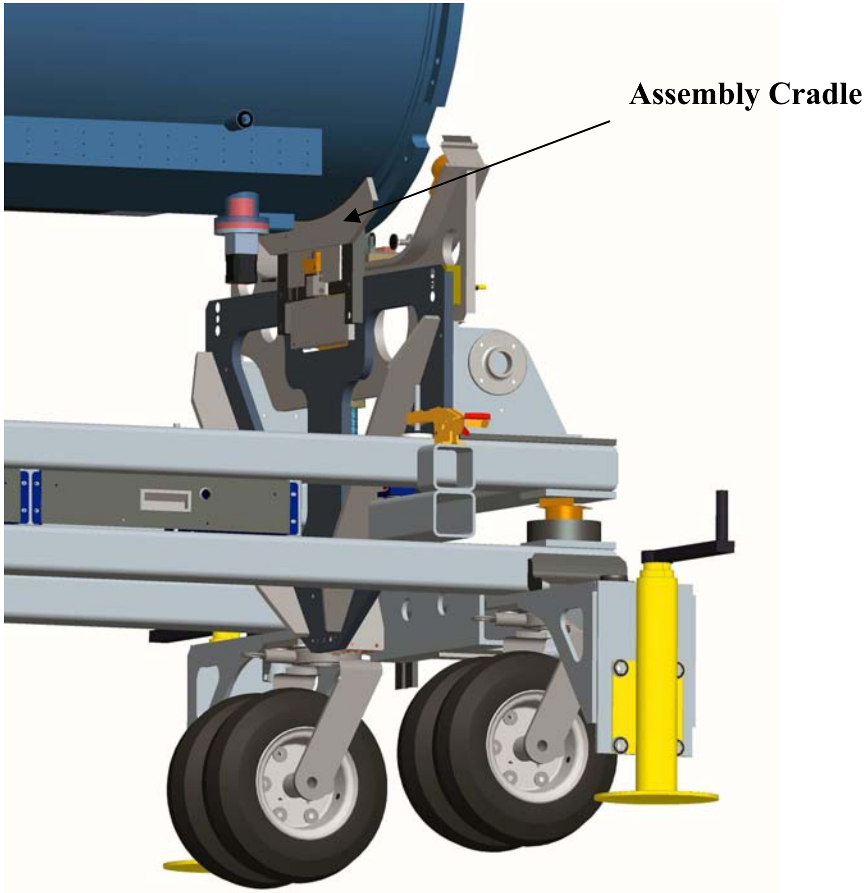


Instrument Cart

Assembly Cradle

The assembly cradle supports the instrument shell prior to the installation of the camera / load ring assembly.

The cradle is driven through +/-0.25 inches of travel by an Acme screw.

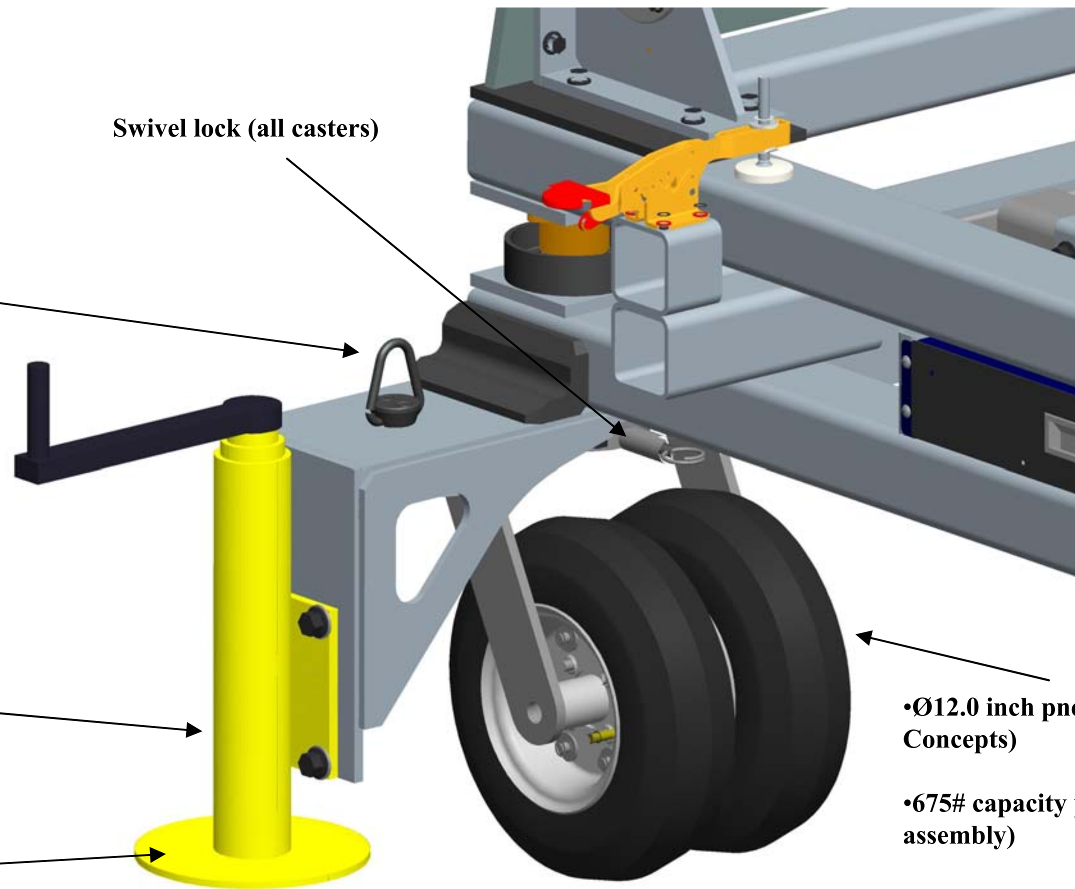


Instrument Cart

Jack Points / Casters / Lift Points

Swivel lock (all casters)

2000# hoist ring (spreader bar / lift fixture probably necessary)



- 1800# capacity jack (Cignys)
- 6 inch stroke
- Removable, ratcheting handle
- Disc may be removed (retained with a nut) to interface with vee-blocks.

- Ø12.0 inch pneumatic wheels (Caster Concepts)
- 675# capacity per wheel (1350# per assembly)
- Dual wheels with swivel locks.

Instrument Cart

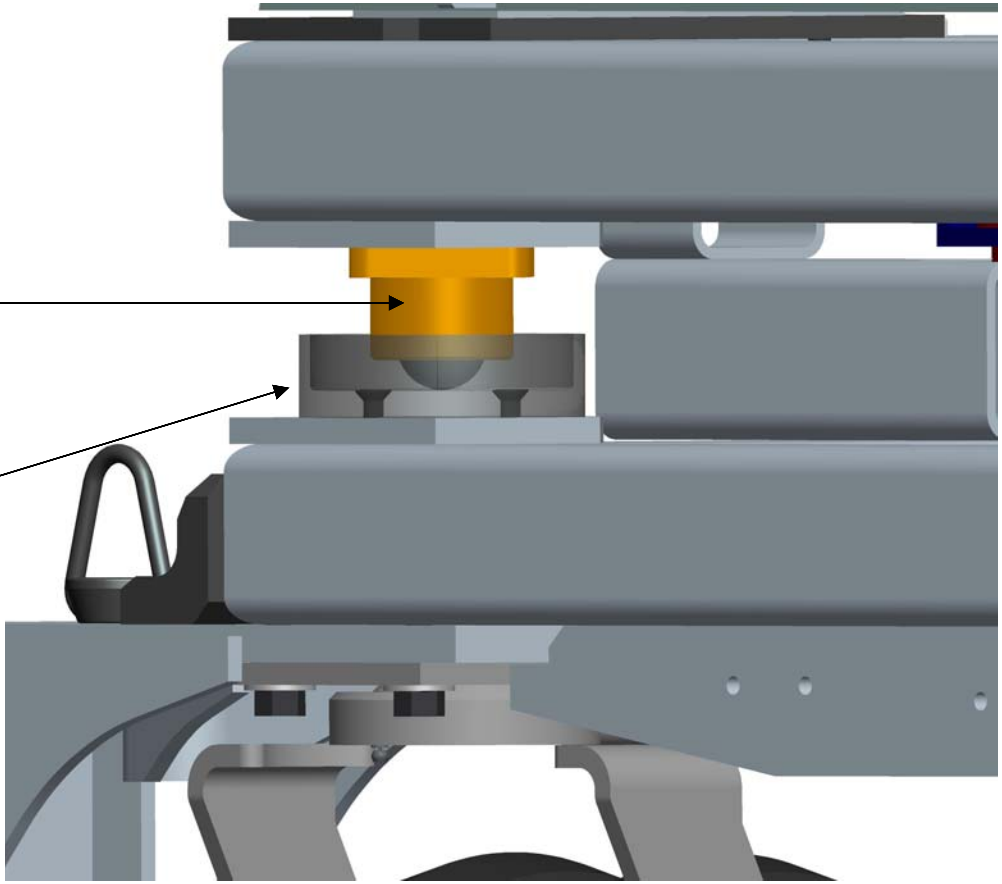
Ball Transfer Units

Cart superstructure floats above cart dolly on four ball transfer units to ease mate / de-mate of instrument and rotator.

• Ball Transfer Unit (OmniTrack)

• Identical to camera-end rollers

Hardened 440C SS cup provides race for ball transfer as well as +/- 1.0 inch travel stop.



Instrument Cart

Ball Transfer Units

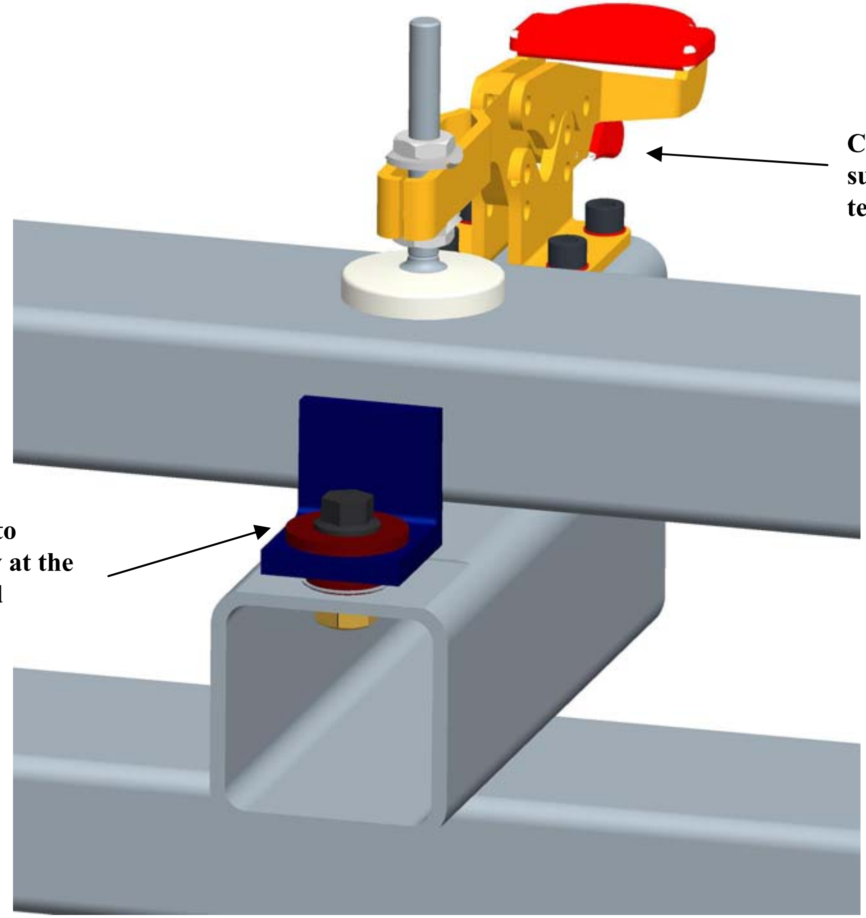
- The OmniTrack 1263 has a 2240# capacity and smooth action. The Ø1.5 inch main ball is hardened and ground chrome steel.

- Two ball transfers support the instrument load ring; four additional units support the entire cart superstructure.

Ball Transfer Units

Ball transfer lock out.

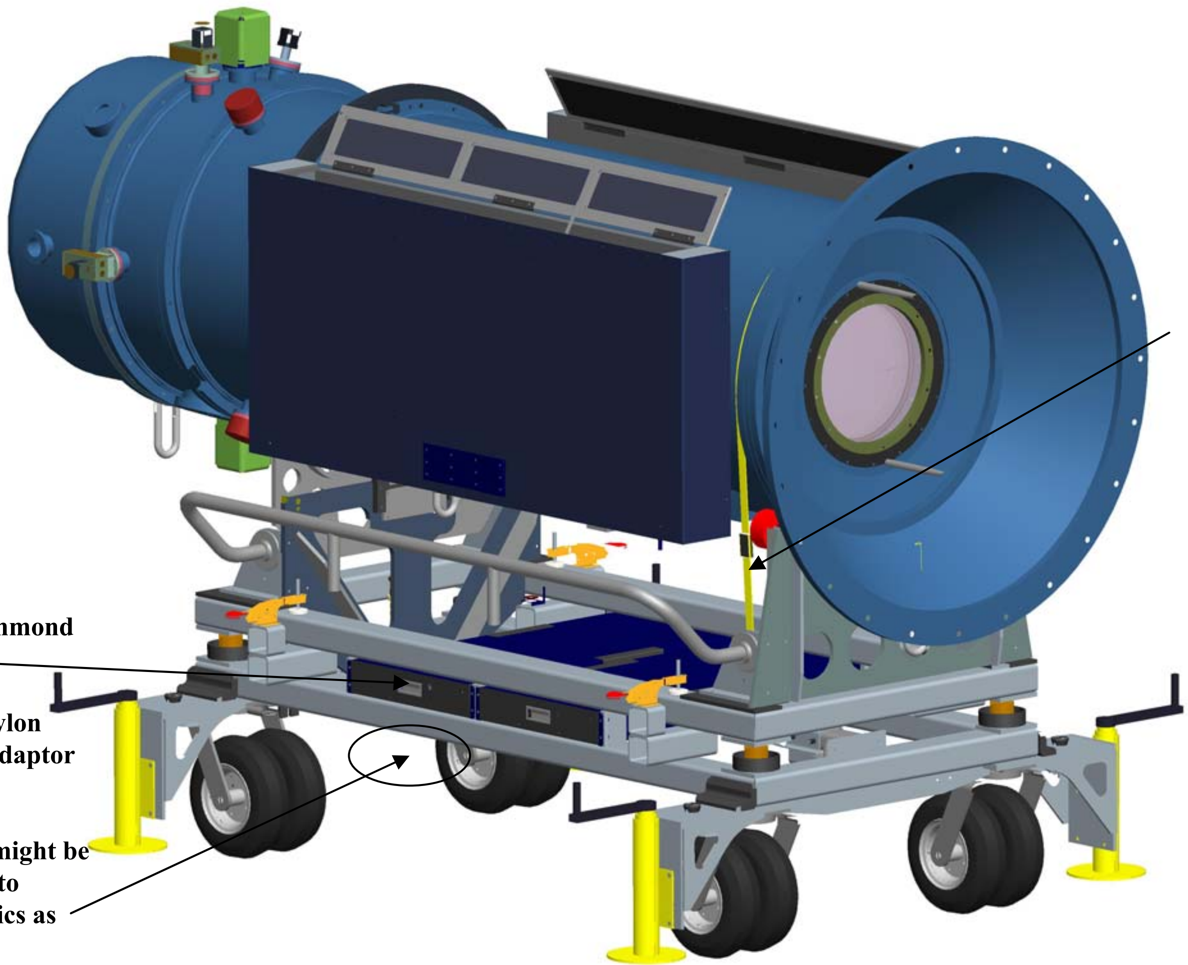
Clamps (DeStaCo) lock together cart superstructure and dolly after instrument / telescope mate. 300-700# applied force.



Captured bolts engage welded-on nuts to positively lock superstructure and dolly at the nominal position (used for shipping and instrument transport).

Instrument Cart

Transport Belt / Auxiliary Storage



•Nylon web belt provides additional security for instrument transport.

•Quick disconnect ends.

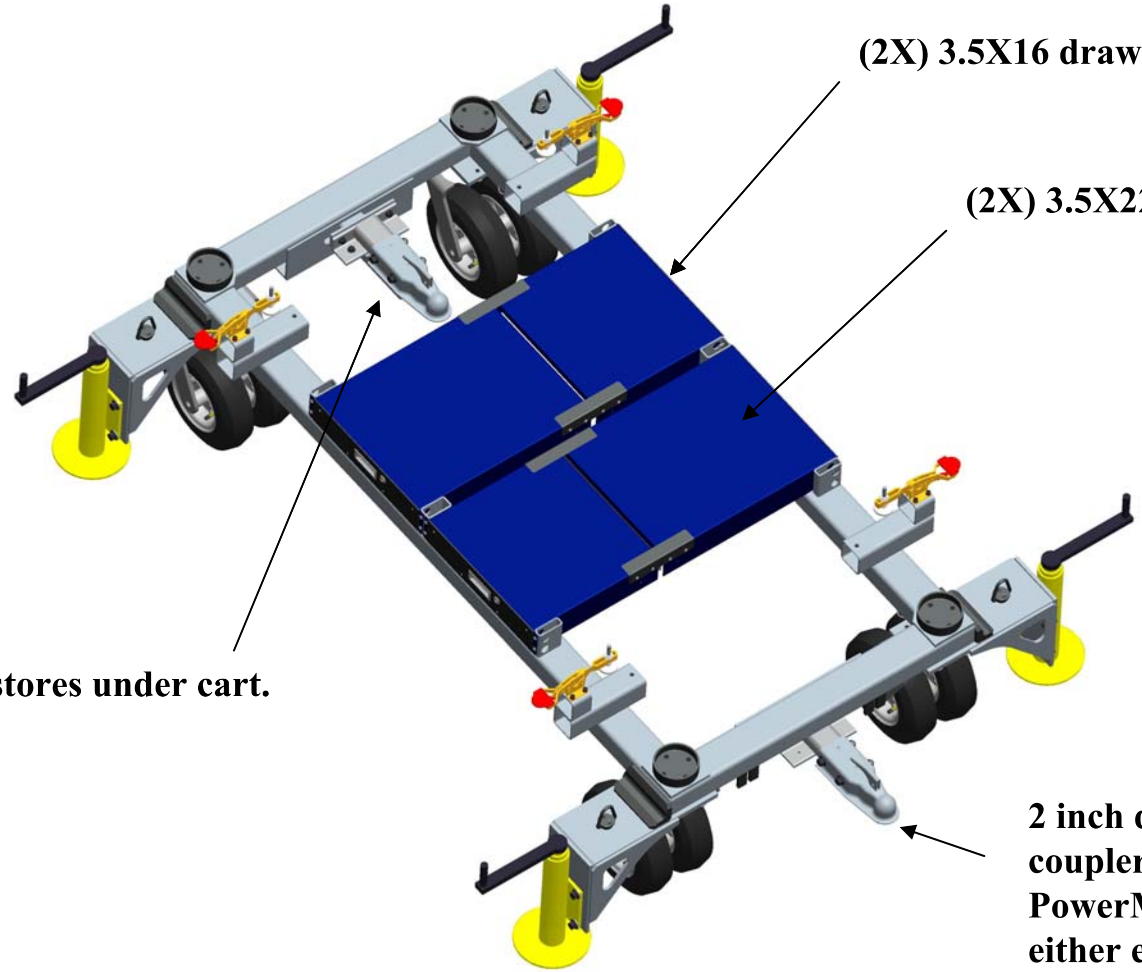
•Cam buckle provides light tension without overloading polyurethane roller assembly.

•Storage drawers (Hammond Mnfg).

•Stows jack handles, nylon webbing, and conical adaptor axial-stop shim.

•Additional DIN rails might be mounted beneath cart to accommodate electronics as necessary.

Ball Coupler and Drawer Details



(2X) 3.5X16 drawers

(2X) 3.5X22 drawers

Ball Coupler self-stores under cart.

2 inch diameter ball coupler interface to PowerMover. Mounts to either end.

Frame Construction / Operating Environment

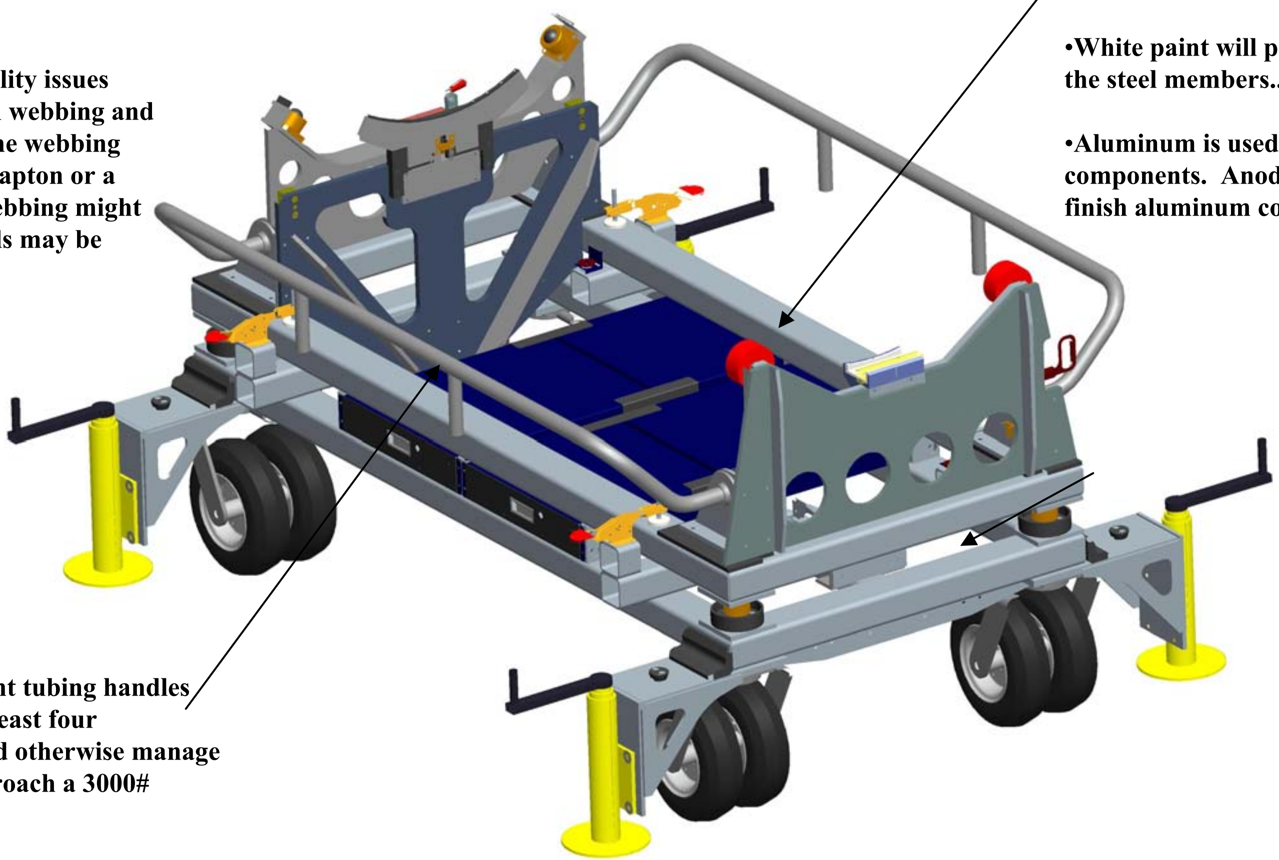
•The -6 °C temperature requirement does not present any particular concern.

•Clean-room compatibility issues might include the nylon webbing and the pneumatic tires. The webbing can be wrapped with Kapton or a polyurethane coated webbing might be specified. The wheels may be bagged.

•The bulk of the frame is composed of welded steel structural members. Main members are 3X4X0.19 in.

•White paint will provide the finish on the steel members..

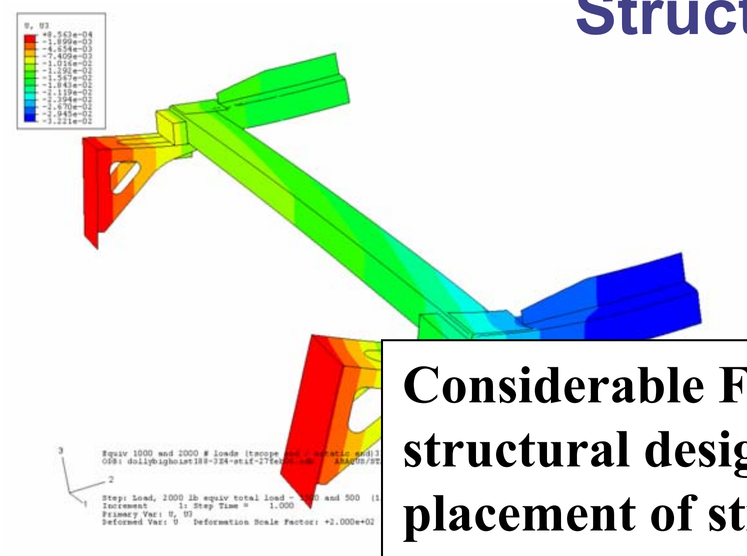
•Aluminum is used for some machined components. Anodize will most likely finish aluminum components.

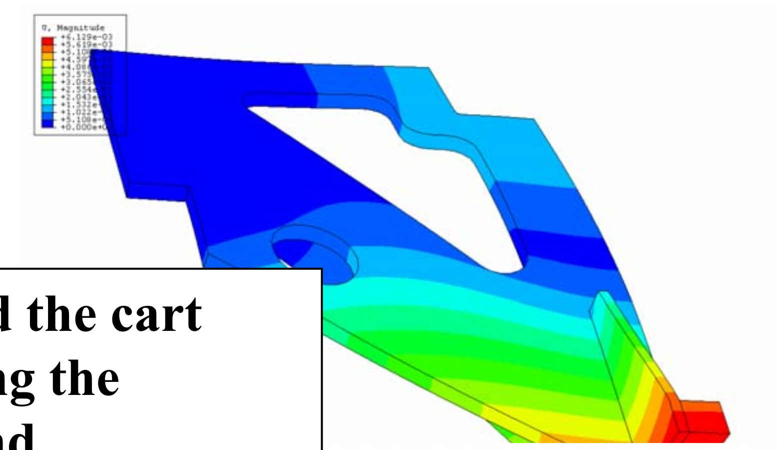


Stout and lengthy bent tubing handles provide room for at least four individuals to roll and otherwise manage what will finally approach a 3000# assembly.

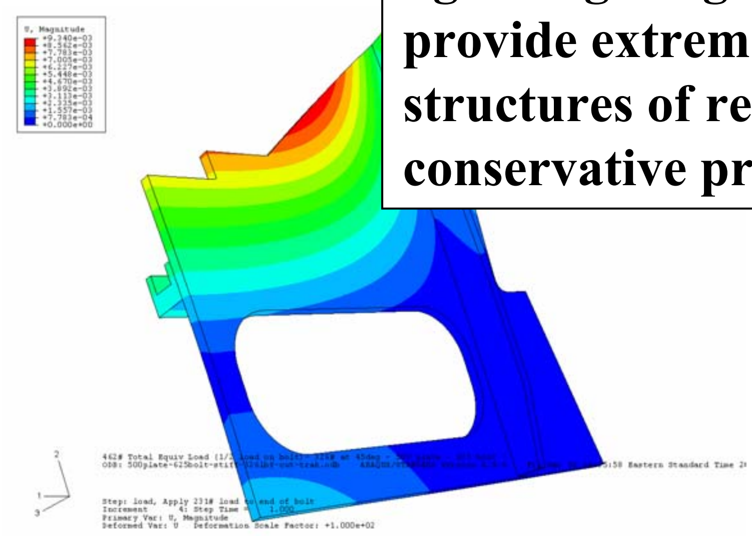
Instrument Cart

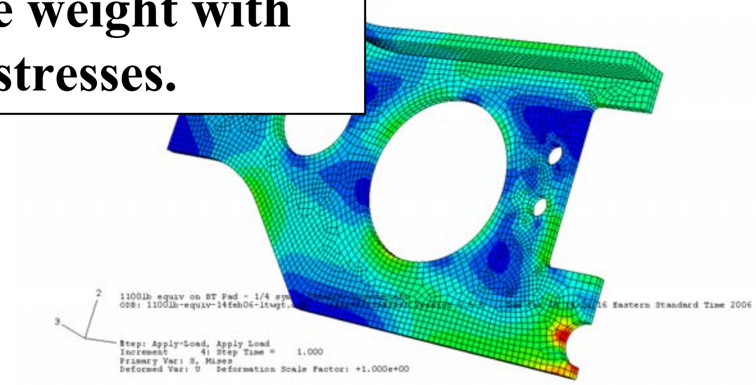
Structural Analysis





Considerable FEA guided the cart structural design including the placement of stiffeners and lightweighting. The goal was to provide extremely stiff supporting structures of reasonable weight with conservative predicted stresses.





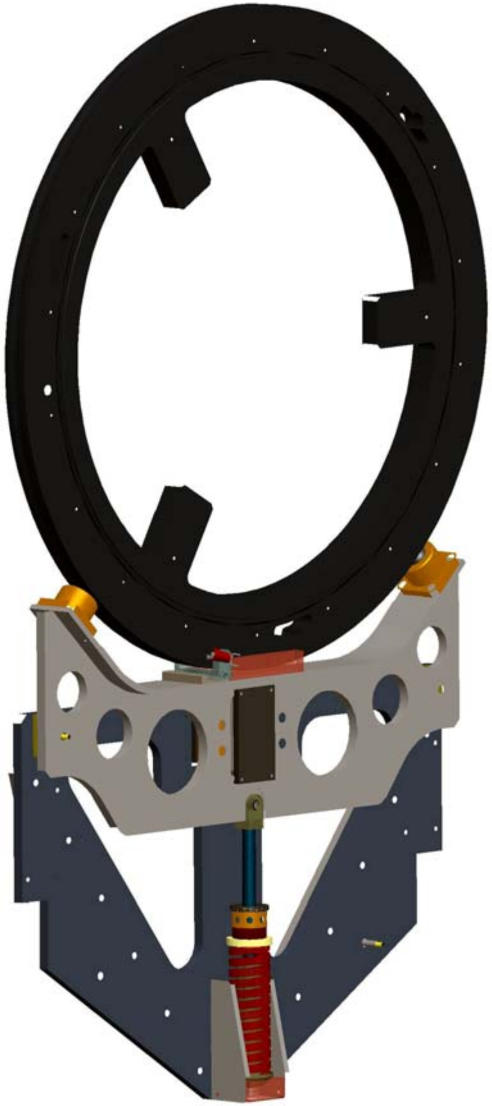
Ball Transfer Contact Stress

Contact Stress Considerations

Two ball transfer units are proposed to support the maximum vertical 1896 lbf load at the load ring. The units are 90 degrees apart, resulting in an expected 1341 lbf maximum normal load per ball transfer (rated to 2240 lbf each).

The load ring is 440C stainless hardened to Rc 57-60; this hardness corresponds to an expected yield strength of 277 ksi, (ultimate is 324 ksi) *

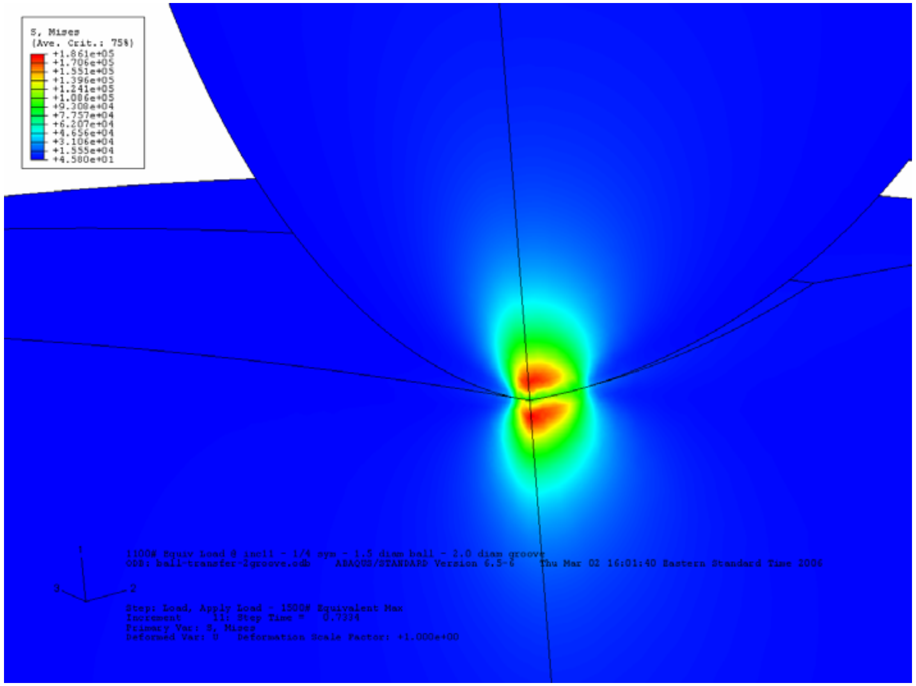
* Timken 440 N-DUR material



Ball Transfer Contact Stress

Contact Stresses

- **Hertzian contact stress models were initially considered.**
- **Additionally, FEA models were used to accurately capture the geometry and to provide a good metric (Von Mises stresses) for comparison to expected material strengths**
- **A groove was added to the load ring to limit contact stresses.**

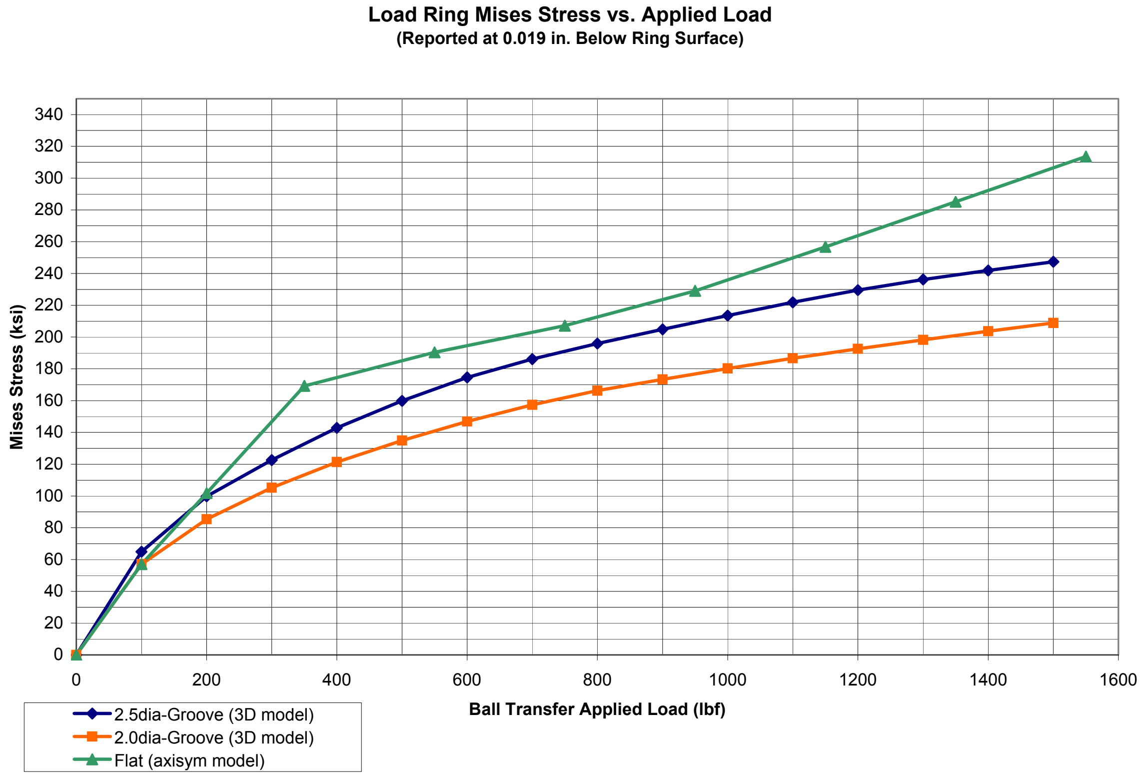


Highly refined ¼ Symmetric 3D FE Model. Ø2.0 groove, Ø1.5 ball.

Ball Transfer Units

FEA-Predicted Stress vs. Applied Load

- A Ø2.0 load ring groove was chosen.
- 200 ksi is predicted in the load ring for a 1340 lbf applied load.

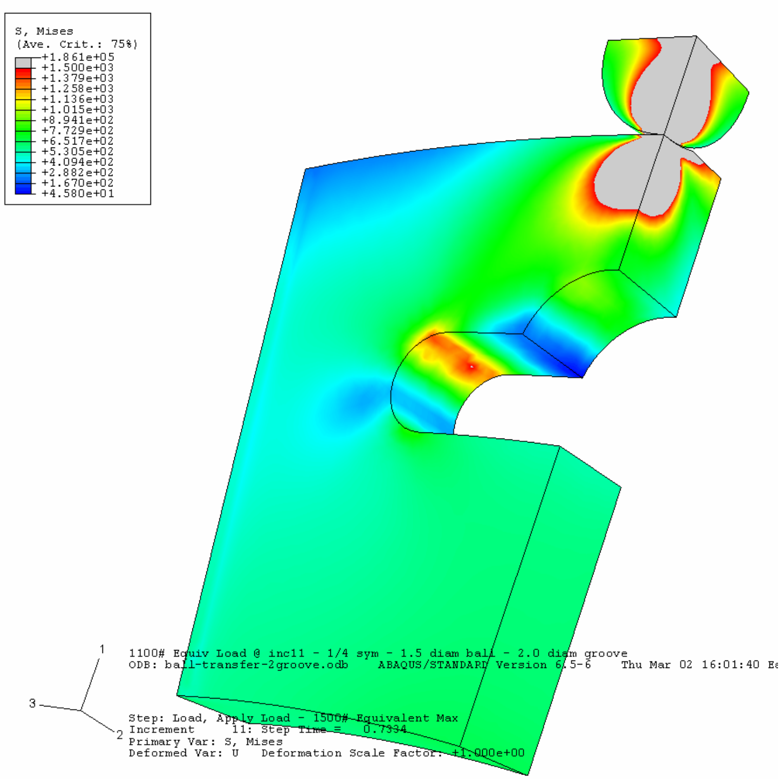


Ball Transfer Units

Contact Stress - Conclusion

- Given the expected strength of the hardened 440C load ring coupled with the Ø2.0 inch groove, the contact stress situation at the ball transfer / load ring interface is adequate.

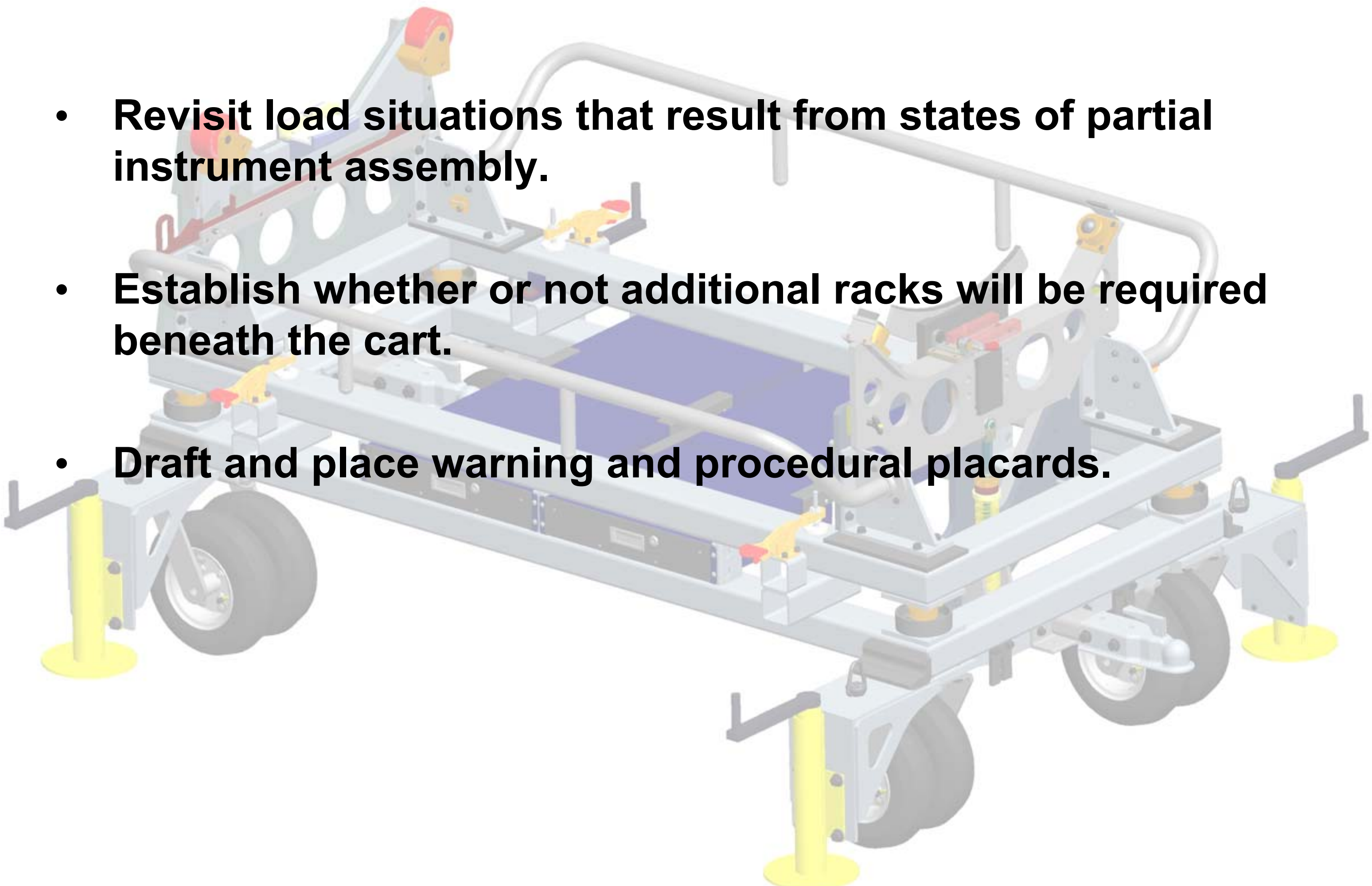
- The ball transfer manufacturer, OmniTrack, was consulted on the same issue. They are entirely comfortable with the expected loading and predict that no indention (Brinelling) of the load ring surface will occur.



Contact Stress FEA model also reveals very conservative stress levels (~1500 psi) in the load ring cable throughway.

Instrument Cart

Remaining Cart 1 Design Effort



- **Revisit load situations that result from states of partial instrument assembly.**
- **Establish whether or not additional racks will be required beneath the cart.**
- **Draft and place warning and procedural placards.**

FourStar

Detector Dewar Assembly Cart (Cart 2)

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22 September 06

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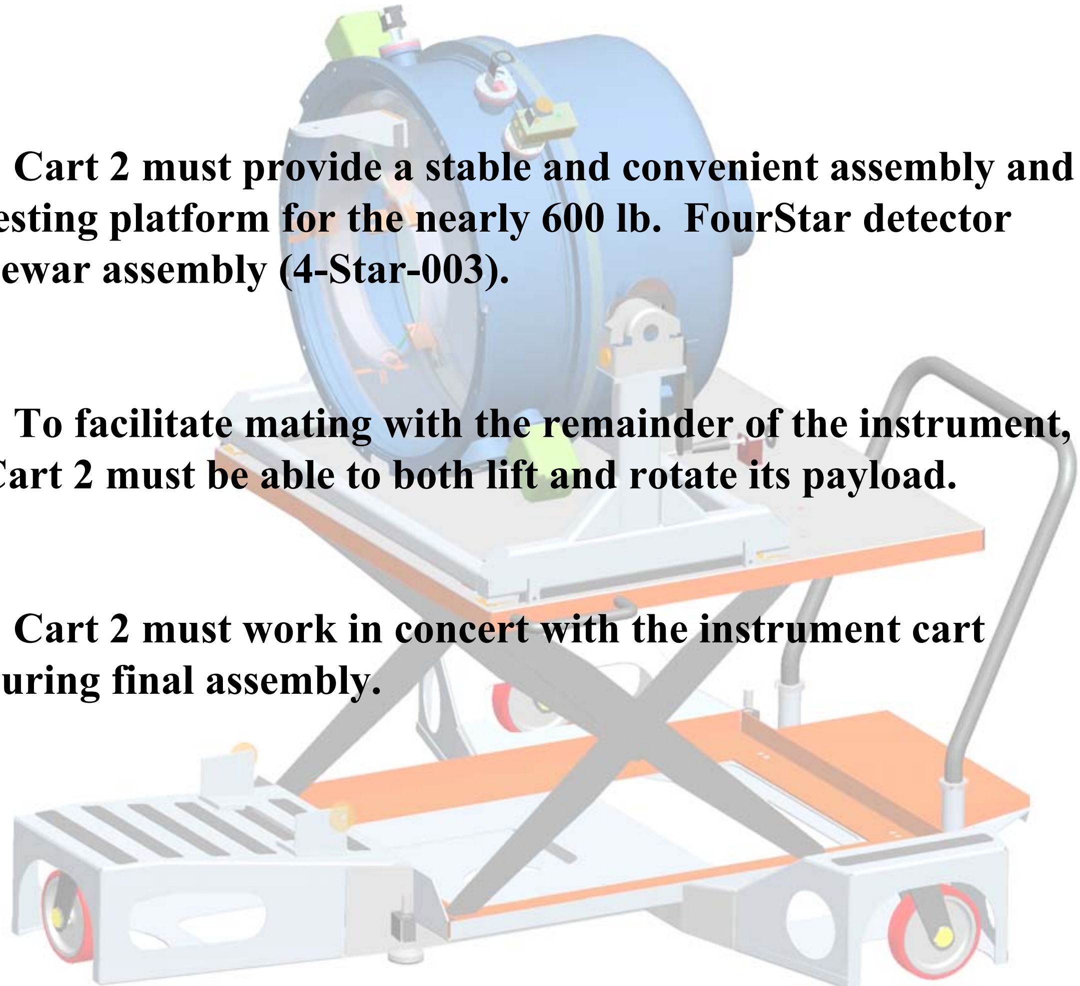
Cart 2

Requirements



- Cart 2 must provide a stable and convenient assembly and testing platform for the nearly 600 lb. FourStar detector dewar assembly (4-Star-003).

- To facilitate mating with the remainder of the instrument, Cart 2 must be able to both lift and rotate its payload.

- Cart 2 must work in concert with the instrument cart during final assembly.

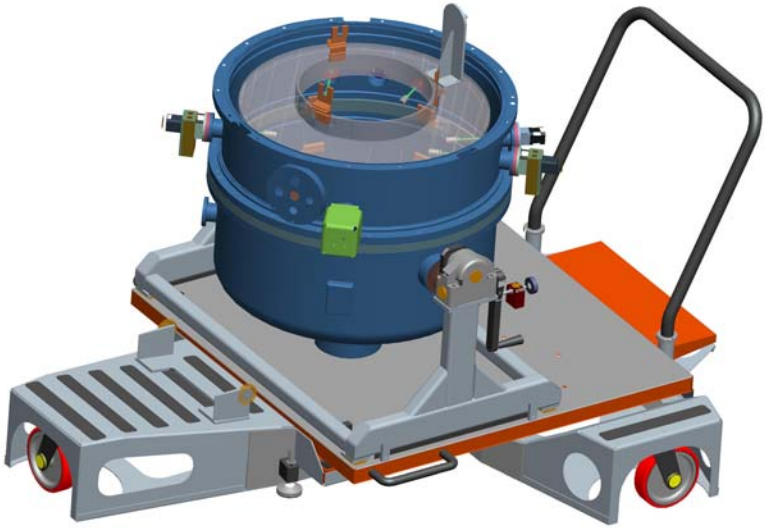
Cart 2

Perspective View

Tricycle Cart Design

Detector Dewar: 538-615#

Cart 2 Weight: 965#

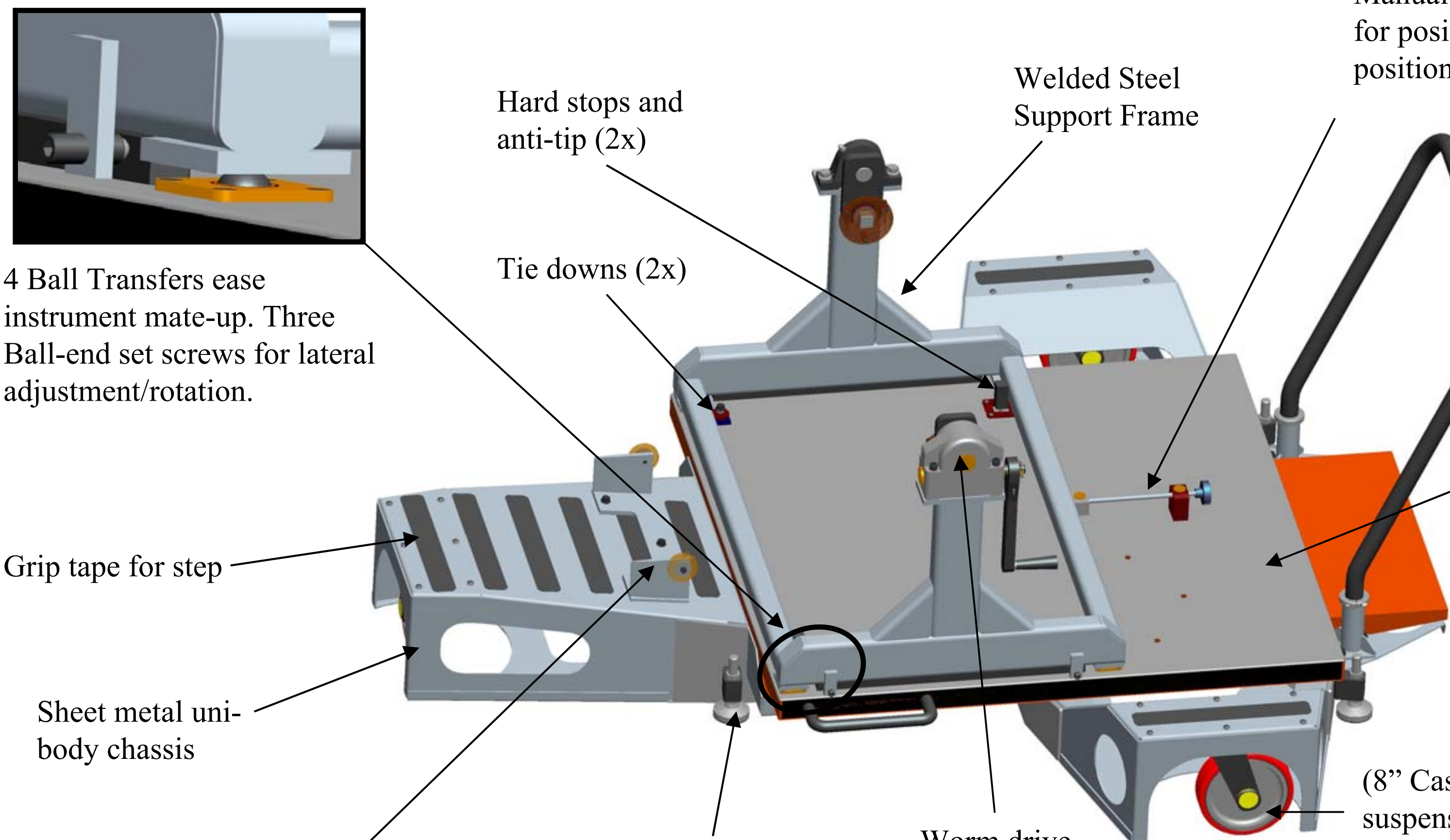


Detector Dewar assembly position

Dewar / Instrument mate-up position

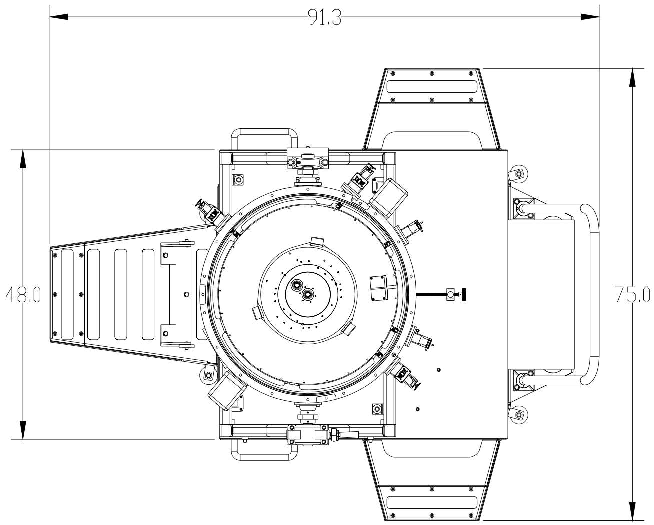
Cart 2

Cart2 Requirements /Features

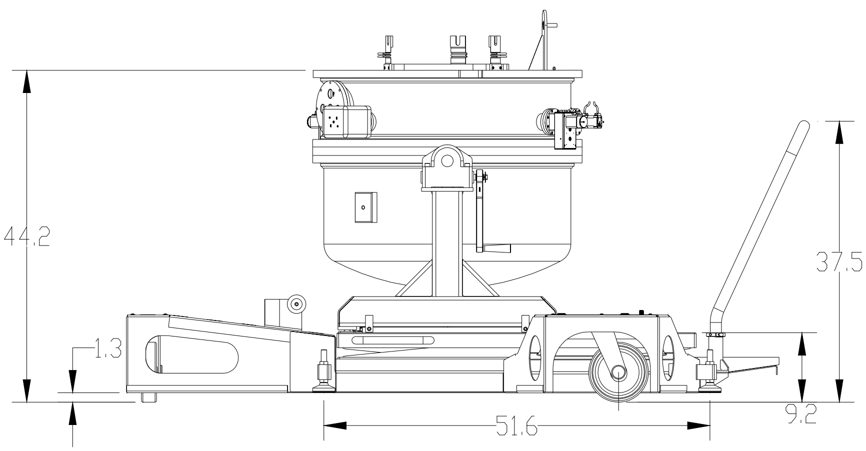


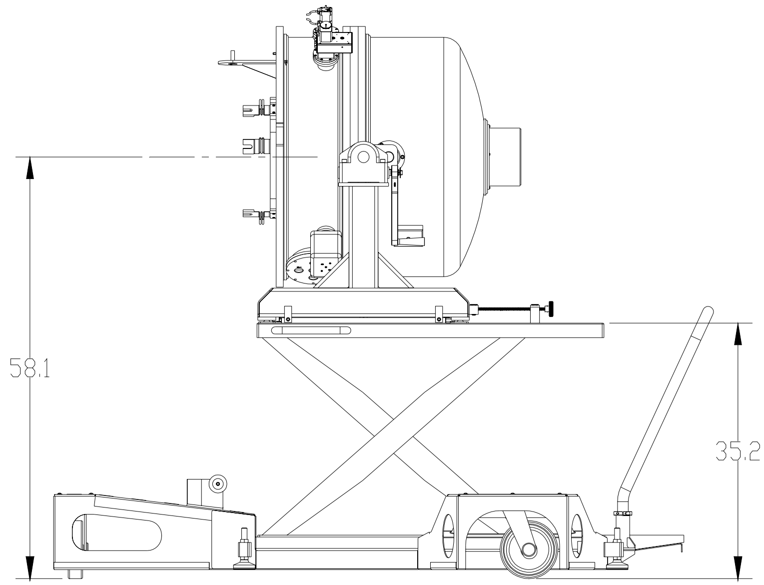
Cart 2

Overall Dimensions



- ~26 in. of scissor lift throw used.
- <45 in. working height for assembly efforts.





Cart 2

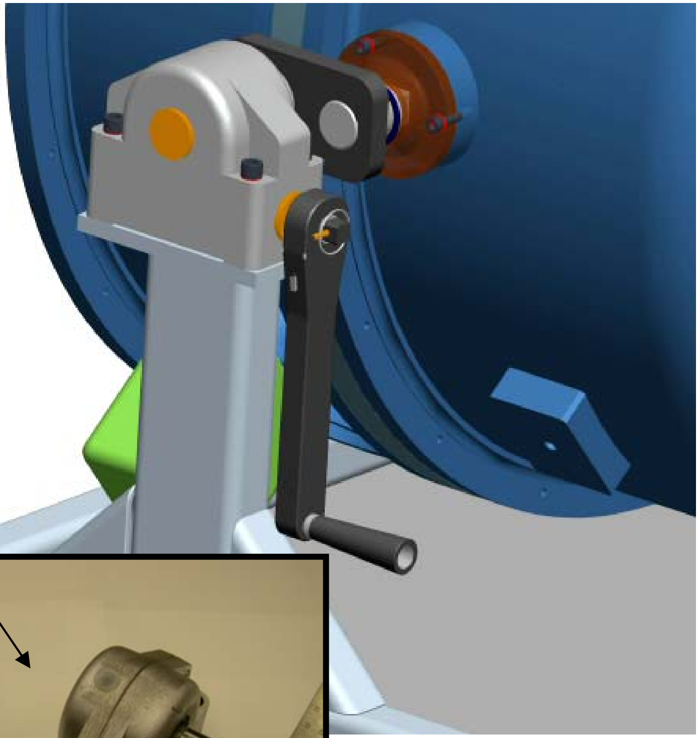
Presto® Lift Table

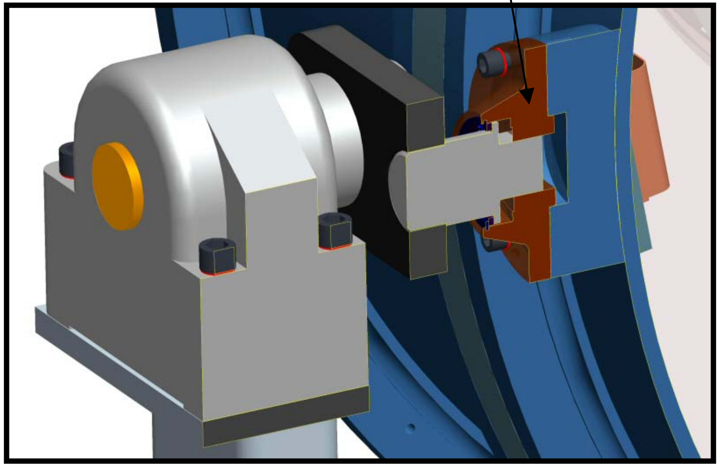
- Manual operation.
- 4X4 ft platform
- 1500# capacity
- 36 inch maximum throw

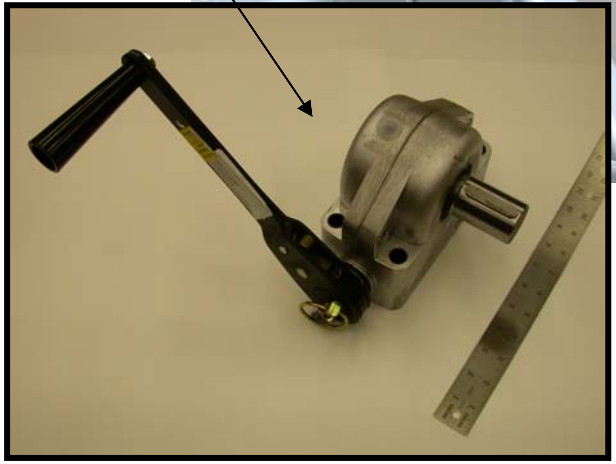
Weight ~500#

Rotation Mechanism

- 266 ft-lb torque capability, 24:1 self-locking worm drive (Pfaff-silberblau)
- Removable, ratcheting handle
- Axis of output shaft @ median CG of full detector dewar assembly
- Mounting flanges have spring return for ease of de-mate and withdrawal of support structure and cart.

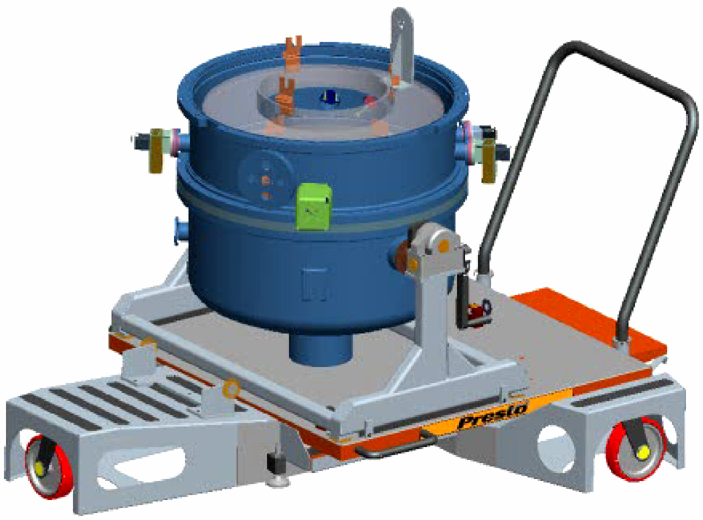






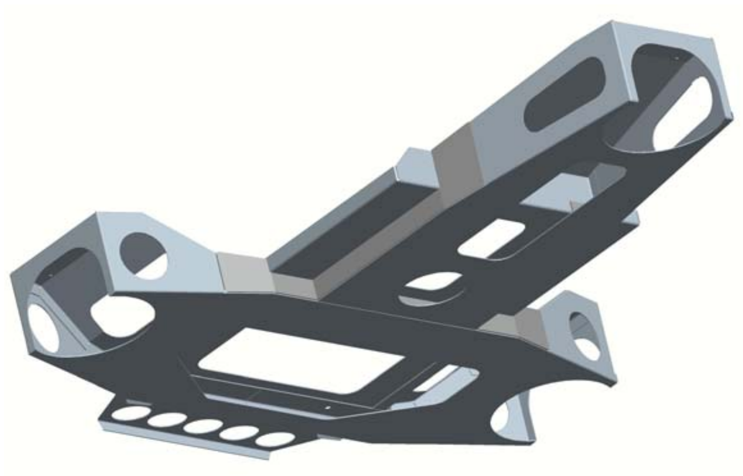
Cart 2

Operation

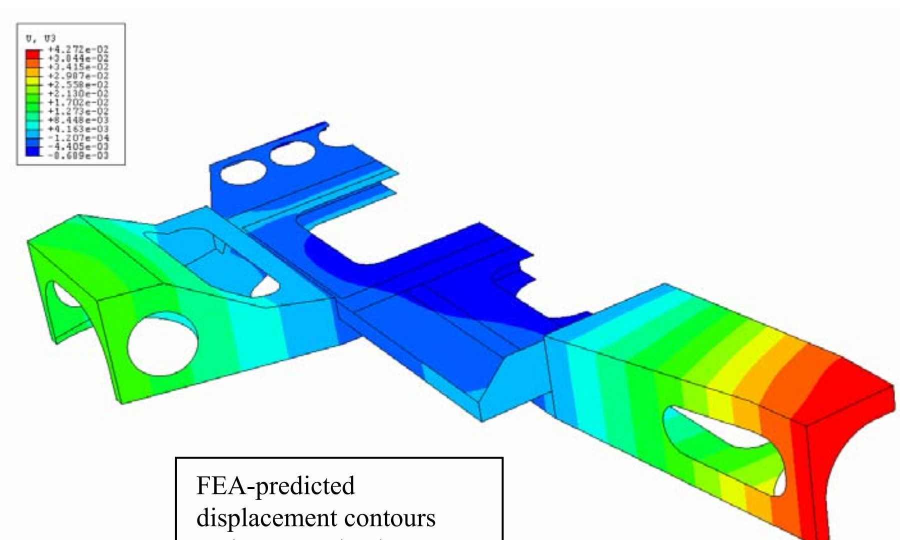


Cart 2

Structural Analysis



- Cart 2 analysis focused on design of the sheet metal uni-body chassis.
- Final design allows <8ksi Mises stresses and 0.04 inch max deflection under 1600# load.

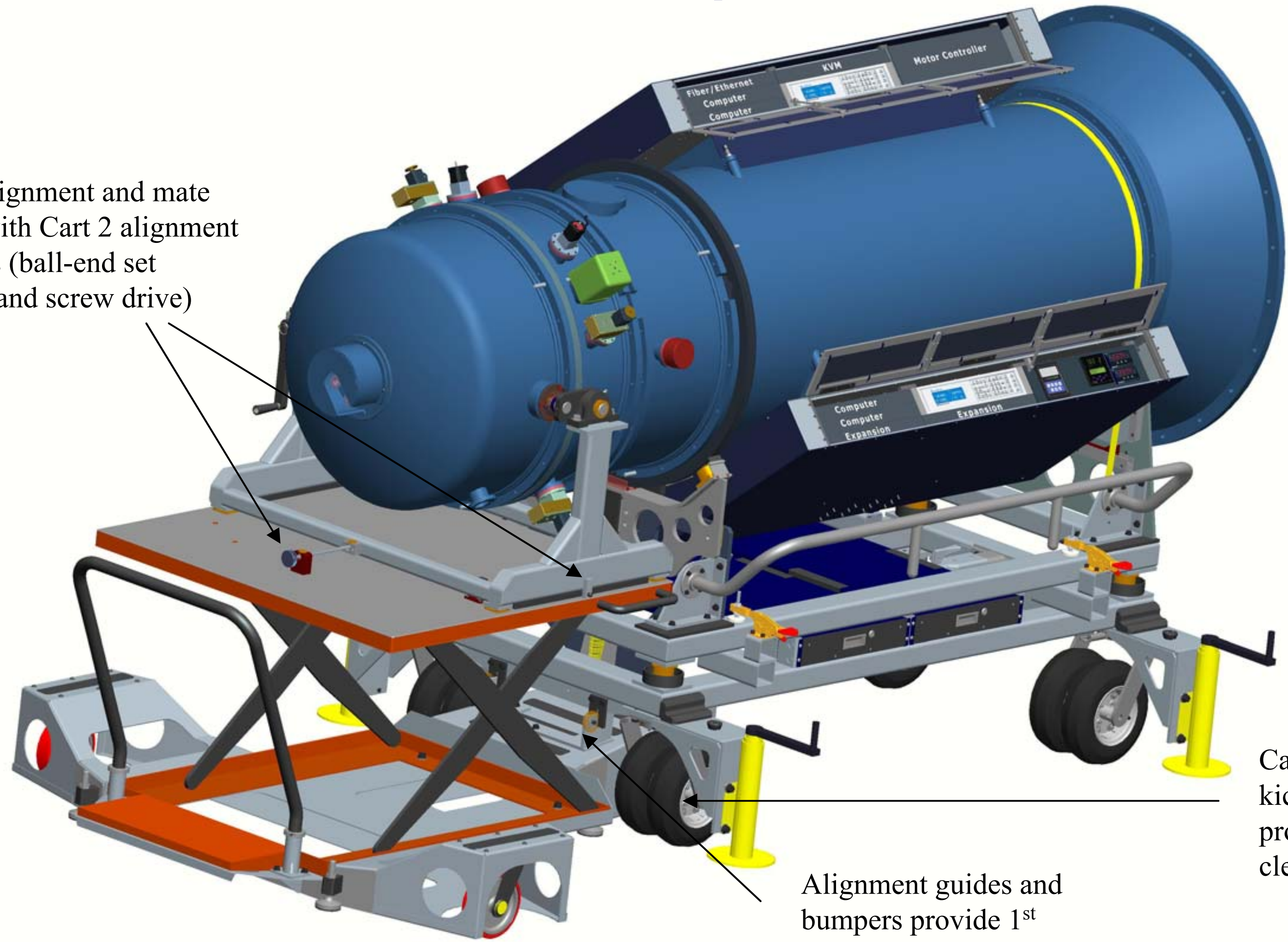


FEA-predicted displacement contours under 1600# load

- 11 gage (0.12 in.) sheet steel, 40-50ksi yield
- ¼ in. thick doublers
- < 300# weight (reduced from 485# through FEA-guided light-weighting efforts)

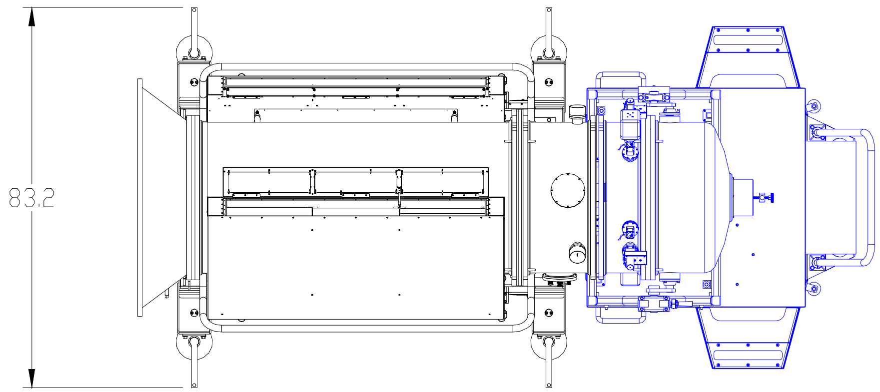
Cart 2

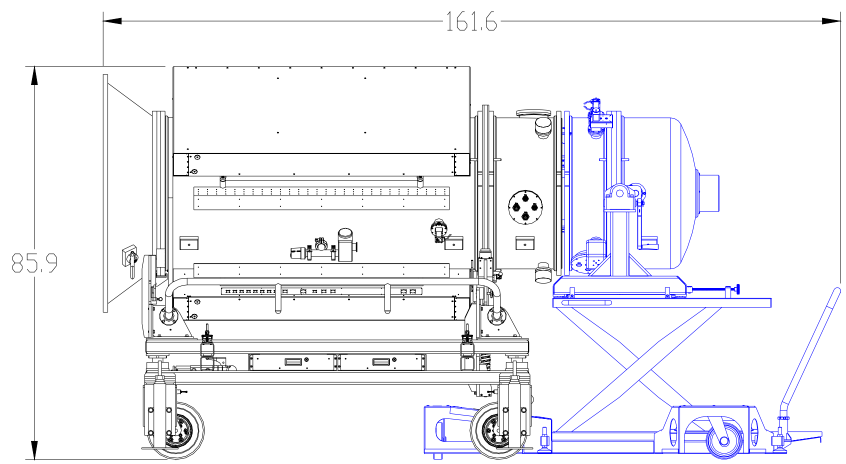
Cart 1 / Cart 2 Mate-Up



Cart 2

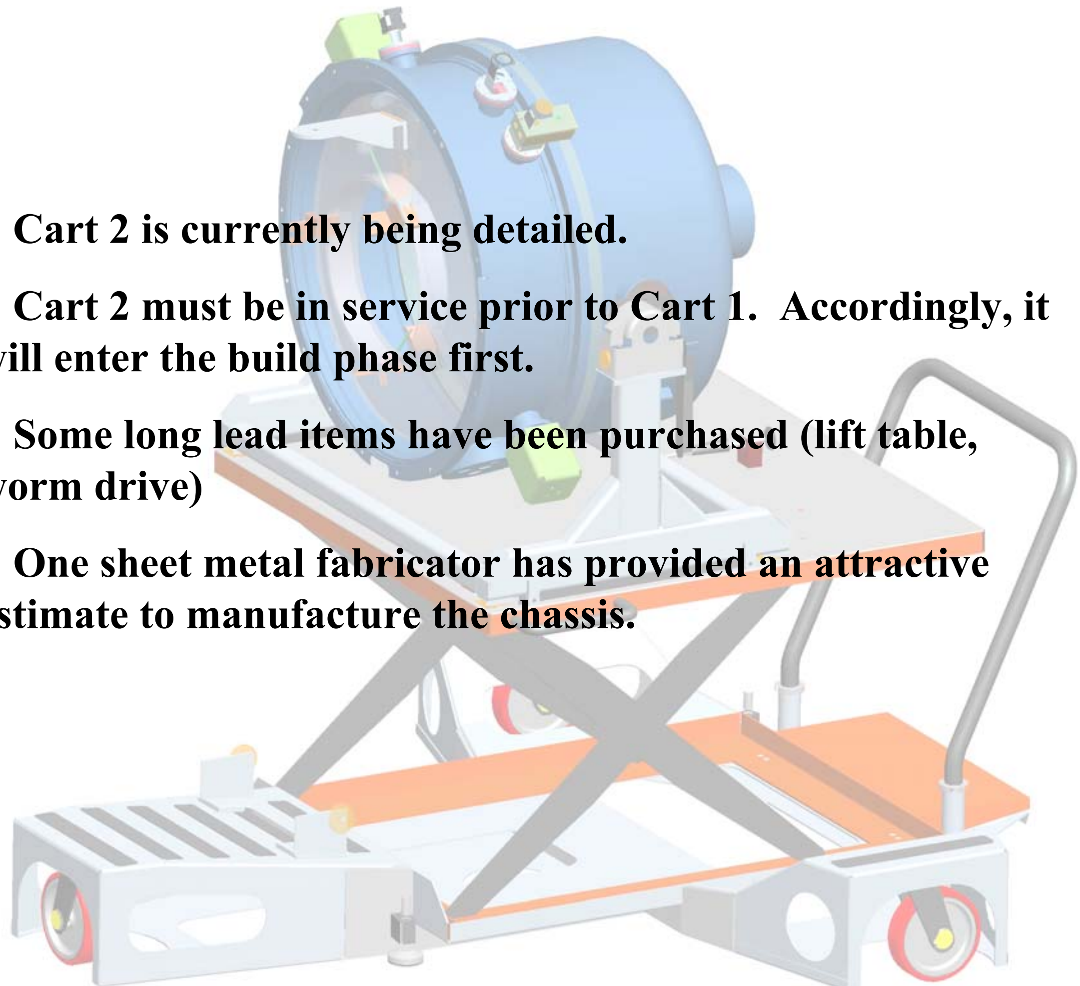
Cart 1 / Cart 2 Mate-Up





Cart 2

Status



- **Cart 2 is currently being detailed.**
- **Cart 2 must be in service prior to Cart 1. Accordingly, it will enter the build phase first.**
- **Some long lead items have been purchased (lift table, worm drive)**
- **One sheet metal fabricator has provided an attractive estimate to manufacture the chassis.**

TAB 11

11. Performance Criteria

There are many criteria by which the camera will be judged. The most important are the image quality, background levels, and throughput. Also important from a data reduction standpoint are stability of the camera electronics, read noise and dark current, and robustness of the overall camera/telescope interface. Robustness of all the subsystems is important, particularly the Data Refinery. Successful implementation of an automated data processing is particularly intolerant to defective image frames, even if they are relatively rare.

A guiding principle in the design has been the avoidance of internal dewar maintenance once FourStar has been mounted on the telescope. Assuming the instrument is producing quality science data and that any residual problems have satisfactory work-arounds which avoid internal maintenance, then FourStar will be a judged a success from this practical, but crucial, standpoint.

Performance Criteria

Image quality

1. Camera should deliver images close to the ZEMAX design spots in the lab, using tiny (<10 microns) light sources and FakeStar. Images should be in focus everywhere in the field (i.e., detectors are aligned properly).
2. If the above is true, then the Camera should not degrade the best seeing (0.21 arcsec FWHM at Ks measured at the telescope) by more than 0.03”.
3. Nothing should go wrong with the images as the camera rotates on the telescope. (This will have been checked in the lab.)
4. The focus across the field (at the telescope) should be the same.

Optics Performance (other than image quality)

1. The throughput for all filters as observed should be close to those calculated from vendors’ numbers.
2. The measured backgrounds (particularly Ks) should agree with expectations.
3. There should be no apparent ghosts, in agreement with the study.
4. The images should flatten properly with twilight flats; this shows that the telescope/camera combination is OK for flats.

Performance Criteria (cont'd)

Electronics Performance

1. Noise versus RWSC claims
2. Dark current is as expected (< 0.1 e/sec)
3. Patterns such as roll-off or interference
4. Noise as function of endpoints or up-the-ramp sampling
5. Use of reference pixel borders
6. Frame failure rate due to ASIC, Jade2, cables, etc

    Most of these will be explored in the lab; the different electrical environment in the telescope is the main thing of concern here.

System Robustness

1. lN2 auto-fill system (capacitive sensors for both dewars)
2. Dewar pressure
3. Focus tracking in practice
4. Electronics and computers in practice

Performance Criteria (concluded)

Motors, encoders, and controllers in practice

Data acquisition hardware and software

Ease of use of the data refinery in real time

That the observer actually does leave the observatory with fully reduced final data

TAB 12

12. Camera Integration and Test

The assembly of the camera components in Pasadena will follow a plan designed to test, modify (if necessary), and certify each in a logical order, with different sub-assemblies being worked on in parallel. Our goal in this is to ensure that the camera is working (in the lab) as well as we can determine, before it is packed up and shipped.

Much of the detector testing will take place in a small test dewar which can be cooled and warmed in 24 hours, and which will not require large amounts of LN2.

All the mechanisms will be first tested warm, then under computer control, then cold.

Optical alignment will be done in stages, with cold alignment being done last. All the mechanisms have been designed to allow placement and/or tip and tilt so that the alignment can be brought to well within the tolerances developed in the optical design phase.

The details are presented in the viewgraphs.

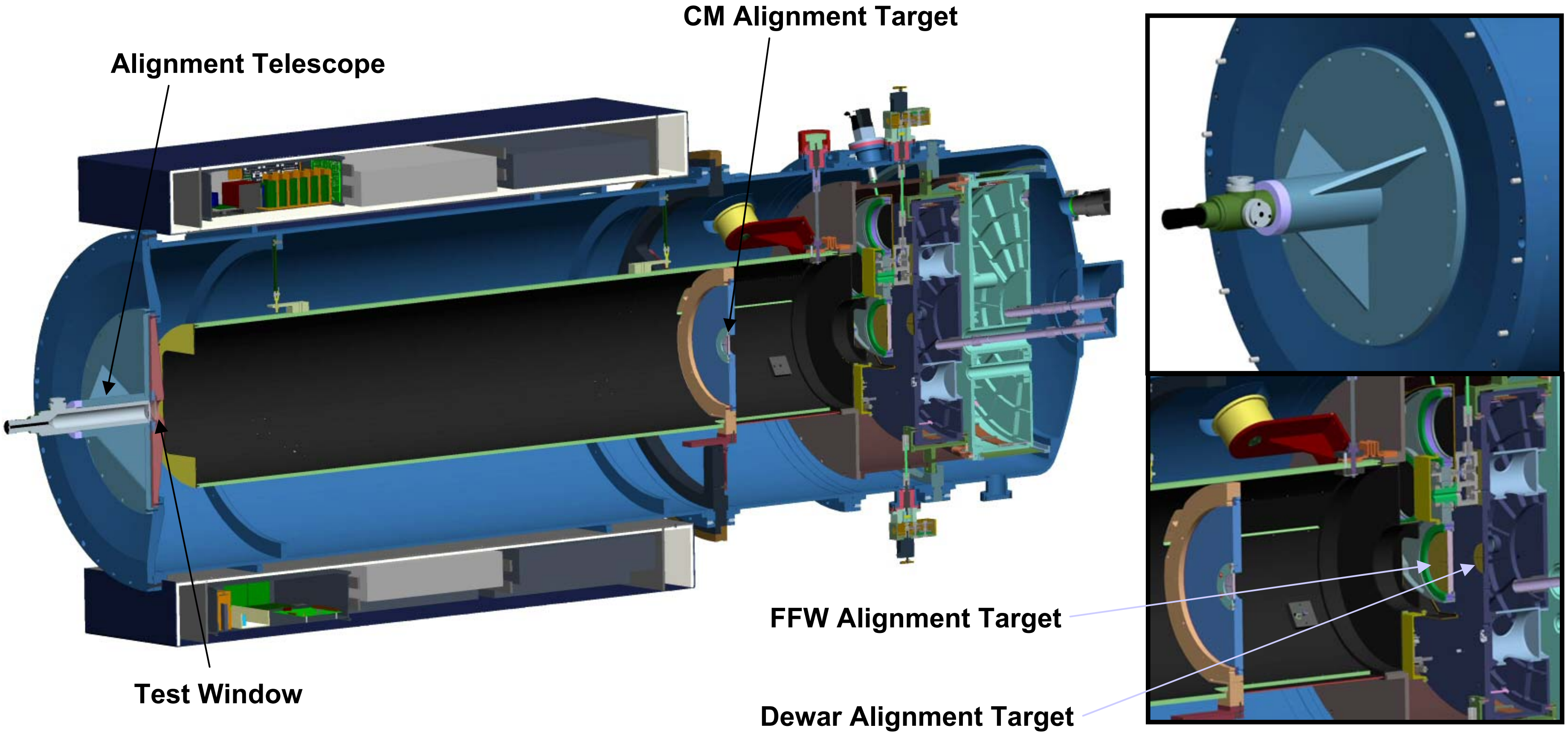
Camera Integration and Test

Overall plan is to completely certify operation before instrument ever leaves the U.S.

1. Vessel warm tests and first alignment of camera module and mechanisms
   - fit of all components
   - flexure and warm alignment of mechanisms
   - optical alignment is via an alignment telescope, reflecting targets, and our fixtures and built-in adjustments
   - do any and all necessary design/machining changes now

FourStar

Cold Alignment Configuration



Camera Integration and Test (cont'd)

2. Vacuum Test

- clean and prep for vacuum test
- vacuum integrity test (final inspection for virtual leaks, welds, O-rings)
- install temperature sensors, Al foil, and MLI

3. Mechanism warm tests

These go on in the lab, not yet installed in the instrument. They can be done in parallel with work being done on the dewars.

- filter wheels, field flattener wheel, detent mechanism, detector module, camera module fit, mechanical and electrical checkout
- computer control checkout of all motors/mechanisms
- warm alignment of TZM blocks

Camera Integration and Test (cont'd)

4. Mechanism cold tests #1

The back-end of the instrument is assembled on Cart 2; no optics are installed.

- Filter wheels, field flattener wheel, and detent mechanism are tested at 77K.
- Computer control is checked; now actual final cables are being used.

5. Test dewar, detector module, and detector tests

- Certify temperature control of test dewar
- Install Bare MUX, ASIC, make first cold tests
- Do the same for Engineering-grade detector

6. Test temperature control of camera module and light baffle

- Paint (Z-306) all critical surfaces for proper thermal exchange
- Determine nominal filling and thermal clamp procedures to bring camera module and detector module to operating conditions at about the same time (1.5 days)

Camera Integration and Test (cont'd)

7. Optical alignment (part 1)

Now cold, but no optics

- repeat warm alignment, but with these changes:
  - small vacuum window instead of L1/L2
  - cross-wire centered on camera module
  - KE targets are in field flattener wheel and detector module
- Make measurements of XY offsets and tip-tilts of each unit.
- Disassemble camera and apply corrections.
- Repeat the tests.

Camera Integration and Test (cont'd)

8. Optical Alignment (part 2)

- Insert engineering-grade FPA and check to see if alignment telescope beam can get a reflection off the surface.
- If so, cool dewar and measure tip-tilt of its TZM mounting block.
- Warm up dewar, insert optics, cool dewar and make first FakeStar test. This should confirm alignment telescope result.
- Warm up dewar, remove optics, insert science-grade FPAs and check coplanarity of detectors using alignment telescope.
- Adjust tip-tilt-piston of TZM blocks. Check with alignment telescope.
- Insert optics, cool dewar, and use FakeStar test to check tip-tilt-piston of TZM blocks.

9. Image Motion Tests

- As instrument is rotated on cart, FakeStar pinhole images should move on detector within spec.

10. Instrument can now be disassembled and shipped to Chile.

TAB 13

13. Data Reduction Pipeline (Refinery)

Requirements

Under normal weather and Ks background conditions, the amount of raw data accumulated during a night (devoted to Ks observations only) will exceed 100 Gbytes. These are 16-bit (double-correlated) frames, being taken at the rate of 4 per minute. For a several-night run, the writing of this much raw data on storage media will take considerable time. We have concluded, therefore, that it is essential to develop a pipeline that will reduce the data during the night and into the next day, such that the observer will be able to leave the mountain with data completely reduced to final form. Storing of the raw data will remain an option, but we intend to make the pipeline so robust that the raw data will seldom if ever need to be reloaded for re-reduction.

Prototype Tests

Operation of the pipeline in this way will require optimal computer hardware generous amounts of disk space. We have created simulated data and prototype code to assess these requirements quantitatively. The results are presented the viewgraphs. In addition to the main data reduction task, we will operate a small subset of the steps in quasi-real time, so that the observer can assess the quality of the data and the night (seeing, transparency, background).

Data Reduction Requirements

1. Observer has data completely reduced by the next day.
   - wcs is in header for each final stack of frames.
   - photometric zeropoints are in headers if possible.

2. Observer has quick-look tools available to judge quality of night and data in real time.
   - PSF, sky background, transparency, quick-look stacks.

3. Observer (or reducer) can influence how the refinery works at some small level, via a GUI-based overall control program.

4. Some fraction of the data are automatically archived.

FourStar Data Refinery

Daniel D. Kelson
OCIW

22 September 2006

JOHNS HOPKINS
UNIVERSITY

Data Refinery

Required Steps in Data Reduction

1. Linearize
2. Subtraction of Dark
3. Division by Flat
4. Quick “first-pass” subtraction of sky background[1]
5. Compute relative shifts between frames
6. Stack the “first-pass” sky-subtracted frames
7. Identify objects in this “deep” stack
8. Detailed “second-pass” subtraction of sky background where objects are now masked
9. Rectify and stack the “second-pass” sky-subtracted frames

[1]Background is a misnomer, as the source is foreground.

Initial calibration of the Data

1. Linearize
2. Subtraction of Dark
3. Division by Flat

These steps are computationally simple, and will occur as frames are readout. Each slave machine operates on the data from a single detector.

Doing these “on-the-fly” assumes that calibration data have already been taken, analyzed, and stored in a library (i.e. flatfields, darks, linearization curve, badpixel masks).

"First-pass" Sky Subtraction

4. First-pass subtraction of sky background

This task is comprised of several subtasks:

4a. Compute the median of each frame and store median in header.

4b. Divide each frame by its median and store these normalized copies of the data on disk.

4c. Every N frames (N≈30ish), take a median of the normalized versions of those N frames. These are normalized "first-pass"sky frames.

4d. Scale these "first-pass" sky frames by each image's median and subtract from the calibrated data

Note: "calibrated" means linearized, dark-corrected, flatfielded.

Getting the Relative Shifts

5. Compute relative shifts between frames

We also break this up into subtasks:

5a. Run SExtractor on the “first-pass” sky subtracted frames

5b. Use the header-stored telescope offsets as approximations for the frame-to-frame shifts and compute accurate shifts from the positions of those objects in the SExtractor catalogs.

Stacking the Frames

6. Create the “first-pass” stack of the data.

Using the frame-to-frame shifts derived by the previous task, create a median of the “first-pass” sky-subtracted frames.

No interpolation is required at this stage.

Accounting for the distortion may be required at this stage but has not yet been incorporated into our prototype.

Identify Objects in the First Stack

7. Run SExtractor on the “first-pass” stack.

This results in a deep catalog of object positions and simple object shape parameters (ellipses: a,b,theta).

The “For-Real” Sky Subtraction

8. Using the known object positions and shapes, construct new sky frames for subtraction of the background.

8a. Create masks for each frame, based on the object positions and shapes, and using the shifts computed earlier.

8b. Compute new medians for each frame, excluding the masked object pixels from the computation.

8c. Store new normalized copies of the data frames using these new medians.

8d. Compute a new sky frame for each exposure, by computing the mean of those exposures from the 3 loops before and the 3 loops after, and using the object masks derived above.

Note: Cosmic-rays can be easily excluded from the mean here as well.
Note: Using a mean instead of a median produces less-noisy sky frames

Get New and Improved Shifts

8e. Run SExtractor on the “second-pass” sky subtracted frames

8f. Use the header-stored telescope offsets as approximations for the frame-to frame shifts and compute accurate shifts from the positions of those objects in the SExtractor catalogs.

Make the Final Stack

9. Make the final stack of the data.

Note: Rectification of (removal of the distortion from) the data must be done when combining the frames into a final, clean version.

Note: Choice to make: stack directly into a final, large, All-4-Chip mosaic? Or make chip-by-chip stacks? *Undecided* right now...
but am leaning towards:

(1) Compute the WCS of what would be a mosaic of all 4 chips.
(2) Create chip-by-chip stacks that *could* be directly inserted into a big mosaic without any interpolation required.

In other words, some interpolation may be required in constructing a stack for a given chip (given the distortion). Thus we wish to then force the pixels of ALL chip stacks to have coordinates that are discretized at every, say, 0.16”.

This would leave users the option of stitching the chips together without worrying about adding a second interpolation.

Can the Data Be Processed Quickly

... or at least quickly enough to satisfy the < one-day turnaround requirement?

The short answer is: Yes

The long answer is: Yes, but we have some work to do.

Prototyping the Pipeline

A simulated dataset: Effectively a single detector's worth of data for one hour of telescope time:

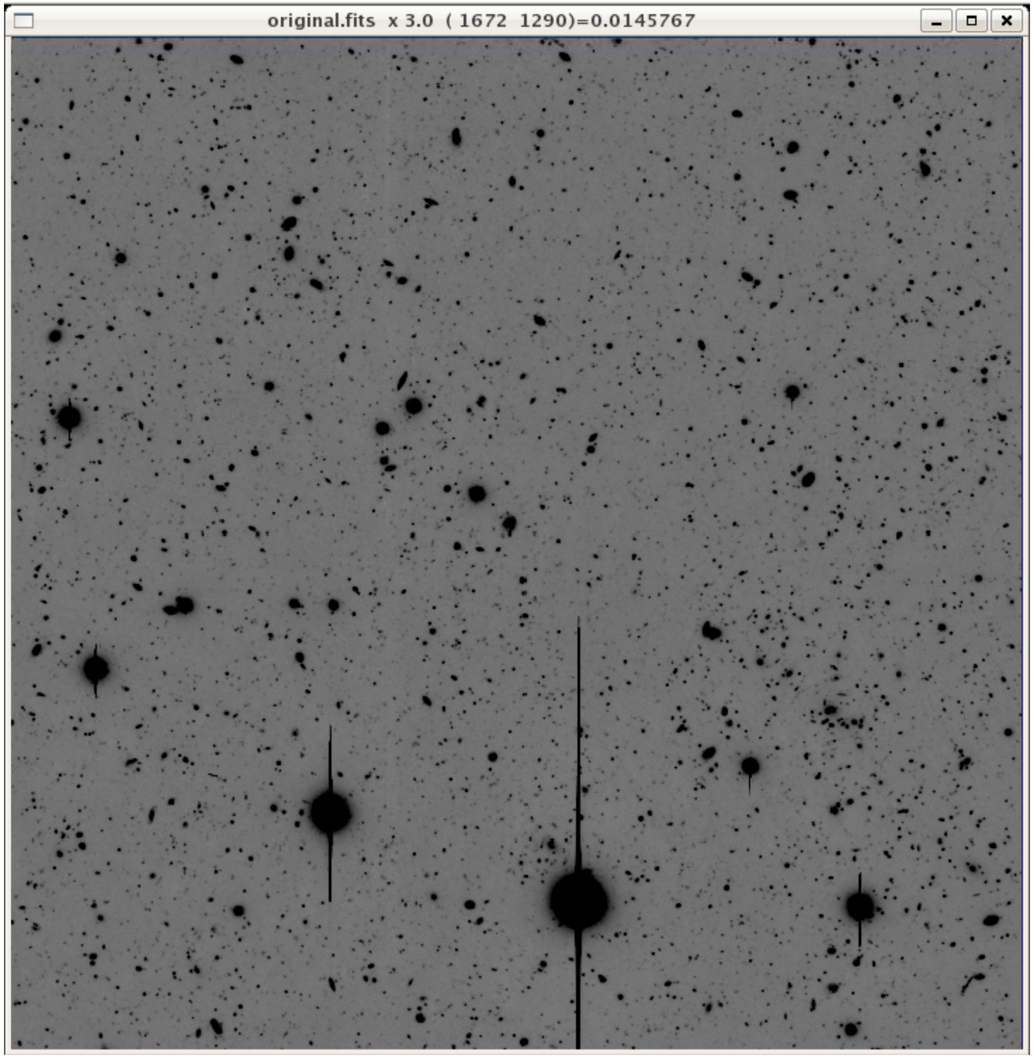
2048x2048 array
60 loops x 3 exposures per loop
15 s exposure time …. (75% dutycycle)
10" dither pattern
<<0.5" jitter in position for each exposure within a loop
Variable sky levels (with 1/4 period = 15min)
Cosmic rays (20-40 per frame) with exponential distribution
Fringe frame derived from H-band image from the IR camera on the duPont
Poisson noise (sky dominated)
Objects from a deep R-band Subaru integration (with 0.2" pixels, so not quite the FourStar pixel size but the seeing was 0.6" FWHM)

(Currently have not incorporated nonlinearity of detector, dark current, or flatfielding)

These 180 frames take up 3Gigabytes of disk space.

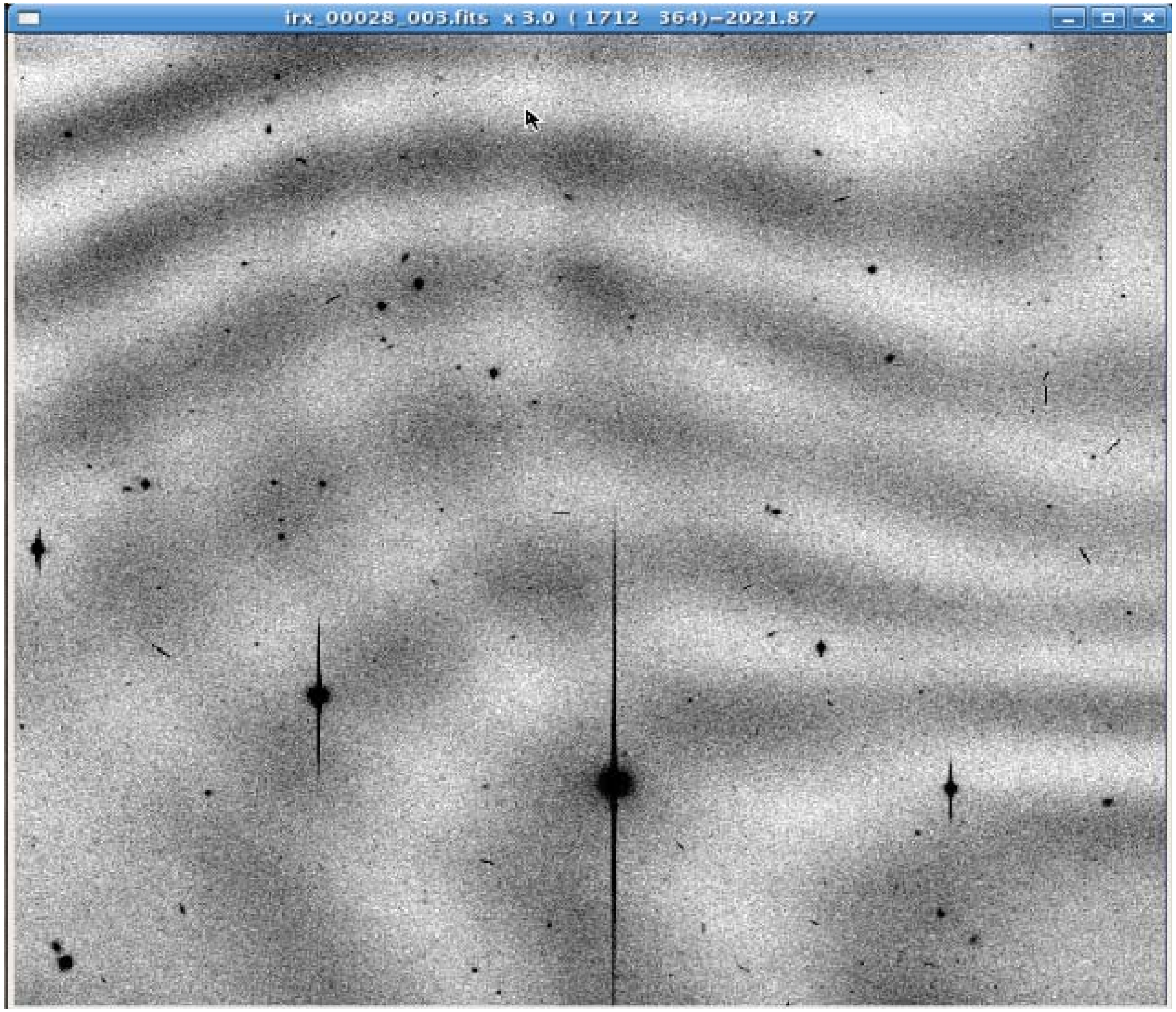
Data Refinery

The R-band Subaru Image (6960 s, SUPRIME)



Data Refinery

A Simulated Data Frame



Prototyping the Pipeline (steps)

(1) Compute medians and copy normalized frames to disk
(2) Compute first-pass sky frames and subtract from the data frames
(3) SExtractor the first-pass sky-subtracted frames and compute image shifts
(4) Stack the first-pass sky-subtracted frames using nearest pixel values
(5) SExtractor the first stack
(6) Create image masks and compute new medians, new normalized frames
(7) Compute running second-pass sky frames and subtract from the data frames
(8) SExtractor the second-pass sky-subtracted frames and compute new image shifts
(9) Create the final stack of the data

Not yet included: linearization, dark-subtraction, flat-fielding, corrections for distortion. (These are not expected to be big hits on CPU resources anyway)

Prototyping the Pipeline (software)

Pipeline prototype is currently written in Python.

CPU-intensive/array arithmetic performed in C/C++ using
(1) The “Numeric” module for Python and
(2) The Visualization Toolkit (VTK) library

Data I/O handled by CFITSIO library using SWIG-based wrappers, generated by D. Kelson

Classes are used to define the exposures. This facilitates writing the pipeline using functional programming techniques. Each operation/step in the pipeline is handled by class methods. This renders the various steps easily parallelizable (e.g. using the Twisted network programming module/libraries).

Intermediate steps are stored using header keyword/value pairs and additional FITS files (e.g. normalized copies of the data).

Prototyping the Pipeline (software)

The 3 Gigabytes of data (i.e. 1ish detector-hour of Ks data) generates an additional 15 Gigabytes of files. This will increase once calibration is included (i.e. by about 9Gb).

Note: All software derived from open source, freely available resources.

Timing is Everything

Without consideration for what steps will be run *on the fly* as data are read-out and written to disk.

This dataset represents a reasonable upper limit on the number of frames obtained in approximately 1 detector-hour.

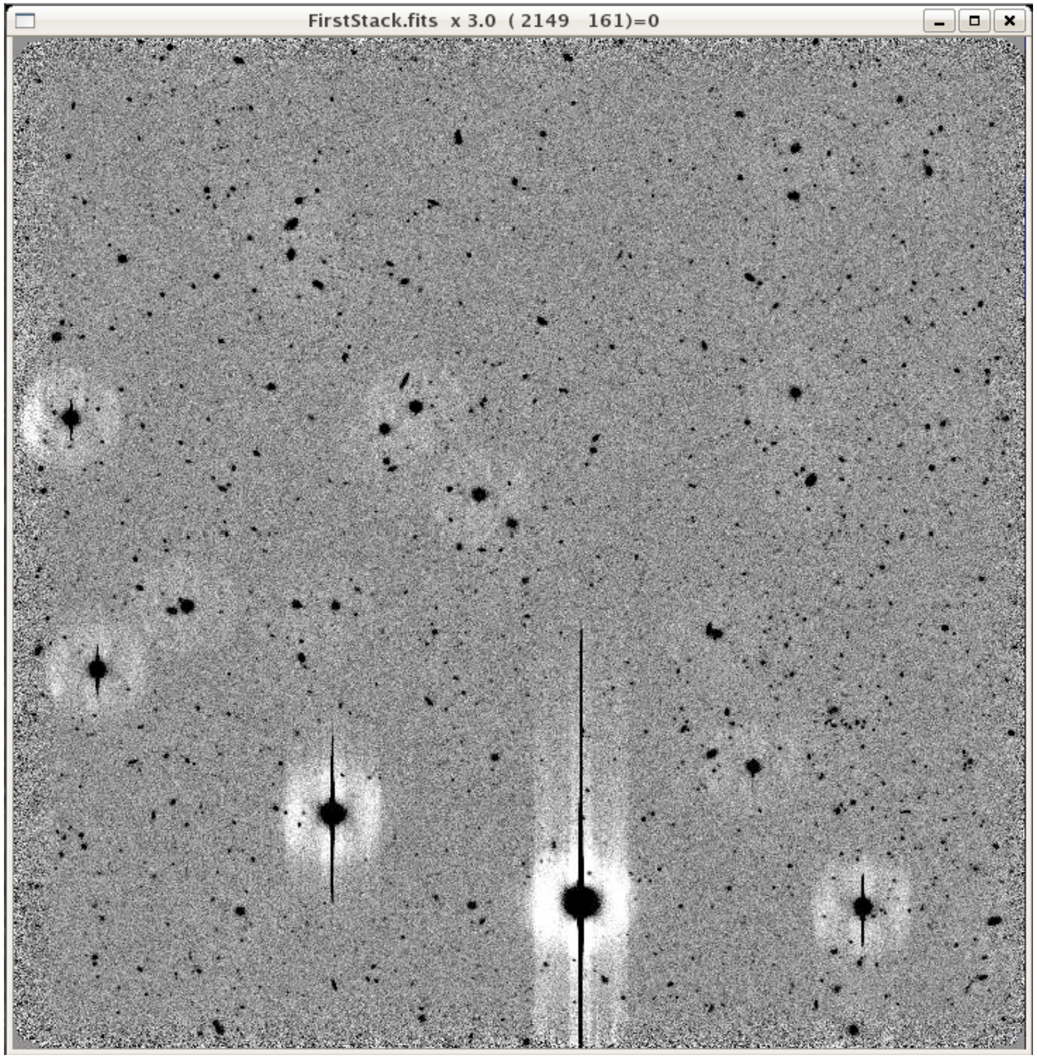
Pipeline prototype was run on a 3.4Ghz Pentium D (Dell workstation) with SATA drives. This represents a “worst-case” - code written in a non-optimized fashion, on a present-day non-souped up machine.

(1) 10 min: Compute the median of each frame and store normalized copies
(2) 10 min: Compute first-pass sky frames and subtract from the data
(3) 4 min: SExtractor the sky-subtracted frames and compute shifts
(4) 18 min: Shift and median the 180 first-pass sky-subtracted frames
(5) 15 min: Generate the image masks,compute new medians, new normalized copies
(6) 60 min: Compute running sky frames and subtract from data
(7) 4 min: SExtractor the new sky-subtracted frames and compute new shifts
(8) 18 min: Final shift and addition of the 180 second-pass sky-subtracted frames

Approximately <2.5h to fully reduce 1h of telescope time.

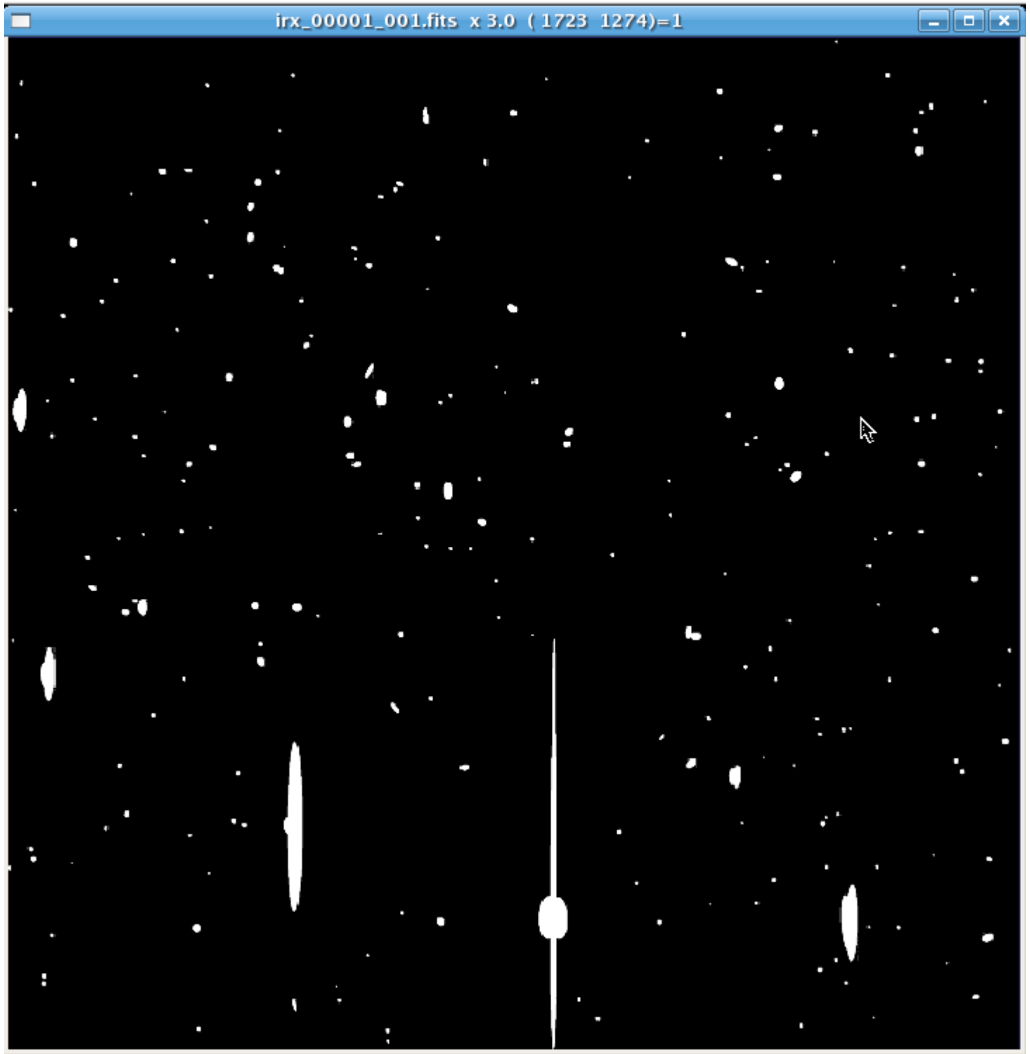
Data Refinery

The First Stack



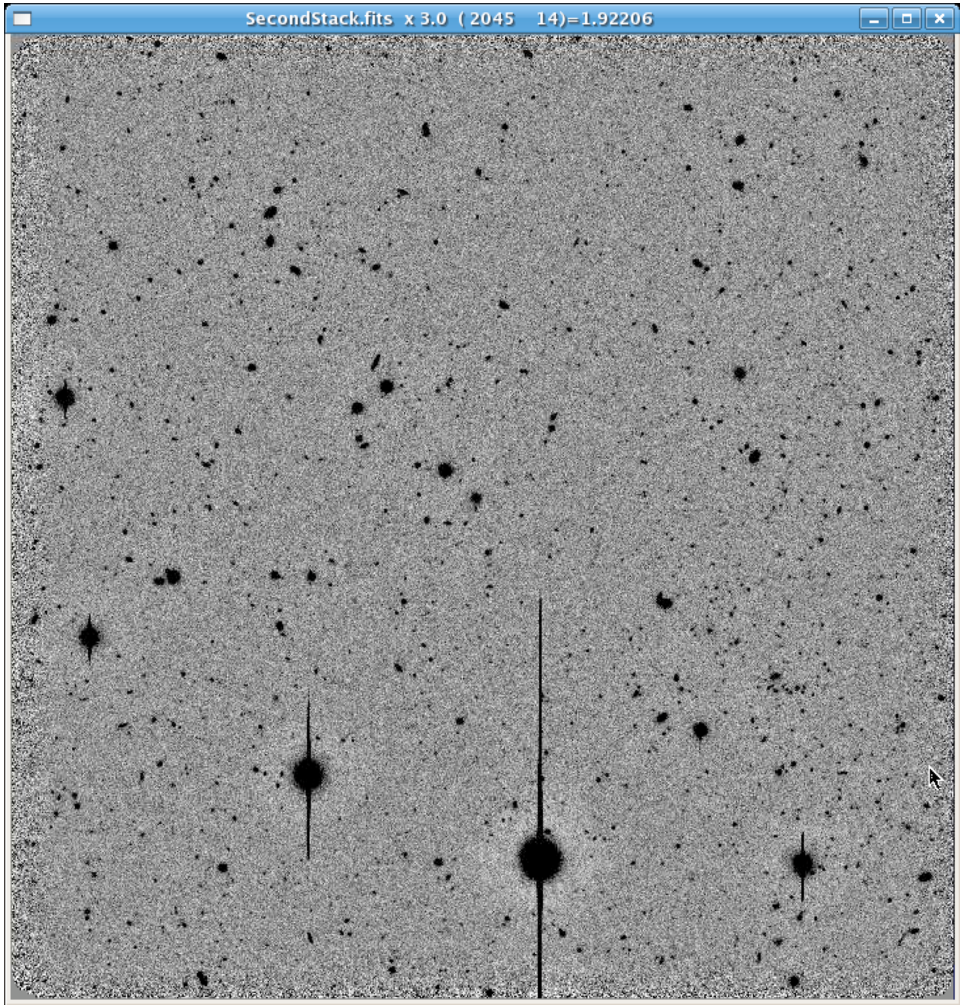
Data Refinery

A Sample Mask Image



Data Refinery

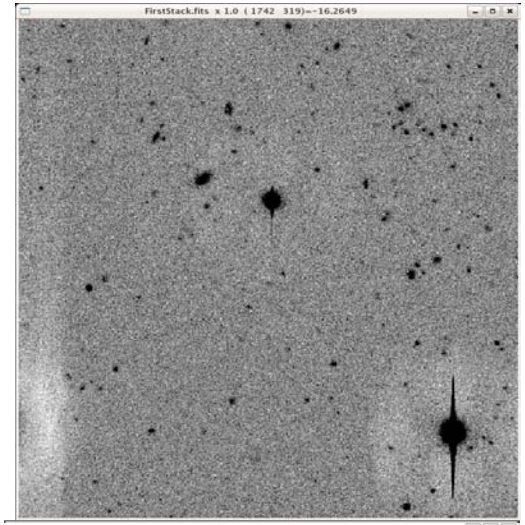
The Second Stack



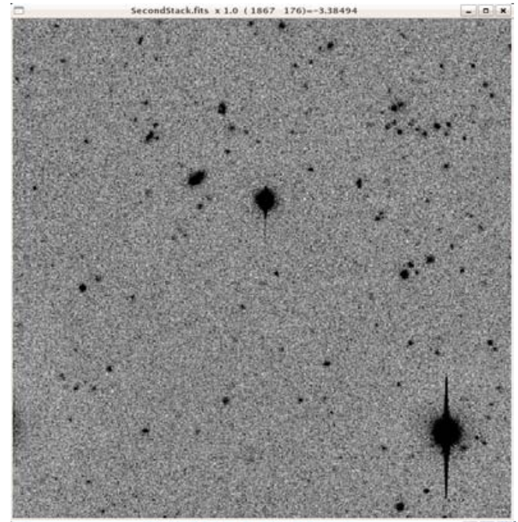
Leftover “halo” around bright star is 0.02% of sky

The First Stack vs the Second Stack

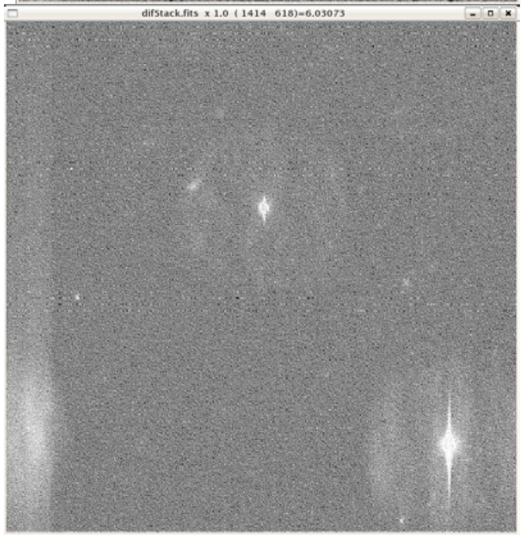
1st



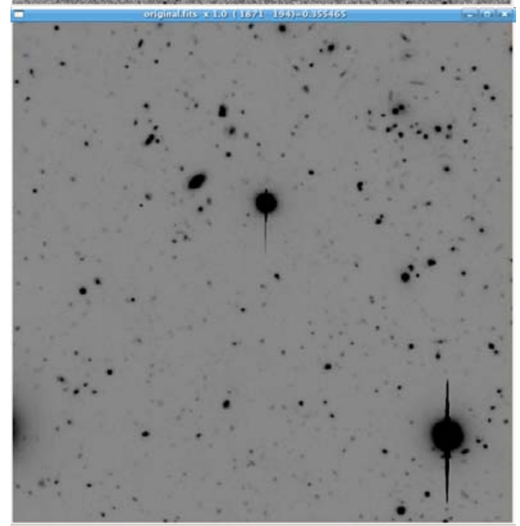
2nd



1st - 2nd



Original



Noise Check

The Poisson statistics of the (simulated) sky frame predict 7.45 electrons, while the final (second stack) image gives 7.65. In the final image, the stacking had 5-sigma clipping applied.

The noise difference may be due to the fringe frame variation which was inserted as a 50% p-p sinewave, which is quite conservative.

Speeding this up...

Speed gains will be obtained by:

(1) Running several steps “on-the-fly” as data are written to disk:
   a. Linearization (an O(n) operation)
   b. Dark correction (also O(n))
   c. Flat-field correction (O(n))
   d. Compute median and normalize frames (nlog(n))
      All four are easily completed before the next exposure is done. For example, Step d took about 2.5s per frame to execute. The other steps will take less time.

(2) Intermittent operations can also be done “on-the-fly”:
   a. Computation of first-pass sky frames every, 30ish exposures.
   b. Subtraction of the first-pass sky frames from calibrated data.
      Step a took about 85s each (there are 6 of these for the dataset).
      Step b takes <1s per frame.
      Thus, in total, Steps a+b essentially complete within “real time” since the executation is about 3 to 3.5s per frame.

(3) Running SExtractor and computing the image shifts also can be done in “real time” as the first-pass sky subtractions are completed.

Speeding this up...

The slow down comes with

(1) Generating the first-stack (was 18 min).

Bad for us:
Must wait until an adequate number of frames exist before this step can occur
Good for us:
The prototype has a moderate number of inefficiencies in the coding, given excess copying of arrays in the deep guts.
This means gains can be made by doing a little C-coding (using, say, Pyrex to do the hard work.
Gains can be made by simply increasing the number of processors as well, say, if the pipeline slave machines (remember there are 4) have multiple CPUs.

Worst-case scenario: Throw multiple processors at the problem for the factors of a few that we need. However, we expect gains from:
- Specialized code hand-written to eliminate the inefficiencies
- The faster processors of the future (we won't be running the pipeline on the machines of today)

Speeding this up...

Further slow down comes with

(2) Generating the “running” second-pass sky frames (was 60 min)

Bad for us:
Must wait until we can do a first stack so that we can get a good, deep object catalog for making the object masks.

Good for us:
Current code has inefficiencies that we expect to code away in C/C++.
Prototype had a shortcut in which we didn’t bother to identify/mask the cosmic-rays and thus had to code for a robust averaging of the sky. So we expect some gains by introducing masking of cosmic-rays.

Overall speed gains of a few should be realizable by dealing with the above two, on top of the expectation of faster (or multiple) processors.
This is currently the most intensive operation, the biggest bottleneck.

The remaining slow step is the creation of the second, final stack and we’ve already sped that code up on the previous slide.

Final Summary of Pipeline

1. Linearize (on the fly, fast)
2. Subtraction of Dark (on the fly, fast)
3. Division by Flat (on the fly, fast)
4. First-pass subtraction of sky background (on the fly, fast)
5. Compute relative shifts between frames (on the fly, fast)
6. Stack the “first-pass” sky-subtracted frames (not fast, but try to do this every 60ish loops)
7. Identify objects in this “deep” stack (fast)
8. Second-pass subtraction of sky background where objects are masked (bottleneck)
9. Rectify and stack the sky-subtracted frames (not fast)

The good news is that the prototype will be the backbone of the real pipeline. It is currently about 530 lines in Python using standard numerical libraries.

With some modest coding efforts, some simple parallelization, and improvements in processor speed, we expect to produce final reductions of a night of data before astronomers leave the mountain on the Bus Blanco at 2pm.

TAB 14

14. Infrastructure

The weather environment at Las Campanas Observatory is benign, but the relative humidity can dip to levels of only a few percent. The wind can be strong, and dust is a problem. The infrastructure improvements necessary to ensure the safety of the camera, its optics and detectors are of utmost importance. The improvements will include the construction of a new support building at Las Campanas. It will serve the needs of FourStar in having a large clean room and lab with ESD workstations so that the instrument can be unpacked and reassembled after shipping in an environment much like that in Pasadena.

TAB 15

15. Schedule and Status

TAB 16

16. Budget