Design and Status of the DES All-Sky IR Cloud Camera

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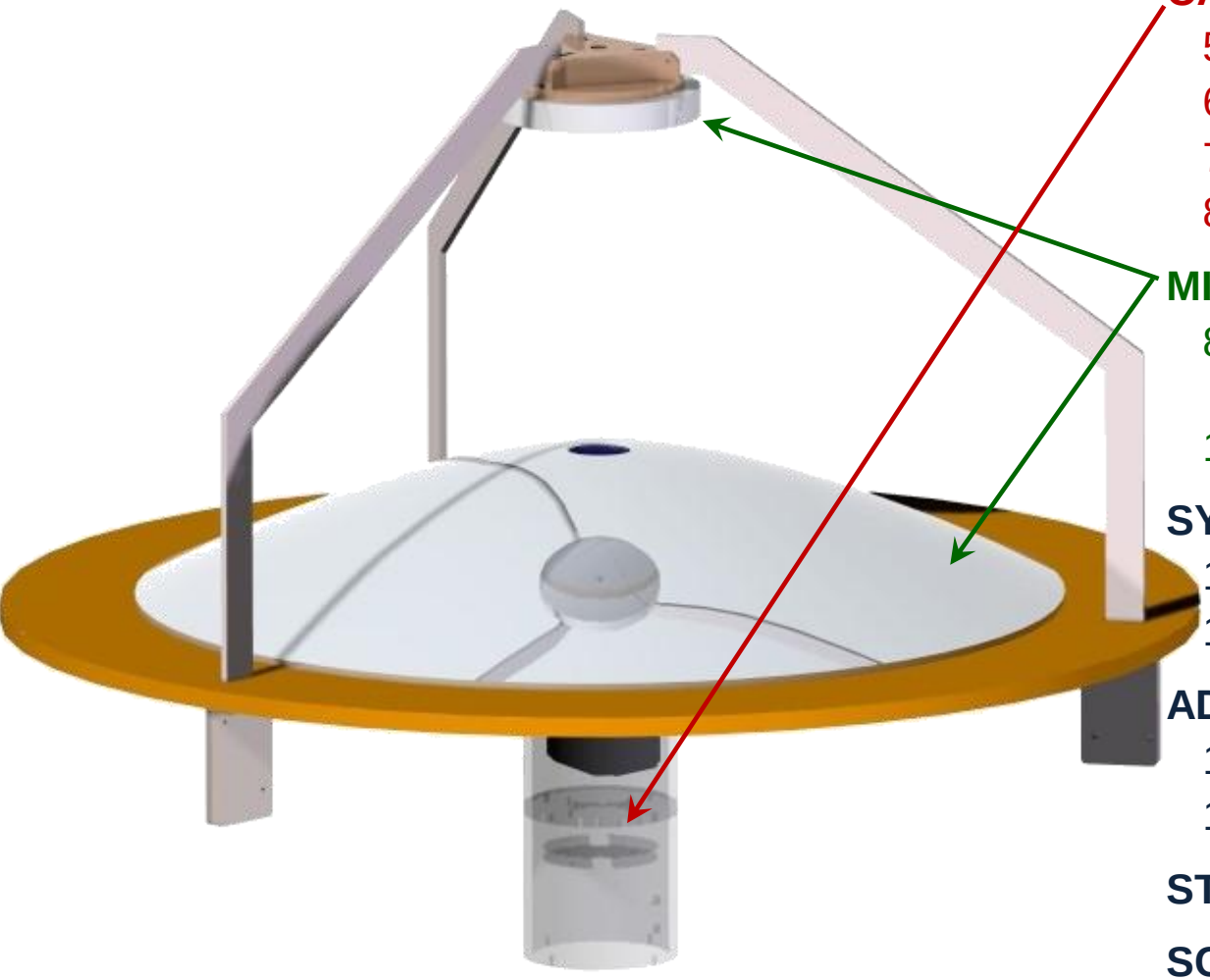
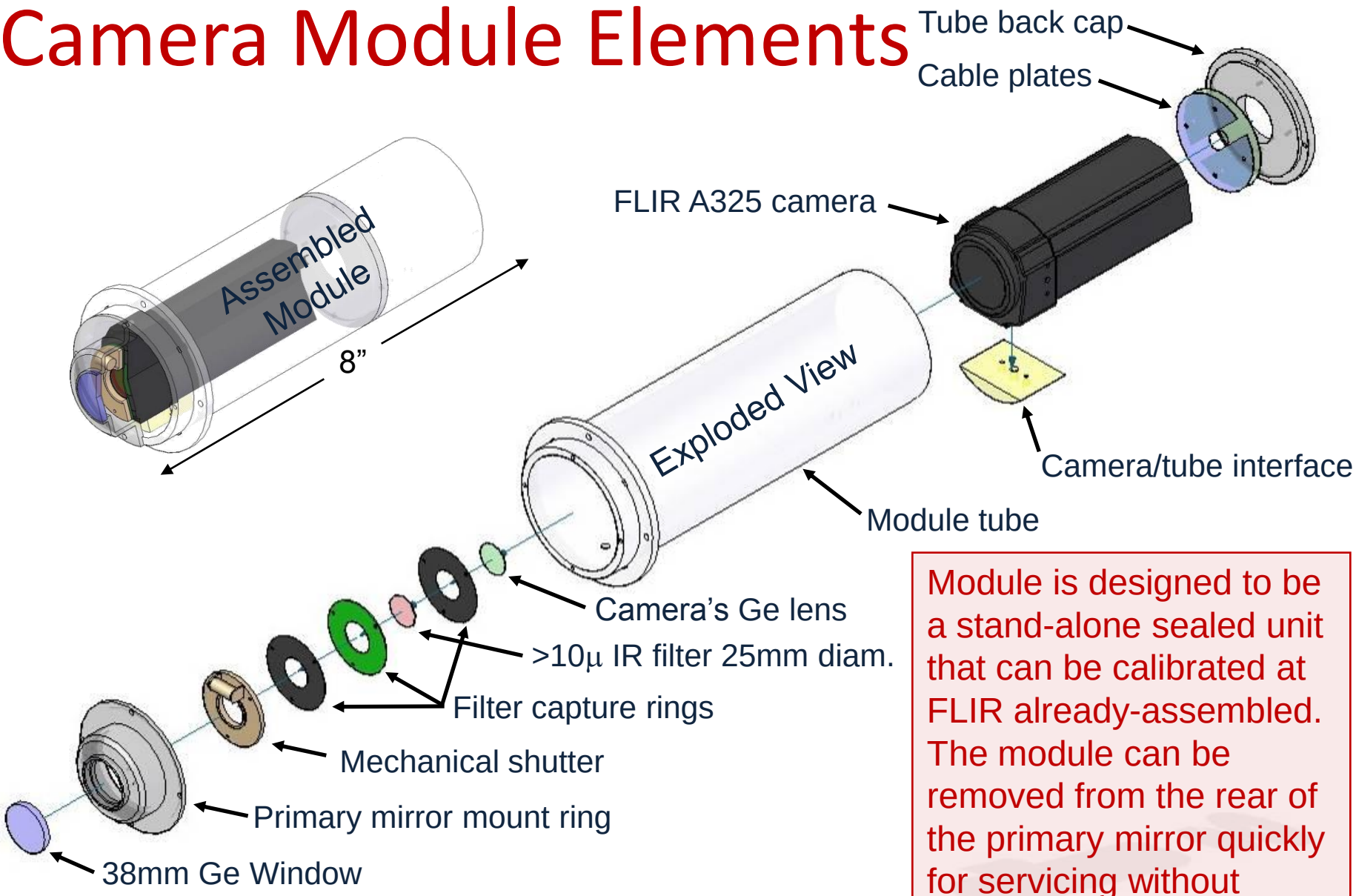
Outline / Design Overview



Cloud Camera Concept

- Quantify the presence of thin high altitude (~8-10km) cirrus clouds and contrails over a large fraction of the night sky
  - Clouds radiate in IR and thus appear hot, sky appears cold
- The Cloud Camera design is based on a two-mirror "equiresolution catadioptic" system:
  - Equiresolution: solid angle imaged does not vary from pixel to pixel
  - Catadioptic: system mixing mirrors and lenses
- A long-wave-pass IR filter in conjunction with camera's IR response will be used to enhance cloud/sky contrast and reduce atmospheric fluctuations
- Absolute thermal calibration, internal or external
- All-sky coverage

Camera Module Elements



Module is designed to be a stand-alone sealed unit that can be calibrated at FLIR already-assembled. The module can be removed from the rear of the primary mirror quickly for servicing without exposing filter and lenses to damage

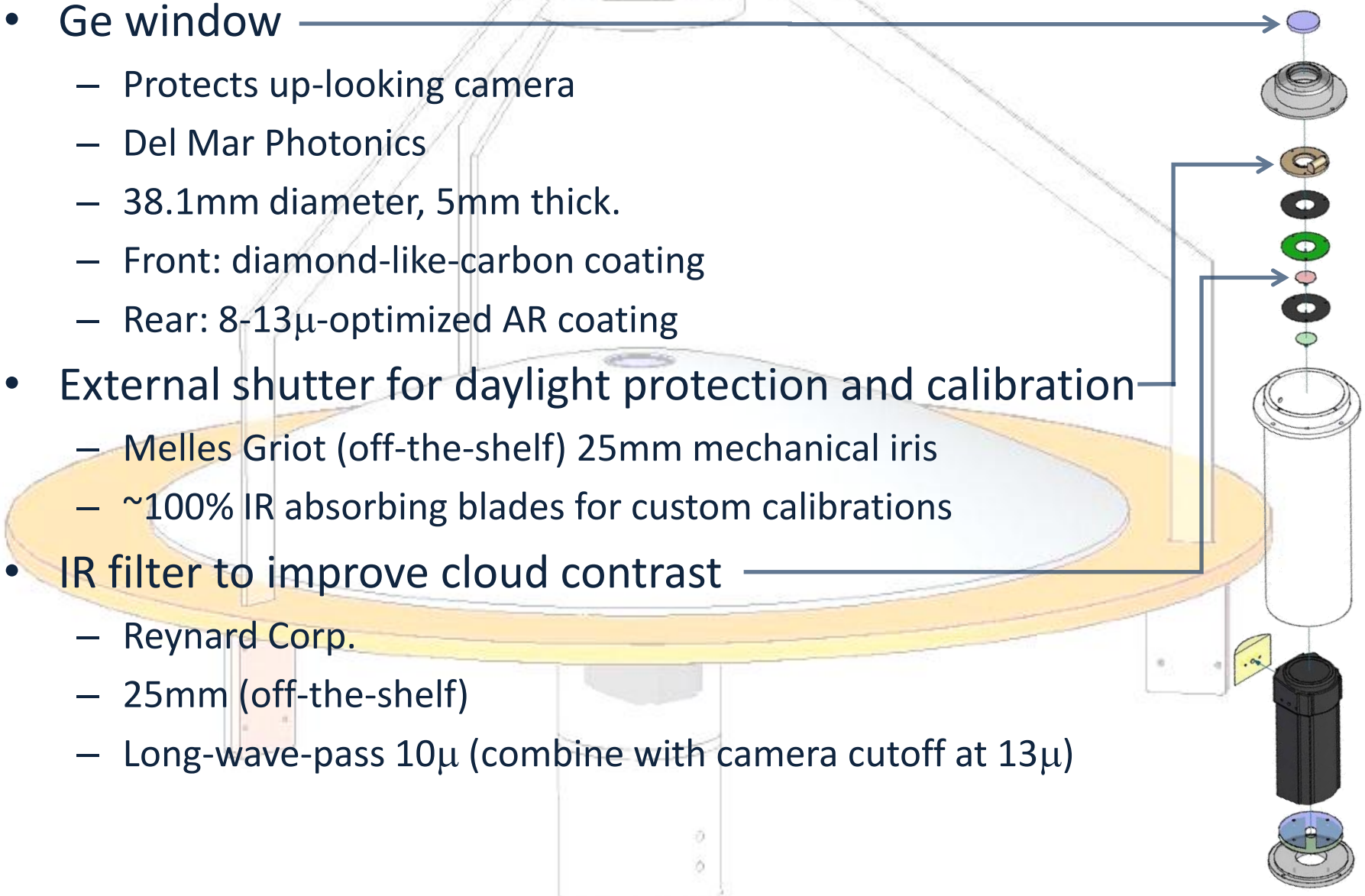
Camera: FLIR A325

FLIR A325 Properties

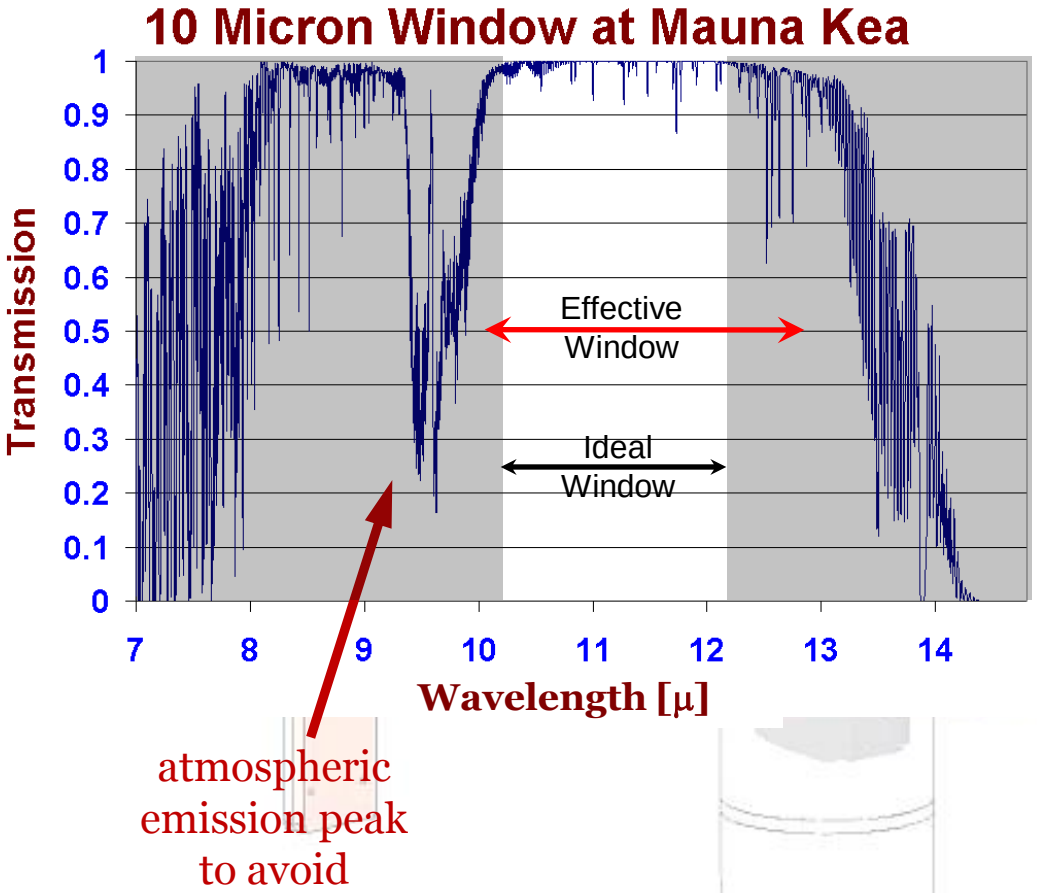
- 240x320 pixel uncooled Si microbolometer array
- Thermal Noise NETD ~ 50mK
- Effective noise after co-addition of frames $NETD_e \sim 6mK$
- 25°x18.8° FOV Lens
- Self-calibrating with internal shutter
- FLIR can recalibrate with our additional optics
- 60 Hz radiometric 16-bit digital output via GigE Ethernet
- Software for control and data handling
- **Industry's first, only radiometric [calibrated temp. output] microbolometer camera → greatly expanded array of data products possible**

Camera Module Other Elements

- Ge window
  - Protects up-looking camera
  - Del Mar Photonics
  - 38.1mm diameter, 5mm thick.
  - Front: diamond-like-carbon coating
  - Rear: 8-13μ-optimized AR coating
- External shutter for daylight protection and calibration
  - Melles Griot (off-the-shelf) 25mm mechanical iris
  - ~100% IR absorbing blades for custom calibrations
- IR filter to improve cloud contrast
  - Reynard Corp.
  - 25mm (off-the-shelf)
  - Long-wave-pass 10μ (combine with camera cutoff at 13μ)



IR Filter



Optimal window shown in gray is 10.2μ -12.2μ

Camera sensitivity: 8μ -13μ

IR long-wave-pass filter > 10 μ

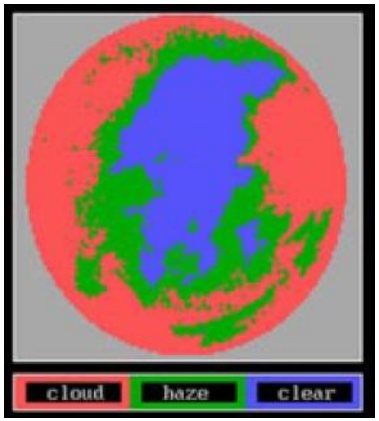
→ **Effective window 10μ -13μ**

NOTE: We chose the available IR Filter as a cost saving measure ($1.2K vs $7.5K for custom filter)

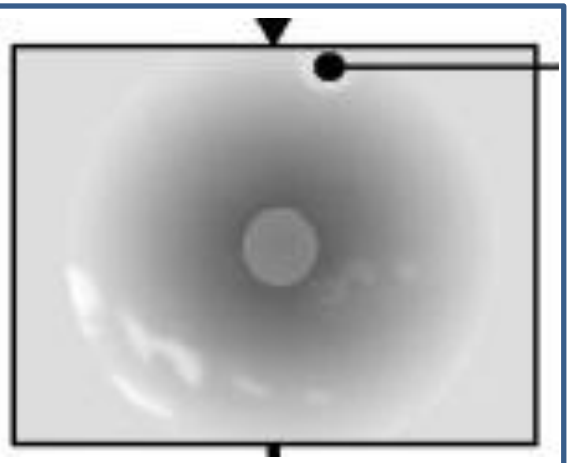
Mirrors: Equiresolution Property

- Microbolometers
  - Collected radiation measured as change in resistance
  - Power absorbed per pixel measured in counts
  - Counts→T mapping [calibration] is 4th order poly

→ Assumes each pixel sees the same solid angle ["equiresolution"]. In general this will not be true:



SLR2000 no flattening



MAGNUM pre-flattening

Previous instruments ignored or flattened out effect

Flattening requires clear-sky flat field which does not correct nonequiresolution in clouds.

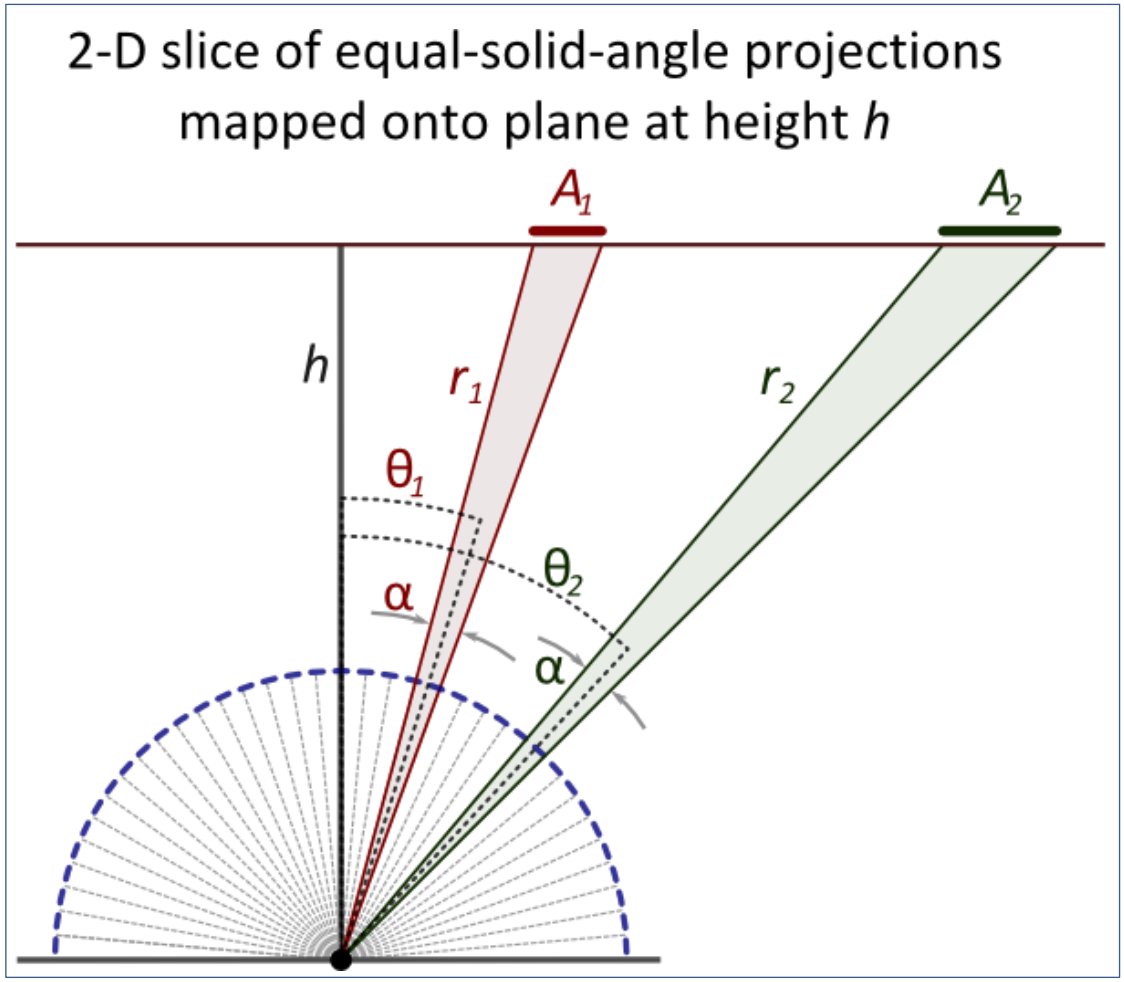
In order to use absolute T in data products, we must have flat field.

And, critically, flattening bypasses the pre-calibration of the camera.

→ Mirror system must be equiresolution

Equiresolution Applicability

- Equiresolution maps pixels to uniform solid angle grid
- Is this a good model for the sky?
- Will a uniformly-lit infinite plane at a height *h* appear uniform when imaged?



Assume pixels square and small enough that A_j are square:

$r_j = h/\cos\theta_j$

$A_j \approx (r_j \sin\alpha)^2$

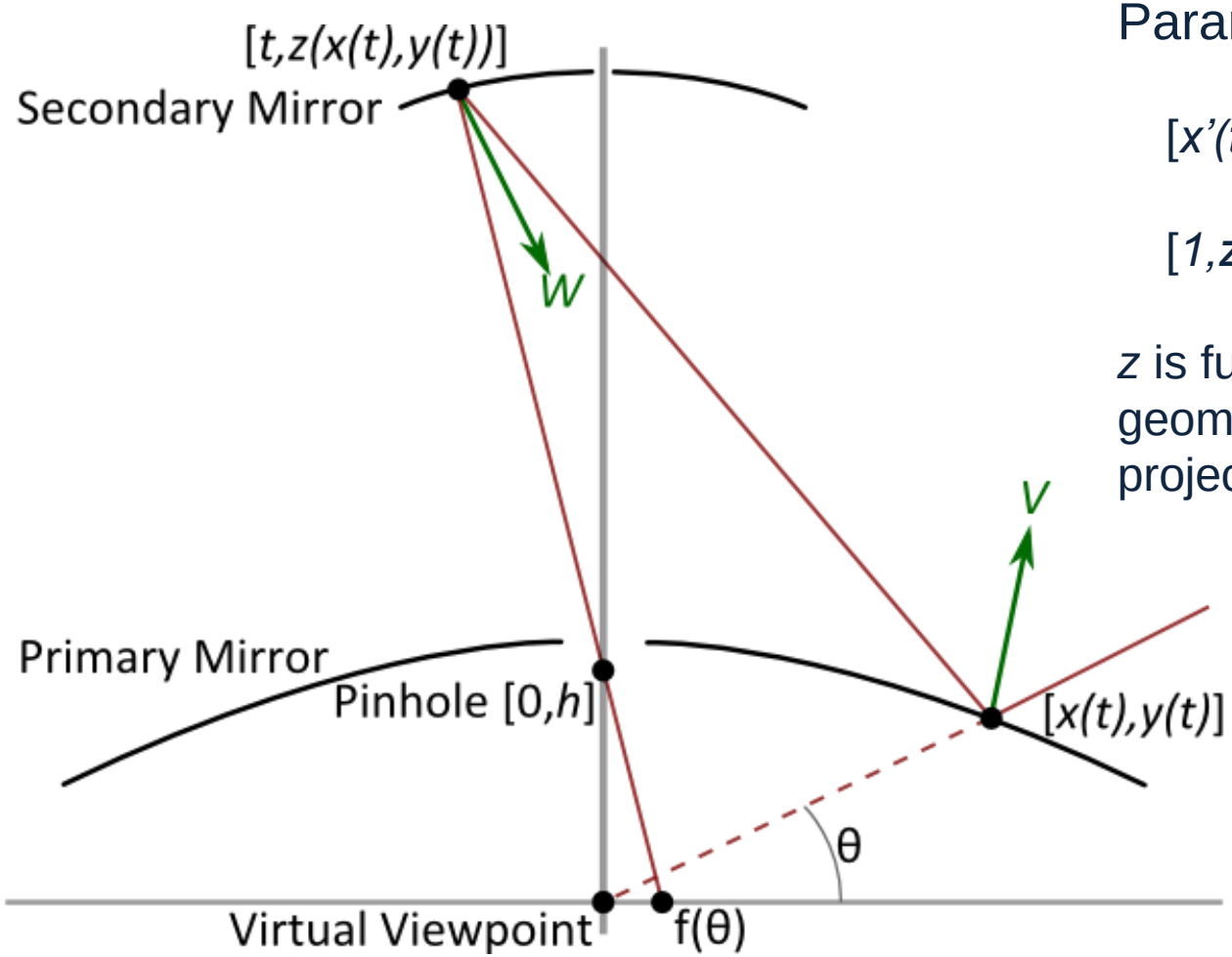
Pixel counts ~ $A_j / r_j^2 = \sin^2\alpha$

Counts do not depend on polar angle ⟶ a [Lambertian] plane source will yield flat response in equiresolution sensor with small pixels.

How good is small pixel approx? Numerical integration with thin clouds at 10km and real pixel size shows deviation in flux of less than 0.001%.

The Equiresolution Projection

- Model system as central projection [see Hicks, Millstone, Daniilidiis, 2006]



Parametrized ODE's:

$[x'(t),y'(t)] \cdot V = 0$

$[1,z'(t)] \cdot W = 0$

z is function of f, x, y by way of geometry, with [this is the projection]:

$f(\theta)=\alpha[2(1-\cos[\pi/2-\theta])]^{1/2}$

Very messy, not analytically solvable; numerical methods used in Mathematica.

Solving For Equiresolution System

- Mathematica code for solution can be found at:
  - http://stanford.edu/~pltrogon/DoubleMirrorProfilePDF4.pdf

Primary constrained to 24” diameter, 4” thickness

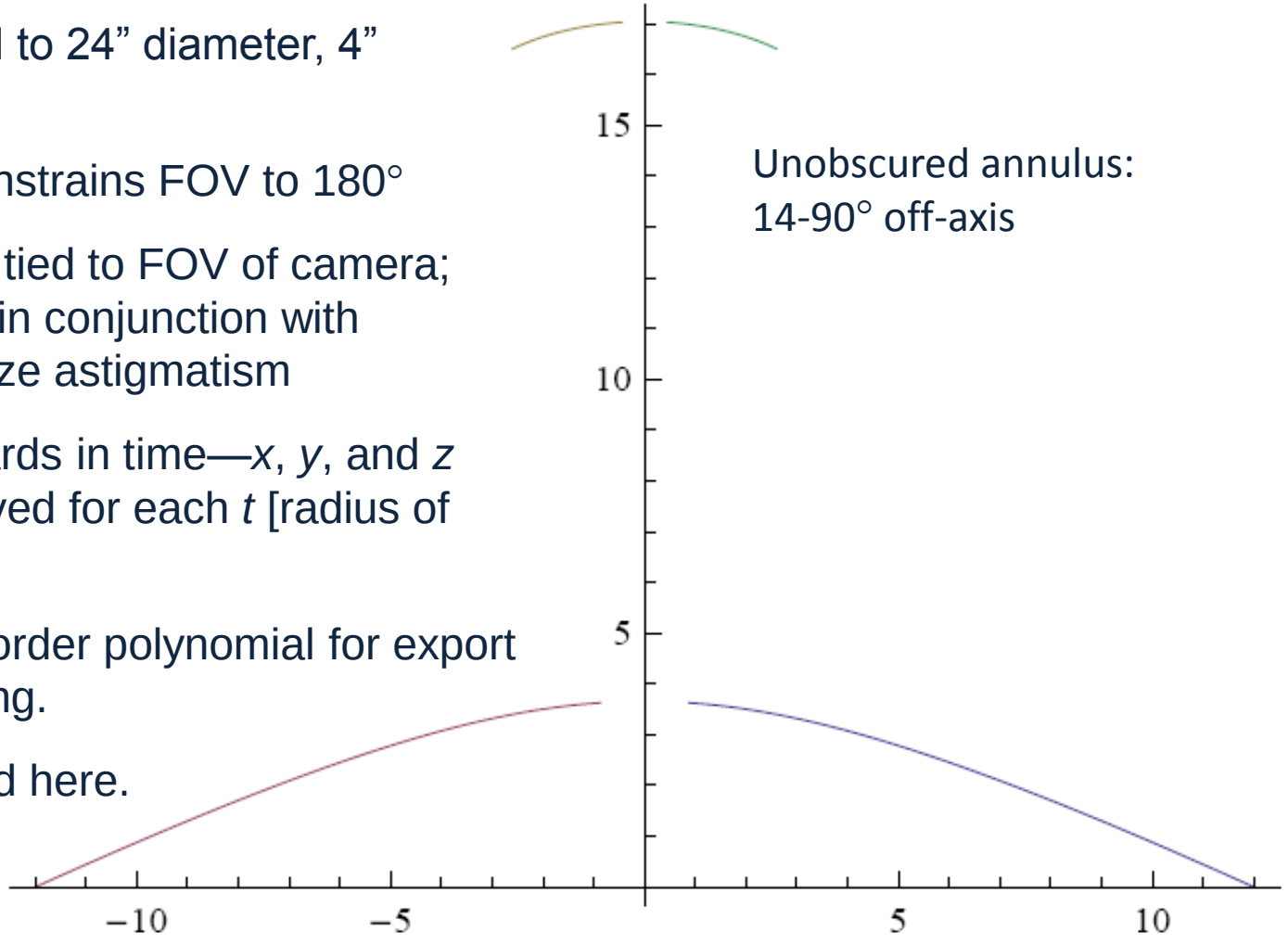
Setting $y(t_{max})=0$ constrains FOV to 180°

Secondary standoff tied to FOV of camera; diameter optimized in conjunction with raytracing to minimize astigmatism

Only solves backwards in time—*x*, *y*, and *z* coordinates are solved for each *t* [radius of secondary]

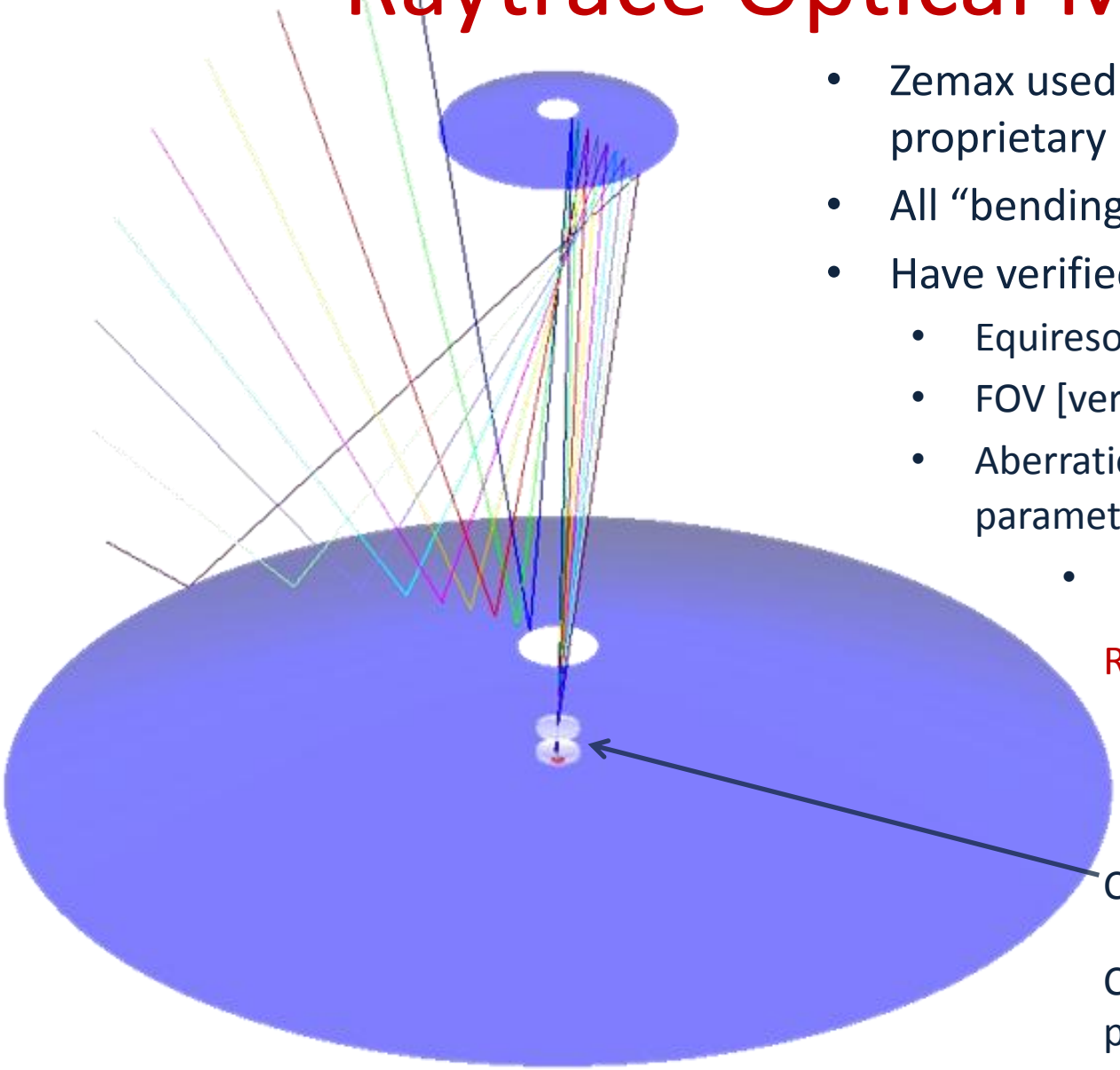
Solution fitted to *N*-order polynomial for export into Zemax raytracing.

Final solution plotted here.



Unobscured annulus:
14-90° off-axis

Raytrace Optical Model



- Zemax used to verify optics, including proprietary FLIR A325 lens figures
- All “bending” optical elements included
- Have verified:
  - Equiresolution
  - FOV [verified by raytrace on left]
  - Aberrations, distortions within parameters
    - Optimal camera height

Rays incident every 10°, aimed at virtual viewpoint. Marginal rays [90° and 14°] verify FOV.

Camera lenses.

Common crossing point at the pinhole verifies fit and solution.

Equiresolution Verification

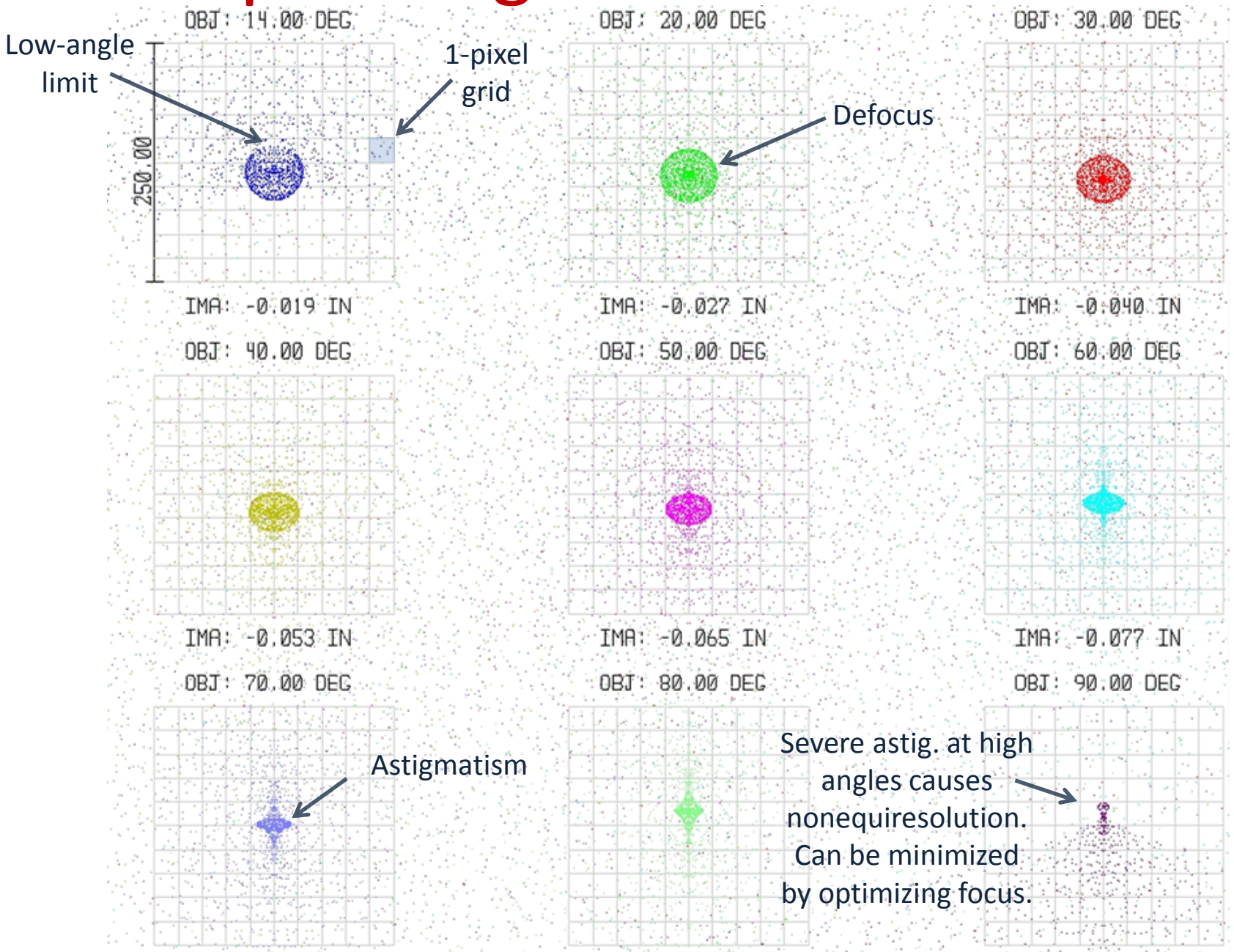
- Equiresolution:
  - All equiresolution bets are off once camera is thrown in
  - "Relative Illumination" plots radial slice of normalized illumination projected through optics onto sensor by infinite Lambertian plane. Equiresolution is verified if plot is FLAT:

Within FOV, deviation is less than 3%, which is diluted by counts→T function $\mathcal{O}(T^4)$.

Deviation can be further minimized by optimizing camera position and focus with camera in-hand.

→ With camera inserted, system is still equiresolution "enough"

Spot Diagram Verification



System Organization

Camera

Control Interface

Conduit

Outddor Site

Control Room

CPU

To LAN

RAID

USB/Ethernet adapter

Ethernet/fiber interfaces

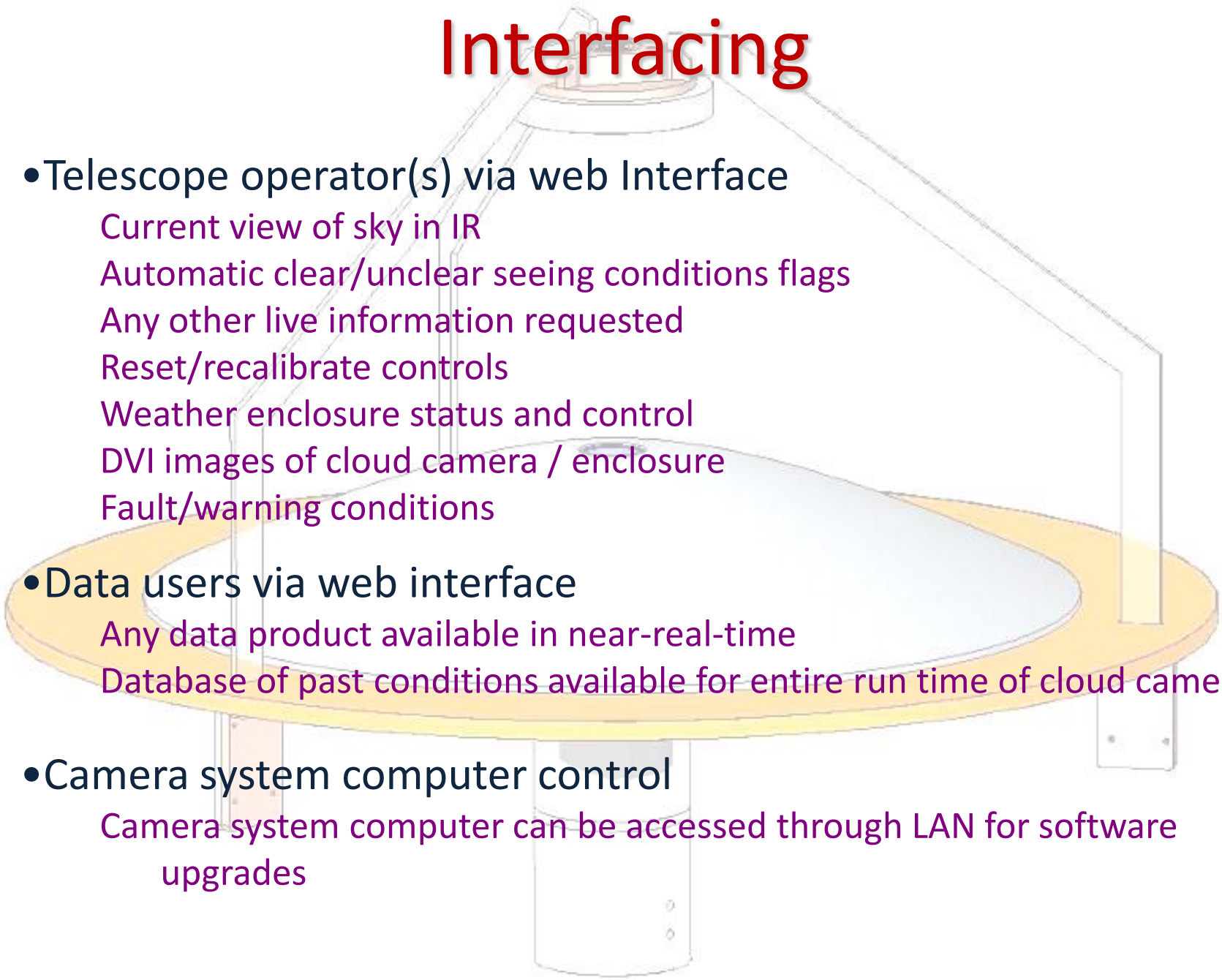
GigE Ethernet

1000BASE-SX fibers

USB

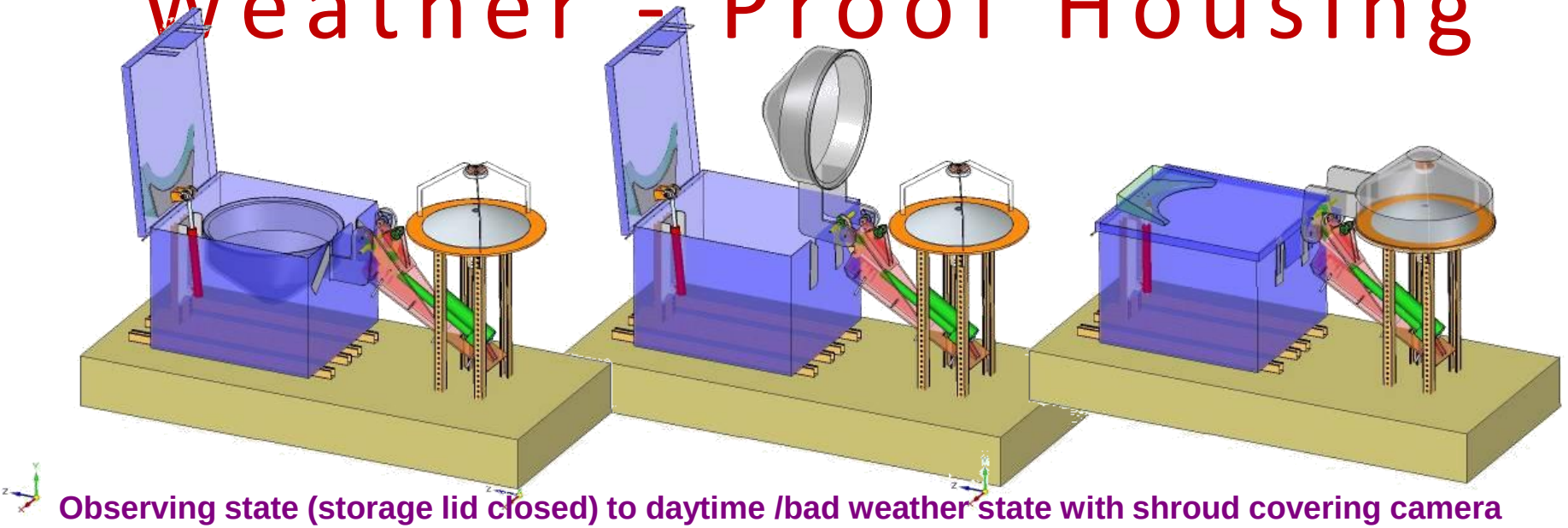
Power

Interfacing



- Telescope operator(s) via web Interface
  - Current view of sky in IR
  - Automatic clear/unclear seeing conditions flags
  - Any other live information requested
  - Reset/recalibrate controls
  - Weather enclosure status and control
  - DVI images of cloud camera / enclosure
  - Fault/warning conditions
- Data users via web interface
  - Any data product available in near-real-time
  - Database of past conditions available for entire run time of cloud camera
- Camera system computer control
  - Camera system computer can be accessed through LAN for software upgrades

Weather - Proof Housing



Observing state (storage lid closed) to daytime /bad weather state with shroud covering camera

- The concept has been CAD modeled in detail to verify motion/interferences
- The shroud will be a fiber/foam composite
- Two actuators (12v DC) will drive the lid and the shroud
- Limit switches will control extremes of motion
- USB interface will control motors (via solid state relays) and sense state of lids
- Physical safety barriers for moving parts, & audible alert when operating.
- Digital video camera will provide visual feedback of system state to operators

STATUS:

Two actuators, USB interface+hub, ss relays, composite matls./epoxy ordered or in hand.

Need to order motor power supply + relays, limit switches and misc materials

Need to complete mechanical drawings of parts & fabricate

Concept For Raptor- and Snow-Proof Housing

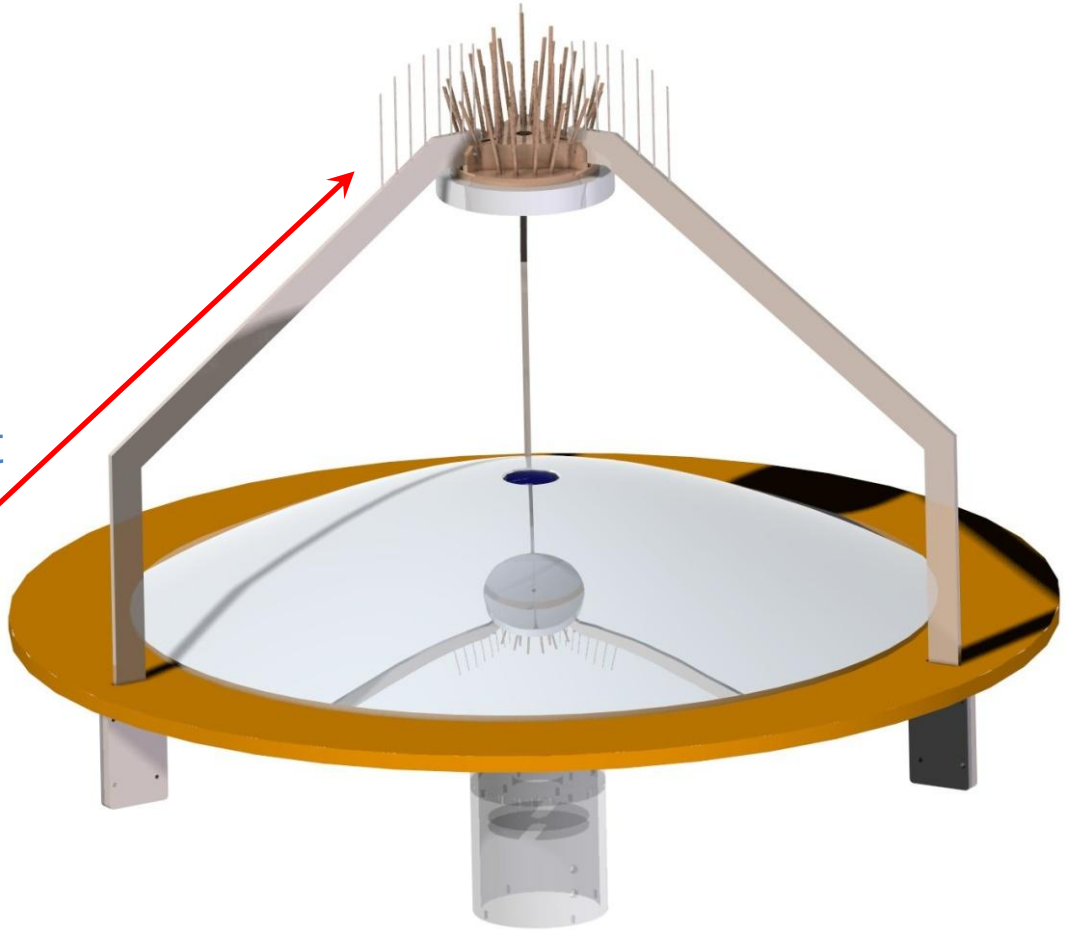
Design measures to protect against damage from condors [~20-30 lbs] using device as perch and to strengthen against snow load:

Reinforcement:

- Thicker struts
- Thicker weather enclosure
- Upgraded secondary mount

Deterrent:

- Blunt spikes on struts and secondary



Status of Computer & Control Hardware

- Optiplex 960 for camera control and image processing
  - FLIR software loaded and working
  - LabVIEW software loaded and working
- Thecus Network RAID Drive (5 X 1 TB) attached (for data backup & external data access)
- GigE ethernet to 1000Base-SX fiber converters ordered
- USB to ethernet converter ordered
- Cole-Palmer USB control interface
  - 8 TC readouts and 8 Digital I/O channels
  - Thermocouple readback, motor controls, limit switch readback, external shutter control, external calibrator control, etc.)

Mirror Fabrication Status

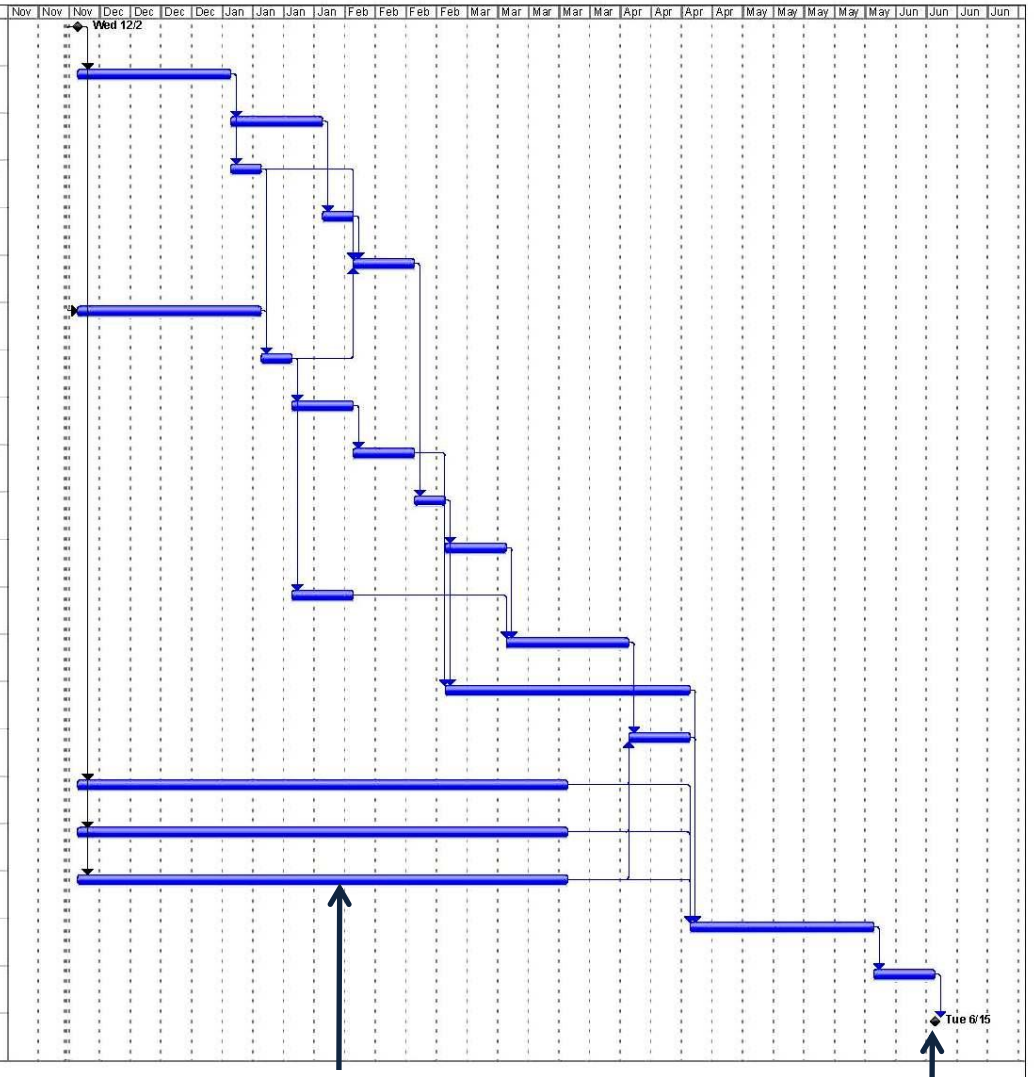
- Three vendors have bid on the mirror fabrication. Delivery Approx. 3 weeks ARO. Expect to Award Next week.
- All vendors can produce the 6061-T6 Al mirrors with better than a 16-32 micro-inch finish on an NC lathe in a single operation.
- We have talked to all vendors to discuss diamond turning techniques (constant cutting speed, tool radii, temp. etc.) to achieve suitable finish.
- SLAC will provide the CAD file (STEP or other) for the mirror profile (3K-30K dimensions) to be used in their NC lathe.
- Rear details of the mirrors will be finished before turning the convex/concave surfaces and all vendors expect to achieve a final profile within +/-2.5 mils.
- SLAC will inspect mirror following fabrication
- Secondary mirror will act as “First Article” and be approved before the primary is fabricated.

Mirror Coating Status

- SLAC will subsequently complete the polishing and cleaning of each mirror. Polishing materials in-hand.
- We will then be in a position prior to gold coating to assemble the entire mirror/camera system and measure its performance.
- Gold coating the mirrors will improve IR reflectivity a few percent and protect the surface from corrosion.
- A hard oxide coating (~50nm) is put on over the gold to reduce damage from exposure to the atmosphere, and allow subsequent cleaning.
- Two and possibly three vendors are being considered for the gold coating. We have informal quotes from two vendors. The coating time is approximately 3-4 weeks ARO

Schedule

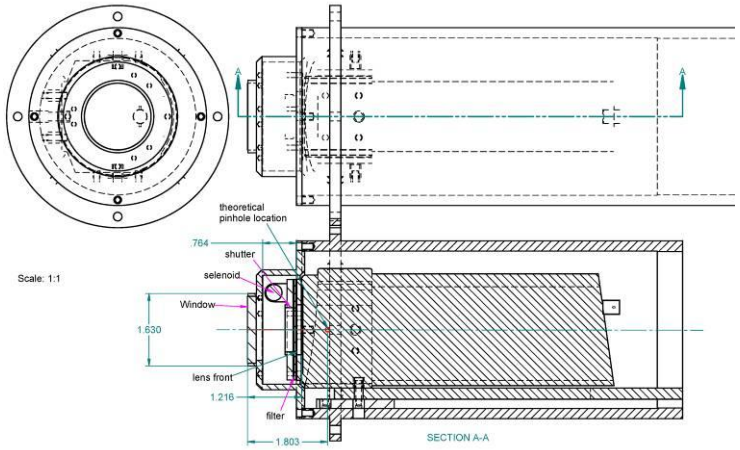
ID	Task Name	Duration	Start
1	Award Mirror Fabrication	0 days	12/2/09
2	Receive/Test First Article (Secondary Mirror)	25 days	12/2/09
3	Release Primary Mirror and Fabricate	15 days	1/6/10
4	Polish Secondary Mirror and Verify Profile	5 days	1/6/10
5	Receive and Test Primary Mirror	5 days	1/27/10
6	Polish Primary and Check Profile	10 days	2/3/10
7	Fabricate Mirror Supports and Alignment System	30 days	12/2/09
8	Assemble Camera Module & Mirror Supports (2ndary only)	5 days	1/13/10
9	Complete Weather Enclosure Drawings	10 days	1/20/10
10	Complete Weather Enclosure Controls Design/Procure Parts	10 days	2/3/10
11	Attach Primary Mirror / Cmplt C_Module Adjustment (Tube)	5 days	2/17/10
12	Send Camera Module to FLIR For Final Calibration	10 days	2/24/10
13	Bid and Award Mirror Coating	10 days	1/20/10
14	Coat Mirrors (Gold + Oxide)	20 days	3/10/10
15	Construct Weather Enclosure and Hardware Controls Fabrication	40 days	2/24/10
16	Receive Coated Mirrors and Re-assemble Camera/Mirror System/Test	10 days	4/7/10
17	Develop Camera Control Software	80 days	12/2/09
18	Develop Camera Image Processing Software	80 days	12/2/09
19	Develop WEB Interface	80 days	12/2/09
20	Integrate Camera and Weather Enclosure and Software	30 days	4/21/10
21	Dissasemble, Pack/ Deliverto Tucson For Shipping to CTIO	10 days	6/2/10
22	Camera Complete	0 days	6/15/10

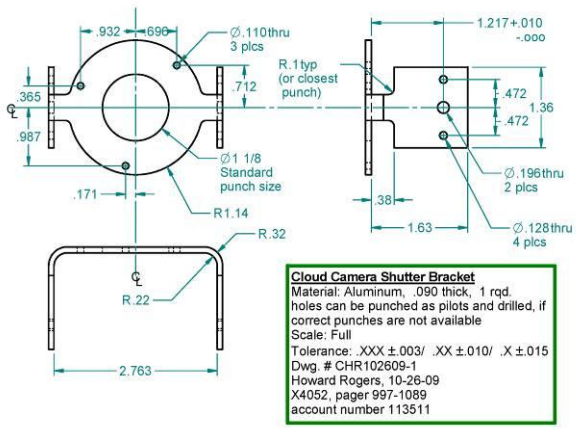


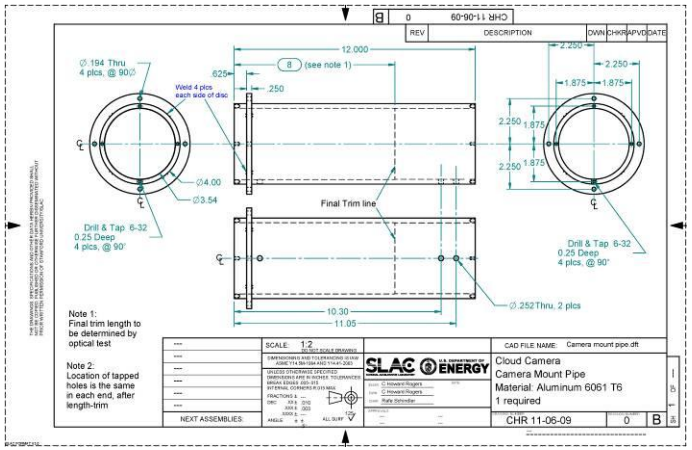
Software development is potential bottleneck

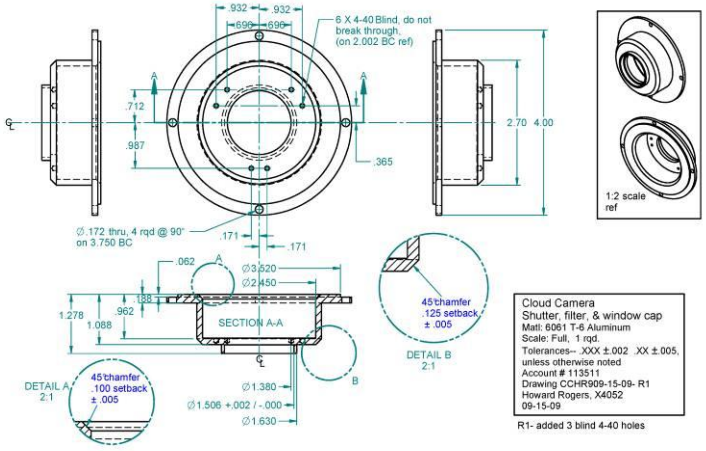
Projected mid-June completion

Camera Module Status



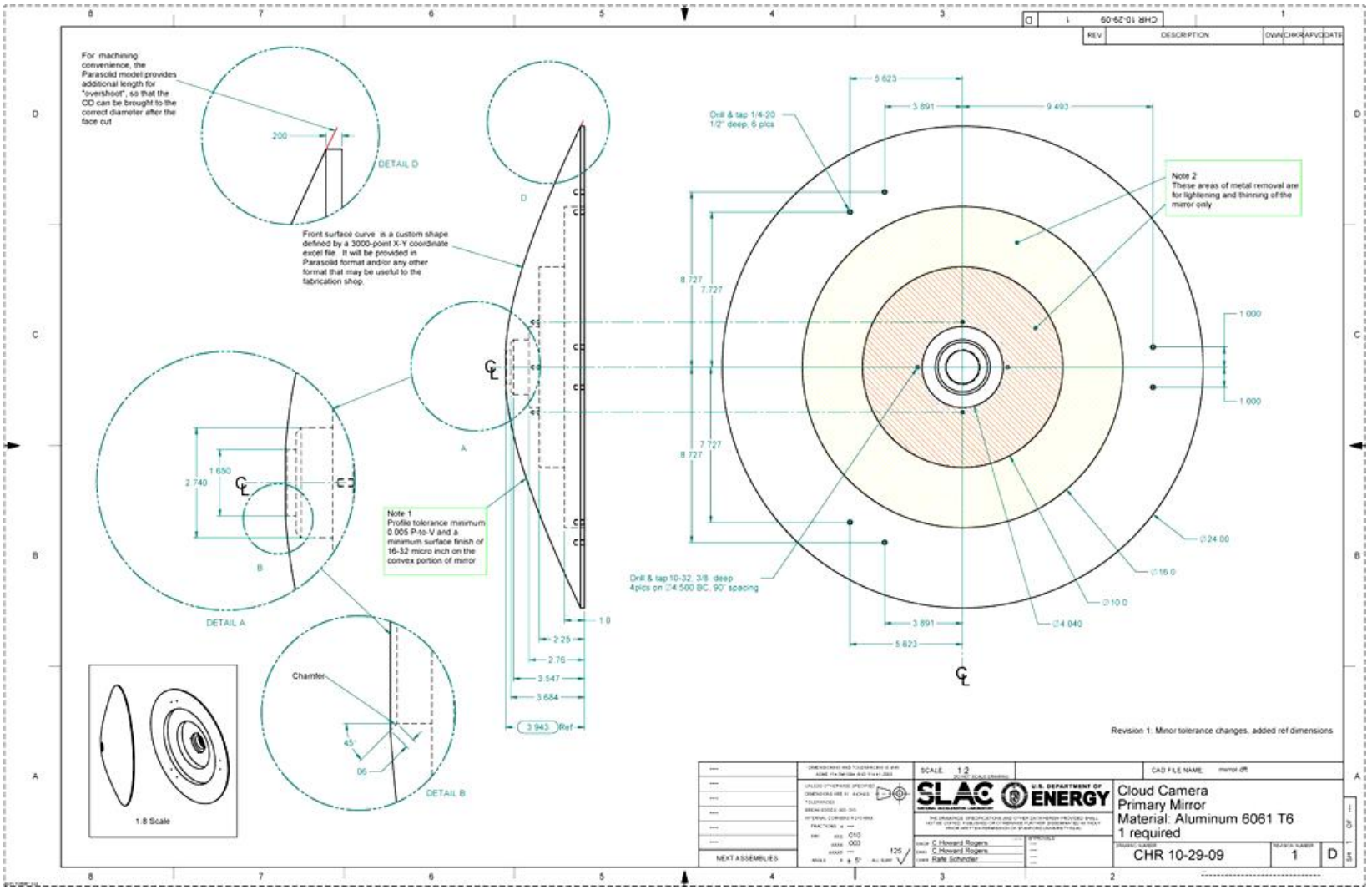




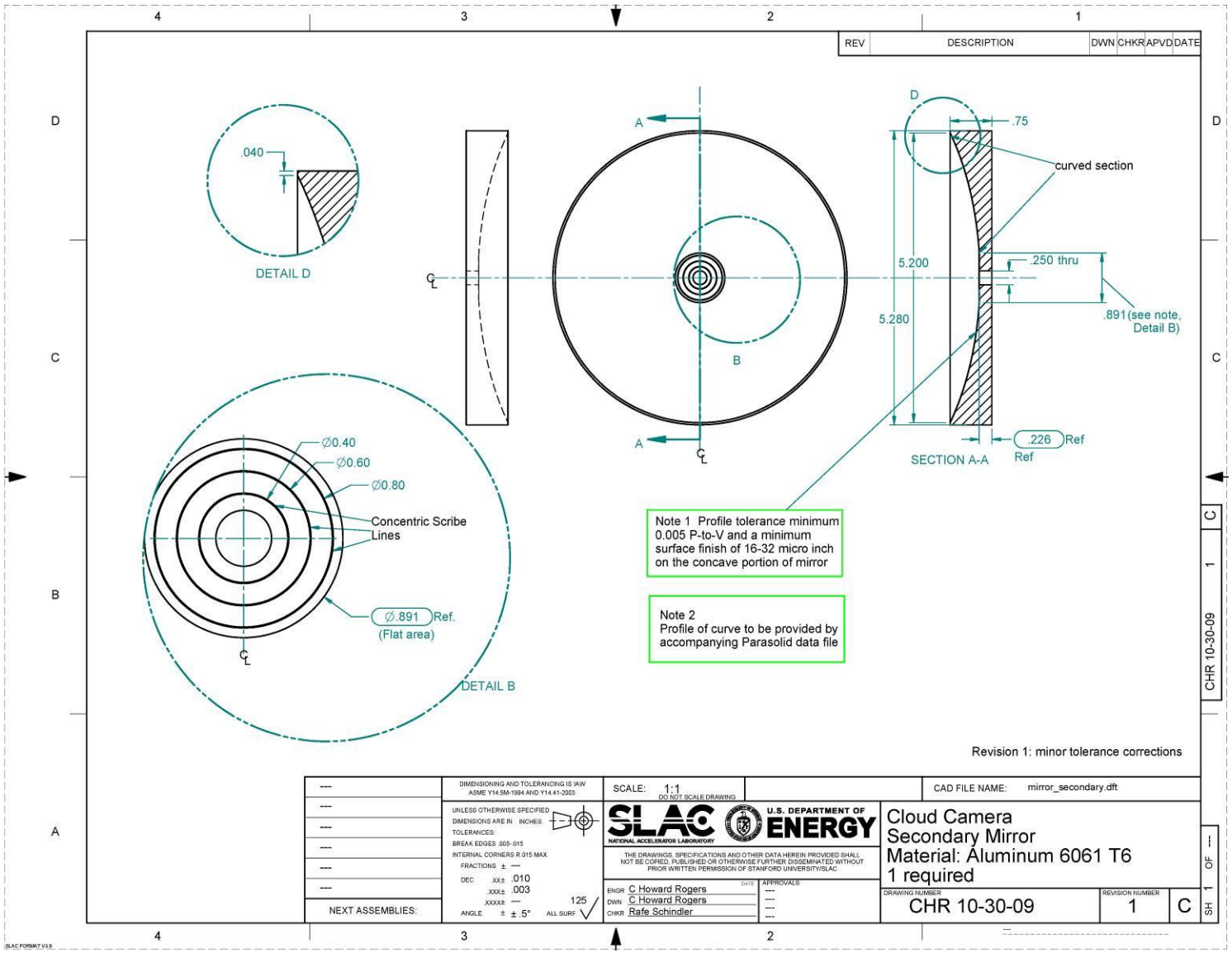


- Coated Ge window, IR filter, shutter, A325 camera in-hand
- All parts machined and cleaned
- Ready for trial assembly and longitudinal adjustment

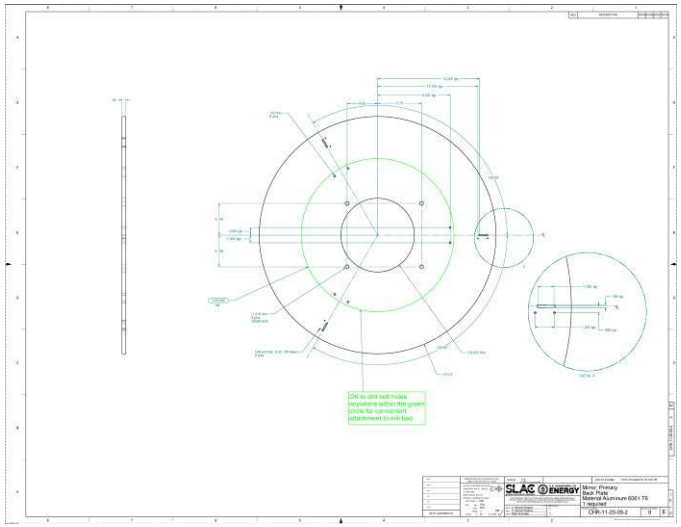
Mirror Fabrication and Coating: Primary



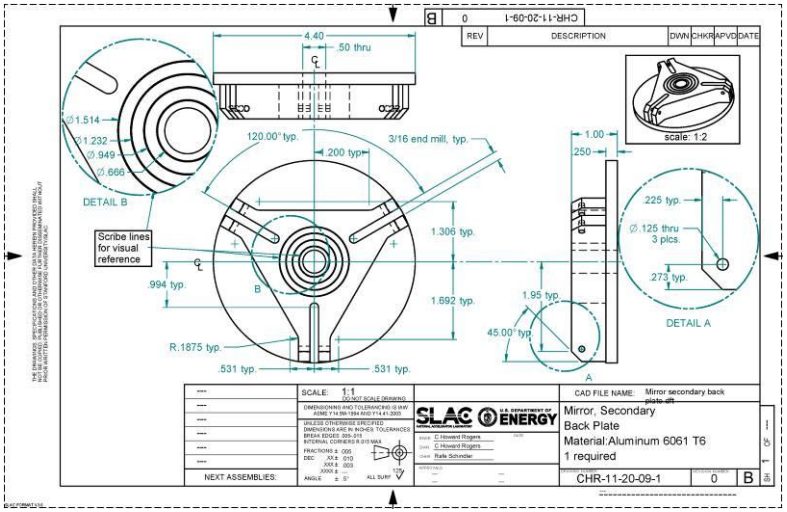
Mirror Fabrication and Coating: Secondary



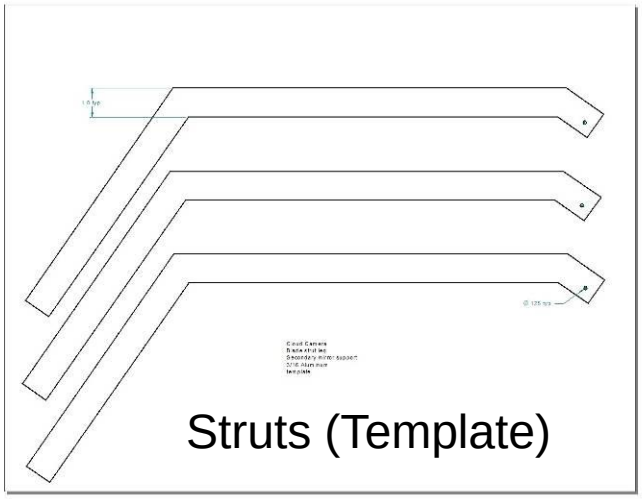
Mirror Support/Adjusters



Primary Support Plate



Secondary Support Plate



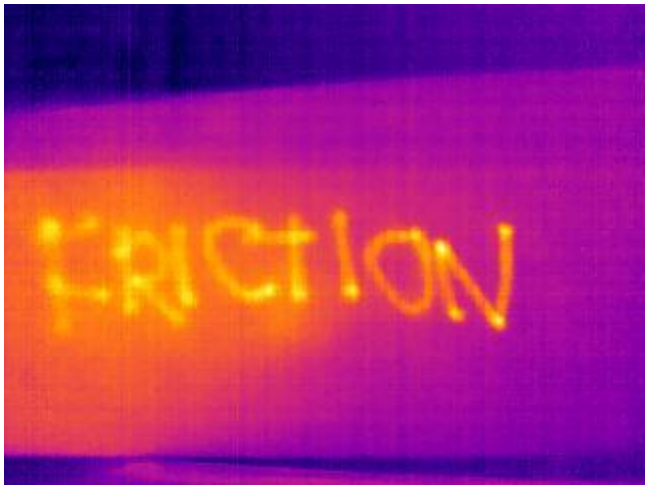
Struts (Template)

STATUS:

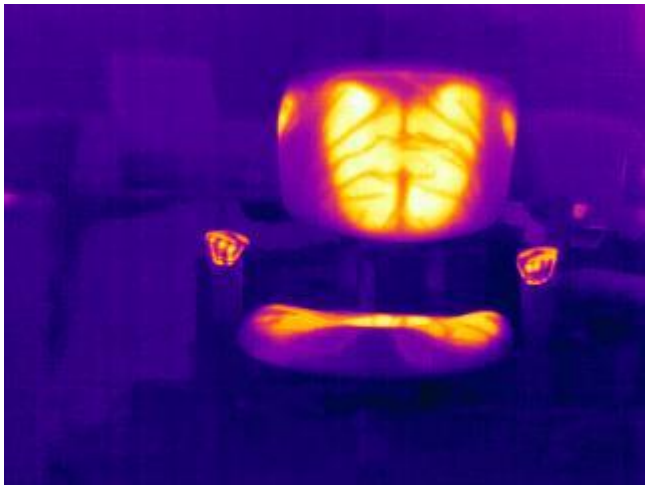
- Drawings complete except for the adjuster hardware
- Materials in hand
- Fabrication of primary plate to start Dec. 1, followed by other parts

Camera Fun

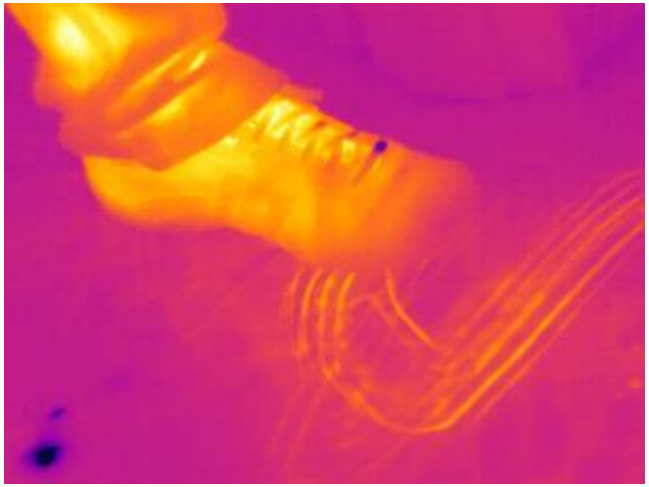
The extraordinarily sensitive FLIR A325:



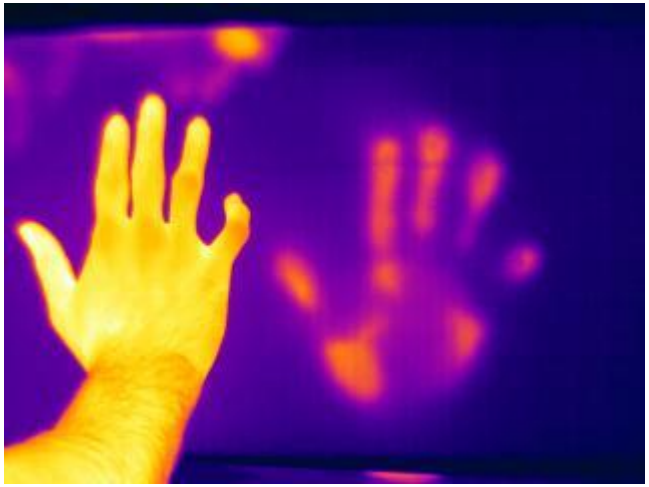
Finger writing on cardboard



Body head left on chair after several minutes



Friction heat left by shoe on floor



Handprint in heat on cardboard visible 10 minutes after contact