Gonio-Reflectometer for the Characterization of Advanced Blackbody Designs

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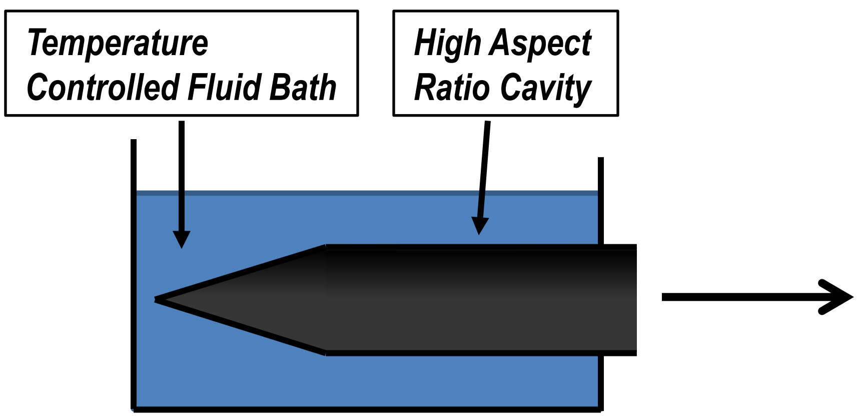
Outline

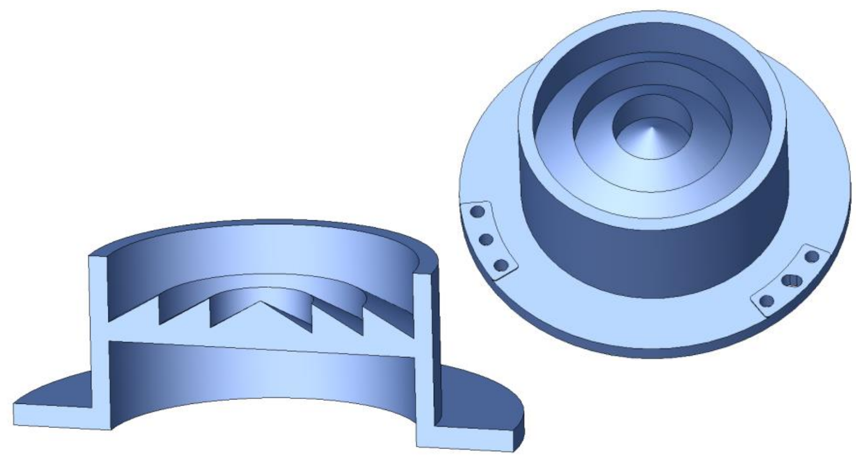
I. Problem statement
II. Measurement & modeling approach
III. Description of EMS hardware
IV. Description of UUT
V. Measurements and Model Correlation Results
VI. Discussion of Issues
VII. Summary

Problem Statement (1 of 2)

- As on-board infrared (IR) calibration requirements become more stringent, so must the performance requirements for on-board calibration IR "blackbody" (BB) sources.
- Likewise, these sources must satisfy increasingly challenging size, weight and power requirements in addition to their traditional temperature accuracy and effective emissivity requirements.
- This combination of requirements leads to more exotic BBs that may be anisothermal, anisotropic, and may deviate significantly from the ideal laboratory BB design.



High Confidence Laboratory Blackbody



Example "Blackbody" Optimized for Flight

Problem Statement (2 of 2)

- It's hard to theoretically predict and/or measure all radiometric characteristics of complex BBs.
  - Temperature uniformity can be an issue (not discussed in the presentation).
  - Effective emissivity is the primary factor involved in the computation of emitted radiance.
- Effective emissivity influences radiance leaving the BB in two ways.
  - Multiplier in front of Planck's Law in the computation of emitted spectral radiance

$$L_{\lambda}(T) = \boxed{\varepsilon(\lambda)} \left(\frac{2hc^2}{\lambda^5}\right) \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

  - Determines the amount of unwanted background radiation that may scatter into the radiometer that is being calibrated.

Measurement & Modeling Approach

- Full knowledge of BB effective emissivity performance means that you know the full BRDF
  - i.e. reflected signal at any and all angles versus incident source at any and all angles.
  - This is a data set that is much too massive to be practical
  - And we don't need to know all of this.

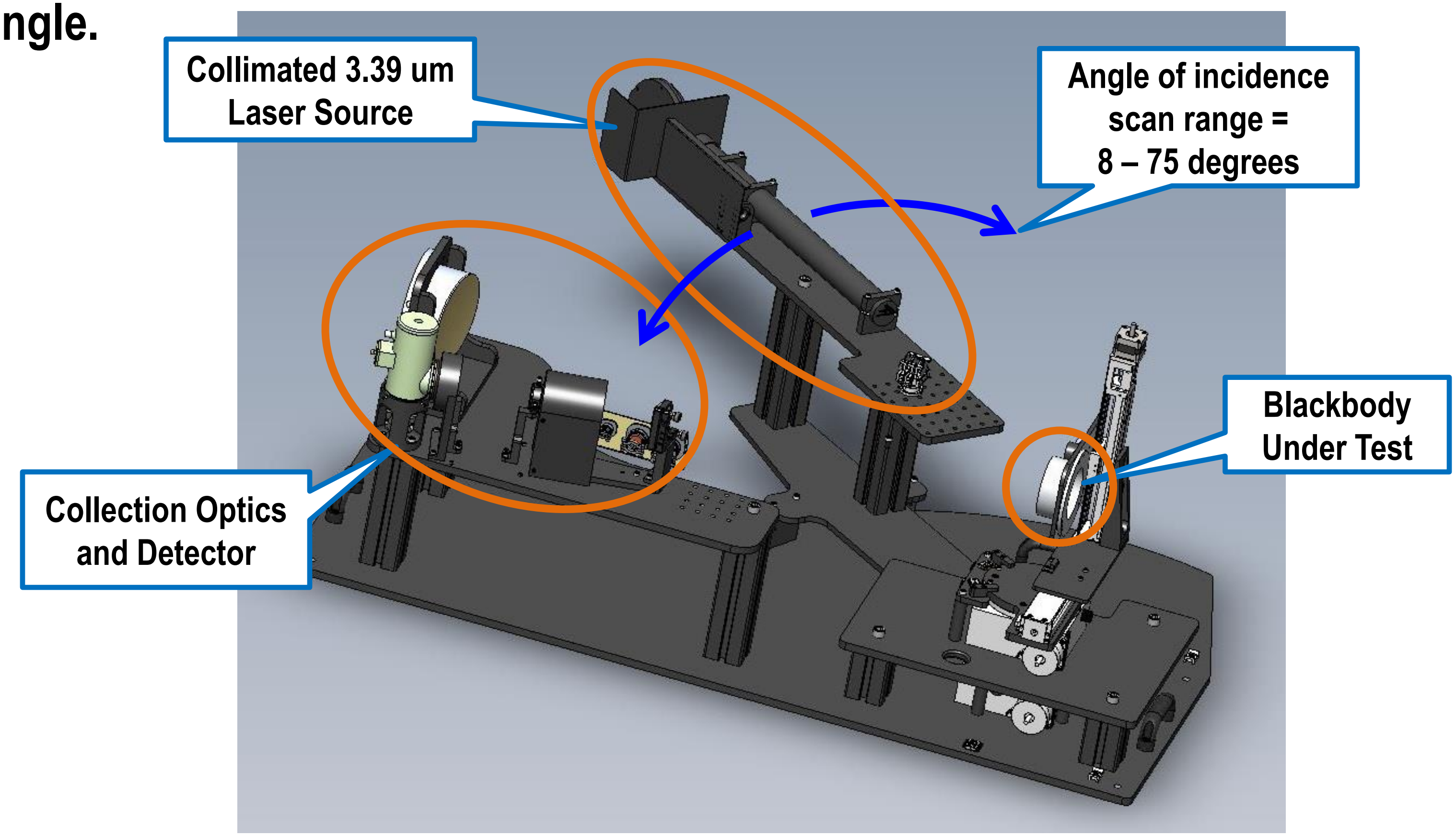
- Instead we model the sensor as it views the BB and then can model various different sources of stray light from outside the sensor field of view.

Measurement & Modeling Approach

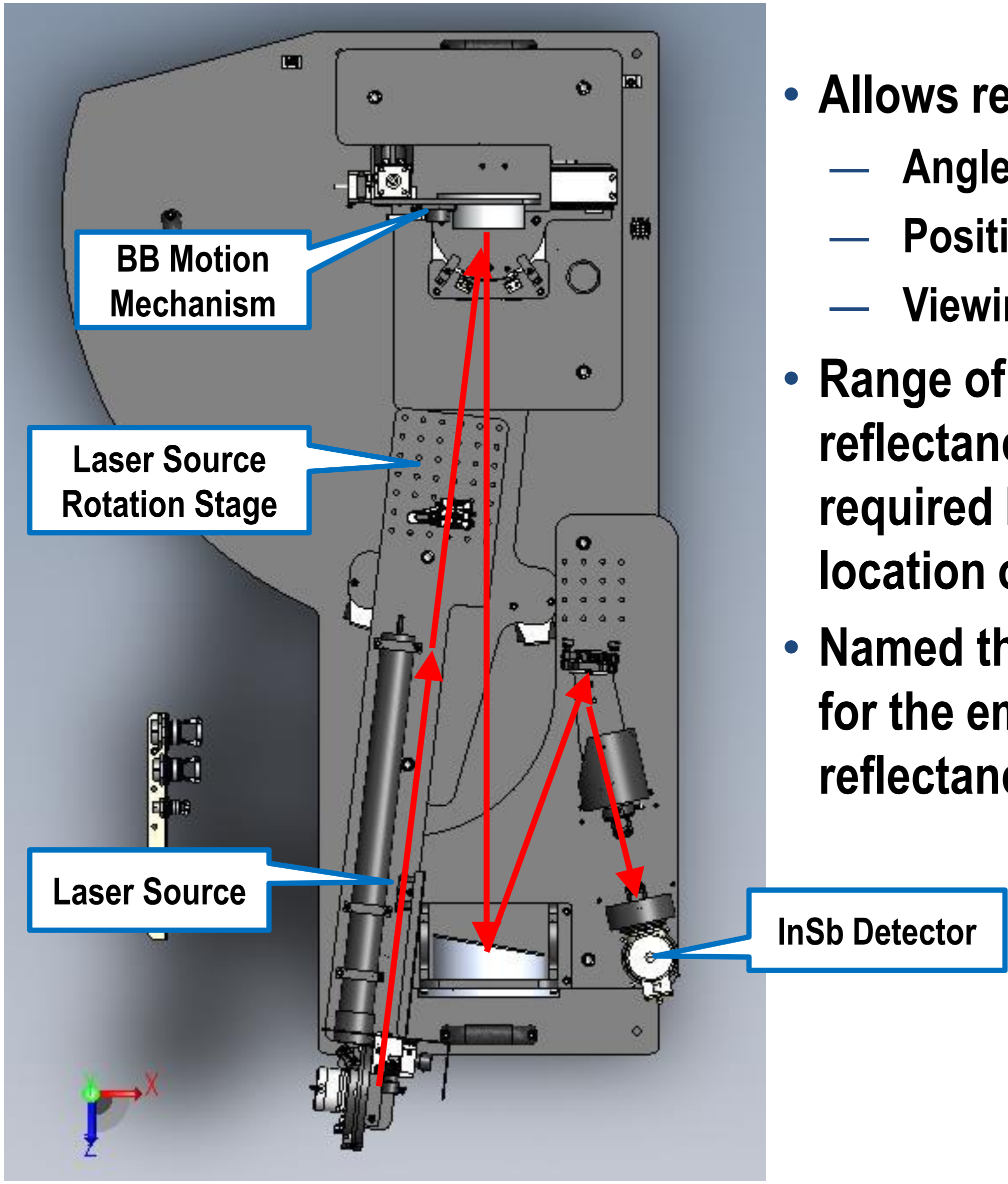
- Modeling the performance of exotic BBs can be a hard sell to the customer without measurement-based correlation.
- A subset of the BB BRDF conditions can be measured and correlated with simulations in order to validate the BB BRDF model.
- The validated BB BRDF model can then be used to answer otherwise difficult questions about the performance of the BB design with respect to effective emissivity and reflected background.

Scatterometer Design

- Laser source is used to illuminate the target over a range of 8 – 75 degrees.
- Collection optics gather and spatially filter photons scattered from BB in a way that simulates the flight sensor for which the BB will be used.
- BB is mounted on a motion stage that can change the sensor viewing position and angle.



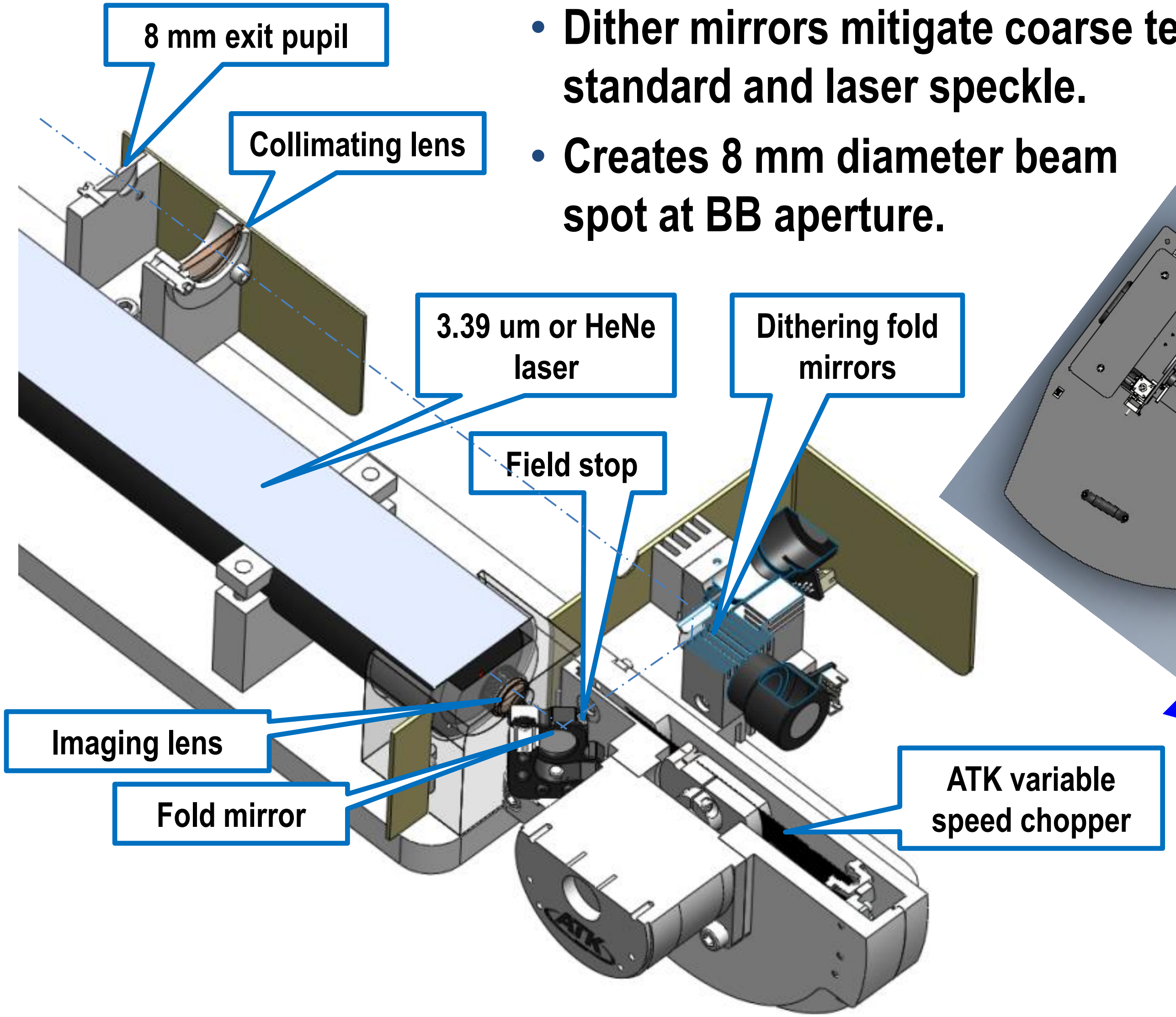
Scatterometer Design

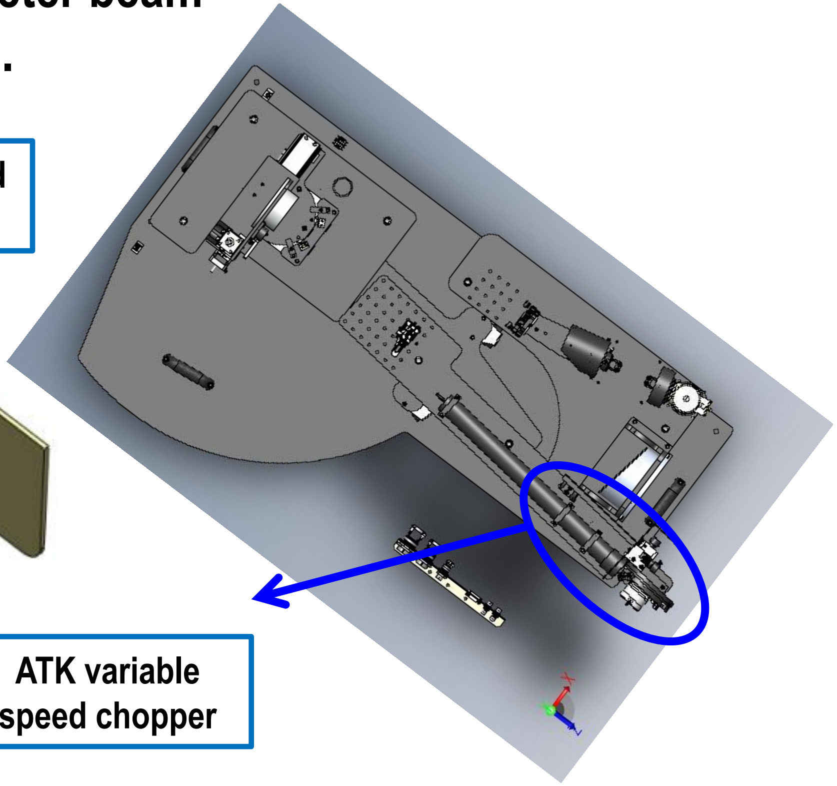


- Allows reflectance measurements versus:
  - Angle of incidence wrt. BB surface normal,
  - Position within BB,
  - Viewing angle wrt. BB surface normal
- Range of motion of moving parts allows reflectance measurements beyond that required by flight system so we can confirm location of design limits.
- Named the "Emissivity Measurement System" for the emissivity performance criteria that the reflectance data is used to demonstrate.

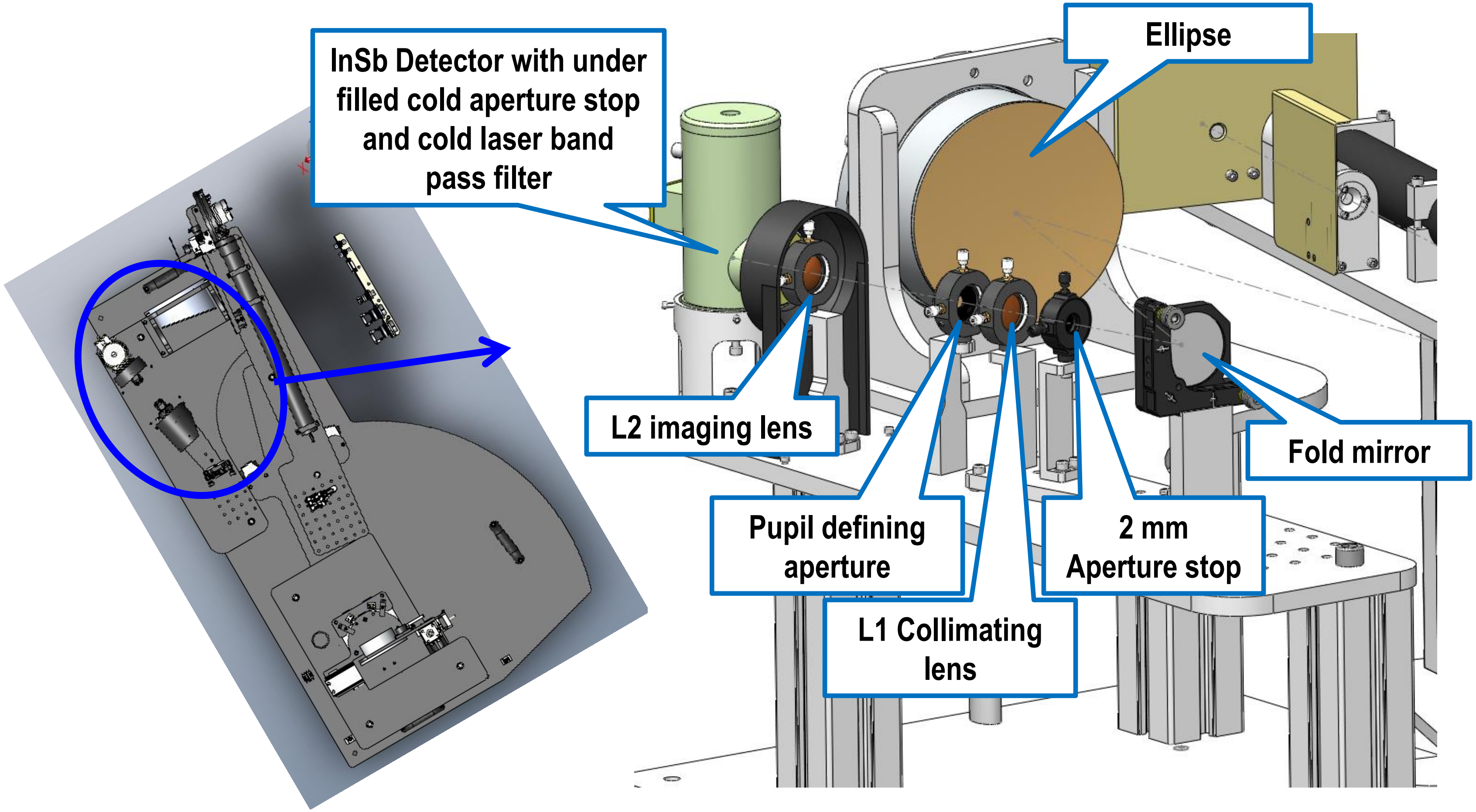
Scatterometer Design, Source Subsystem

- Chopper allows for phase sensitive detection.
- Dither mirrors mitigate coarse textured reflectance standard and laser speckle.
- Creates 8 mm diameter beam spot at BB aperture.



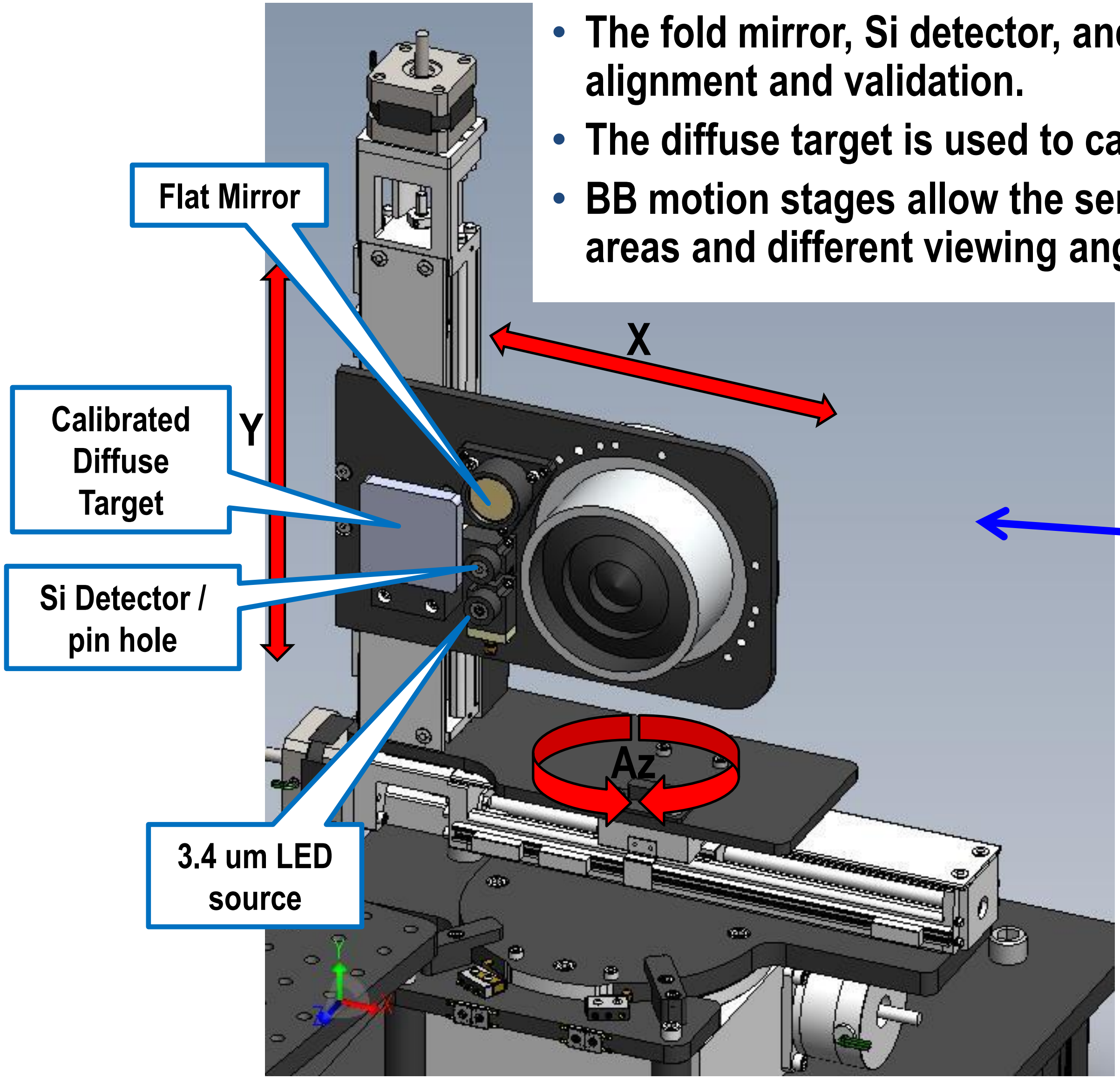


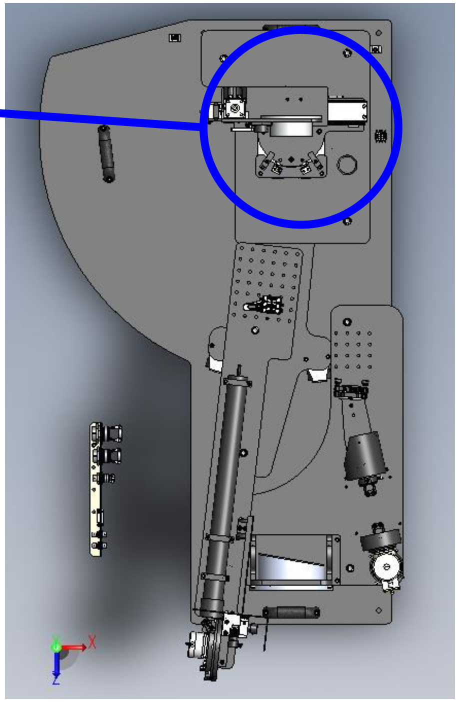
- Sensor subsystem designed to view BB in a manner very similar to flight optical system (i.e. BB sampled area & ray angles)



Scatterometer Design, BB Motion

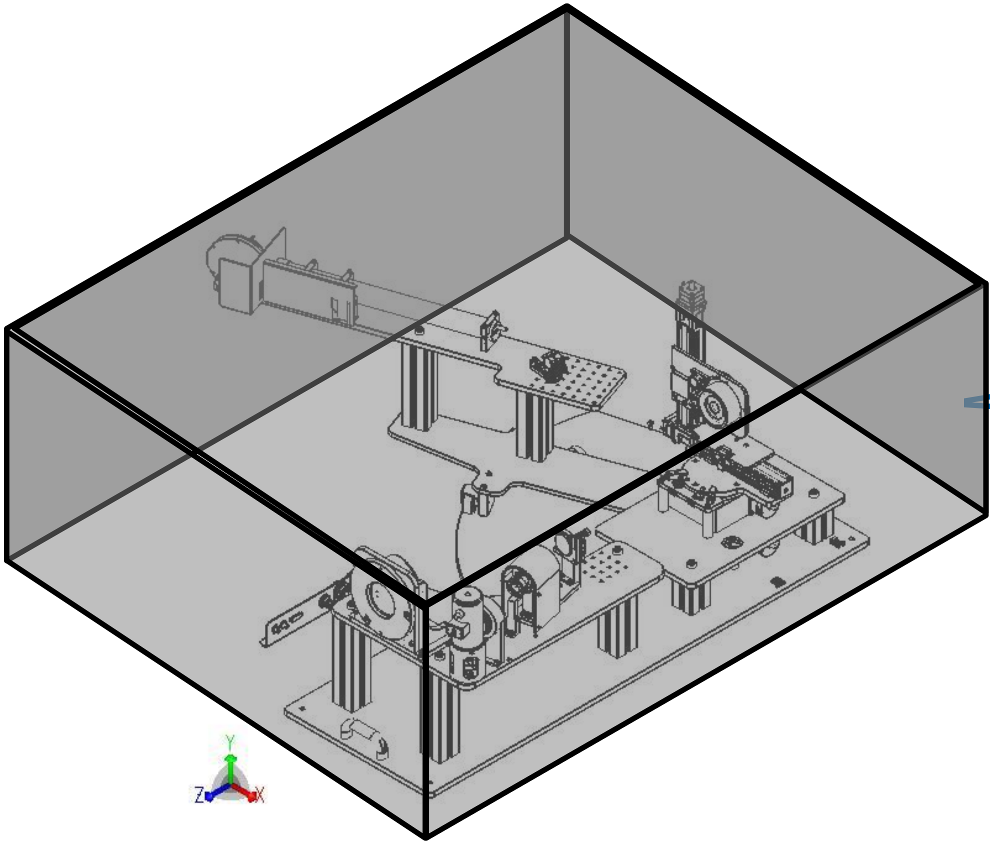
- The fold mirror, Si detector, and LED source are used for EMS alignment and validation.
- The diffuse target is used to calibrate the throughput of the EMS.
- BB motion stages allow the sensor to sample the BB at different areas and different viewing angles.





Other Features

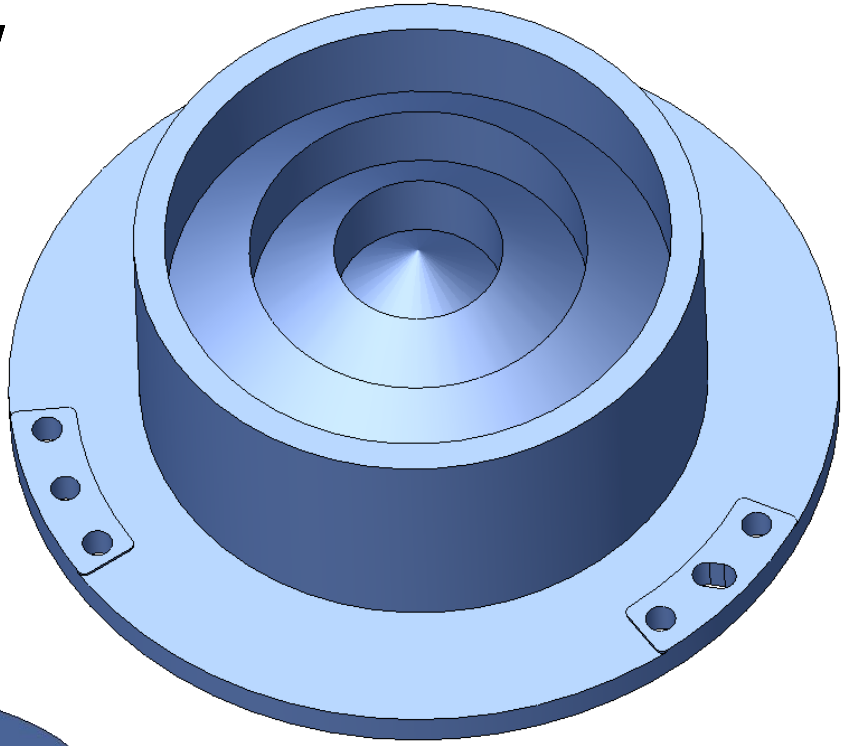
- The EMS hardware is maintained in a clean room.
- Data acquisition is fully automated.
- The EMS hardware is contained in a laser safety enclosure.

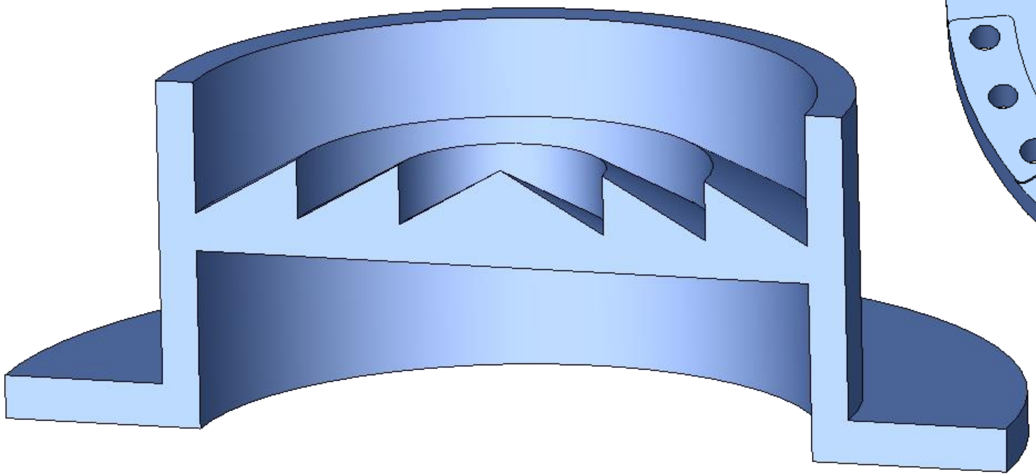


Eye-safe protective Cover / laser power interlock

Description of Unit Under Test (UUT)

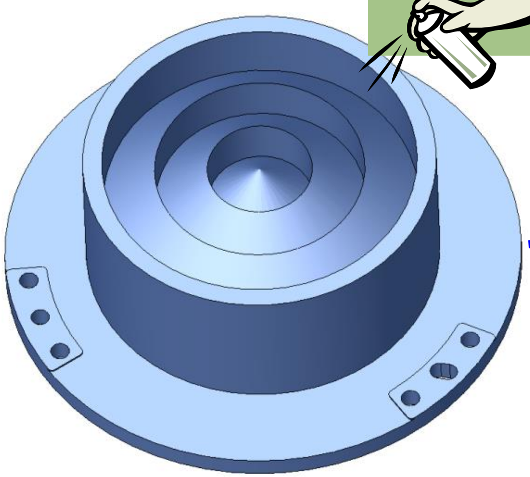
- Created a surrogate blackbody strictly for EMS demonstration purposes.
- Not designed for highest possible emissivity
- Intentionally designed to exhibit distinctive reflectance behavior that could be clearly compared and contrasted with modeling efforts of the measurements.





UUT Fabrication

- **UUT was fabricated out of plastic in 3-D printer at Ball Aerospace.**
- **No post-polishing of substrate or coated surface**
- **Painted with Krylon Gloss Black**



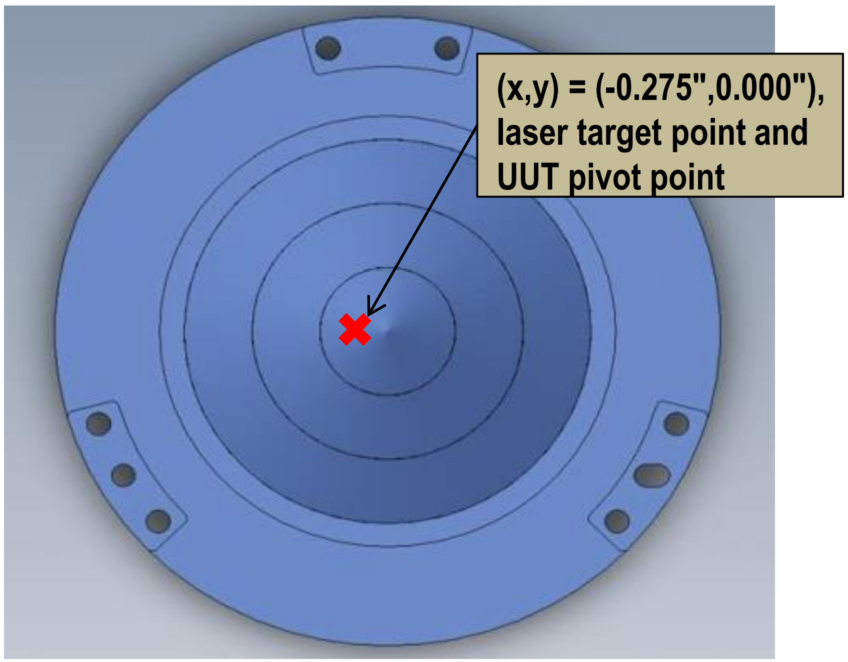
Painted UUT

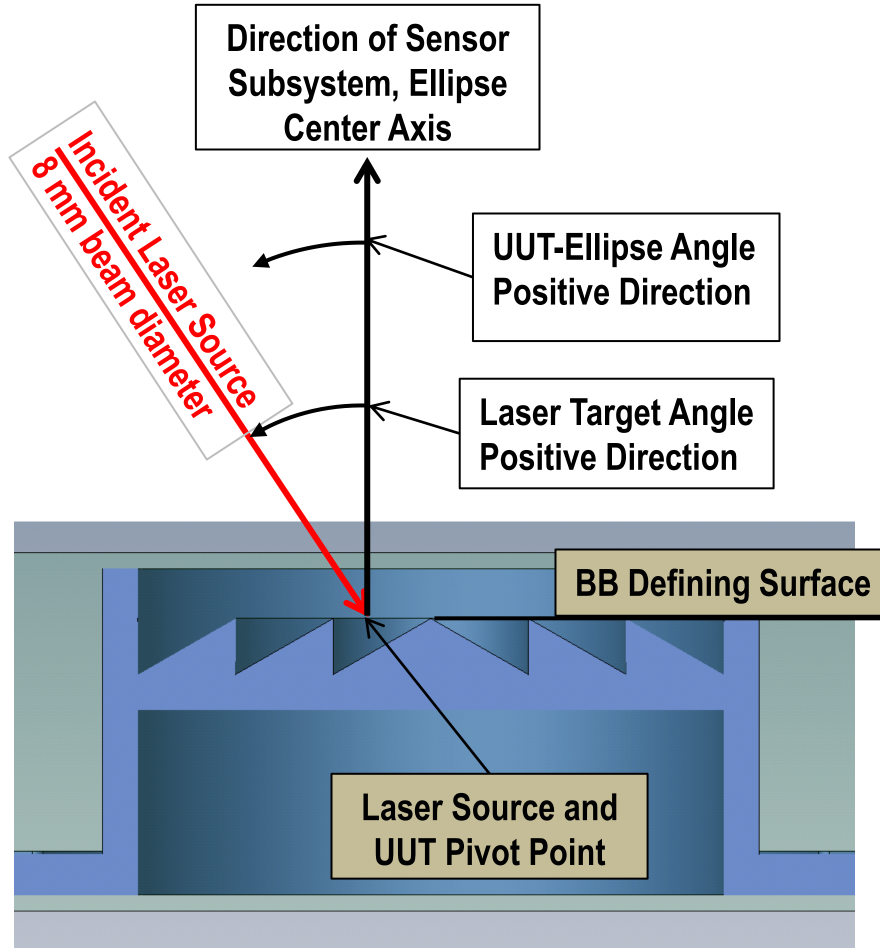
- **Characteristics of Krylon High Gloss Black on printed plastic.**
  - Final painted part exhibited high gloss characteristic of this paint.
  - Imperfections dominated by "orange peel" & substrate texture print-through.
  - Roughness period ~3x smaller than 8 mm beam spot of EMS source so it adds to angular width of specular reflection and local variations are probably not washed out.
  - A sample coupon was also printed and painted for BRDF measurement.

BRDF coupon

Painted UUT

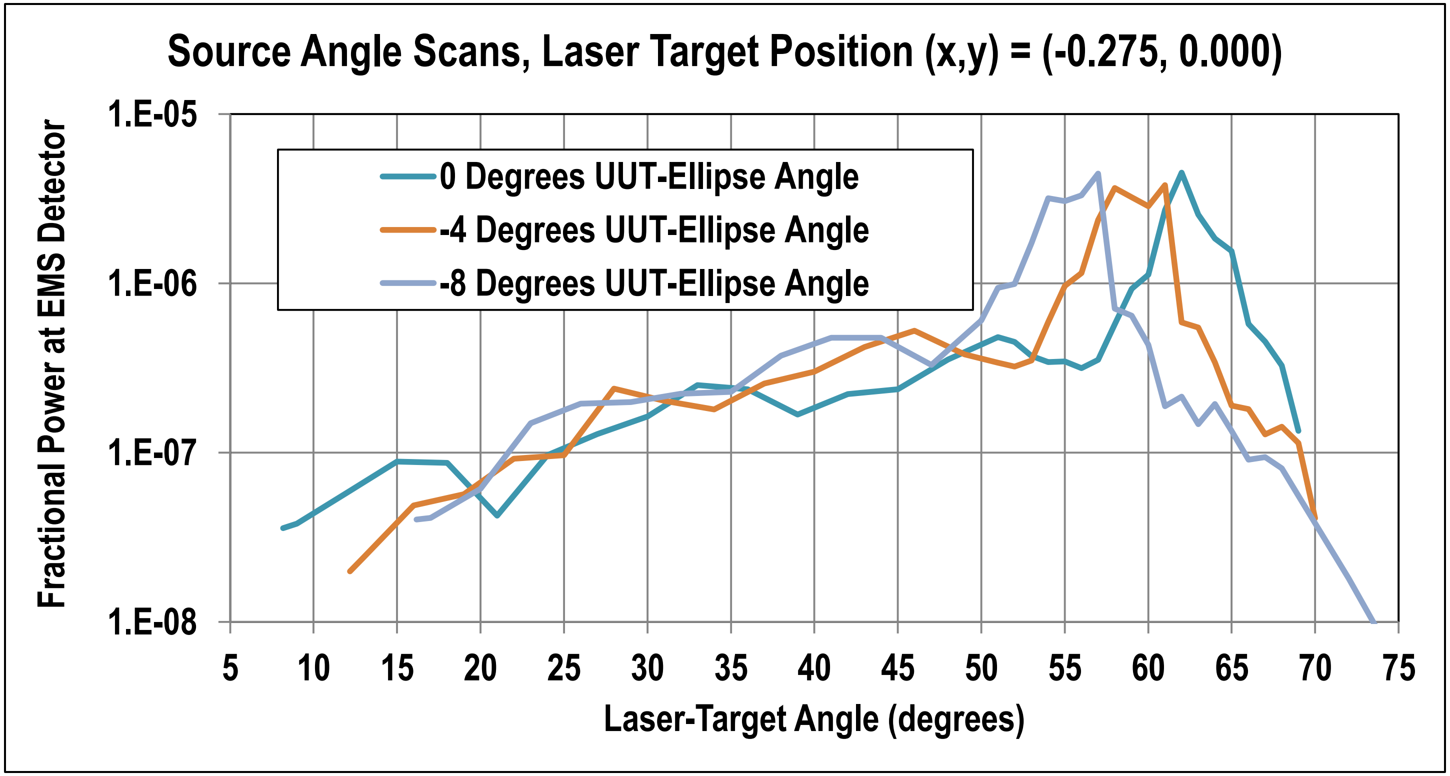
- **Blackbody remains stationary as Laser Source Scans in Angle.**
  - 3 scans with UUT normal to Ellipse axis angles of 0, -4, and -8 degrees.





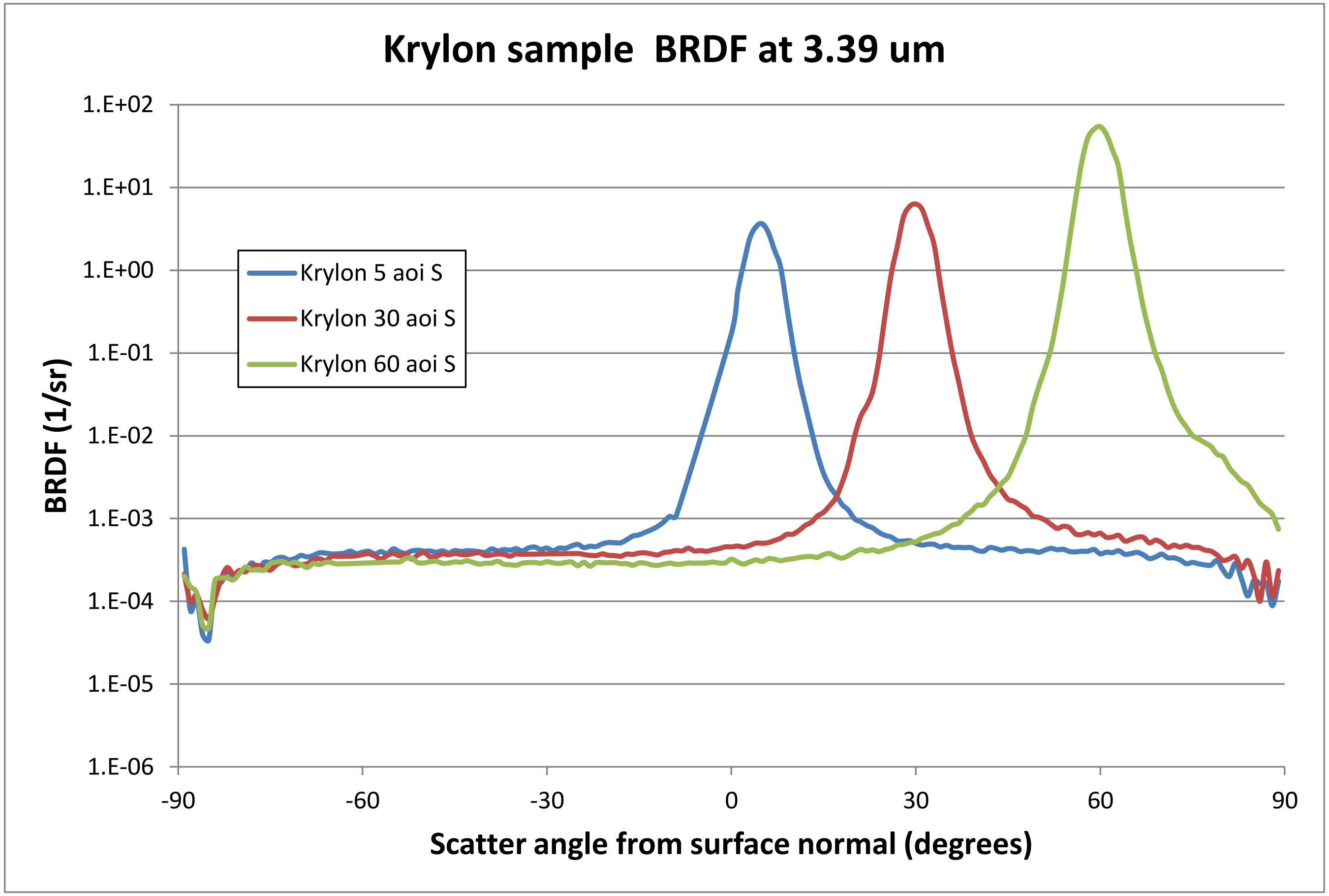
Reflectance Measurement Type 1

- Vertical axis is power on detector divided by incident power.
- Noise floor is at 1e-9.
- Peaks in reflectance appear at expected specular reflectance angles.
- Reflectance peak shifts are consistent with tilt in UUT normal with respect ellipse chief ray direction.



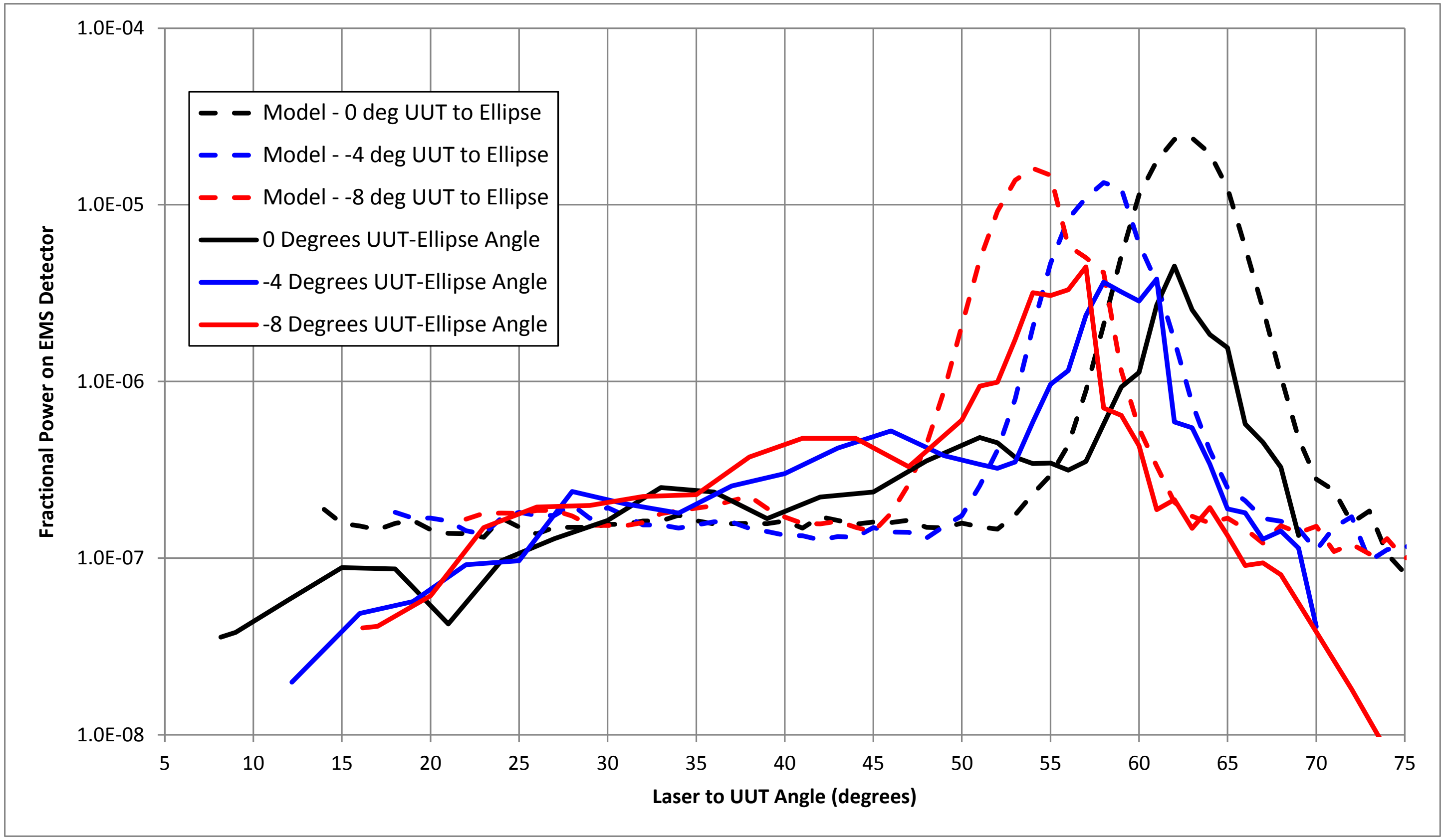
Krylon Black Coupon BRDF

- The Krylon Black BRDF from a sample coupon was measured so that the reflectance properties could be entered into the non-sequential ray-trace tool (FRED).



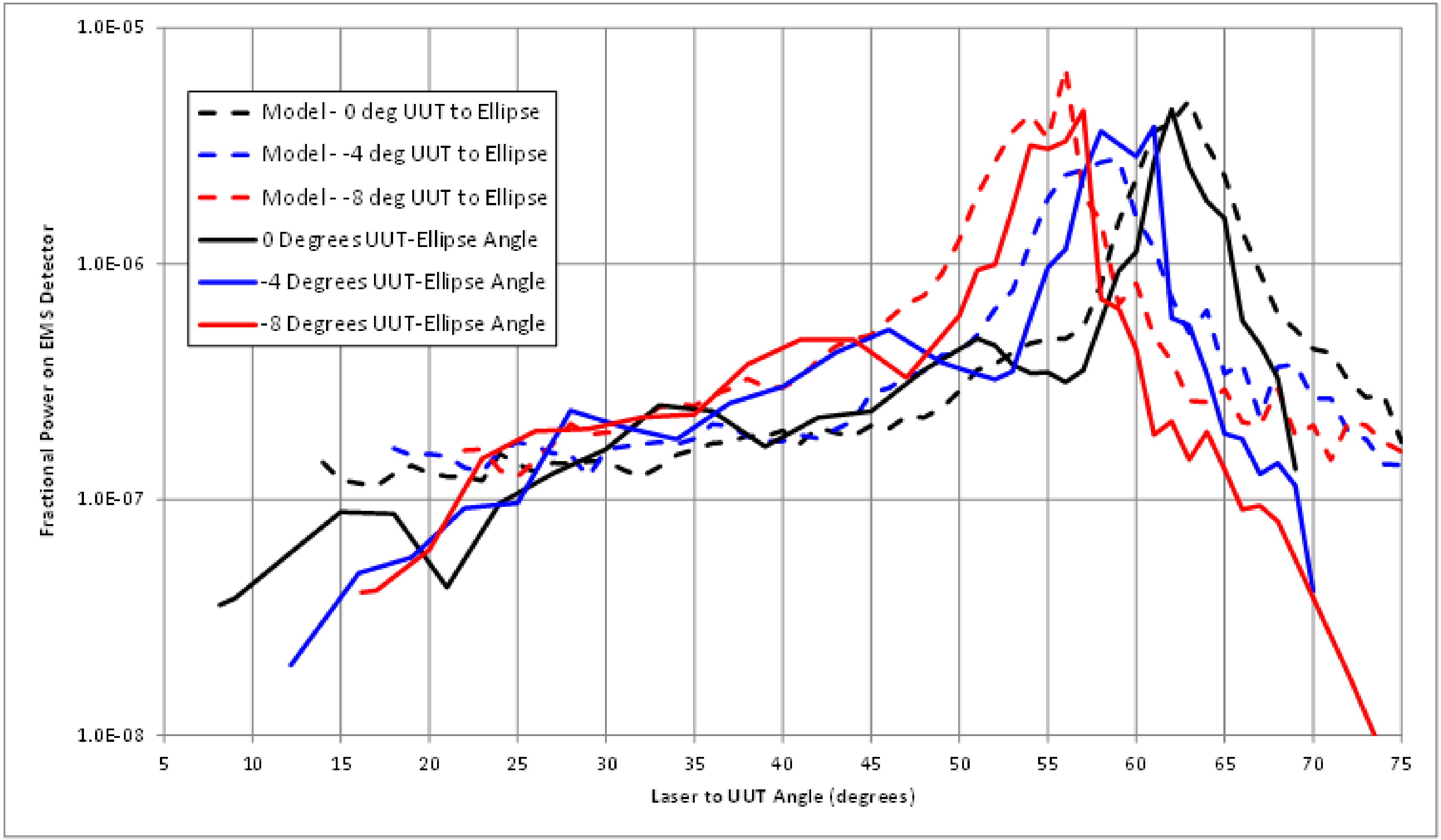
Type 1 Measurement vs. Model

- Using the measured BRDF, the large features were duplicated in the model.
- But...
  - Amplitude at the peaks is different by 10x.
  - Amplitude in the wings also has significant differences.



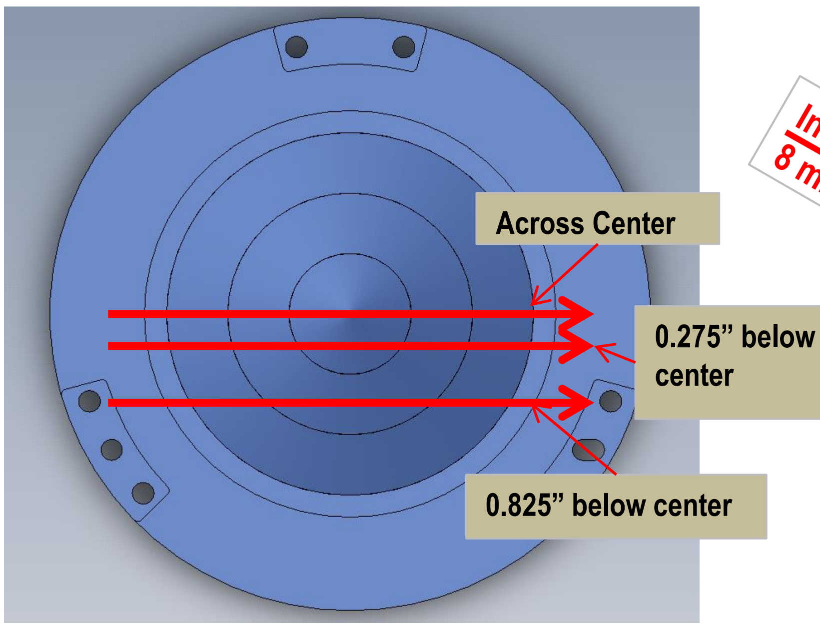
Type 1 Measurement vs. Model

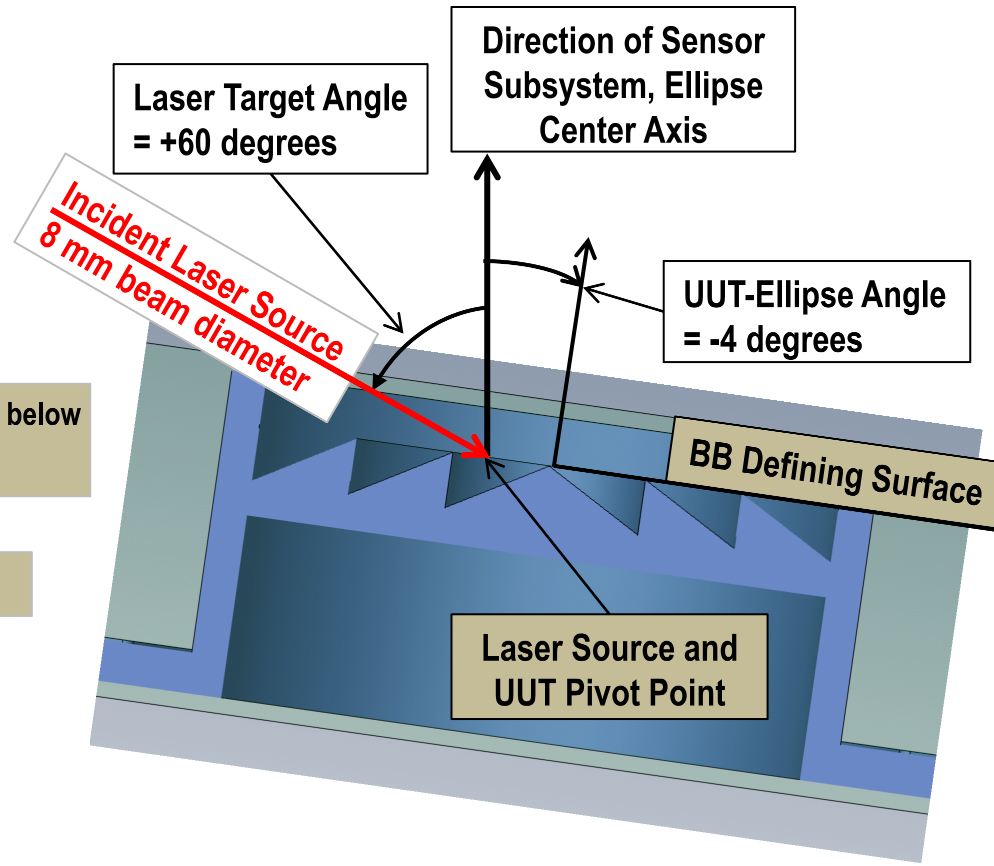
- **Alternate BRDF could be created that matched the measured data better.**
- **But total integrated BRDF from coupon was unrealistically low.**



- Three Blackbody scans across Sensor field of view with Laser Source at fixed angle of 60 degrees and UUT angle at -4 degrees.

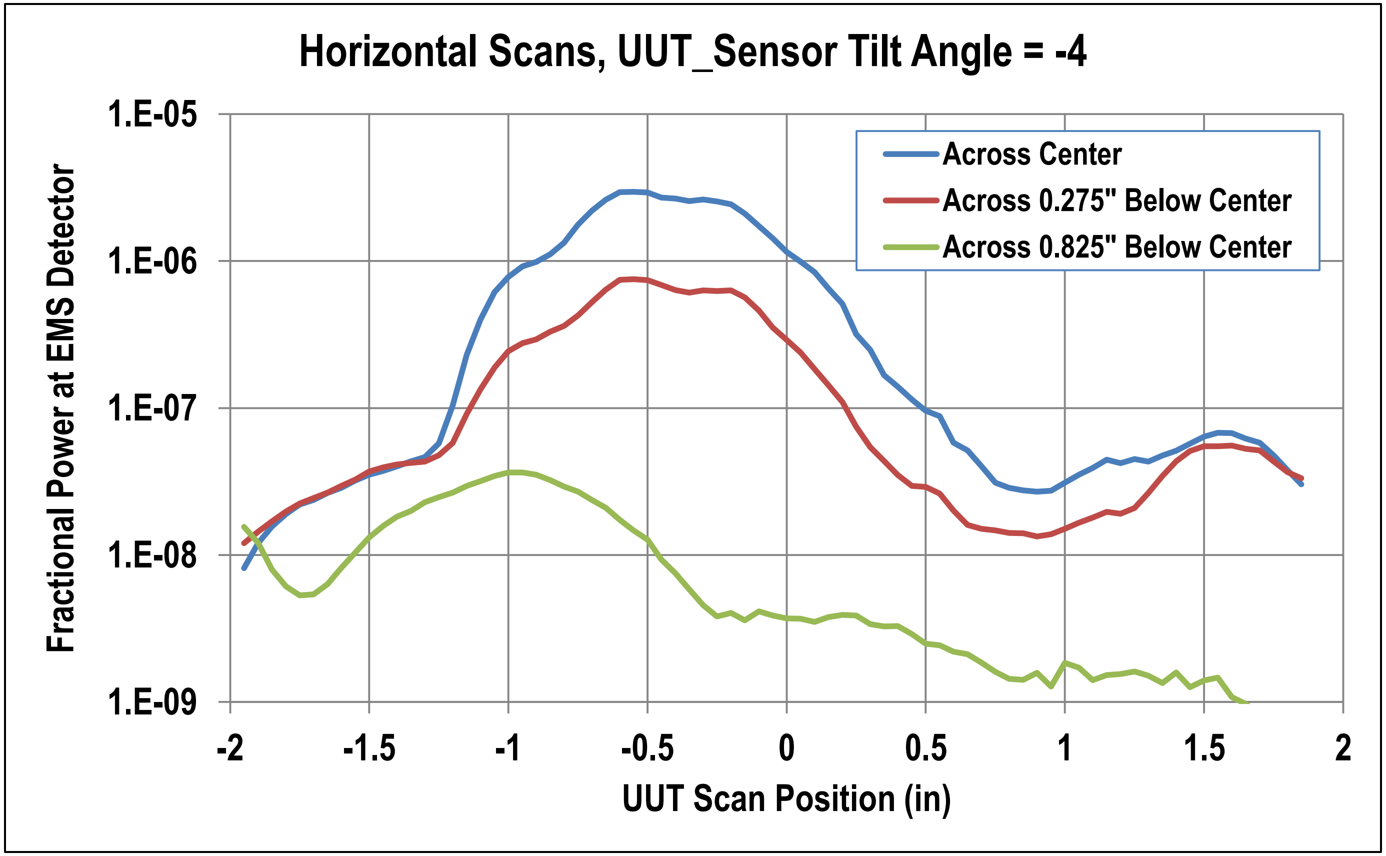
Red lines are the laser beam spot trace as it scanned across the BB.





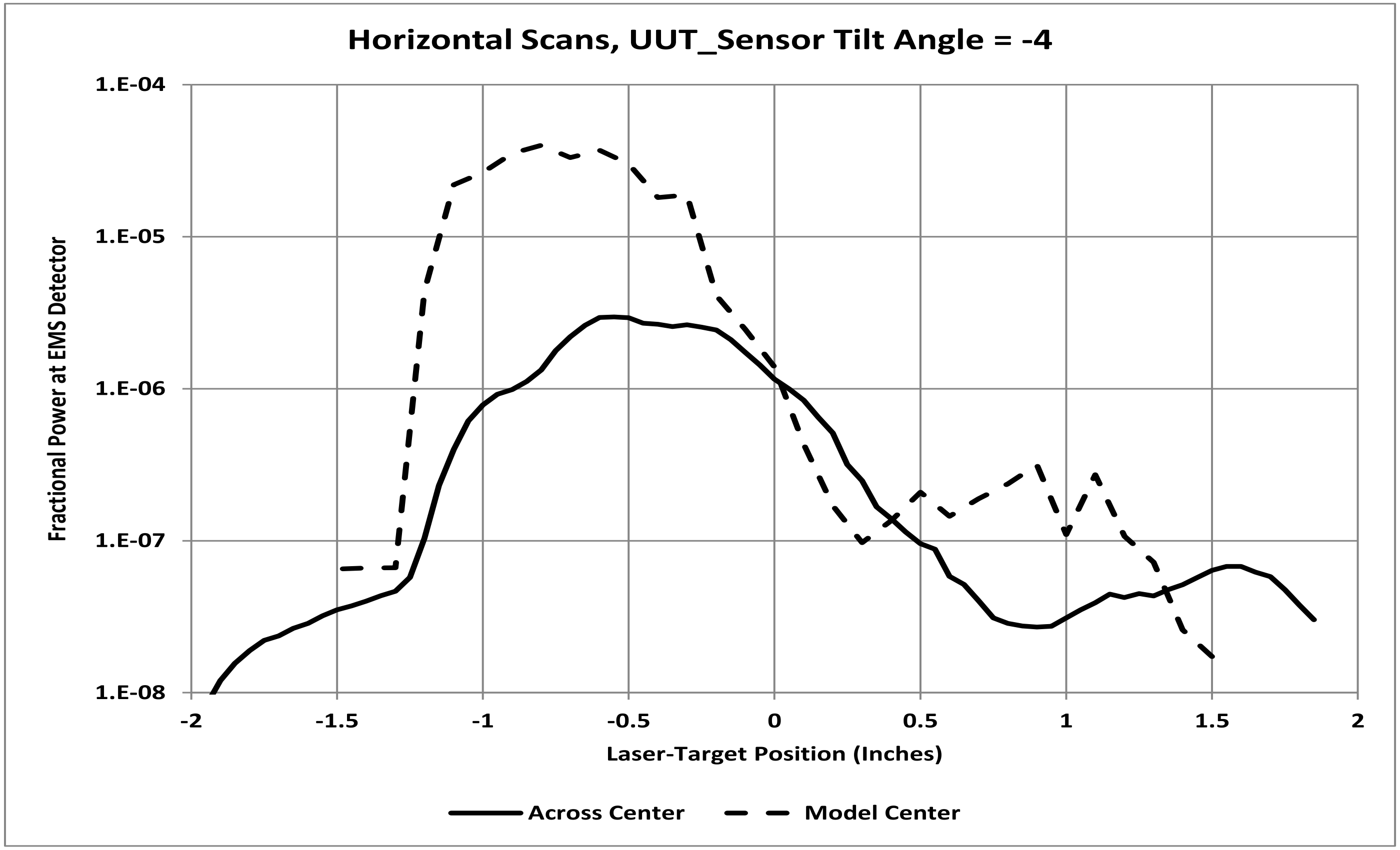
Reflectance Measurement Type 2

- Peaks in reflectance diminish as expected as the Laser Sources scans across the BB at lower positions
- Note the very wide dynamic range of the EMS signal.



Type 2 Measurement vs. Model

- Using the measured BRDF, the large features were duplicated in the model.
- But...
  - Amplitude of the peak is shifted and different by 10x.
  - Amplitude in the wings also has significant differences.



Measured to Model Correlation Discussion

- Gross reflectance features are being reproduced by the model, but important differences are also observed.

- Self consistency checks indicate that the EMS was performing normally during data acquisition.

- Previous measured to modeled comparisons on flight hardware imply that the analysis methodology works well.
  - Amplitudes matched to within ~20%.
  - Angles matched to less than 5 degrees.

Measured to Model Correlation Discussion

- **Possible causes of Measured vs. Modeled differences.**
  - EMS malfunction (not-likely)
  - Modeling inadequacy (some possibility)
  - Sample coupon BRDF measurement system inadequacy (some possibility)
  - Poor coupon representation of BB surface (significant likelihood)
    - Is 3D printer texture on flat surfaces the same as angled surfaces?
    - Differences in painted surface properties, not so noticeable in the visible, but in the IR?
  - Stray light issue (significant likelihood)
    - Stray light issue was known to have spoiled some of the test conditions for flight hardware testing.

Summary

- EMS was a successful effort to build a tool for characterizing the behavior of complex blackbody designs.
- Those characterizations lead to better model fidelity and enhanced confidence in performance predictions.
- Although a useful instrument, care must be taken to manage the sources of systematic error.

- Additional acknowledgements:
  - Ball Aerospace: Doug Harvison, Ian Moore, & Zongying Wei
  - ATK-MS: Dave Higham, Nelson Palmer, & Cody Barrus