Primary Realization of Spectral Radiance, Emittance and Reflectance in the Mid- and Far-Infrared

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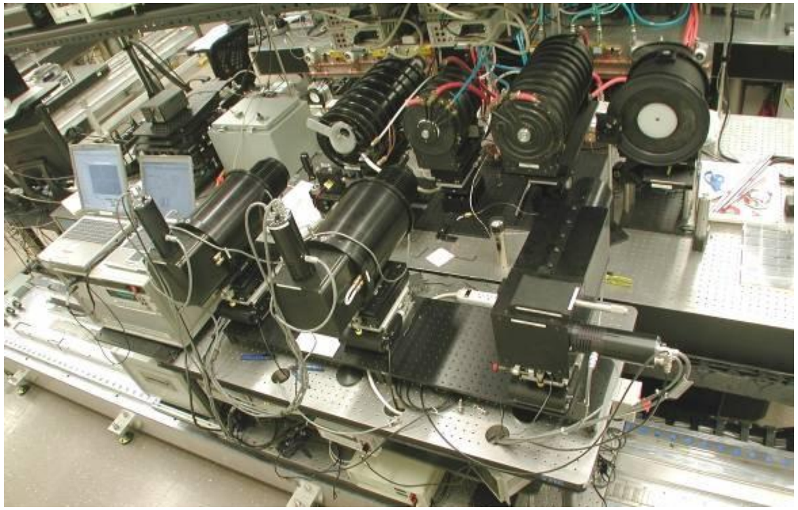
Outline - Intro

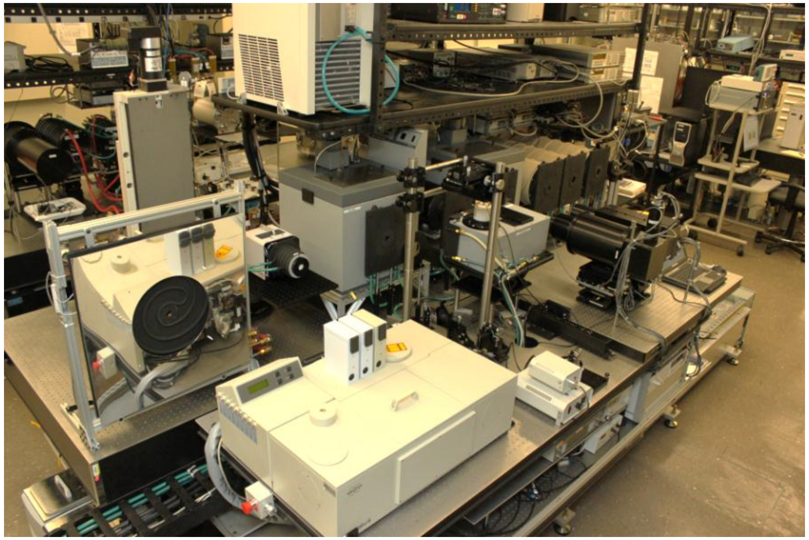
- **Current Status of IR Spectroradiometry and Spectrophotometry**
- Unfulfilled Demand
- Common solution: vacuum chamber with a high accuracy spectral comparator, plus application-specific tools. Physics behind each scale realization approach.
- Concept of the multifunctional modular IR testbed for infrared radiometry and spectrophotometry support of spaceborne, airborne and ground-based targets and sensors.
- Performance goals and results of the detailed design and analysis. Critical technologies for implementation.
- Current budgetary constraints. Action plan and cooperation opportunities.

AIRI - National Primary Standard of Radiance Temperature and IR Spectral Radiance

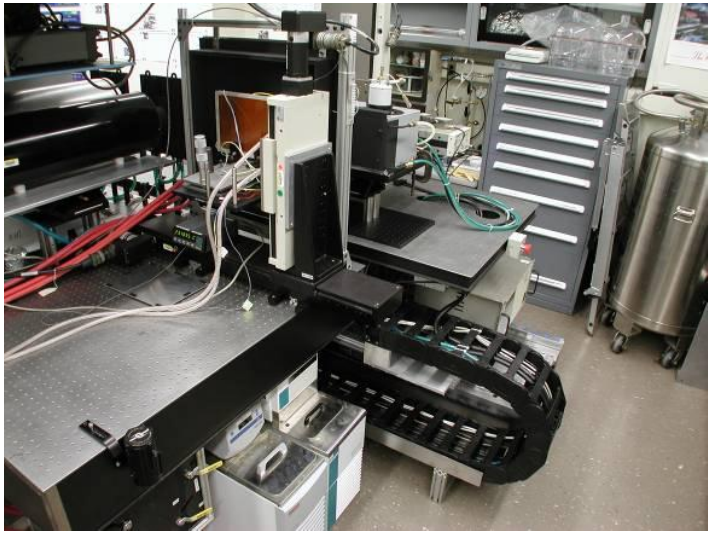


Fixed Point BB Bench

Advanced Infrared Radiometry and Imaging (AIRI) facility, among other functions, is enabling a national level traceability for measurements of absolute spectral radiance and spectral emissivity of BB sources and targets at near ambient and elevated temperatures at ambient environment.



Variable Temperature/Spectral Bench



Scene plate/Out-of-Field Scatter Tool

Outline - Requirements

- Current Status
- **Unfulfilled Demand**
- Common solution
- Concept of the multifunctional modular IR testbed for infrared radiometry and spectrophotometry support of spaceborne, airborne and ground-based targets and sensors.
- Performance goals and results of the detailed design and analysis. Critical technologies for implementation.
- Current budgetary constraints. Action plan and cooperation requirements.

Unfulfilled Demand

- Approximately 30 % of requests for IR calibrations cannot be fulfilled
  - (1) extended geometry (DHR),
  - (2) controlled background (vacuum/high purity purge or radiation background),
  - (3) extended temperature (lower Ts) and spectral range (longer wl),
  - (4) improved uncertainty (very few),
  - (5) clean room/controlled contamination lab (very few)

- Most of these customers can afford substantial calibration fees, but cannot sponsor extensive facility upgrade or wait until it happens;

- We are supporting these requirements, such as via reflectometry of paints and BB cavities as a proxy for direct radiance measurements;

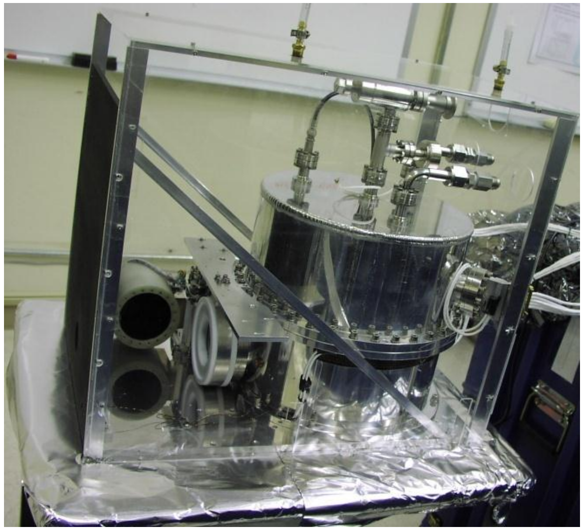
- This addresses most of immediate needs, but in the long run it is essential to offer direct support, not relying on modeling or other assumptions;

- Report describes recent design efforts to address a number of those shortcomings on calibration services. The effort was programmatically tied to the climate science mission but had much wider objectives.

Example: TXR Traceability

• The Thermal-infrared Transfer Radiometer (TXR) is a two-channel portable radiometer for providing thermal- infrared scale verifications of large-area calibration sources

• For many years, stays central for maintaining nationwide TIR traceability, was deployed multiple times for both ambient and thermo-vacuum applications



Traceability Options

- Current - WBBB
  - Scale based on ITS-90 and emissivity data
  - Easy to use; excellent for reproducibility studies
- IR SIRCUS / ACR (Future Possibility)

Summary – Present Status:

- Remains to be the primary tool for IR Radiance scale transfer in Tvac

- Limitations: calibrated in the ambient air and radiation background

Example: CLARREO IR Traceability Requirements

Decadal Study, Section 3-2:
Design of climate observing and monitoring systems from space must ensure the establishment of global, long-term climate records, which are of high accuracy, tested for systematic errors on-orbit, and tied to irrefutable standards such as those maintained in the U.S. by the National Institute of Standards and Technology.

Ibid., Section 4-10:
The Climate Absolute Radiance and Refractivity Observatory (CLARREO) will provide a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards. (4-10)

-What are the relevant national and international standards?

-What is the best way to tie CLARREO (or it's successor) to them?

-What it IRREFUTABLE?

Outline – Integrated Approach

- Current Status

- Unfulfilled demand

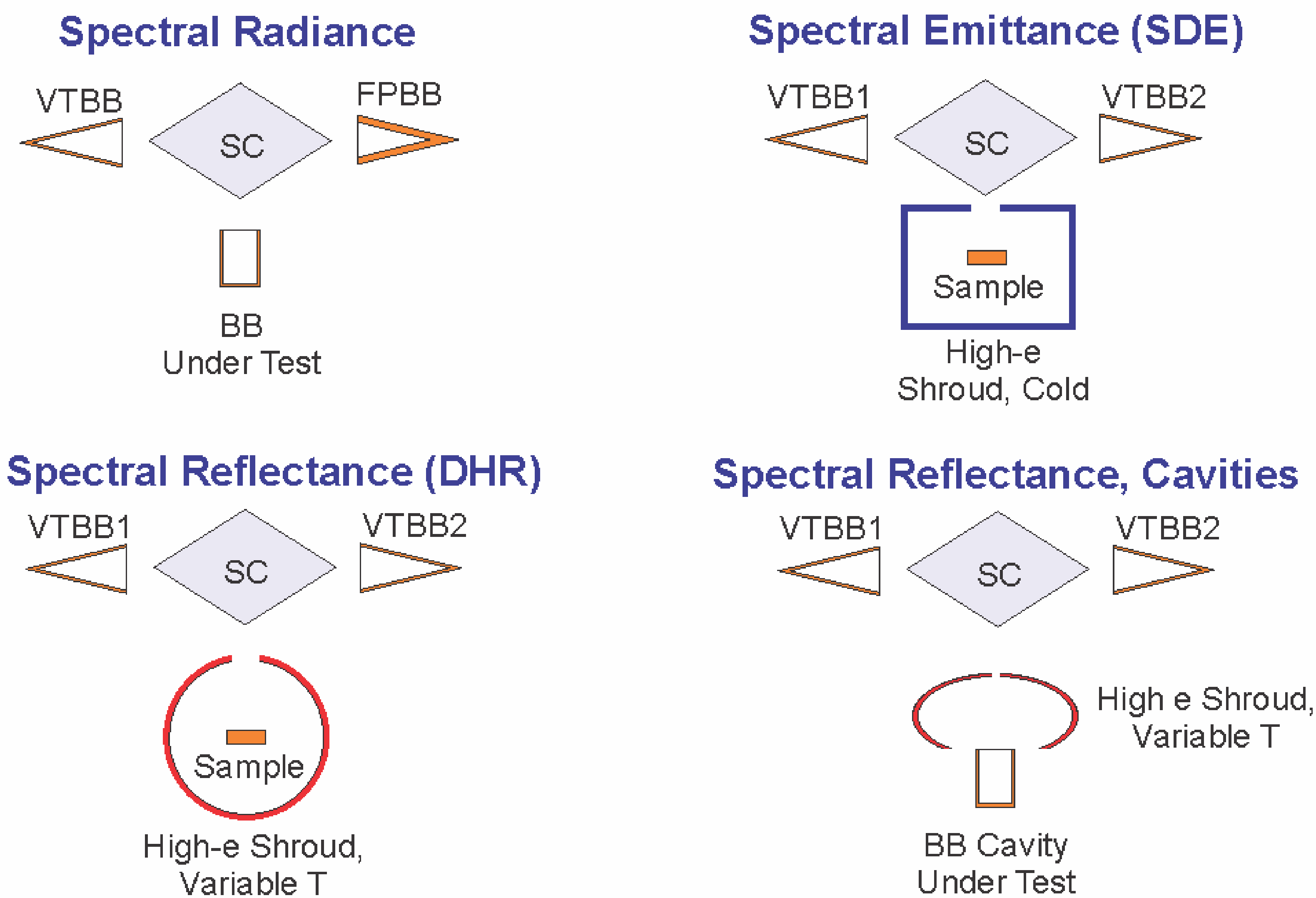
- **Common solution to SR / SDE / DHR: vacuum chamber with a high accuracy spectral comparator, plus application-specific tools.**

- Concept of the multifunctional modular IR testbed for infrared radiometry and spectrophotometry support of spaceborne, airborne and ground-based targets and sensors.

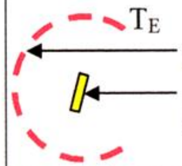
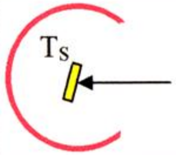
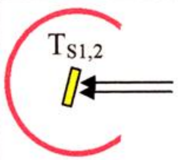
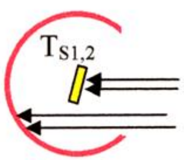
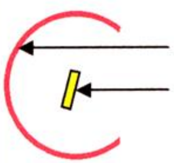
- Performance goals and results of the detailed design and analysis. Critical technologies for implementation.

- Current budgetary constraints. Action plan and cooperation requirements.

Anything in Common?



T&FIR Reflectance and Emittance Realization - 1

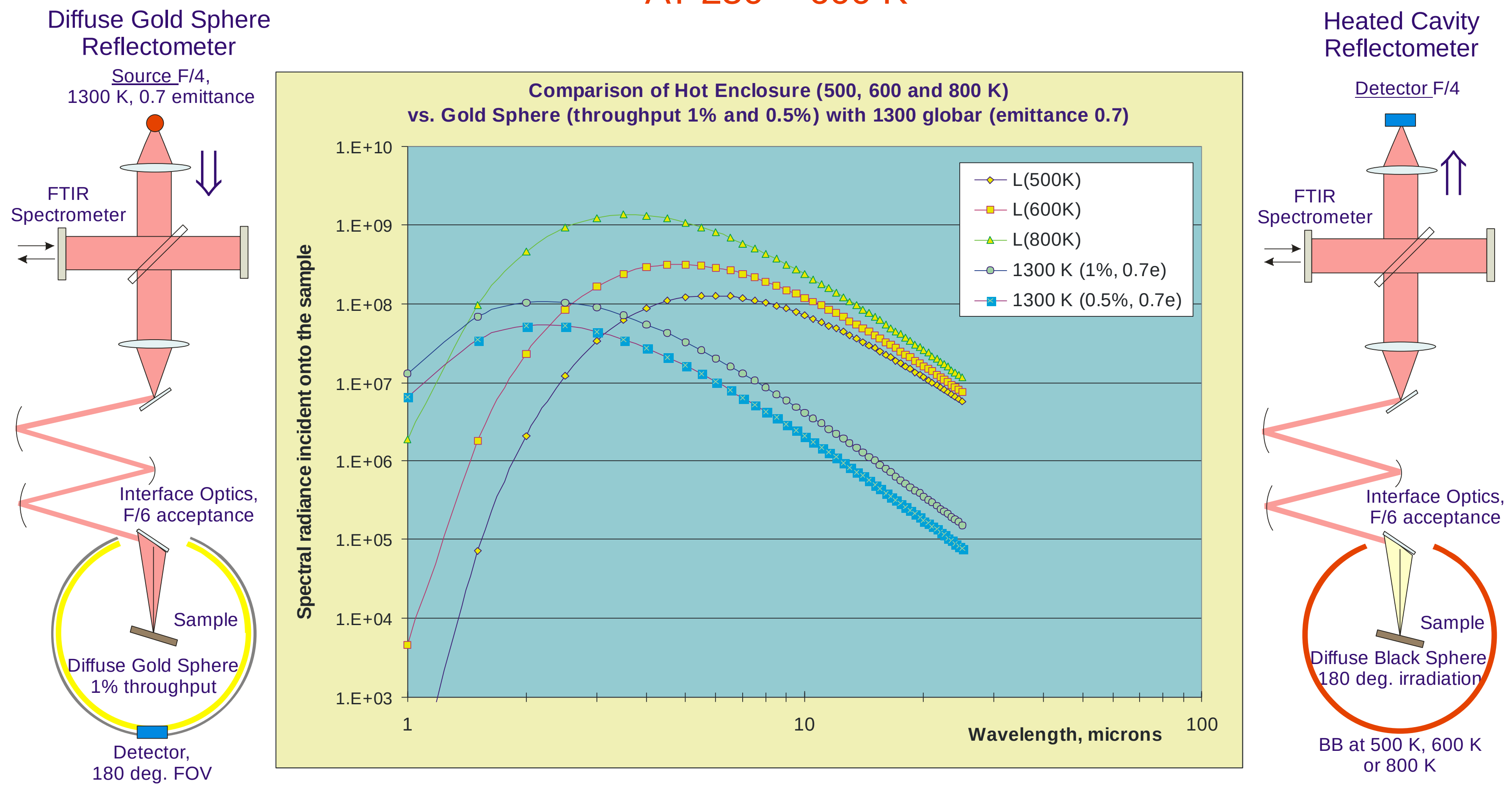
No.	Method	Measurement Equation	Assumptions or Practical Limitations
1.	 **Background Measurement (BM)** L_E $L'_S = \varepsilon_S(T_S)P(T_S) + (1-\varepsilon_S(T_S))L(T_E)$	$\varepsilon_S(T_S) = \dfrac{L'_S - L_E}{P(T_S) - L_E}$	$\rho_E \cong 0$
2.	 **Cold Enclosure (CE)** $L_S = \varepsilon_S(T_S)P(T_S)$	$\varepsilon_S(T_S) = \dfrac{L_S}{P(T_S)}$	$\rho_E \cong 0$ $T_E << T_S$
3.	 **Two Sample Temperatures (2ST)** $L'_{S1} = \varepsilon_{S1}P(T_S) + (1-\varepsilon_{S1})L(T_E)$ $L'_{S2} = \varepsilon_{S2}P(T_{S1}) + (1-\varepsilon_{S2})L(T_E)$	$\varepsilon_S(T_S) = \dfrac{L'_{S2} - L'_{S1}}{P(T_{S1}) - P(T_{S2})}$	$\varepsilon_S(T_S) = \varepsilon_S(T_S + \Delta)$ $T_E < T_S$
4.	 **Two Enclosure Temperatures (2ET)** $L'_{S1} = \varepsilon_S(T_S)P(T_S) + (1-\varepsilon_S(T_S))L_E(T_{E1})$ $L'_{S2} = \varepsilon_S(T_S)P(T_S) + (1-\varepsilon_S(T_S))L_E(T_{E2})$ $L_E(T_{E1}), L_E(T_{E2})$	$\varepsilon_S(T_S) = 1 - \dfrac{L'_{S2} - L'_{S1}}{L_E(T_{E1}) - L_E(T_{E2})}$	$\rho_E(T) = \rho_E(T + \Delta)$ $T_E > T_S$
5.	 **Hot Enclosure (HE)** $L'_S = (1-\varepsilon_S(T_S))L_E(T_E)$ $L_E(T_E)$	$\varepsilon_S(T_S) = 1 - \dfrac{L_S}{L_E}$	$\rho_E \cong 0$ $T_E >> T_S$

Assumptions common for all methods but #2:
-Enclosure creates isotropic hemispheric irradiation of the sample
Enclosure radiance in all directions equal to the measured (or calculated) one

Specific Assumption for #1, #2, #5:
-Influence of external (lab) background radiation, entering through the port, is negligible

Thermal and Far IR Reflectance Realization - 2

HEATED CAVITY REFLECTOMETER AS COMPLEMENTARY METHOD FOR ANGLE-RESOLVED REFLECTANCE AND TRANSMITTANCE MEASUREMENTS AT 250 - 600 K



Variable Background (Black Sphere) Reflectometer

- MW- and LW- IR – major throughput advantage compared with diffuse gold sphere reflectometers
- Smaller port loss can help to reduce uncertainty in MW- and LWIR
- In the Far IR it is very attractive due to lack of diffuse materials (most of which become either specular or low reflective in FIR) for building an efficient sphere reflectometer
- Has to be large due to lower emissivity of wall coating in Far IR, to reduce multiple reflections of the sample-emitted radiation.
- Can be non-spherical – if we can maintain good uniformity of shroud temperature, we DO NOT NEED the sphere

Outline - Multifunctional Modular IR Testbed Concept

- Current Status

- Unfulfilled requests

- Common solution

- **Concept of the Multifunctional Modular IR Testbed for IR radiometry and spectrophotometry support of spaceborne, airborne and ground-based targets and sensors**

- Performance goals and results of the detailed design and analysis. Critical technologies for implementation.

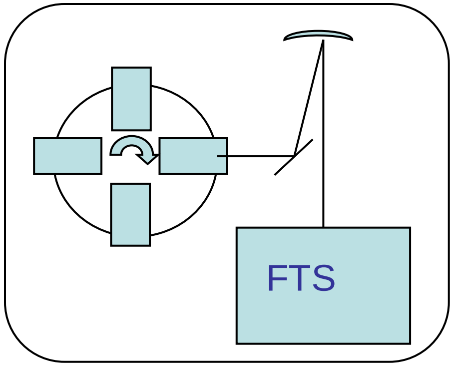
- Current budgetary constraints. Action plan and cooperation requirements.

CBS3 - Design Principles

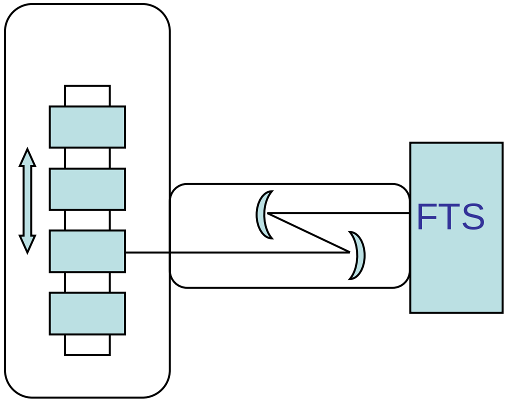
- After analysis of emerging requirements in metrology of thermal emission sources and optical materials and components, and evaluation of several existing IR calibration facilities, a Controlled Background Spectroradiometry and Spectrophotometry System (CBS3) concept was developed;

- Criteria in selecting CBS3 design included:
  - **Multifunctionality**: facility should advance state of the art in all our three main areas – spectroradiometry of IR sources and sensors, and spectrophotometry of materials and BB cavities;
  - Widely **variable environmental conditions** for the UUT: form high vacuum to atmospheric pressure and from LN_2 to above-ambient radiation background;
  - **Modularity**: separate functional modules should be easily replaceable, serviceable and upgradable;
  - **Advanced optical alignment and diagnostic capabilities**, both before and during the measurements;
  - **Low contamination environment**: use only technical solutions which allow, if necessary, certification of environment to allow handling clean artifacts

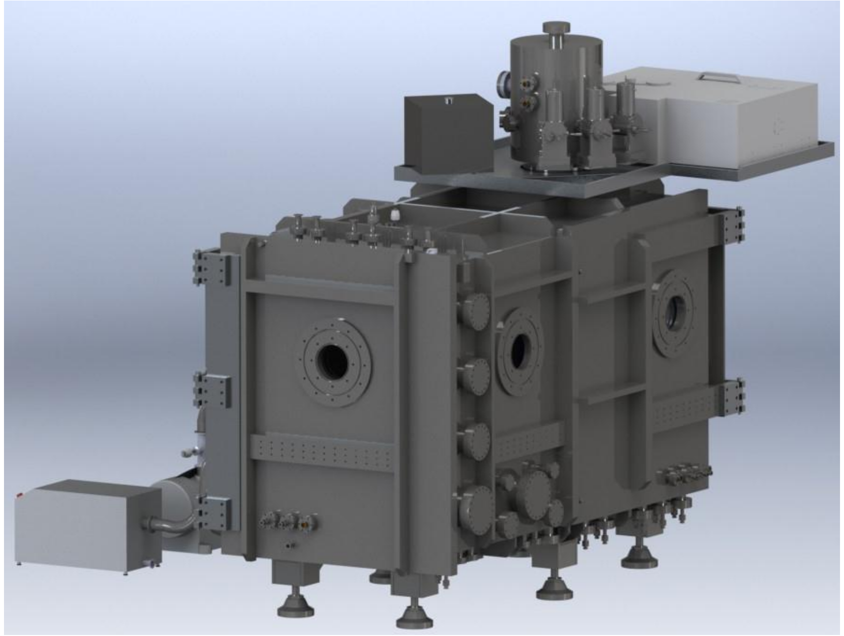
Vacuum Radiance Comparator Arrangements

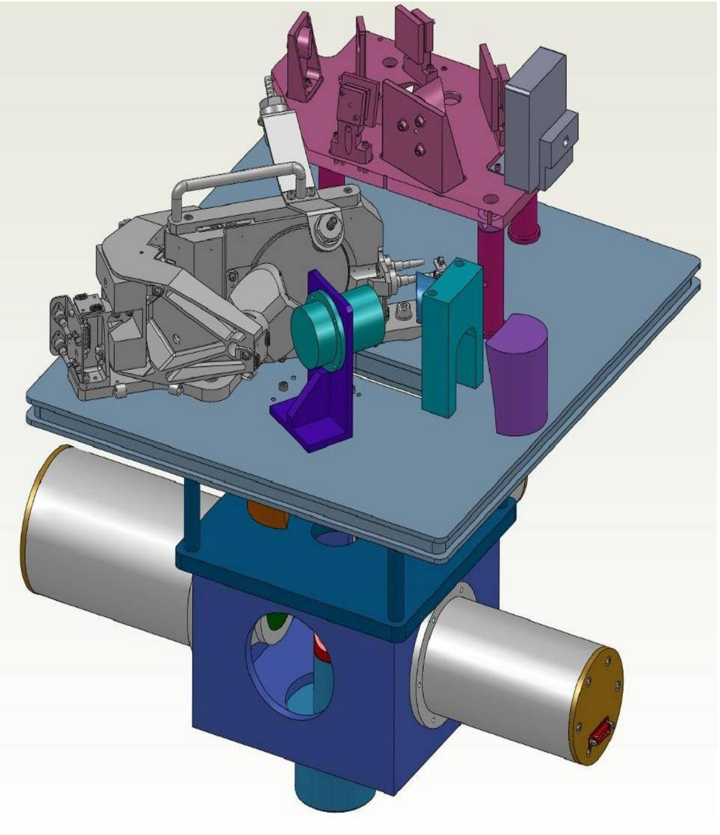


Harvard U. Chamber



PTB RBCF





U.Wisconsin SSEC
Breadboard Prototype

Selected Box Chamber design was suggested by Joel Fowler (NIST, ret.), who originally came up with this design 15 years earlier setting up MBIR

Concept of Radiance Scale Realization and Transfer

Thermal and Far IR Spectral Radiance Scale Realization and Validation

CAVITY EMISSIVITY MEASUREMENT VIA REFLECTOMETRY

Assumptions:
- T distribution is uniform
- Measurement geometry is identical to used in the sensor

Facility	*Method:*
CHILR (24 um)	Laser Reflectometer (QCL)
SFIRR	Laser or Synchrotron (PTB)
CBS3	Variable Background Reflectometer

Effective Emissivity

Step 1. Scale Realization

Planck Equation

$$L_{bb}(\lambda) = \varepsilon(\lambda) \cdot \frac{c_{1L}}{n^2\lambda^5} \cdot \frac{1}{\exp\left(c_2 / (n\lambda T)\right) - 1}$$

THERMOMETRY

Assumptions:
- Temperature distribution across the cavity is well known
- Thermowell (or crucible) temperature has KNOWN OFFSET from the emitting surface tempertaure

Temperature

	Facility
- Phase transition cells	
- Contact Thermometry (PRT or Thermistors)	CBS3

CAVITY TEMPERATURE DISTRIBUTION MODELING

Calculation of cavity temperature distribution, including gradient from the sensor to the radiating service, using two- and three-dimensional heat transfer analysis

Step 2. Scale Validation

Facility	*Method: INTERNAL COMPARISONS*
NIST CBS3	- Comparison of BB with different geometry, coating and thermometry principles - Varying aperture size and ambient background for one of two compared Bbs
	Method: INTERLABORATORY COMPARISONS
NIST CBS3 PTB RBCF KRISS	- Comparison via Transfer Standard Blackbody Source

CAVITY EFFECTIVE EMISSIVITY MODELING

Assumptions:
- T distribution is CORRECTLY MODELED
- Coating is uniform

Software	*Input Property Required*	*Facility*	*Method:*
STEEP3.15	BB Coating Emittance	SOC 100	Mirror reflectometer
		NIST Emittance PTB Emittance	Direct
		NIST FIRES	Black sphere reflectometer

Step 3. Scale Transfer

The Spectral Radiance Transfer can be implemented in the following ways:

COMPONENT LEVEL CALIBRATION:

- Calibration at CBS3 of the IR Sensor on-board Internal Calibration Sources

SYSTEM LEVEL CALIBRATION:

- Calibration at CBS3 of the Transfer Standard Source, to be subsequently used for calibration of the complete sensor at the integrator facility
- Deployment of the CBS3 primary BB at the integrator facility for direct sensor calibration

CBS3 - Design Effort Scope and Results

Developed design is supported by detailed analysis and optimization, which included:

- Structural analysis, including stress and deformations (L-1);
- Optical performance analysis (L-1);
- Thermal performance for the shrouds (L-1);
- Effective emissivity analysis for the primary blackbody cavities (NIST / Virial)
- Thermal analysis for the primary fixed point blackbodies (Pond Engineering)
- Effective emissivity analysis for the variable background reflectometer (NIST / Virial)

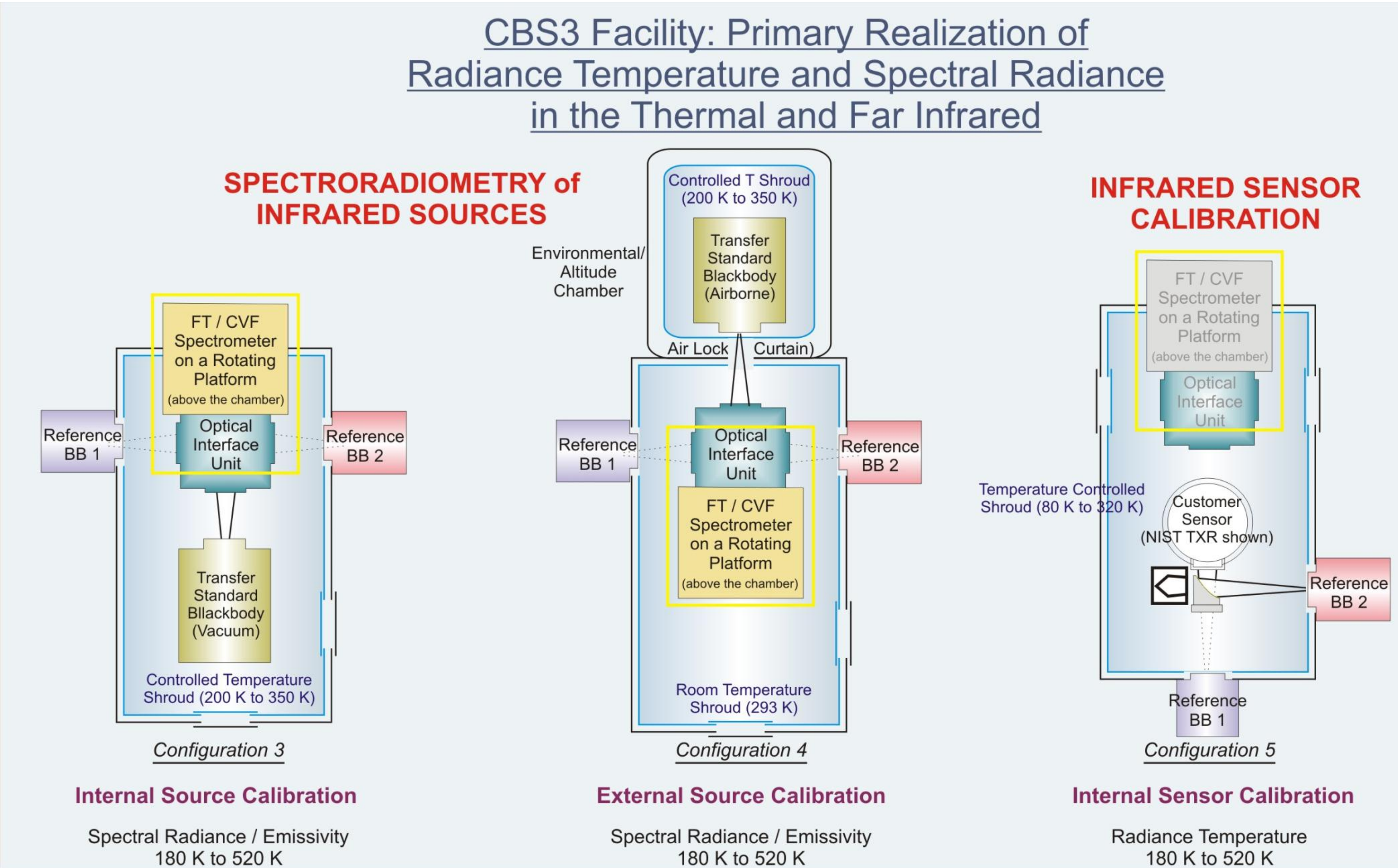
Remaining activities in this area include:

- Diffraction analysis of the foreoptics
- Thermal analysis for the primary variable temperature blackbodies (pending optical and thermophysical properties of the paint)

Results of the design effort:

- Machine-ready design for the vacuum chamber and spectral comparator
- Advanced stage of the primary BB sources design
- Conceptual design stage for reflectometry components

Radiance Temperature Modes of CBS3

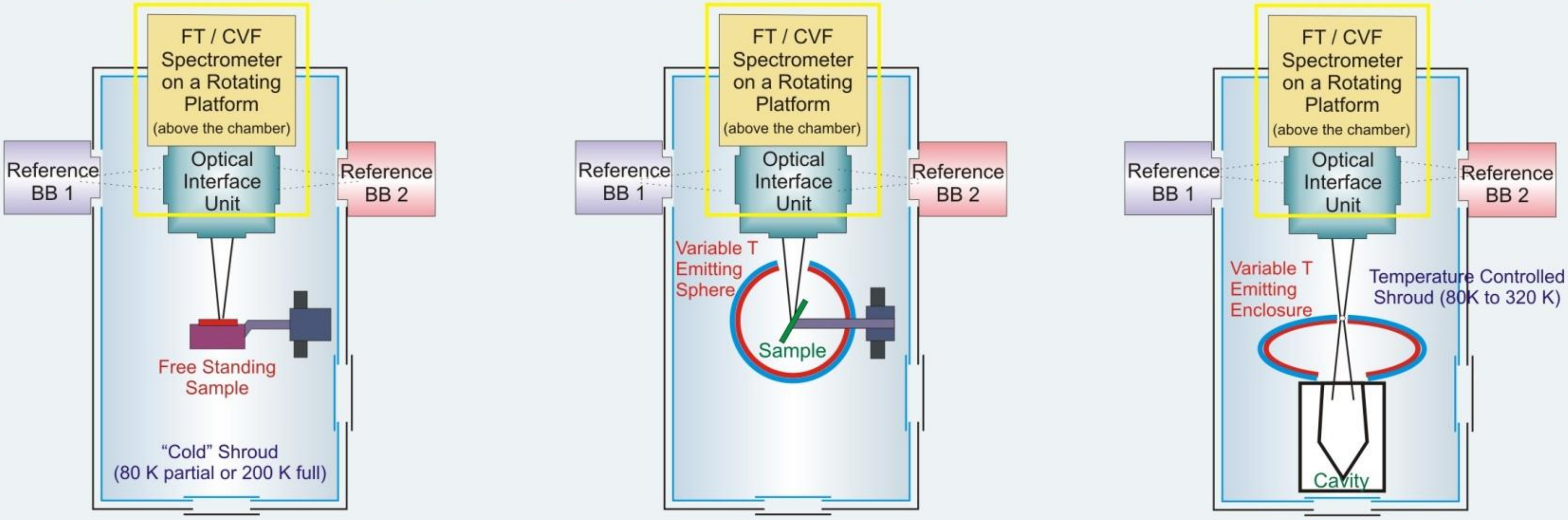


Optical Property Metrology Modes of CBS3

CBS3 Facility: Primary Realization of Spectral Directional Emittance and Hemispherical-Directional Reflectance in the Thermal and Far Infrared

OPTICAL MATERIALS AND COATINGS CHARACTERIZATION

BLACKBODY CAVITY CHARACTERIZATION



Configuration 1

Sample Emissometry

Unit: Spectral Directional Emissivity
Sample at: 250 K to 520 K

Works best for: Hot black targets

Configuration 2

Sample Reflectometry

Scale: Hemispherical-Directional Reflectance
Sample at: 80 K to 350 K

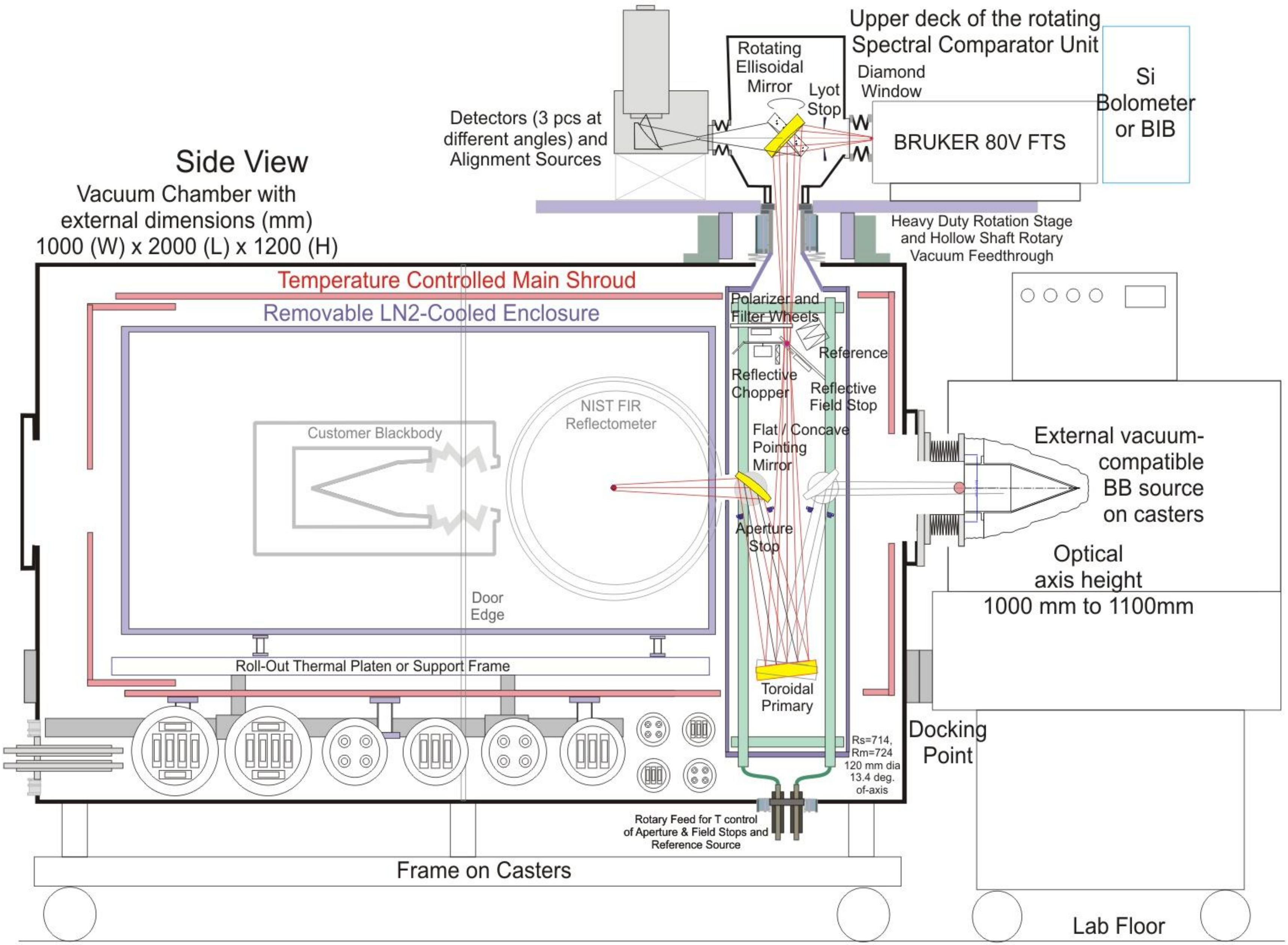
Works best for: Cold grey targets

Configuration 3

Cavity Reflectometry in Mid/Far IR

Scale: Hemispherical-Directional Reflectance
Cavity at: 80 K to 200 K

Schematic Cross-Section of the CBS3 Concept



Outline – CBS3 Design and Critical Enabling Technologies

- Current Status of IR Radiance (AIRI + TXR), Emittance (SDE Facility) and Reflectance (FT DHR Facility)

- Unfulfilled requests

- Common solution: vacuum chamber with a high accuracy spectral comparator. Physics behind each scale realization approach.

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- **Performance goals and results of the detailed design and analysis. Critical technologies for implementation.**

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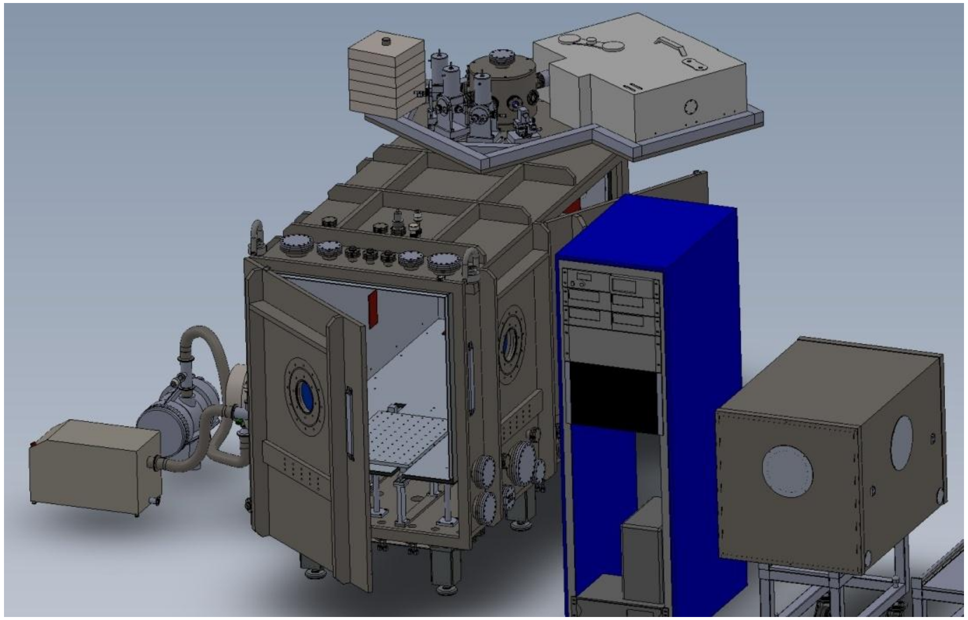
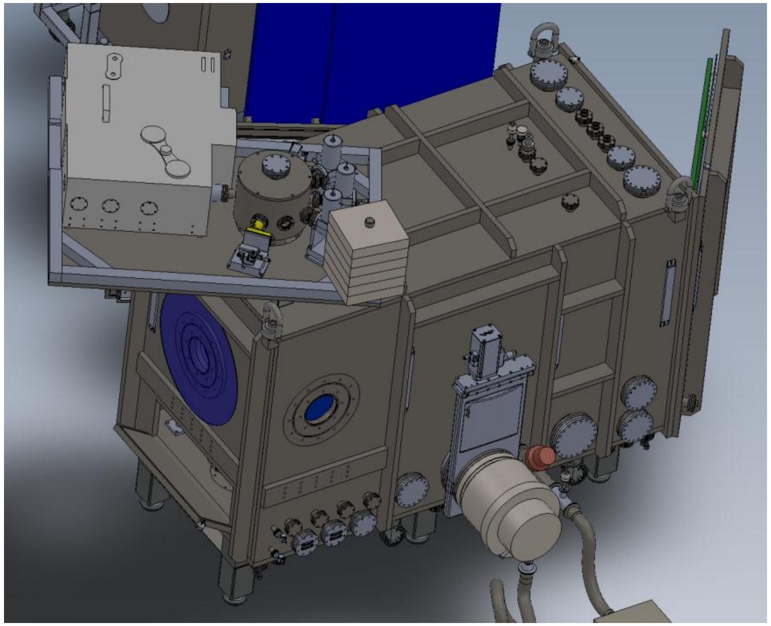
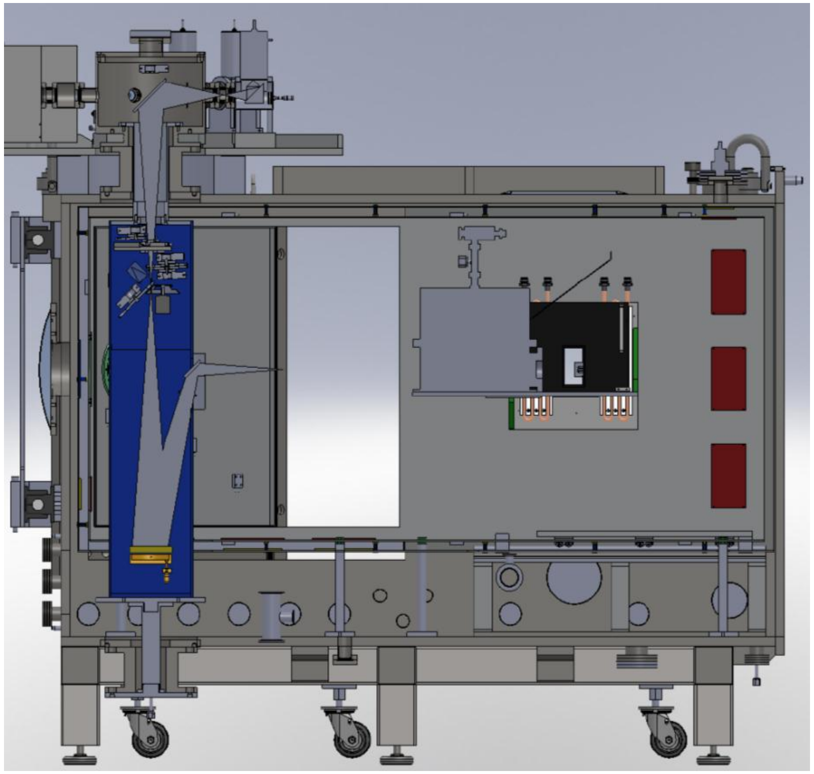
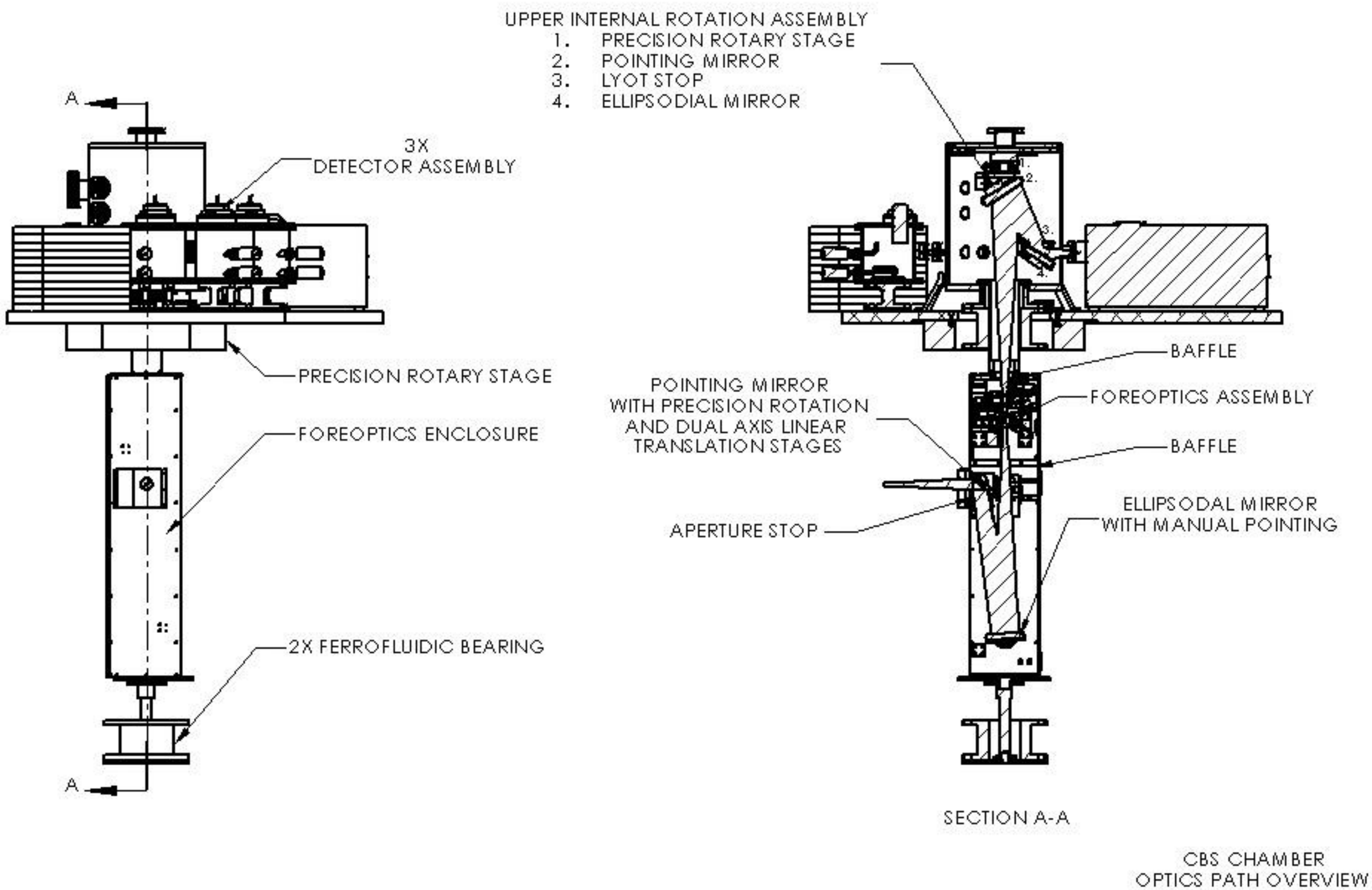
CBS3 3D Model Views (with TXR in the right figure)



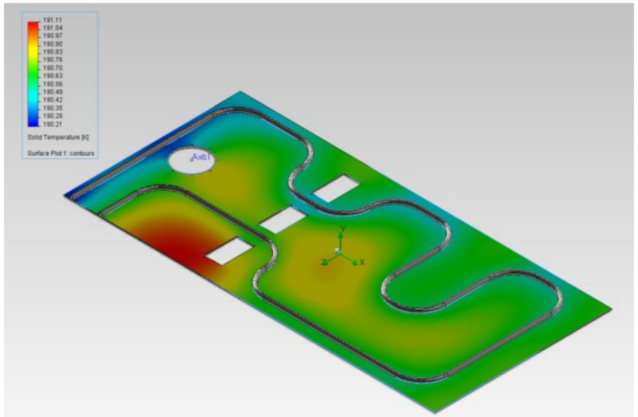




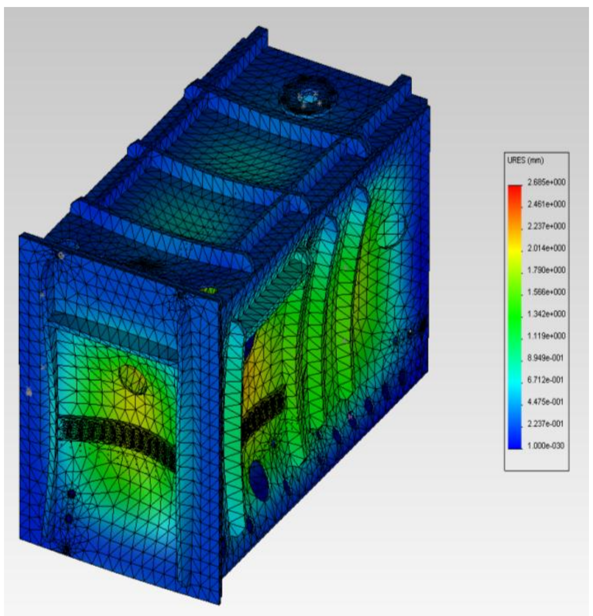
Foreoptics and Upper Chamber Assembly Design



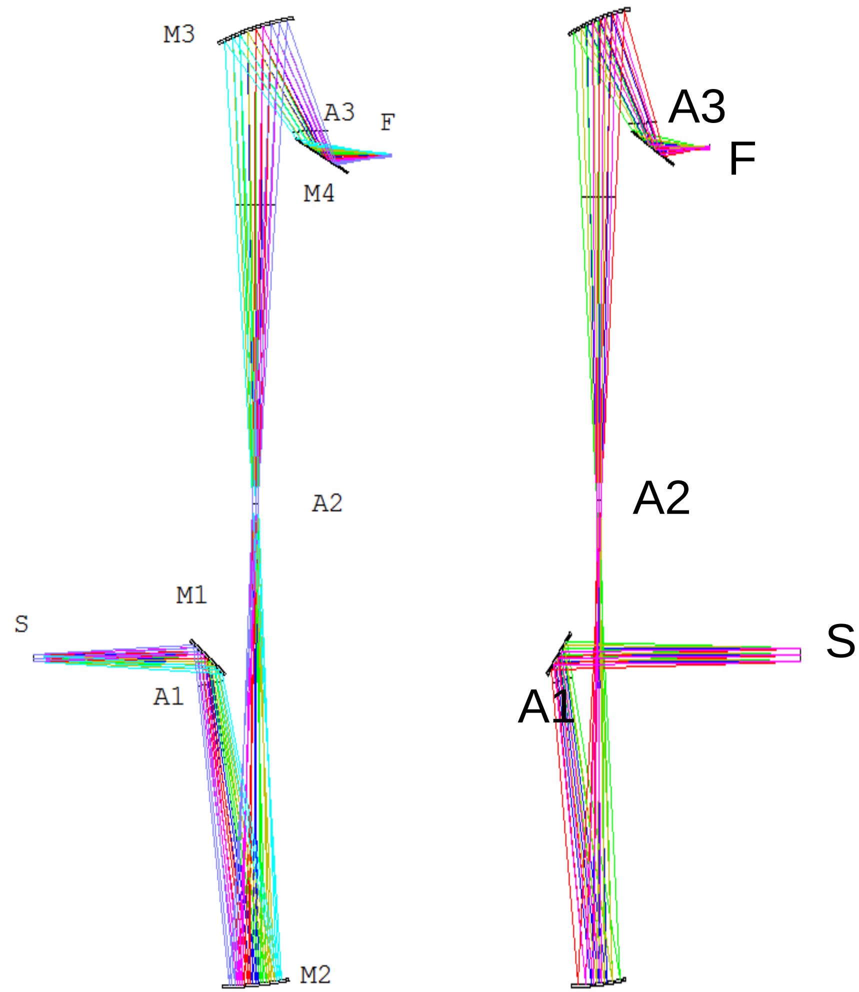
Modeling and Design Results (L-1)



The Left plate's temperature ranges from 190.21 to 191.11 K.



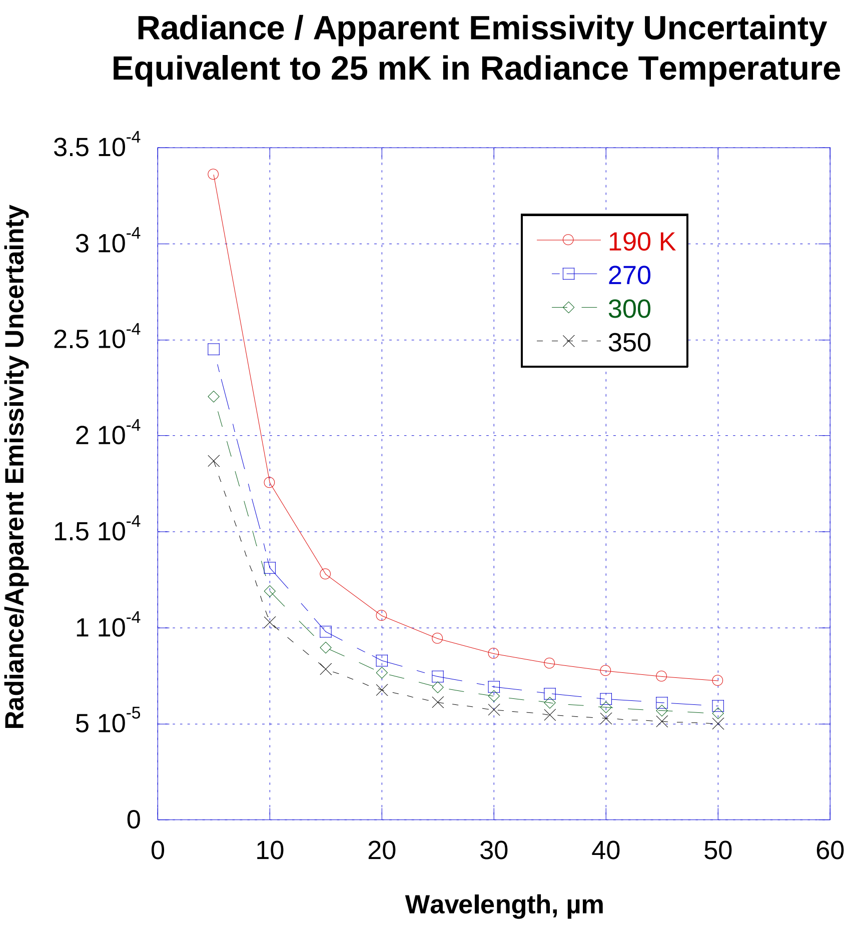
Isometric view of Stress Test, Trial 2 (12.7 mm plates).



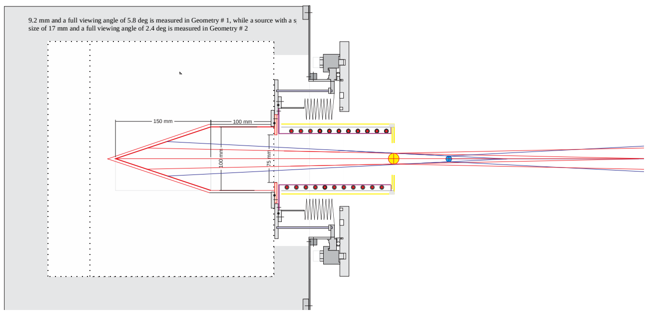
ZEMAX layout for tow geometries. The image at Lyot Stop using the image analysis tool in ZEMAX.

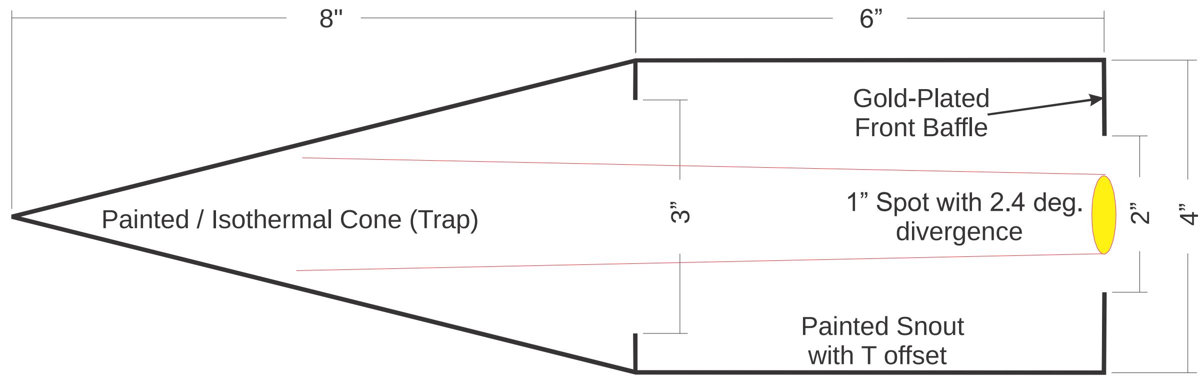
Blackbody Emissivity Requirements

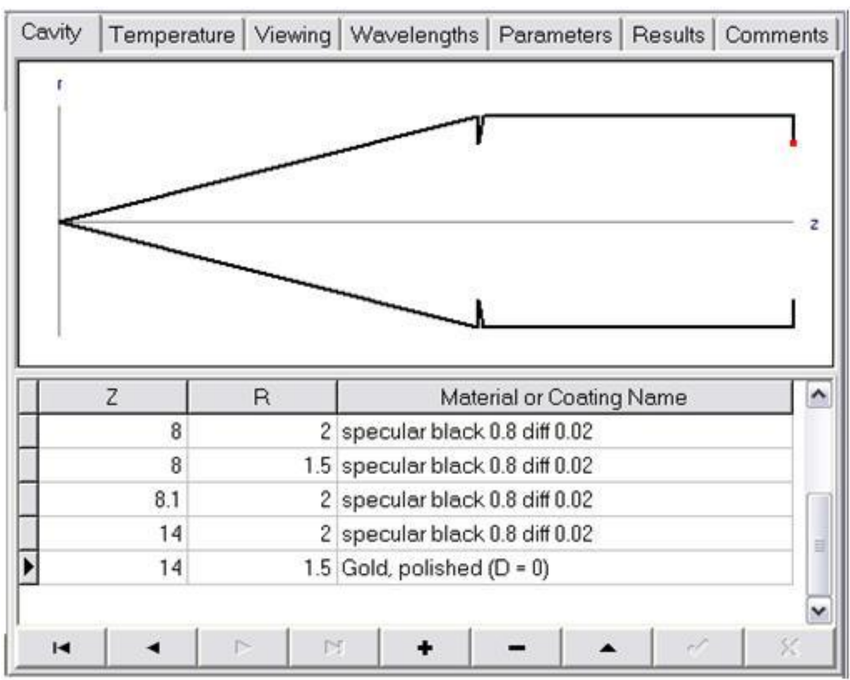
End user requirements in radiance temperature uncertainty at the level of 25 mK, such as CLARREO, translate into effective emissivity requirements for the primary blackbody sources to be at the level of 0.99995 or greater (see Fig. below left). Some existing near-ambient sources, such as the water bath variable temperature BB and Ga fixed point BB meet these specifications in the thermal IR. Their performance in the far IR has to be evaluated and potentially improved



Cavity Absorptivity Modeling – Input Parameters

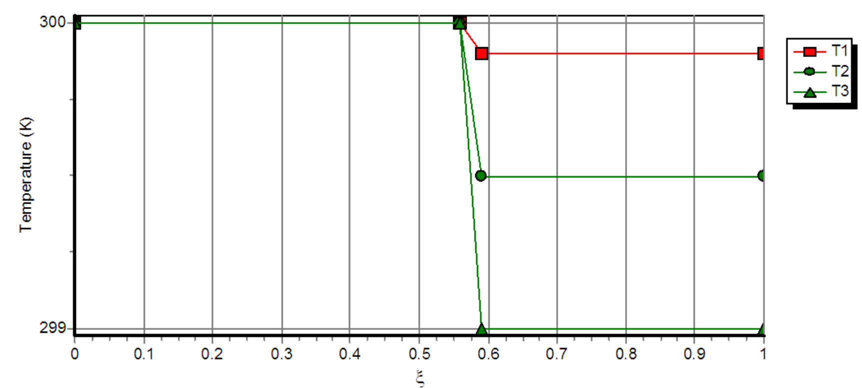






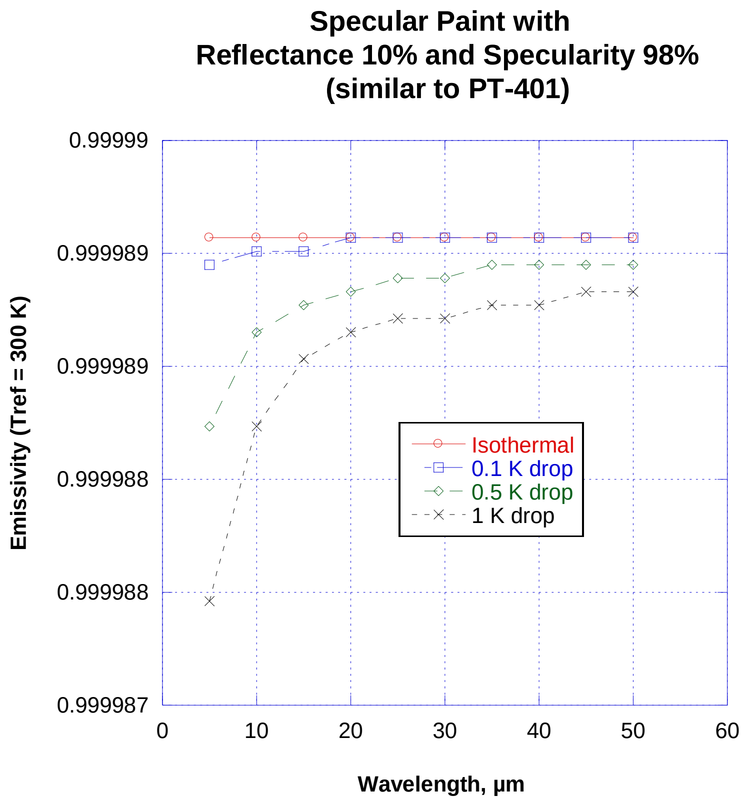
Temperature Distributions along Cavity Generatrix

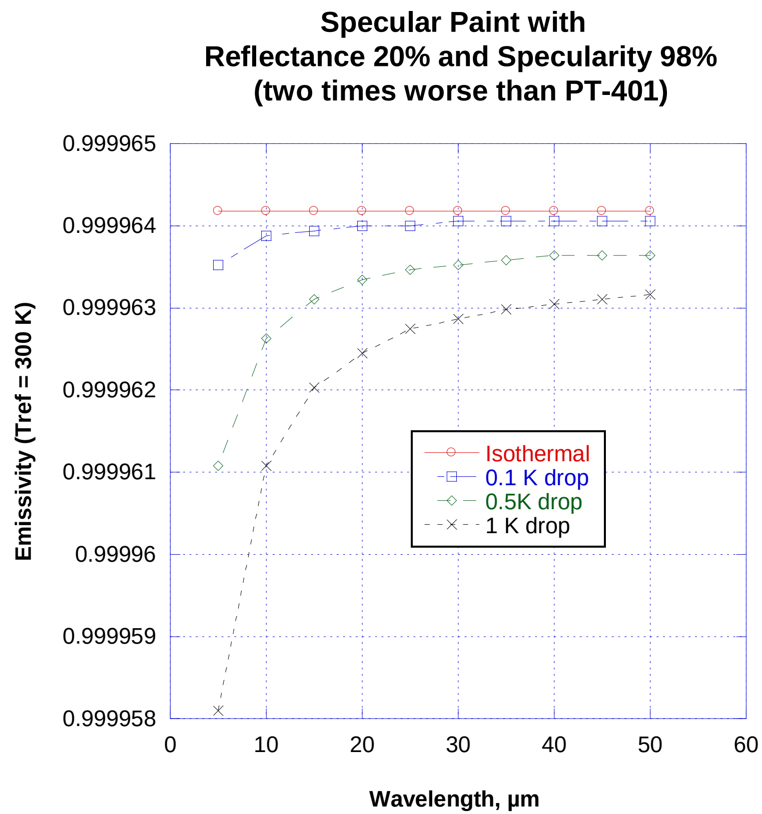
Surface No.	ξ	Z	R	T1	T2	T3	T4	T5	T6	T7	T8
1	0.0000	0.0000	0.0000	300	300	300					
3	0.5586	8.0000	1.5000	300	300	300					
4	0.5912	8.1000	2.0000	299.9	299.5	299					
5	0.9991	14.0000	1.5144	299.9	299.5	299					



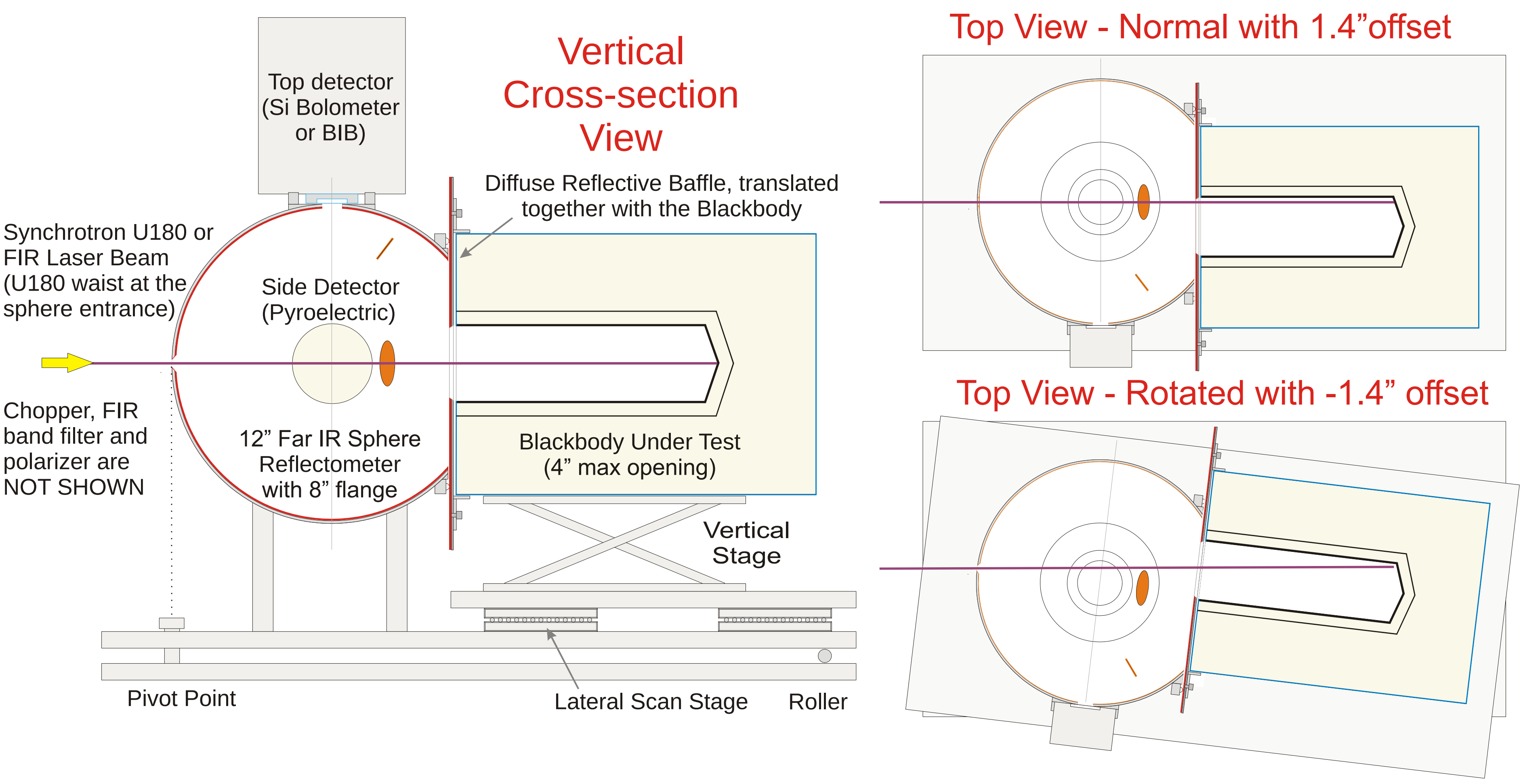
Results of Cavity Emissivity Modeling for Diffuse and Specular Paint Cases

Calculations performed using Monte-Carlo - based software show that emissivity requirements can be met with a modest size cavity, if a specular black similar in performance to LORD Z302 or PTI PT-401 is used. Calculations were made with reflectance values TWICE as large as those actually measured, to account for high incidence angle effects.





Underlying Technologies: SFIRR (Spherical Far IR Reflectometer) For BB Cavity Metrology



Outline – Near Future Tasks

- Current Status of IR Radiance (AIRI + TXR), Emittance (SDE Facility) and Reflectance (FT DHR Facility)

- Unfulfilled requests

- Common solution: vacuum chamber with a high accuracy spectral comparator. Physics behind each scale realization approach.

- Concept of the multifunctional modular IR testbed for infrared radiometry and spectrophotometry support of spaceborne, airborne and ground-based targets and sensors.

- Performance goals and results of the detailed design and analysis. Critical technologies for implementation.

- **Current budgetary constraints. Action plan and cooperation opportunities**

Impact of the Current Budgetary Constraints

- In spring of 2011 NASA terminated or descoped a number of large (≥ $1 Billion) missions in the early phases, which included astrophysical (LISA, IXO) and planetary science (DESDynI and CLARREO);

- Without CLARREO as immediate requirement, in absence of clarity with successors to the current EOS and NPOESS instruments, and in anticipation of further budgetary corrections, CBS3 facility construction in the presented scope was suspended;

- The reported concept of CBS3 is not likely to be implemented in its totality; radiometric and spectrophotometric components are likely to be separated (next slide);

- An integrated concept was nevertheless presented, because of several advantages it offers.

Future Plans

- Critical Supporting Technologies, Modeling and Concept Demonstration
  - Far IR Optical Properties of Materials / Preliminary Scales
    - *Achieved progress (with PTB and SOC) is adequate for the purposes of the project (a small part of the paint study is yet to be finalized);*
  - Far IR Optical Properties of BB Cavities
    - *NIST has adequate capability for Thermal IR performance evaluation. At this point we can rely on extrapolation of the Far IR portion, using new coating data and developed software;*
    - *SFIRR design and implementation, in cooperation with PTB, is likely to continue;*
  - Concept Feasibility
    - *A concept demonstration study (with Harvard U. and U. of Wisconsin-Madison) completed, with results to be reported / published at the TMSCI in March 2011;*

- Realization and Transfer of Spectral Radiance for Thermo-Vacuum Environment
  - Primary and transfer standard FIR BB sources
    - *Design and prototyping is likely to continue (with possible cooperation with PTB RBCF Facility), if required modest resources are available;*
  - Spectral Comparator Facility
    - *Multipurpose facility is fully designed but now defunded;*
    - *Now the concept is being re-formulated, leaving core features with at least 50% cost reduction and shorter production time, to allow prompt implementation when requirements arise;*

- Realization of Far IR Spectral Emittance and Reflectance
    - *Uncertainty requirements in terms of radiance are at least 10 times lower those for climate or remote sensing applications;*
    - *Planning a dedicated small vacuum chamber with shared use of FTS and other assets*