Support for the IR Radiometry at NIST – Status Update

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2011 Workshop on Far-Infrared Remote Sensing

November 09, 2011 Madison WI

Newly (Oct. 01, 2011) Formed NIST Sensor Science Division 685

- Temperature and Humidity (contact and radiation temperature above 960 C)
- Fluid Metrology
- Optical Radiation (collision induced absorption – Baranov/Lafferty)
- Infrared Technology
- Lighting and Color
- Laser Applications
- Ultraviolet Radiation (NIST Synchrotron Radiation source)
- Pressure and Vacuum

Introduction

NIST IR Spectrophotometry and Spectroradiometry Project
(PI Leonard Hanssen):

– IR Optical Properties of Materials	DHR, Variable angle DHR, Variable Angle Regular Transmittance and Reflectance, BRDF, Emittance
– IR Reflectometry of Blackbody and Absolute Radiometer Cavities	DHR with Laser and Thermal Sources
– IR Radiometry	Spectral Radiance and Radiance Temperature

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

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

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 1. Scale Realization

Effective Emissivity

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

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

Facility

CBS3

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

Step 3. Scale Transfer

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

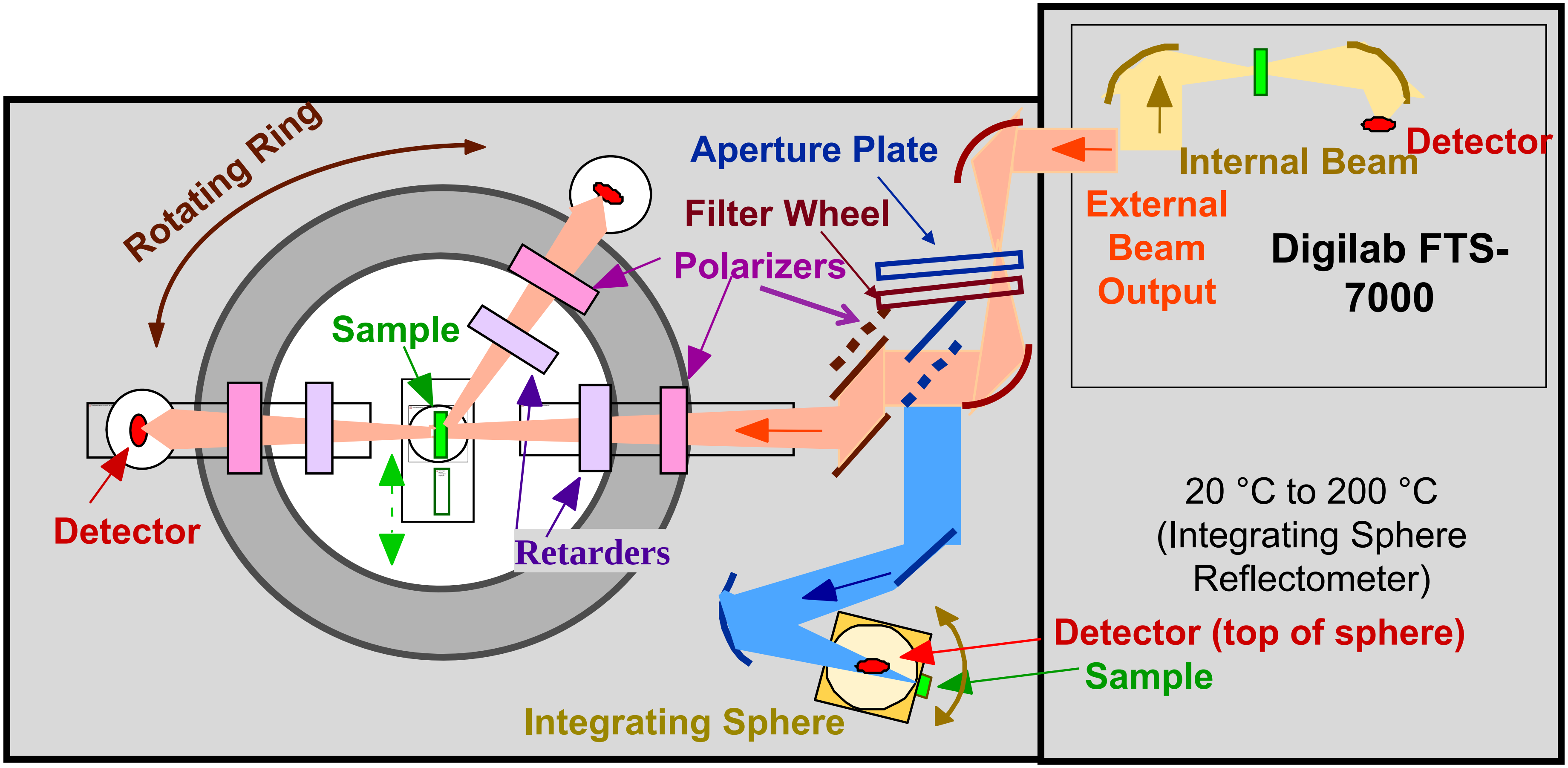
COMPONENT LEVEL CALIBRATION:

- 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

NIST Capabilities: Reflectance / Transmittance



Optical Tables w/ Purged Enclosures

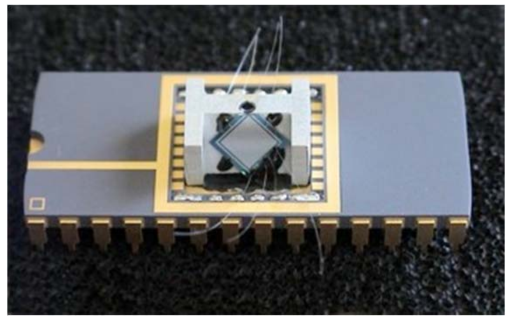
$$\rho\left(\nu, T_{Sample}\right) = \frac{V_{Sample}(\nu) - V_{Sample}^{FT \cdot source \cdot off}(\nu)}{V_{Sphere}(\nu) - V_{Sphere}^{FT \cdot source \cdot off}(\nu)} = 1 - \varepsilon\left(\nu, T_{Sample}\right)$$

New Equipment for Reflectometry Extension to 30 μm

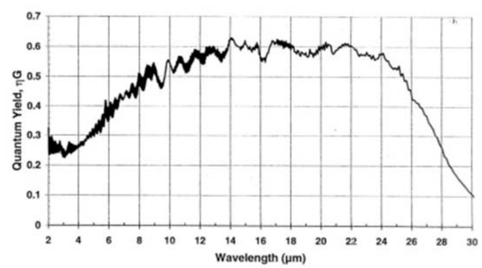
QMC LHe Cryostat (TK1813)

Height 20 " x Dia 9 "
Mass: 20 Kg

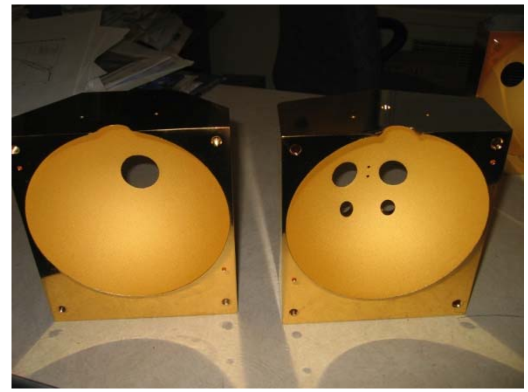
Si:As BIB Detector (Trap)



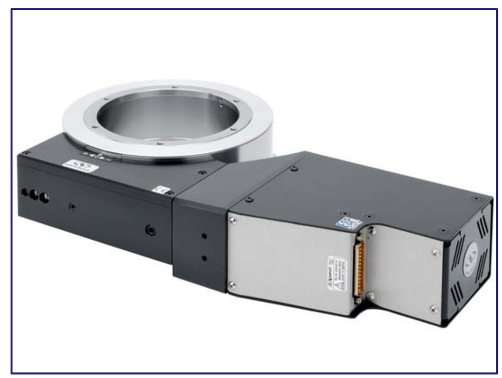
Relative Responsivity



New IR Sphere

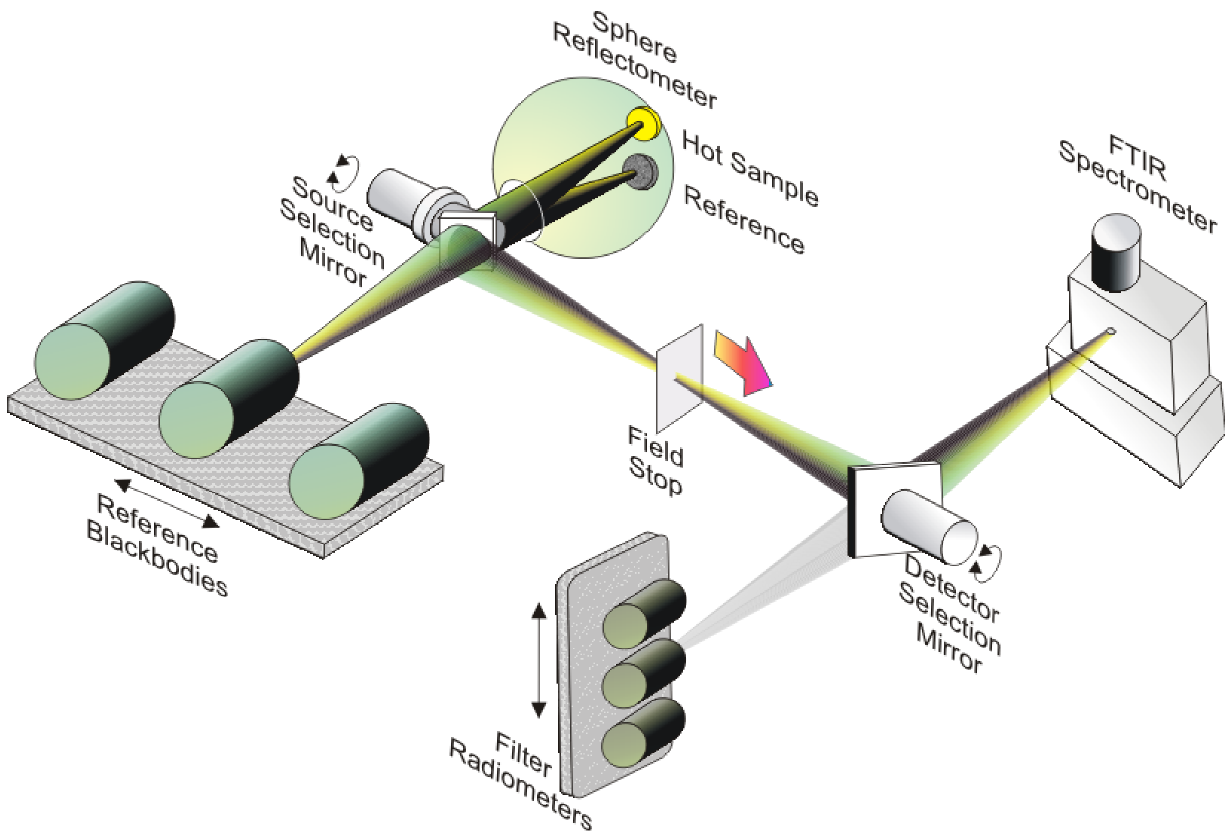


Heavy Duty Rotation Stage



NIST Capabilities: Emittance

200 °C to 900 °C: FT-Based Spectral Radiance Comparator (includes Near IR Sphere)



$$L_{Sample}(\nu, T_{Sample}) = \mathrm{Re}\left[\frac{\left[V_{Sample}(\nu) - V_{BB_{Cold}}(\nu)\right]}{\left[V_{BB_{Hot}}(\nu) - V_{BB_{Cold}}(\nu)\right]}\right]\left[L_{BB_{Hot}}(\nu) - L_{BB_{Cold}}(\nu)\right] + L_{BB_{Hot}}(\nu)$$

$$and \quad L_{Sample}(\nu, T_{Sample}) = \varepsilon_{Sample}(\nu, T_{Sample}) \cdot B(\nu, T_{Sample}) + \left[1 - \varepsilon_{Sample}(\nu, T_{Sample})\right] \cdot B(\nu, T_{Ambient})$$

International Comparisons

- ## Regular Reflectance and Transmittance
- **Participants: NPL, NIST**
- **Year: 2000-2001**
- **Spectral Range: 2.5 µm to 18 µm**
- **4 Materials**
- **C.J. Chunnilall, F.J.J. Clarke, M.P. Smart, L.M. Hanssen, S.G. Kaplan, "*NIST-NPL comparison of mid-infrared regular transmittance and reflectance*," Metrologia 40, S55-S59, (2003).**

- ## Regular Reflectance and Transmittance
- **Participants: NIST IR vs. UV-VIS-NIR Scales**
- **Year: 2002**
- **Spectral Range: 1 µm to 2.5 µm**
- **6 Materials**
- **S. G. Kaplan, L. M. Hanssen, E. A. Early, M. E. Nadal and D. Allen, "*Comparison of near-infrared transmittance and reflectance measurements using dispersive and Fourier transform spectrophotometers*," Metrologia 39, 157-164 (2002).**

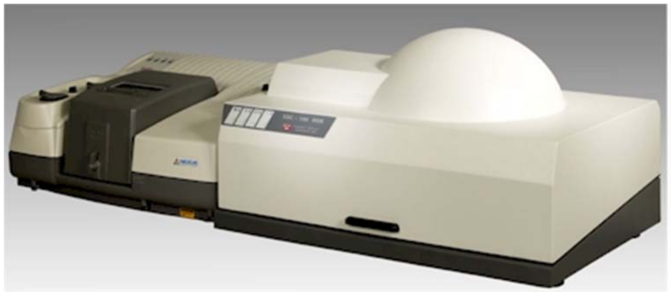
- ## Directional-Hemispherical Reflectance
- **Participants: NRC, NIST**
- **Year: 2006**
- **Spectral Range: 2.5 µm to 18 µm**
- **3 Materials**
- **L.M. Hanssen, N.L. Rowell, "*Comparison of NRC and NIST Infrared Diffuse Reflectance Scales from 2 µm to 18 µm* ," 5th Oxford Conference on Spectrometry, June 26-28, 2006, Teddington, UK (2006).**

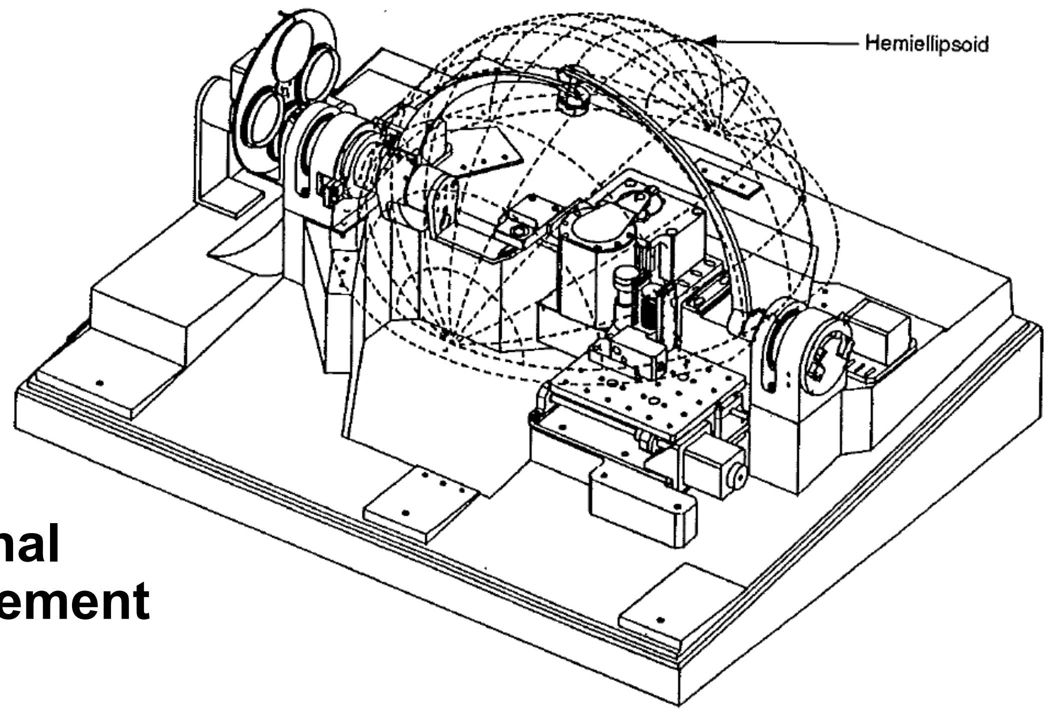
- ## Near Normal Absorptance
- **Participants: NMIJ, NIST**
- **Year: 2004**
- **Spectral Range: 2.5 µm to 10 µm**
- **5 Materials**
- **J. Ishii, L.M. Hanssen, "*Comparison of mid-infrared absorptance scales at NMIJ and NIST*," Proc. 9th NEWRAD, ed. J. Gröbner, Davos, Switzerland, 2005, p. 241-242 (2005).**

- ## Near Normal Emittance
- **Participants: INRIM, LNE, NMIJ, PTB, NIST**
- **Year: 2007-2009**
- **Spectral Range: 2 µm to 14 µm**
- **Temperature Range: 23 °C to 800 °C**
- **3 Materials x 11 Temperatures**
- **L. M. Hanssen, B. Wilthan, C. Monte, J. Hollandt, J. Hameury, J.-R. Filtz, F. Girard, M. Battuelo, J. Ishii, "*Inter-laboratory Comparison of Infrared Emittance Scales*," Book of Abstracts, TEMPMEKO 2010, ed. J. Bojkovski, et. al, Potorož, Slovenia, Vol. B, p. 431 (2010).**

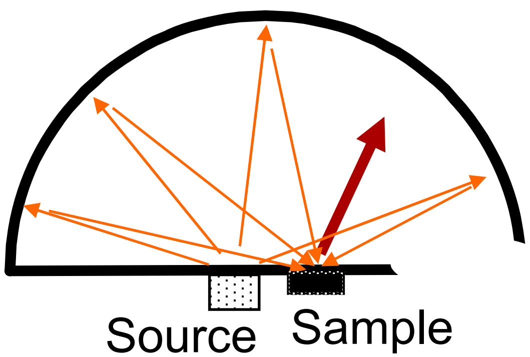
INRIM: Instituto Nazionale di Ricerca Metrologica (Italy)
LNE: Laboratoire National de Métrologieet d'Essais (France)
NMIJ: National Metrology Institute of Japan (Japan)
NPL: National Physical Laboratory (United Kingdom)
NRC: National Research Council (Canada)
PTB: Physikalisch-Technische Bundesanstalt (Germany)

SOC-100 Design and Features





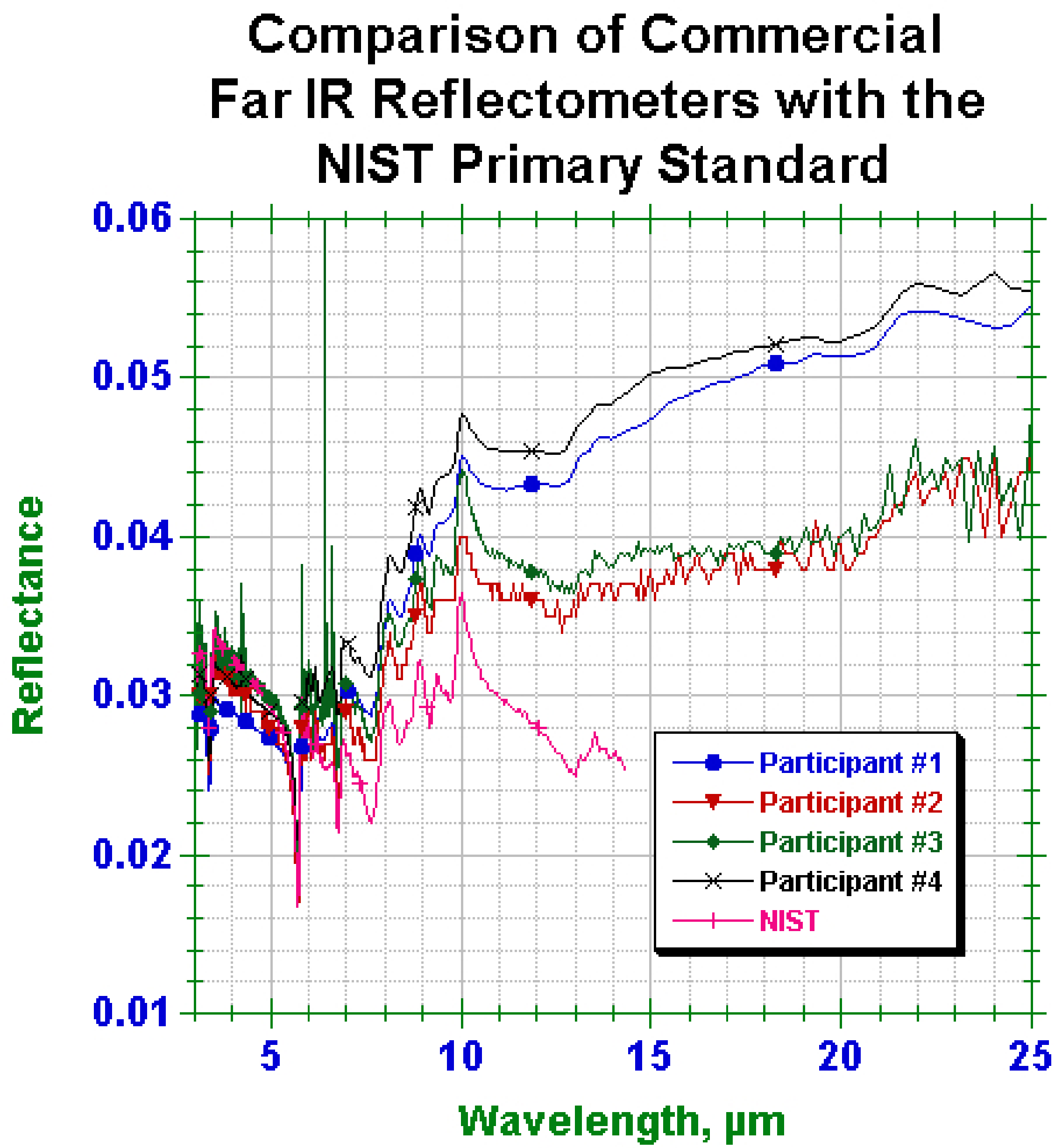
Hemispherical-Directional Reflectance Factor Measurement



$$\frac{V_s}{V_r} = \frac{R_{s,h,d}\Omega_d \rho_m \Phi_i}{\rho_m \Phi_i \Omega_d} = R_{s,h,d}$$

HDR DATA AS A FUNCTION OF	RANGE OF MEASUREMENT
a. Directional Angles θ: 20, 30, 40, 50, 60, 70, 75, 80°	Near-normal, 20 to 80°
b. Azimuthal Angles ϕ	0 to 360°
c. Wavelength	2.0 to 25.0 μm, 2.0 to 45.0 μm,* 2.0 to 200 μm*
d. Beam Polarization	Parallel and Perpendicular
e. Sample Temperature	Room temperature to 500°C w/heated sample holder

Evidence of Need for FIR Reflectance Standards



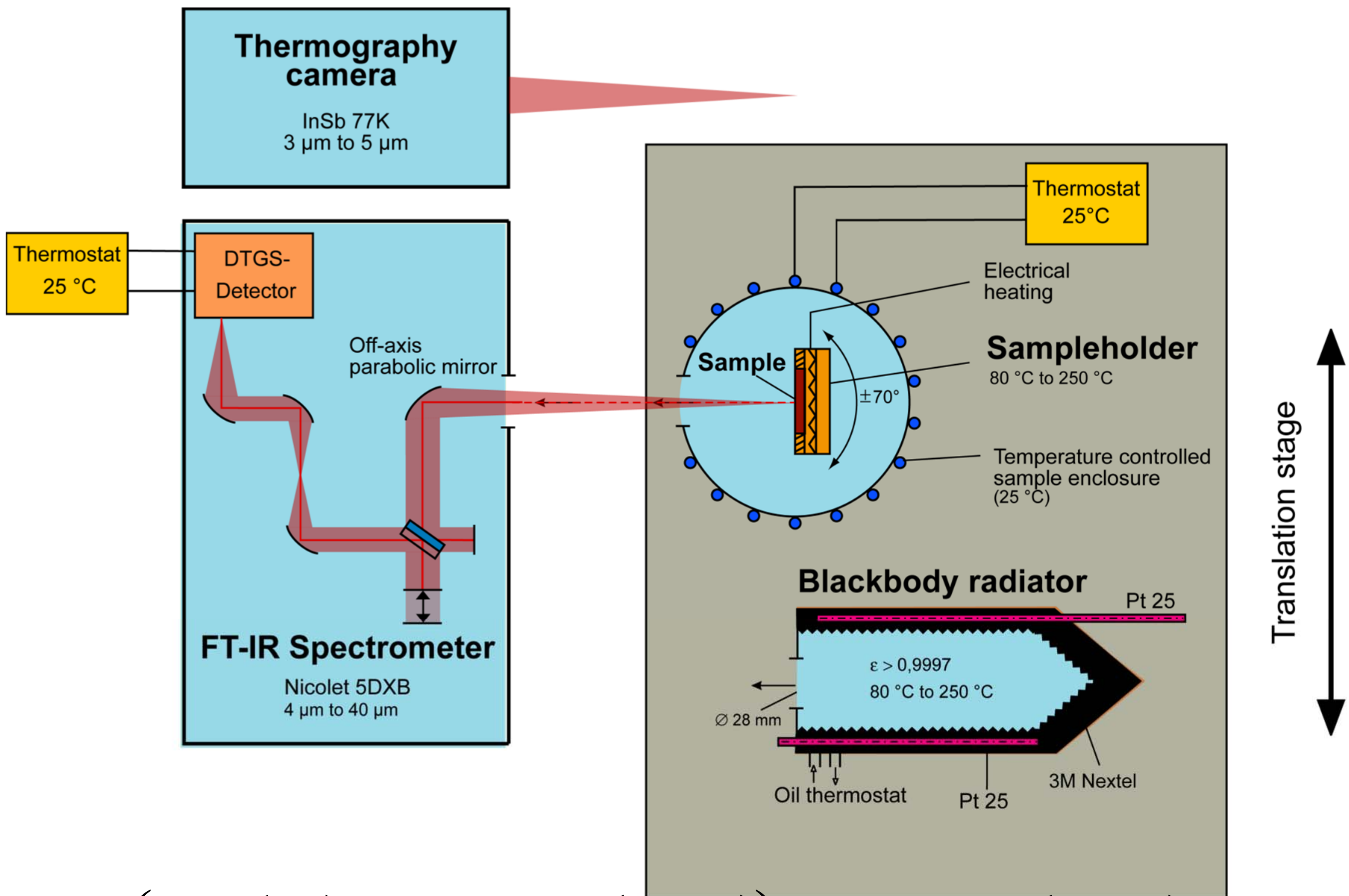
Establishing Intermediate FIR Emittance Scales for Near –Ambient Targets

	Lab	NIST	PTB	SOC
Measurement Type	Temp., °C	Spectral Range, µm	Spectral Range, µm	Spectral Range, µm
Directional Emittance	200	3 - 100, variable angle	3 - 40, variable angle	
HD Reflectance, Specular/Diffuse Resolved	RT	2 - 14, fixed angle		2 -100, variable angle
	200			

At the time of conception of the study, NASA had immediate requirement in Specular/Diffuse Resolved Hemispherical-Directional Reflectance in Far IR at near-ambient temperatures. Such measurements are supported by the SOC Calibration Lab, which until now has no direct SI traceability. One of outcomes of the study should be establishing indirect traceability for calibration labs.

Properly addressing the issue requires building dedicated primary facilities, such as RBCF (operational at PTB) or CBS3 (may be built at NIST).

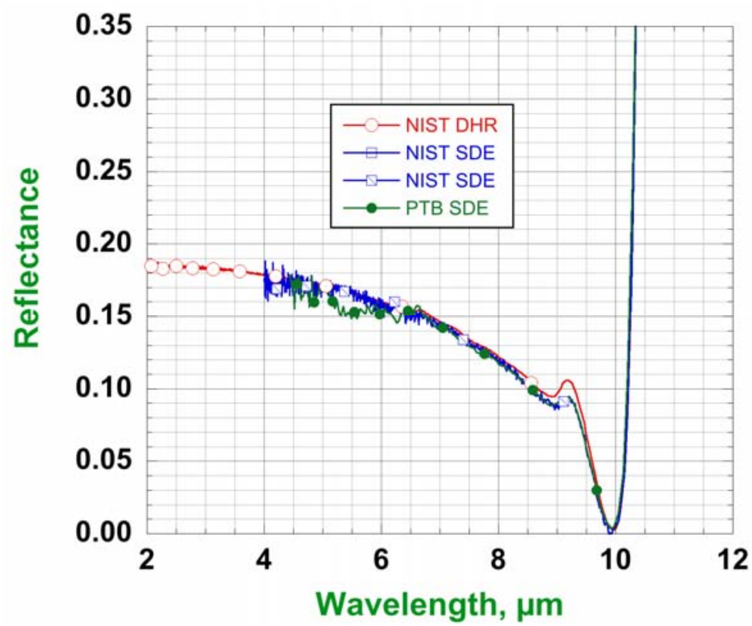
PTB Directional Emittance System



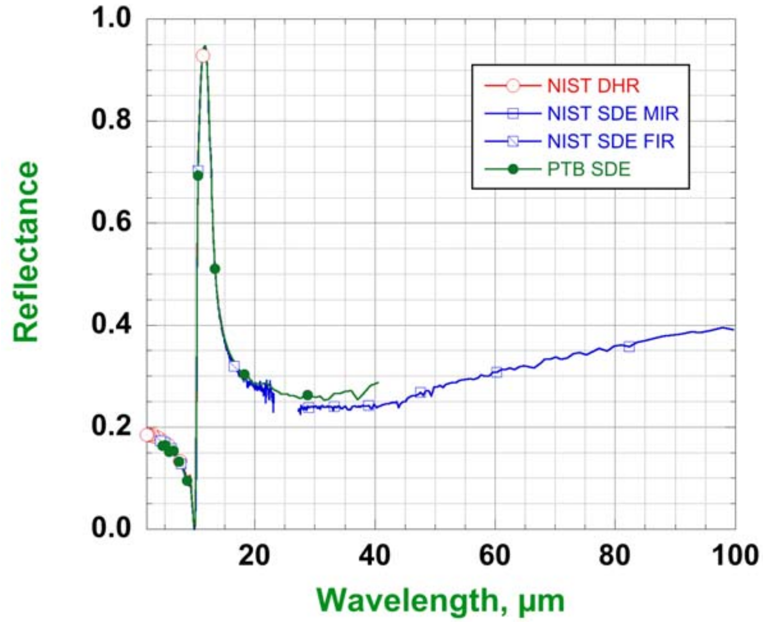
$$\varepsilon_{\text{Sample}} = \frac{Q \cdot \left(L_{\text{Planck}}\left(T_{\text{BB}}\right) - \varepsilon_{\text{Detector}} L_{\text{Planck}}\left(T_{\text{Detector}}\right)\right) + \varepsilon_{\text{Detector}} L_{\text{Planck}}\left(T_{\text{Detector}}\right) - \varepsilon_{\text{Env.}} L_{\text{Planck}}\left(T_{\text{Env.}}\right)}{L_{\text{Planck}}\left(T_{\text{Sample}}\right) - \varepsilon_{\text{Env.}} L_{\text{Planck}}\left(T_{\text{Env.}}\right)}$$

Silicon Carbide Sample Results

200 °C MIR Detail



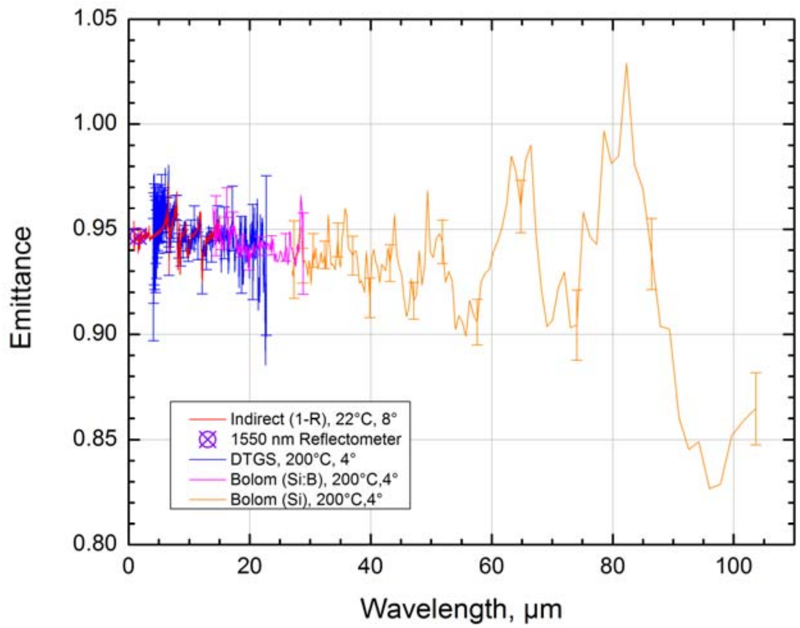
200 °C (NIST, PTB)



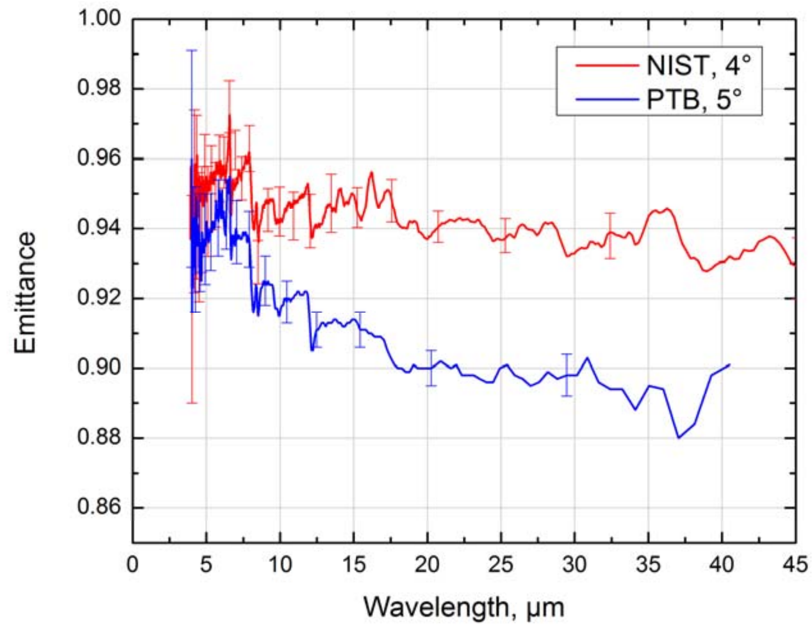
- Agreement very good at for λ > 25 µm, differences to maximum of 5% at 100 µm.

PT-401 (Specular) Paint Results

NIST 3 detectors – 2 systems

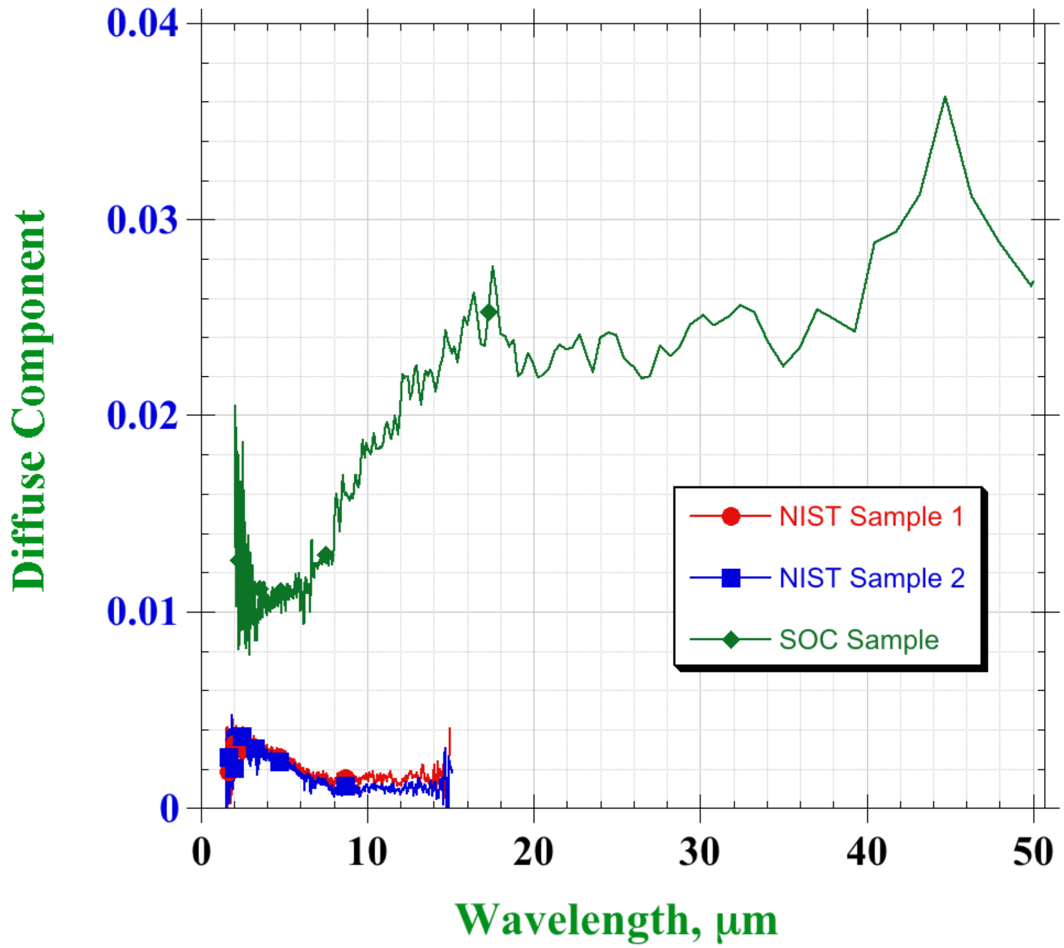


NIST / PTB Composite



- PT-401 being studied as potential specular black paint replacement for discontinued standard.
- Plot shows paint thickness dependence; effects of primer also to be evaluated.

SOC and NIST Results of PT-401
(Diffuse Component)



- Diffuse component – limit on performance of cavity designed for specular surfaces
- NIST and SOC have similar effective geometries for diffuse component measurements
- Discrepancies to be discussed with SOC

Conclusions and Future Plans – Far IR Emittance of Materials

- Initial results are reasonable, but challenge to sort out differences remains.
- Both labs have active internal projects to further improve respective capabilities
- Candidate specular black paint standard (PT401) shows promise (low overall and very low diffuse reflectance) for FIR
- A new batch of PT401 samples will be prepared for full evaluation
- Near-future improvements (PTB Emittance Facility upgrade with new Vertex 80 FTS and new emittance capabilities of RBCF, and BIB and Boron doped Si detectors at NIST) will further enhance both partners capabilities in the area

Path to reflectance standards / emittance calibrations to 100 µm is started

Blackbody Emissivity – a Misnomer

Effective Emissivity:

- Used mostly to in radiometry as a convenient descriptor for spectral signature of a complex system, allowing to calculate and interpolate spectral radiance from nominal (reference) temperature.

- May include effects of reflected background radiation, multiple reflections in a cavity, non-uniform cavity temperature, radiation background, atmospheric absorption and definition of reference temperature.

- Unlike EMITTANCE (which NIST now prefers to use to characterize materials), blackbody emissivity has no other meaning than a CATCH-ALL MEASURE OF NON-IDEALITY of the radiation source compared to one abiding by the Planck Law and HAS NO PHYSICAL MEANING beyond that.

It may be helpful to talk about reflectance (absorptance) if it is what is being measured (such as with QCL or halo)

Flavors of Emissivity:

Wavelength Related:

-Spectral (Monochromatic)

-Band

-Total

Spatial:

-Directional

-Conical

-Hemispherical

***Generalized*:**

- Intrinsic - *most common* (material property)

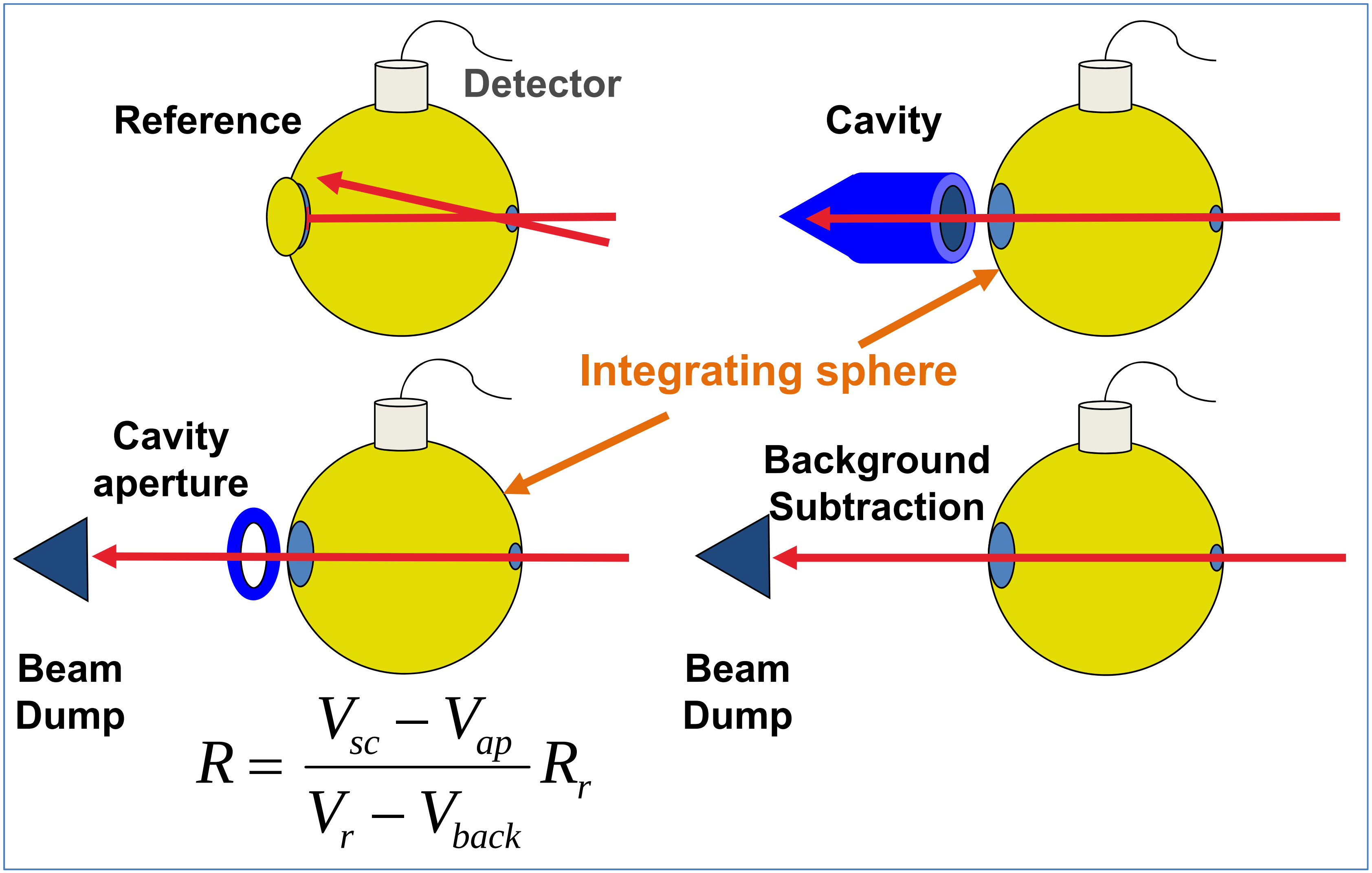
- Effective isothermal (includes multiple reflections)

- Effective non-isothermal (for given reference T)

- Apparent (includes reflected background radiation)

There is no such thing as directional-hemispherical or directional-conical emissivity – only OBSERVATION GEOMETRY qualifier is used

Cavity Reflectometry (DHR) Measurement Sequence



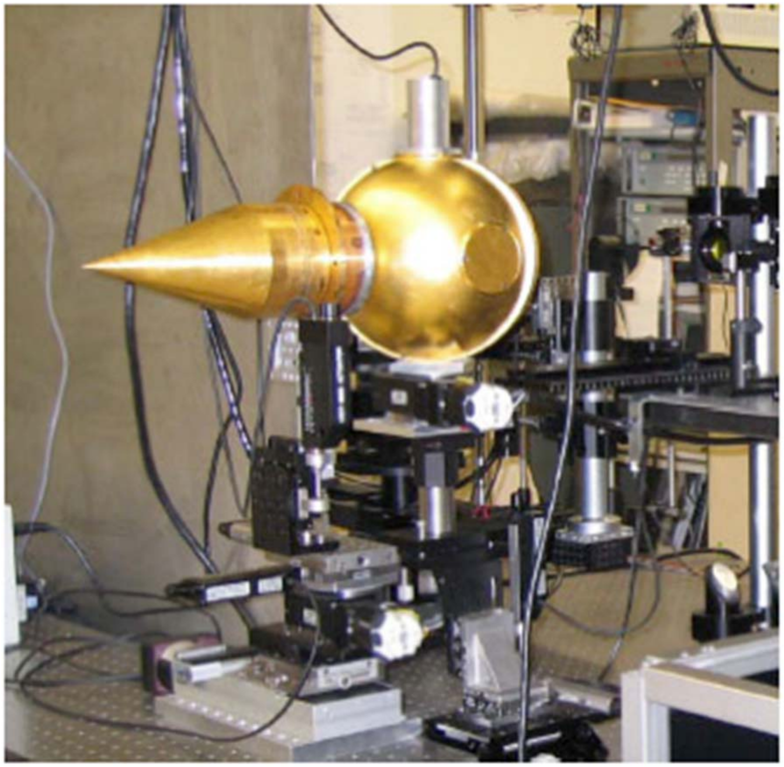
$$R = \frac{V_{sc} - V_{ap}}{V_r - V_{back}} R_r$$

NIST Complete Hemispherical Infrared Laser-based Reflectometer (CHILR)

- 8 inch diameter gold-coated integrating sphere
- Input port: 6 mm diameter
- Collecting port: 50.8 mm diameter

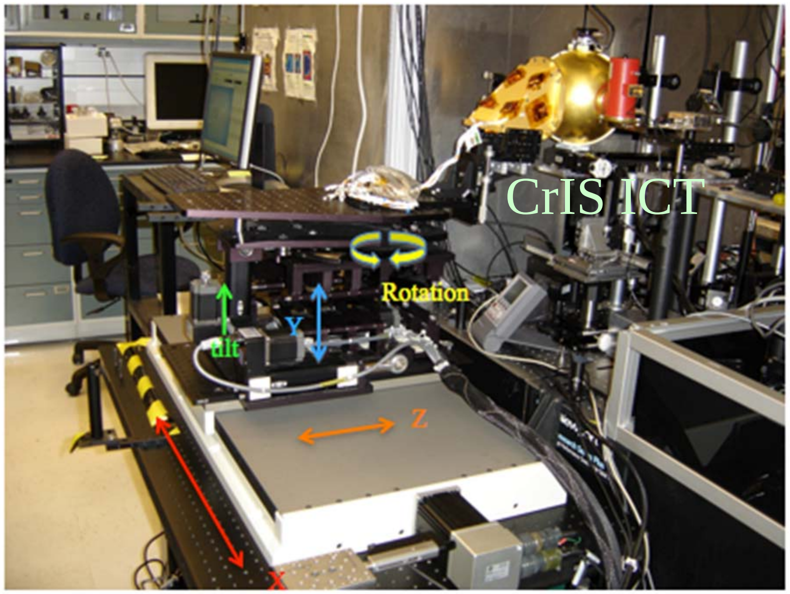
Laser sources:

- OPO tunable laser- 1 µm to 5 µm
- CO_2 laser - 9 to 11 µm
- QCL: 4 µm and 5 µm
- Ability to measure reflectance to <0.00001



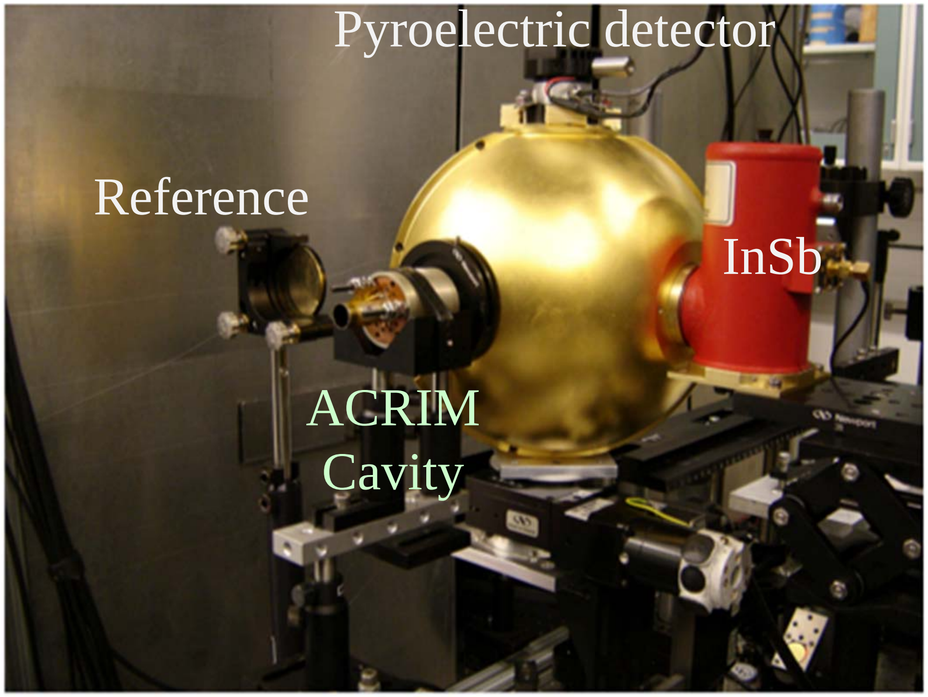
Recent CHILR Measurements of Specular Cavities

CHILR with CrIS ICT Cavity



X	Y	Z	Tilt	Rotation
600 mm	76 mm	100 mm	± 10 °	± 30 °

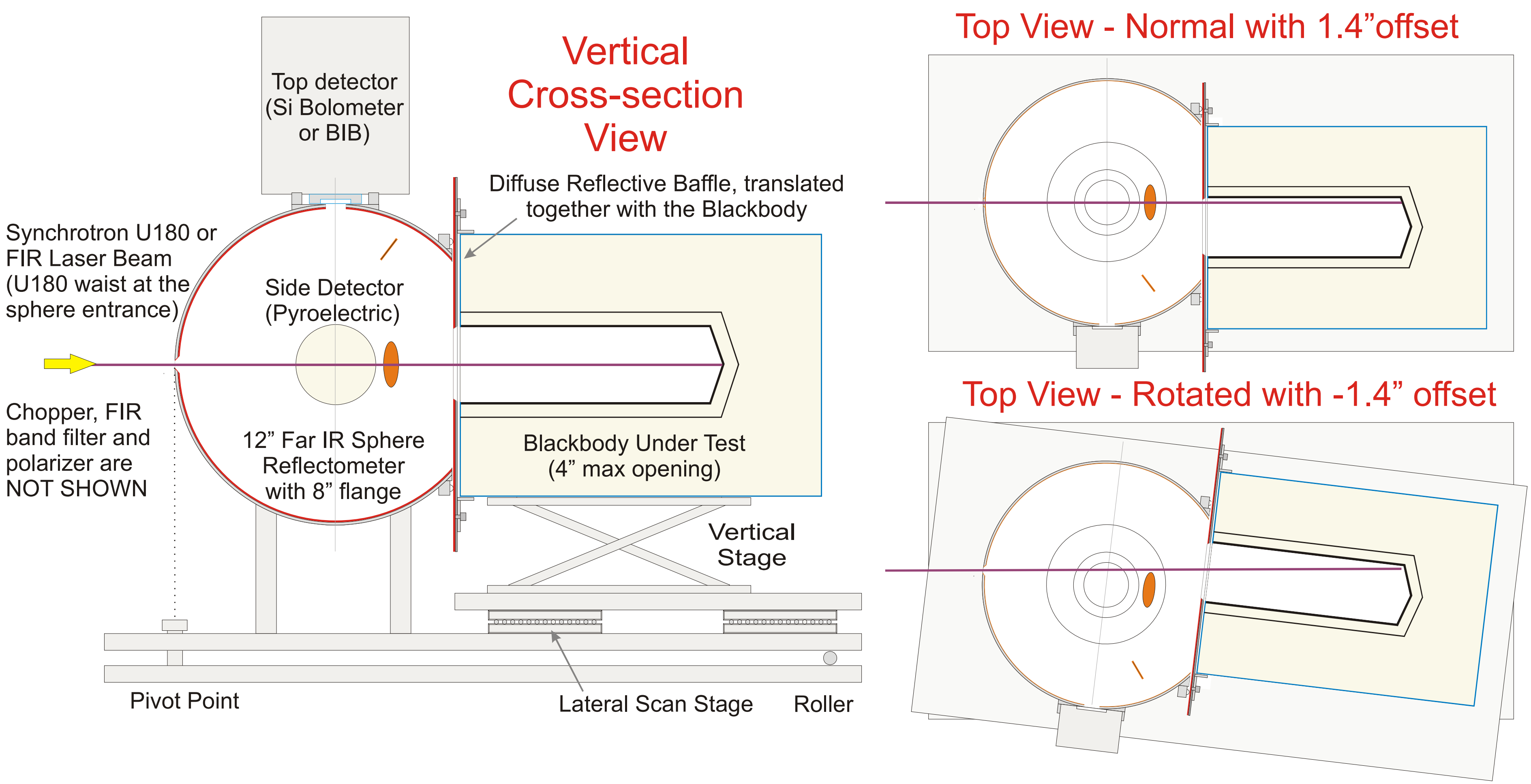
CHILR with ACRIM III Cavity



Future Spherical Far IR Reflectometer (SFIRR) Implementation Steps

- Design Sphere appropriate to Far IR and source geometries
- Find / develop / test and validate diffuse coating
- Obtain sphere pricing, determine construction process / place orders
- Assemble, complete sphere system including detectors
- Characterize sphere: overall throughput, throughput uniformity
- Test with “known” samples, local laser sources
- Transport to appropriate Far IR sources – synchrotron, lasers

SFIRR (Spherical Far IR Reflectometer) Simplified Schematic



Description of 23 μm QCL system

Cryostat system:

Janis Research Supertran (ST) System ---- a continuous flow research cryostat from 1.5 to 325 K using LHe or LN2

Cryostat head, Laser holder, Cryo-shield, Cryostat cap, Output window (KRS-5 for optimal transmission at 23 μm)

Lake Shore Cryotronics temperature controller, model 325

23 μm QCL, pulser, driver, and power supply:

1. LN2-P-FPQCL-430 (s/n sb3233) by Alpes Lasers ---- generates the cryogenic temperature pulsed multimode emission centered at 430 cm-1 or 23.25 μm with average power < 1 mW @ 80 K. The divergence of output beam: far field elliptical (FWHM), vertical 60°, and horizontal 40°

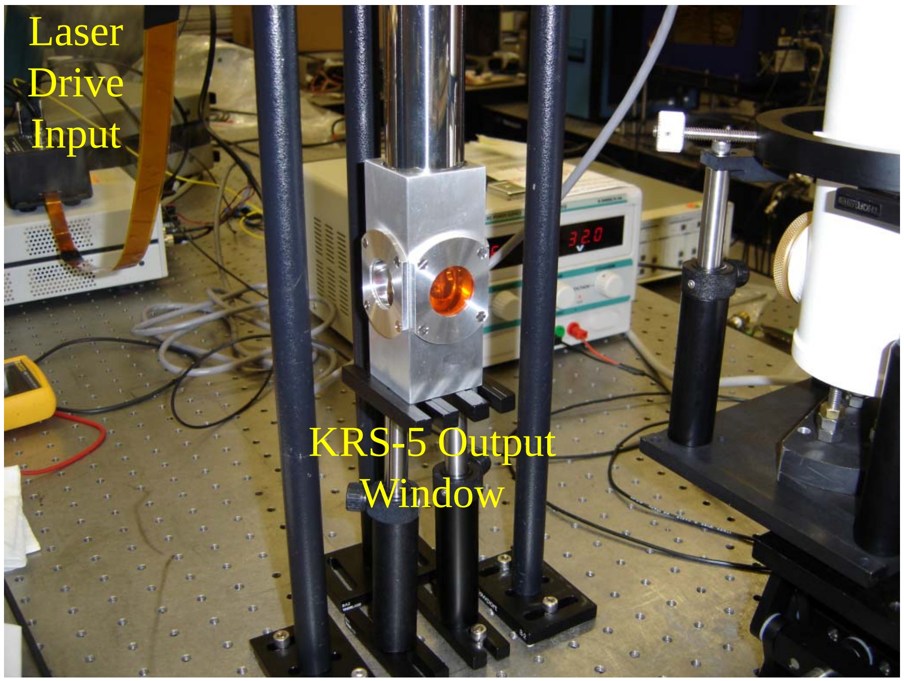
2. TPG pulser ---- timing pulse generator
pulse duration: 0 ~ 200 ns, pulse period: 200 ns ~ 105.1 μs

3. LDD QCL driver ---- pulser switching unit
Up to 30 A, 60 V (DC), Rep rate 1MHz, controlled by TPG, and power by DC PS

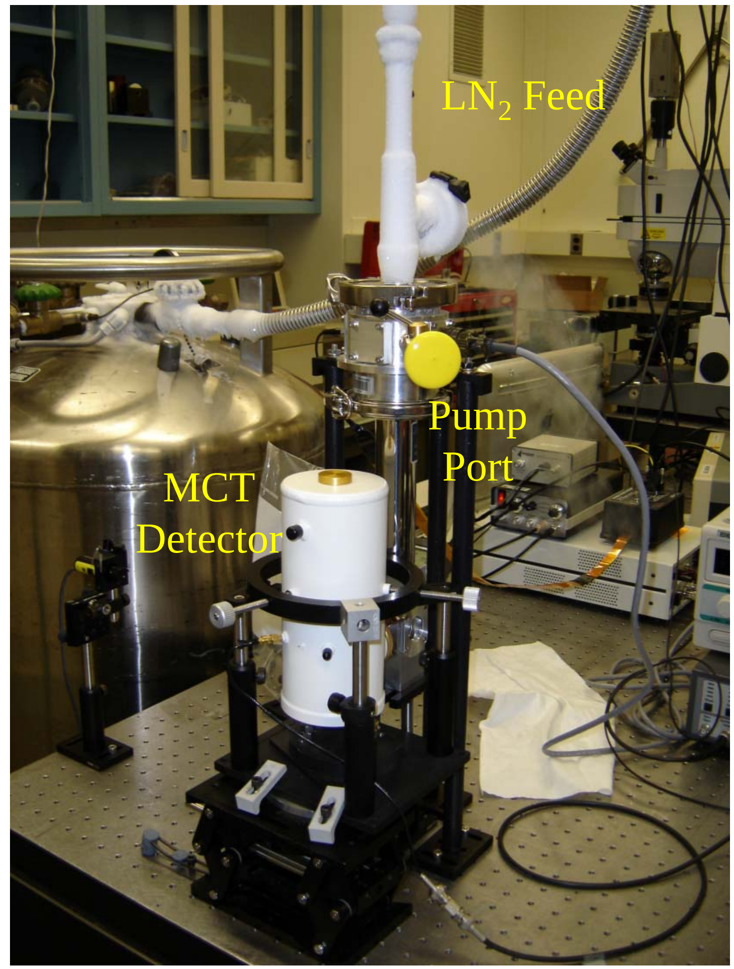
4. High-precision DC adjustable power supply
Model: PS5005U, Boston Electronics, Output voltage: 0 ~ 50 V, Output current: 0 ~ 5A

23 µm QCL and Test Setup

QCL Output Window (KRS-5) & Electronics (in background)



Operational Setup w/ Cryogen Flow and Intermittent Vacuum

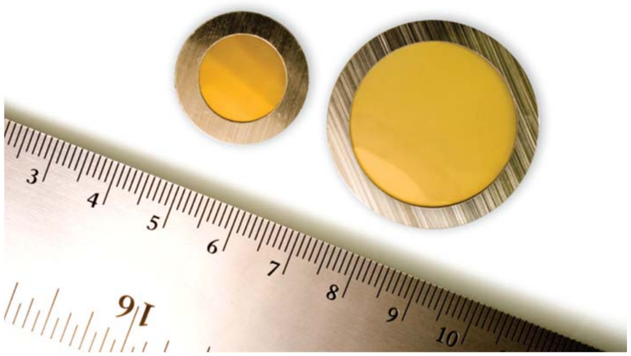


Future improvement needed

- Detection: MCT (cutoff 24 μm), BIB detector or Bolometer
- Beam focusing: Lens, focusing mirror
- Large volume cryostat to hold LN_2 longer with flow regulation
- Use the transfer line with flow regulator
- Re-evacuation due to outgas and o-ring permeation causes insulation problem between the cryostat and a pump to ground
- Insulation from ground between the cryostat and LN_2 container during flowing.
- Shield the flowing gas for the pyro-detector
- Plastic box to prevent the KRS5 window from the dripping water of transfer pipe

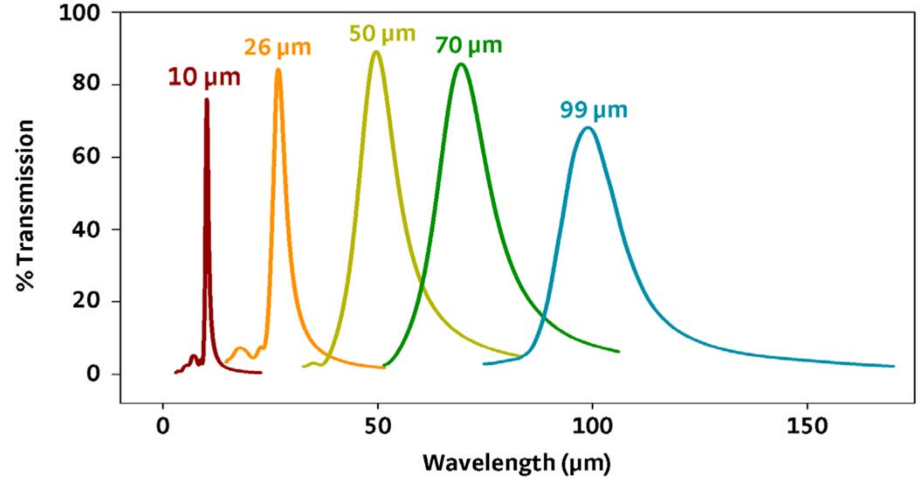
Far IR Bandpass Filters

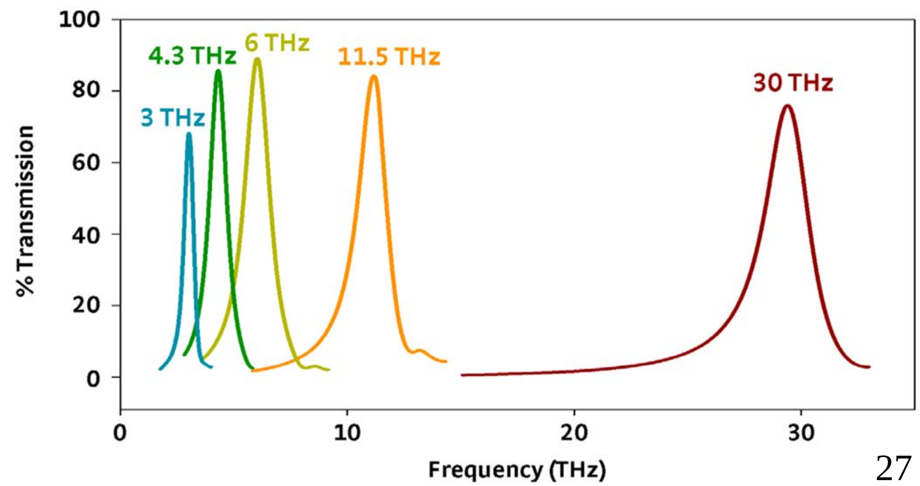
Freestanding Mesh Filters



- **From Lakeshore Cryogenics**
- **Any center wavelength available**
- **Wings extended – needs to be characterized**
- **23 µm filter in hand; available for use.**

Example Filter Spectra





PTB Far-IR Laser Facility

SIFIR-50 CO_2-pumped laser

Gas and QCL lasers are typically operated at wl > 100 microns, although there is one minor gas line at 48 microns

IOP PUBLISHING METROLOGIA

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Towards traceable radiometry in the terahertz region

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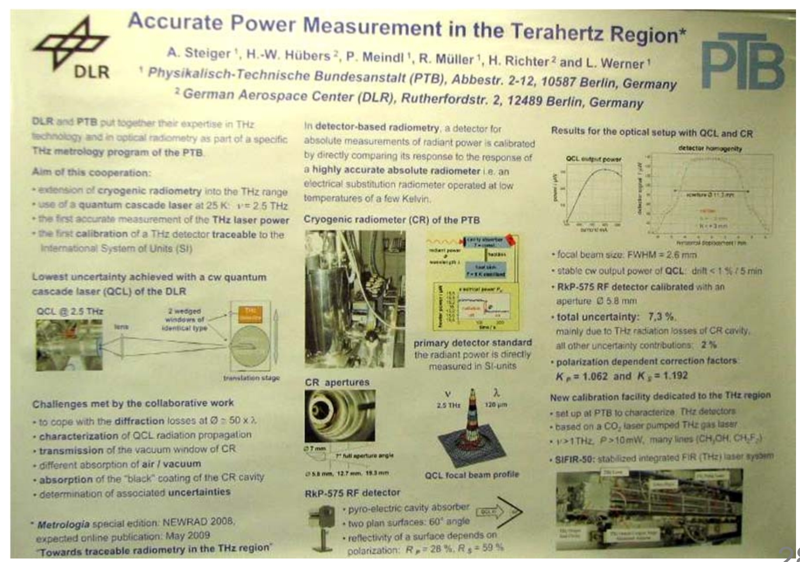
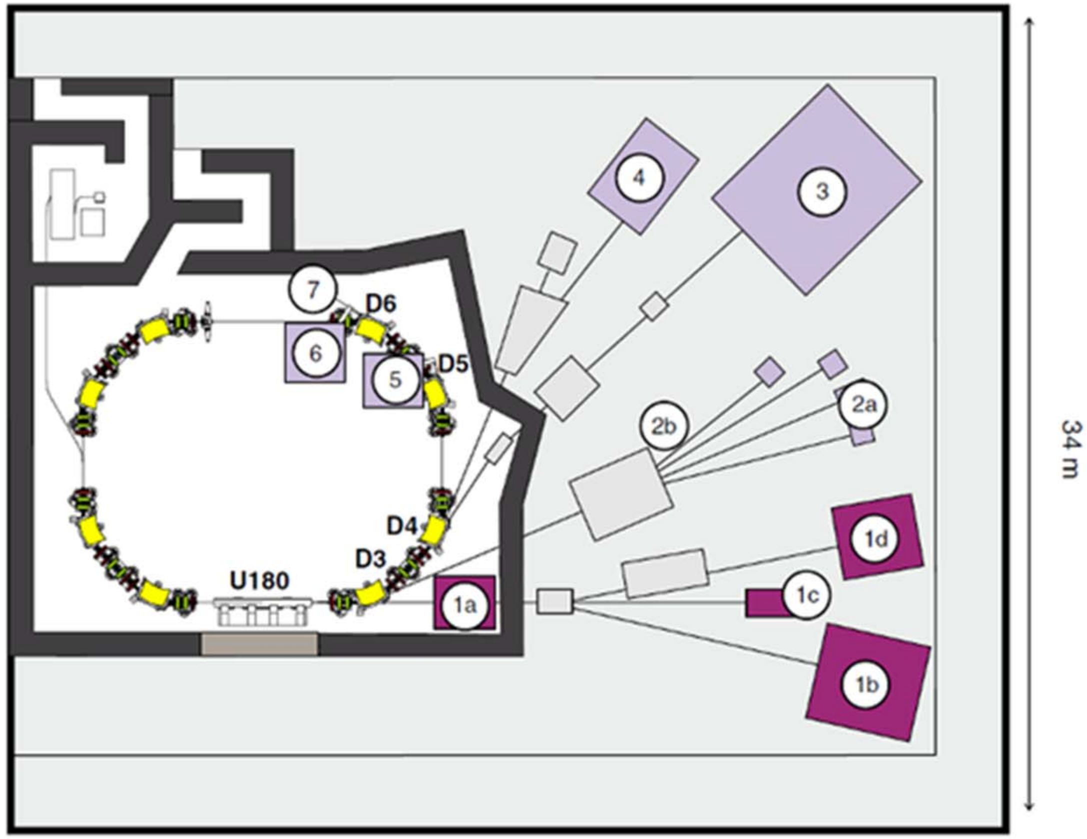
Abstract

PTB and DLR join their expertise and experience in optical radiometry and in THz techniques to perform what is to our knowledge the first traceable measurement of radiant power of a THz quantum cascade laser and the first absolute calibration of a THz radiation detector against a cryogenic radiometer (CR). A total standard uncertainty of 7.3% was achieved at a frequency of 2.5 THz corresponding to a wavelength of 120 µm. This uncertainty is dominated by the limited knowledge of the absorptance of the CR cavity. All other uncertainty contributions including those arising from diffraction are only 2%.

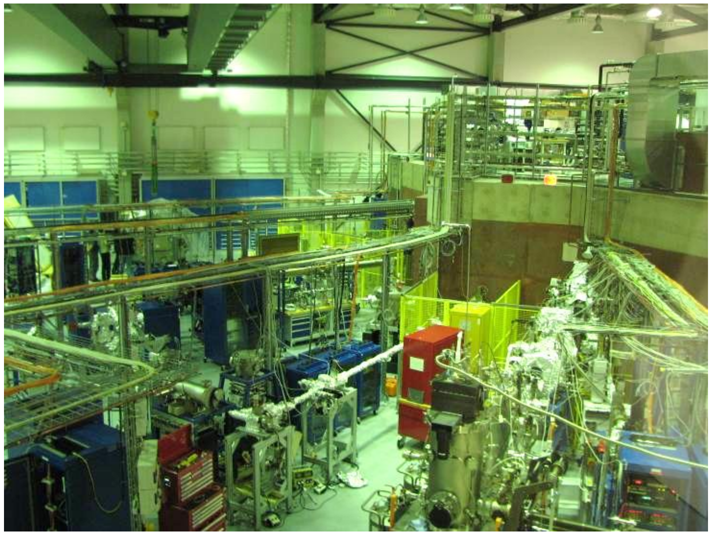


PTB Metrology Light Source (MLS) – Layout

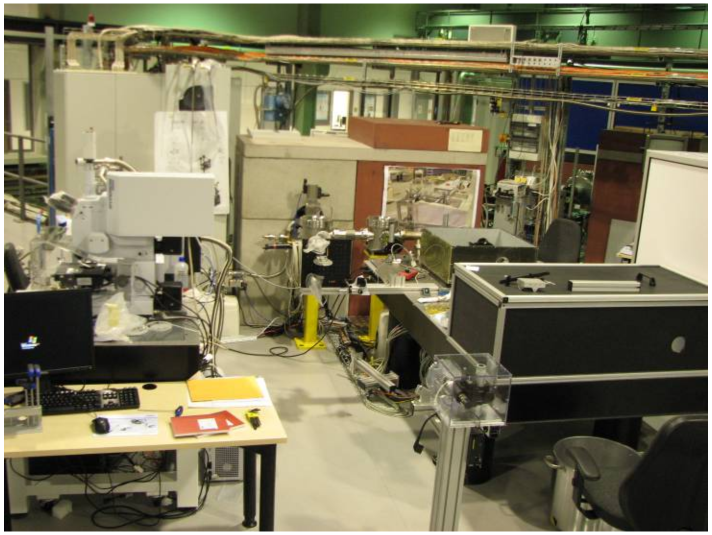


Beamline	Wavelength	Radiant power
Undulator IR	2 μm – 20 μm	up to mW
IR beamline	0.6 μm – 7 mm	up to μW
THz beamline	100 μm – 7 mm	up to μW (mW with CSR)

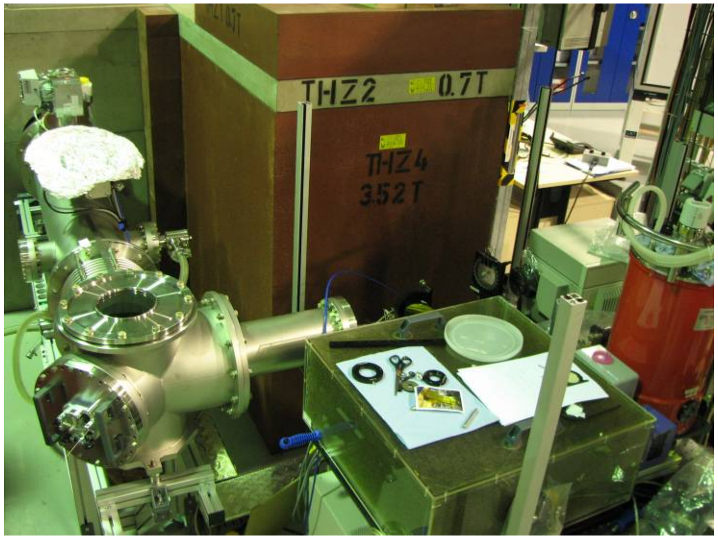
Synchrotron Storage Ring MLS - Photos



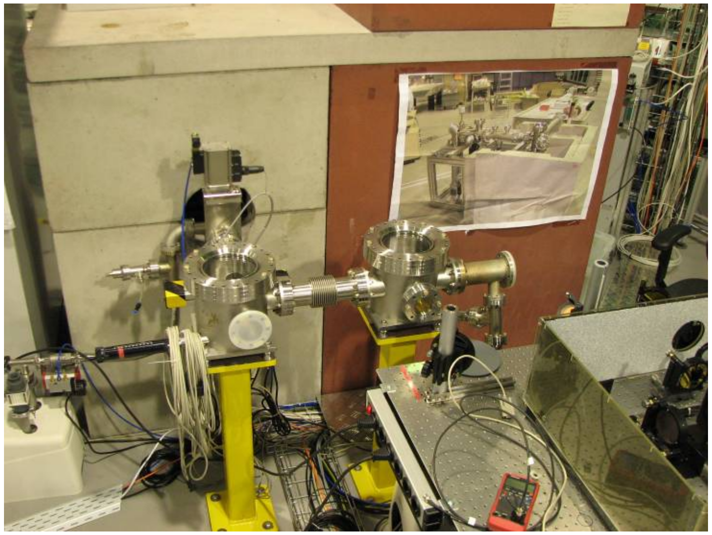
General View



IR Beamline with BRUKER on left



Undulator U180 Port

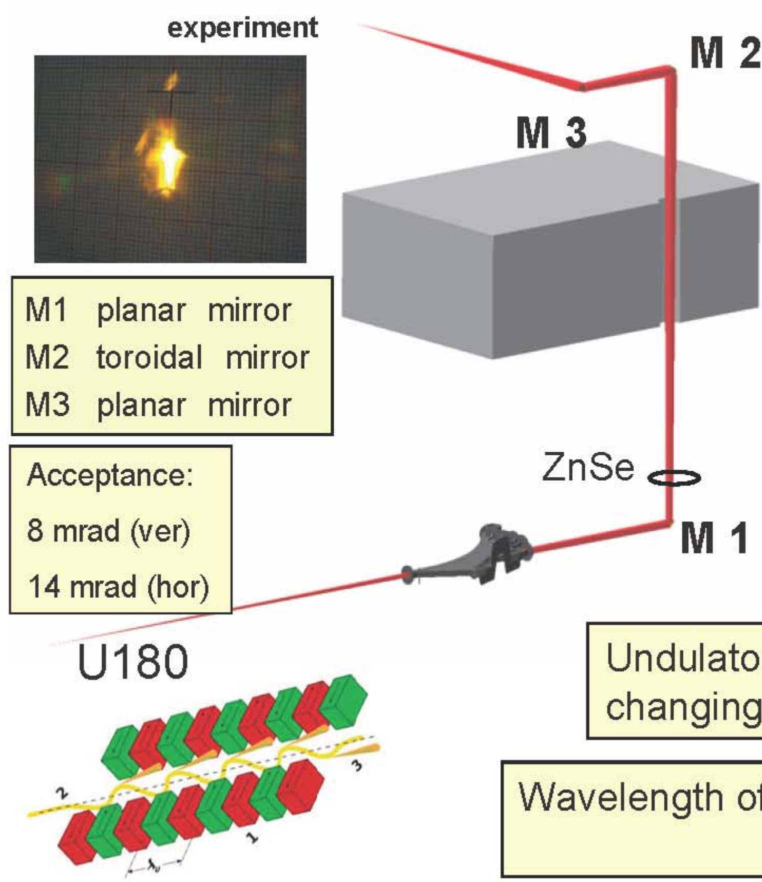


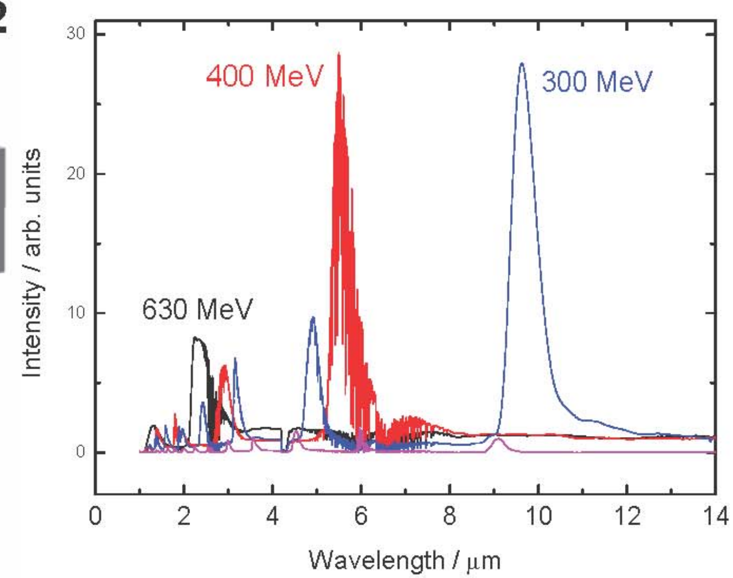
IR Beamline Close-Up

Spectral Tuning Capabilities of MLS U180 Undulator

Undulator radiation at the IDIR beamline

PTB
Radiometry with synchrotron radiation



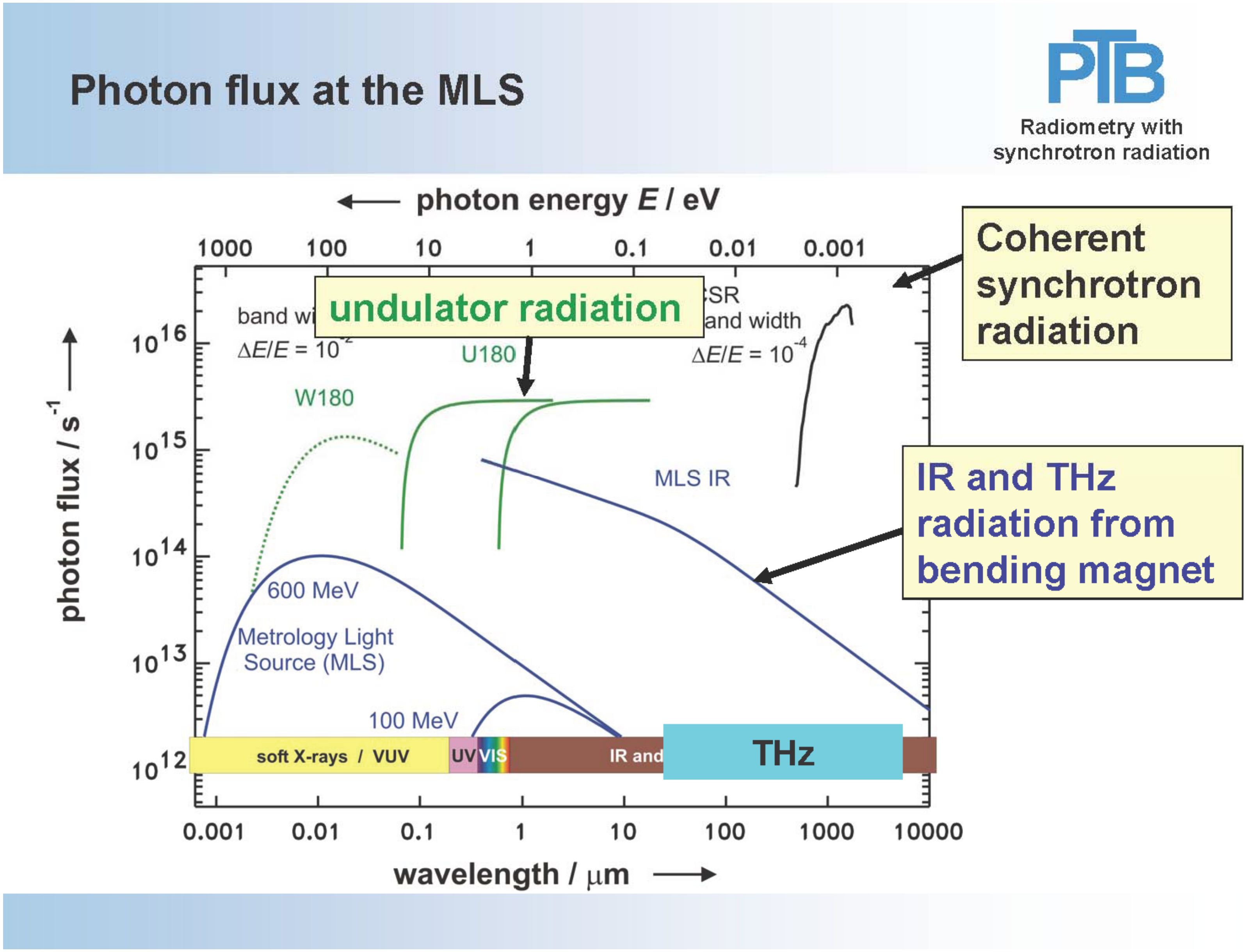


Undulator radiation wavelength can be tuned by changing the electron energy of the storage ring

Wavelength of 1. harmonics:	2 µm (630 MeV)	
	80 µm (105 MeV)	

Operational Spectral Band of Undulator U180

(can be expanded using diamond optics)



Power and Spectral Properties of MLS Source

Summary and Outlook

PTB

- PTB is operating a new low-energy electron storage ring, the Metrology Light Source (MLS). Start of user operation was in April 2008. MLS is no multi-user facility – more time for special operation modes.
- First results: IR, IDIR and a dedicated THz beamline are operational
  IR/THz radiation is polarised, focused
  High THz power at the THz beamline (up to 60 mW)

Beamline	Wavelength	Radiant power
Undulator IR	2 μm – 20 μm	up to mW
IR beamline	0.6 μm – 7 mm	up to μW
THz beamline	100 μm – 7 mm	up to μW (mW with CSR)

Effective Power of the Far IR QCL, currently procured from Alps Electronics, is below 0.05 mW at the only band at 23 microns !

- What comes next? Metrology and radiometry in the IR/THz

R. Müller et al., Planned infrared beamlines at the Metrology Light Source of PTB, Infrared Physics & Technology **49**, 161 (2006)
R. Klein et al., The Metrology Light Source – the new dedicated electron storage ring of PTB, Nucl. Instr. Meth. B **258**, 445 (2007)
R. Müller et al., First commissioning results in the IR/THz range at the electron storage ring MLS, EPAC08, 2058 (2008)

Spectroradiometry - Outline

- Current Status of IR Spectroradiometry
- 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.

PTB: Reduced Background Calibration Facility (RBCF)

The Reduced Background Calibration Facility for Detectors and Radiators at the Physikalisch-Technische Bundesanstalt

Christian Monte*, Berndt Gutschwager and Jörg Hollandt
Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Germany

ABSTRACT

The Physikalisch-Technische Bundesanstalt (PTB) operates a Reduced Background Calibration Facility (RBCF) which provides traceable calibrations of space based infrared remote sensing experiments in terms of radiation temperature and spectral radiance. Traceable measurements from space require the use of calibrated stable detector systems and/or calibration standards on board of the satellites. In any case they should be calibrated under space like conditions to ensure traceability at a minimized uncertainty. This is possible with the RBCF which enables the calibration of radiators and detectors under cryogenic and/or vacuum conditions.

The general concept of the RBCF is to connect several sources and detectors under vacuum via a liquid nitrogen cooled beamline. The beamline connects a source- with a detector chamber which also incorporate cooling facilities. Translation units in both chambers enable the RBCF to compare and calibrate different sources and detectors at cryogenic temperatures and under a common vacuum.

The radiation of the reference sources and the source under test can additionally be imaged on a vacuum Fourier-Transform Spectrometer (FTIR) to allow spectrally resolved measurements. The FTIR covers the wavelength range from 0.4 µm to 1000 µm. Here several detectors are employed, ranging from an Si-Photodiode to a liquid helium cooled Si-composite bolometer. Two reference blackbody radiators enable measurements with respect to two reference temperatures, simultaneously. Hereby a compensation of background radiation can be performed and the measurement of very faint sources becomes possible.

Keywords: calibration, radiance, radiation thermometry, radiometry, remote sensing, emissivity, blackbody, vacuum

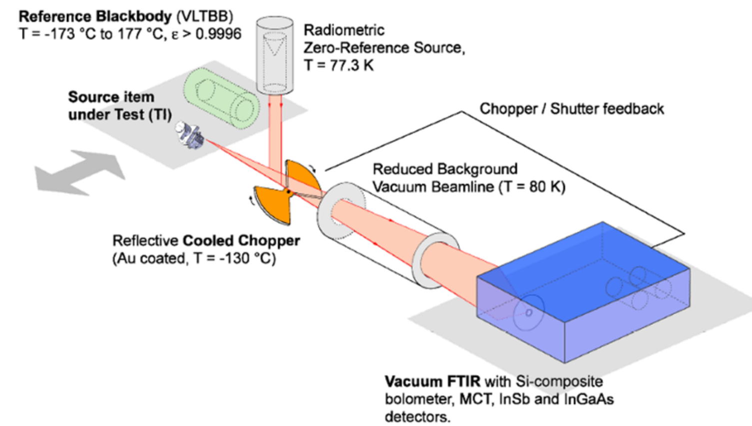


Fig. 4. Schematic view of the Reduced Background Calibration Facility (RBCF) in the configuration for very low flux source calibrations.

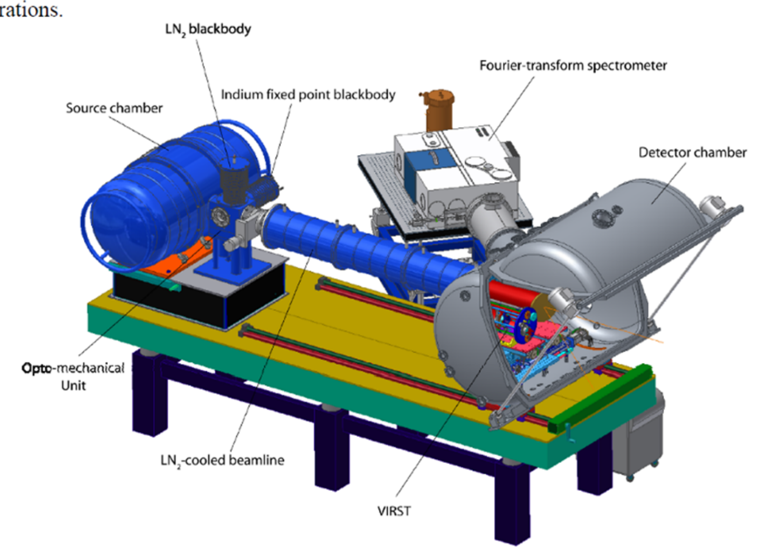
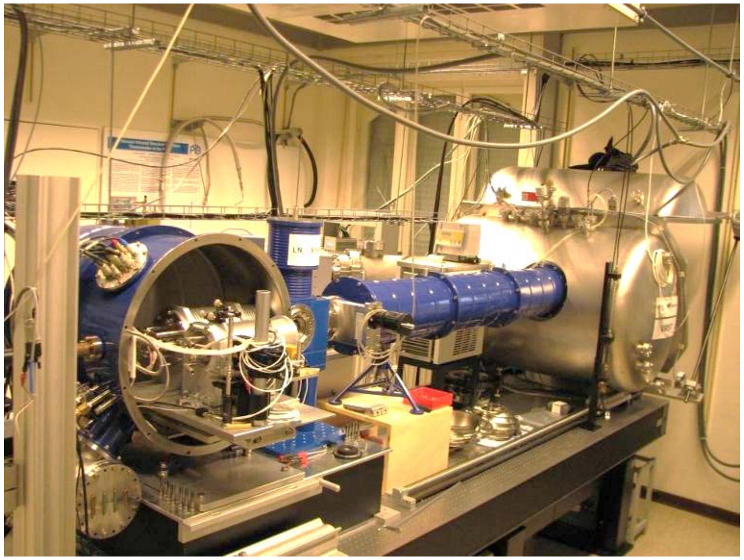


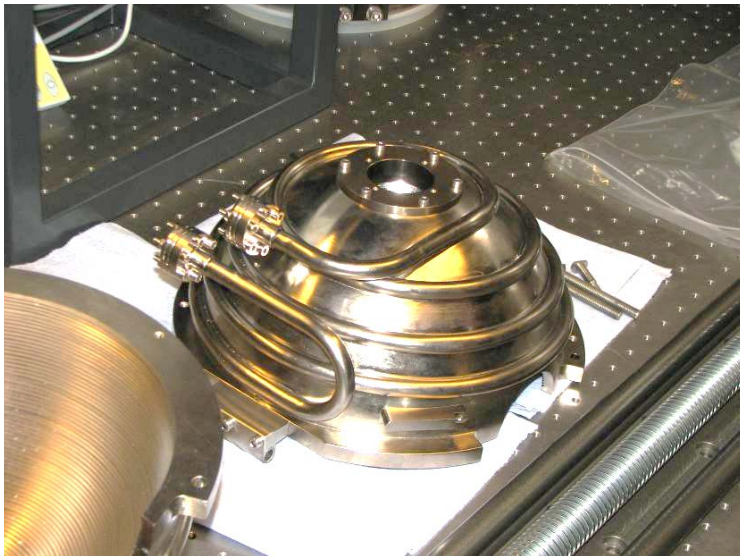
Figure 1. Overview of the construction of the reduced background calibration facility (RBCF). The source chamber is connected via the LN_2-cooled opto-mechanical unit and the beamline to the detector chamber. The LN_2-cooled blackbody and the indium fixed point radiator are mounted on the opto-mechanical unit. They are imaged with a high reflective chopper-wheel or a gold mirror mounted on a vertical translation stage, respectively, towards the detector chamber. In the opened detector chamber the radiation thermometer VIRST and the off-axis ellipsoidal mirror are shown on their translation stages. In the background the vacuum Fourier-transform spectrometer with its bolometer detector is shown.

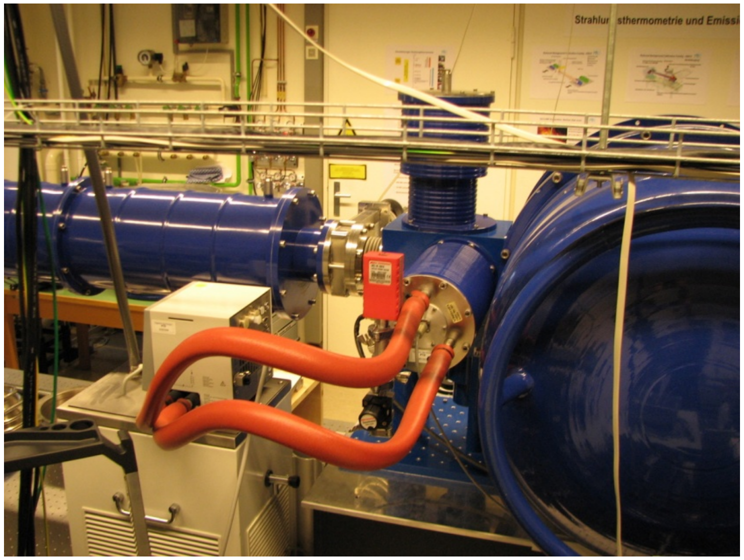
Certainly the most sophisticated of all reported facilities for thermo-vacuum calibrations of IR BB sources at near-ambient temperatures.

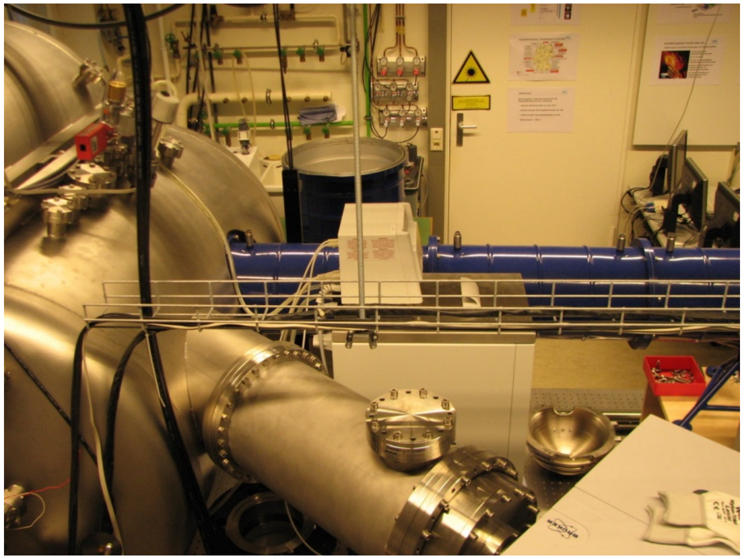
No actual measurements in the radiance mode were reported yet (expected later this year).

Reduced Background Calibration Facility RBCF– Photos









NPL: Detector-Based Radiation Thermometry

RADIOMETRIC MEASUREMENTS OF σ AND T 91

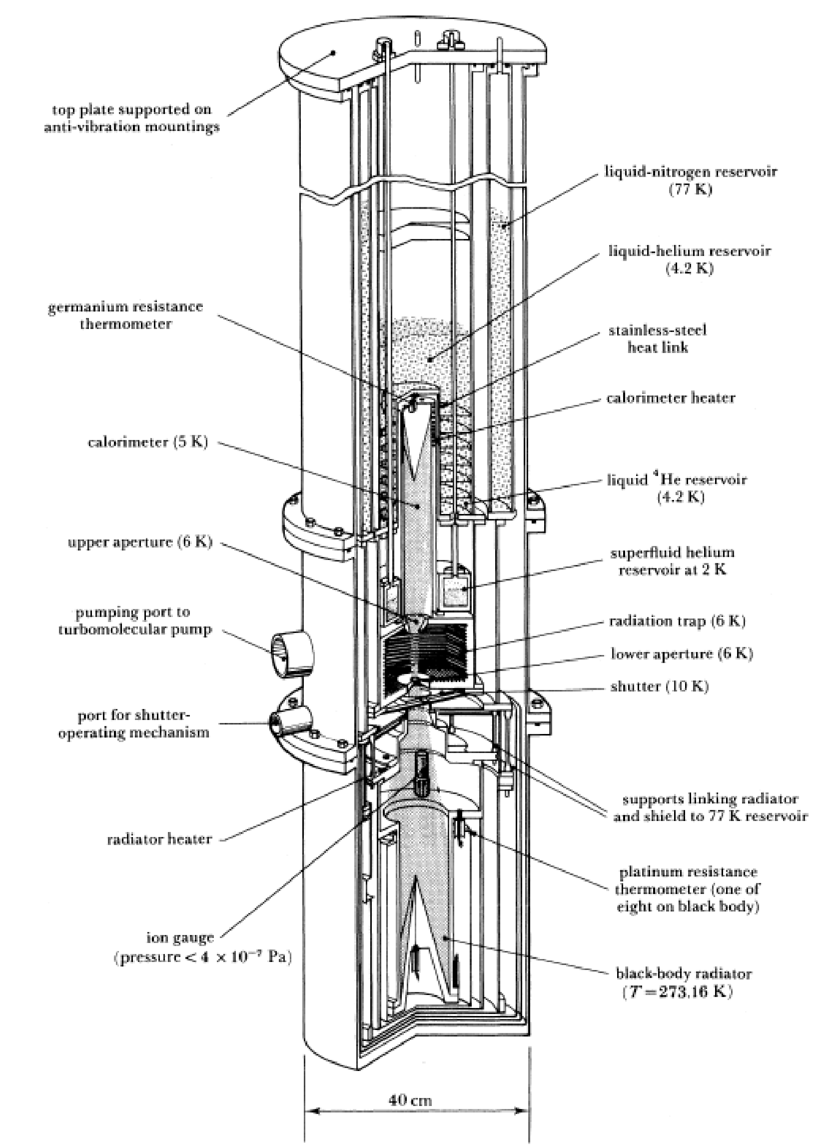
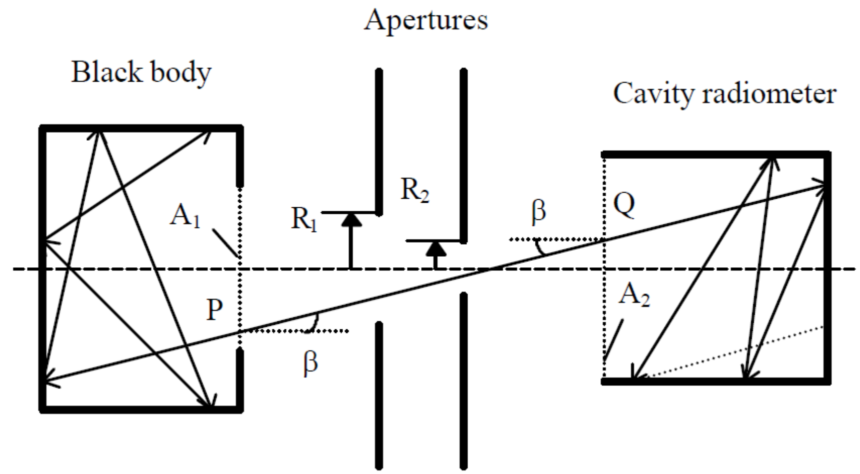


FIGURE 1. Cut-away drawing of the apparatus. The temperatures indicated are typical of those found when the radiator is at a temperature near 273 K.



T. J. Quinn, J. E. Martin: Phil. Trans. R. Soc. London, Ser. A 316,85-189 (1985)

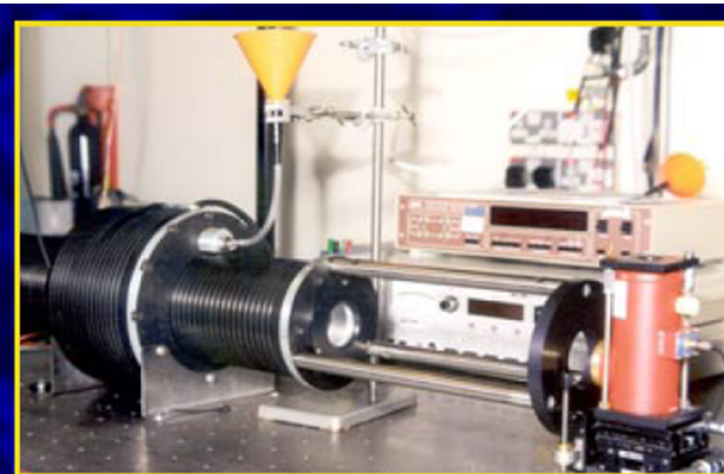
The only successful experiment with high accuracy (mK level) radiometric measurements of near-ambient temperature.

Used TOTAL (spectrally unresolved) measurements, which limits its relevance for CLARREO.

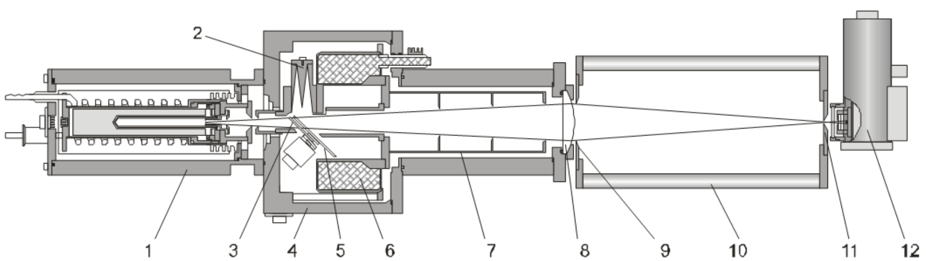
NPL: Attempt at ACR-Traceable Measurement of Near-Ambient Source Band Limited Radiance

AMBER (Absolute Measurement of Black body Emitted Radiance)

NPL has championed the use of radiometrically calibrated filter radiometers as a means of measuring and disseminating spectral radiance and irradiance. In particular for the direct determination of the thermodynamic temperature of black bodies for temperature scales and as a means of calibrating sources used for Earth Observation. This technique has been extended into the thermal infrared (and near ambient temperature black bodies) with a facility called AMBER (Absolute Measurement of Black body Emitted Radiance)[iii]. As the title states, this measures the emitted radiance in a defined spectral band, using a radiometrically calibrated filter radiometer, rather than by calculation and thermometry. The facility obtains its traceability to the SI directly through radiometric standards in the form of a cryogenic radiometer rather than through the ITS-90.



Photograph of the AMBER facility



metrologia

Absolute measurements of black-body emitted radiance

E. Theocharous, N. P. Fox, V. I. Sapritsky, S. N. Mekhontsev and S. P. Morozova

Abstract. Near-ambient-temperature black-body sources are routinely used for calibration in terms of radiance of a variety of infrared instruments such as those used in remote sensing and thermal imaging. The black-body radiance is usually determined by reference to a measured temperature and a calculated effective emissivity. The temperature is measured with one or more contact thermometers positioned close to the emitting black-body surface. In this case traceability to the International System of Units (SI) is to the kelvin through the ITS-90. This paper describes an alternative, more direct method based on the use of absolutely calibrated filter radiometers. These filter radiometers form part of a new facility called AMBER (Absolute Measurements of Black-body Emitted Radiance) which has been designed to determine the radiance of an ambient-temperature black body with an uncertainty of about 0.1 % (which corresponds to a radiance temperature difference of 25 mK at 4 μm) and a resolution of 0.001 % (0.3 mK). The facility obtains its traceability to the SI directly through radiometric standards in the form of a cryogenic radiometer rather than through the ITS-90.

Since it's construction in 1996 and initial paper with general description, no results from AMBER setup were reported

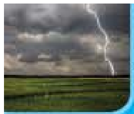
Virtual European Metrology Centre for Earth Observation and Climate (EMCEOC)

Confirmed Euramet Project. Starts in July 2011 / 3 years duration

Goal: establish new transfer standards and methodologies to enable improved accuracy and traceability (factors of 2 to 10) for:

- Pre-flight calibration of optical and microwave imaging cameras (air and vacuum)
- In-flight (on-board) calibration for optical imagers and atmospheric limb sounders
- Surface based “test-sites“ for the post-launch calibration and validation of Land and Ocean imaging radiometers
- Models and algorithms to improve performance and traceability of L2 Land products
- Prototyping techniques to enable the establishment of “SI traceable benchmark measurements from space“ to facilitate and underpin the upgrade of current sensors to the performance needed to form a global climate observing system
- 320 man-months (~27 man-years) + equipment

IR CLARREO-relevant results may be anticipated only in the follow-up to current project, which is Vis-NIR only



Pre-flight laboratory-based calibration standards and methodologies

WP1

Adapting NMI-based state-of-the-art to enable climate quality pre-flight calibration/characterisation.

- Tuneable lasers for stray-light characterisation of optical imagers
- High uniformity large aperture radiance source for wide FOV sensors
- In-vacuum, on-site, traceable spectrally resolved radiance calibration of satellite imagers
- Traceability for microwave radiometers

Partnership: NPL, PTB, DLR + (CNES / RAL / SSTL ..) 65 MM +

On-board calibration standards

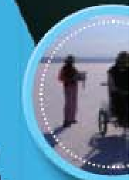
IR limb sounders drift – radiometric uncertainties of 0.1% (relative) and 1% (absolute) need to be maintained during operation

- Establish capabilities to achieve uncertainties on ground
- Design, characterise, test aircraft-based standard
- Evolve design and test balloon-based standard
- Design Satellite-based standard

Partnership NPL, PTB, BUW, FZJ (76 MM)

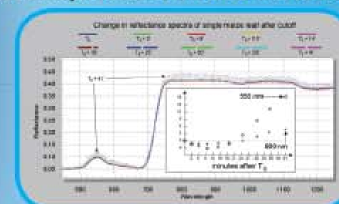
WP2

WP3



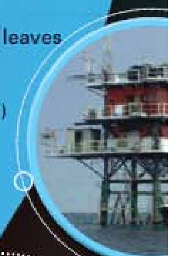
Recovering/establishing in-flight traceability through reference standard measurements and test-sites

All optical sensors degrade in-orbit, and measure radiation at top-of-atmosphere to infer the properties of the Earth's surface. Representative 'test-sites' are a critical element of any EO Calibration/Validation strategy and a major focus of the GEO and CEOS community.



- Evaluate and reduce uncertainty 5% → 1% for Ocean Colour: in-water, spectral radiance, effects of oceans...
- Autonomous maintenance of traceability
- SI traceable validation of Radiative Transfer Codes
- In-situ measurement of 'live' leaves

Partnership: NPL, AALTO, INRIM, JRC, MIKES, FGI (122 MM)



Creating impact

WP5

Primary impact through technical work packages - dissemination and use:

Also increase stakeholder awareness of the importance of traceability and the limitations of existing data products. Key interfaces to the EO community are through the major international organisations but must also include industry, academia and policy makers.

- Community website linked to international portals to provide focal point for European EO metrology
- Identify metrological requirements for next generation sensors
- Provide EO tailored training on uncertainty analysis
- Develop concept of EMCEOC with key stakeholders
- Papers, presentations, media news items
- European focus for international EO metrology (CEOS, QA4EO, GEO, WMO, GSICS, GEWEX, GCOS)

Partnership: NPL, LNE, PTB (13 MM) + All (WP1-4)

WP4

An 'NMI in space' for benchmark measurements of climate

Climate-quality uncertainties and a 'global climate observing system' requires regular traceability directly to primary standards. Since satellites cannot be brought back to the NMIs on Earth, the primary standards need to be flown in space.

- Evaluate performance of prototype primary standard designed for space
- Prototype techniques to use primary standard in space
- Design and test transfer radiometer needed to link primary standard and imaging spectrometer (also for use in WP1).

Partnership: NPL, LNE, PTB, SFI-Davos (44 MM)

team

…ical leadership of JRP
…ll WPs by internationally
…gnised experts in EO metrology
…rtium is already active with
…g links to key international
…isations
…alised nature of sector needs
…d delivery nodes

Collaborators

Spectral Radiance Metrology at NIST

- PYROMETRY Setup + FASCAL: T > 962 °C, λ < 2.5 μm (Howard Yoon)
  - Principle: Extrapolation from Au point (+ compared with ACR at 900 nm)
  - New: R2T facility (not yet fully operational). Numerous improvements planned, including use of multichannel spectrometers for much faster scale transfer. DETAILS BEYOND THE SCOPE OF CURRENT TALK

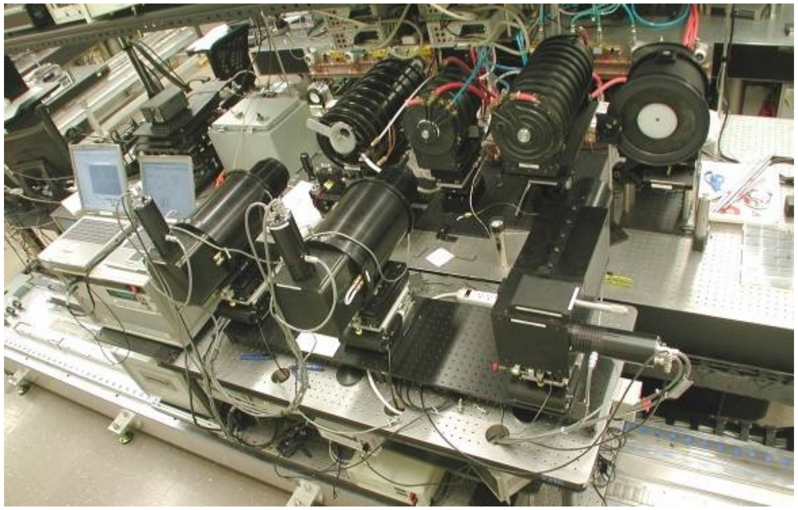
- SDE Facility: 150 °C < T < 1000 °C, 3 μm < λ < 23 μm, purged.
  - Principle: Interpolation between VTBB, using FTIR;

- AIRI: -45 °C < T < 1000 °C, 2.5 μm < λ < 14.8 μm, not purged.
  - Principle: Interpolation between FP and VTBB, using filter radiometers;
  - RT Comparisons with NMI of Germany, UK and Canada in the -50 to 300 °C temperature range, in the 8 μm -12 μm spectral band;
  - Now a regular calibration service

- LBIR (new capability with LHe cooled FTIR)
  - Spectral coverage up to 28 microns, performance limited by the FTIR stability (0.5%)

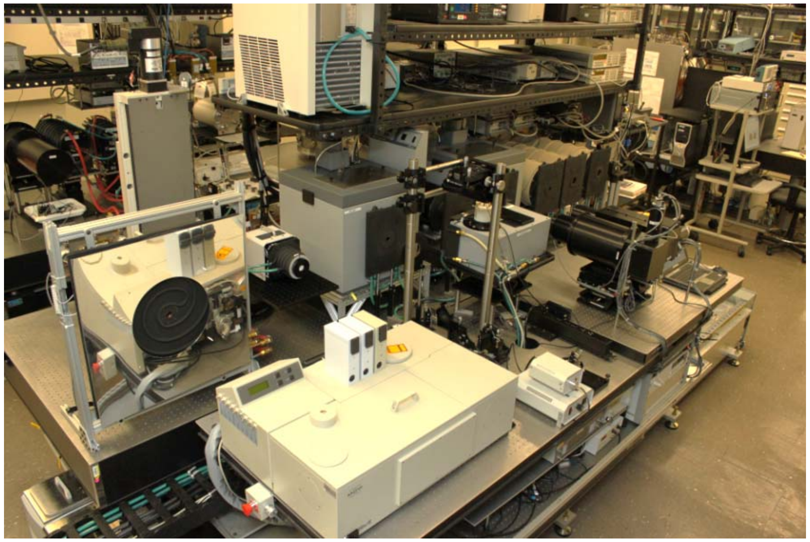
In spite of substantial experience in realization spectral radiance scales, no immediately usable capability exists to support CLARREO-type applications

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

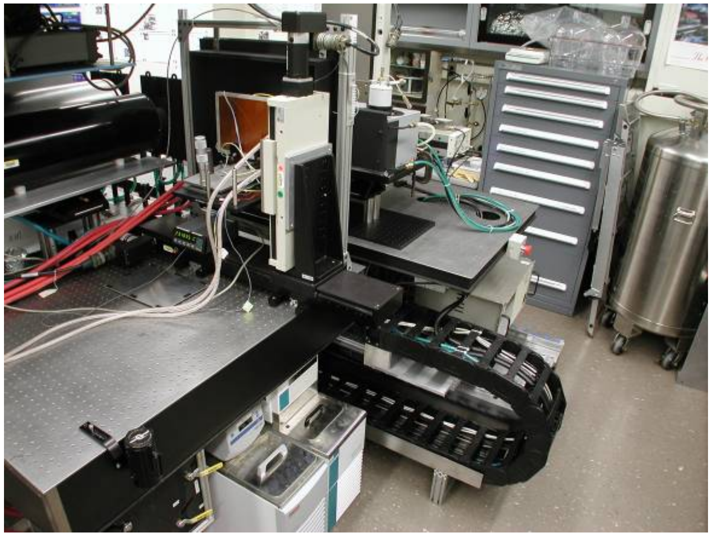


Fixed Point BB Bench

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 (FTS)



Scene plate/Out-of-Field Scatter Tool

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;

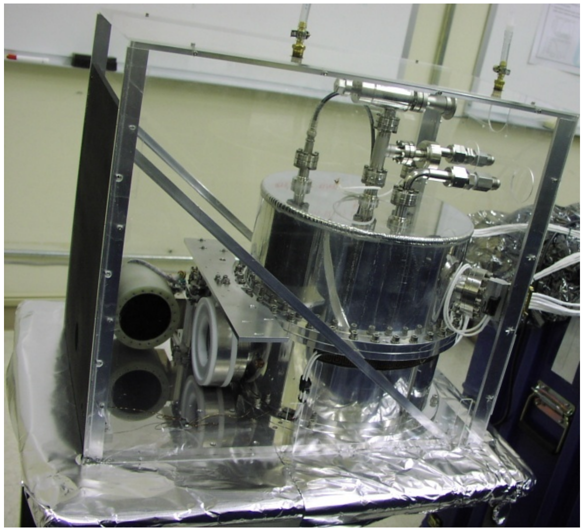
- This addresses most of immediate needs, but in the long run it is essential to offer direct support, not relying on modeling or other assumptions;

- 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 Issues

• 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

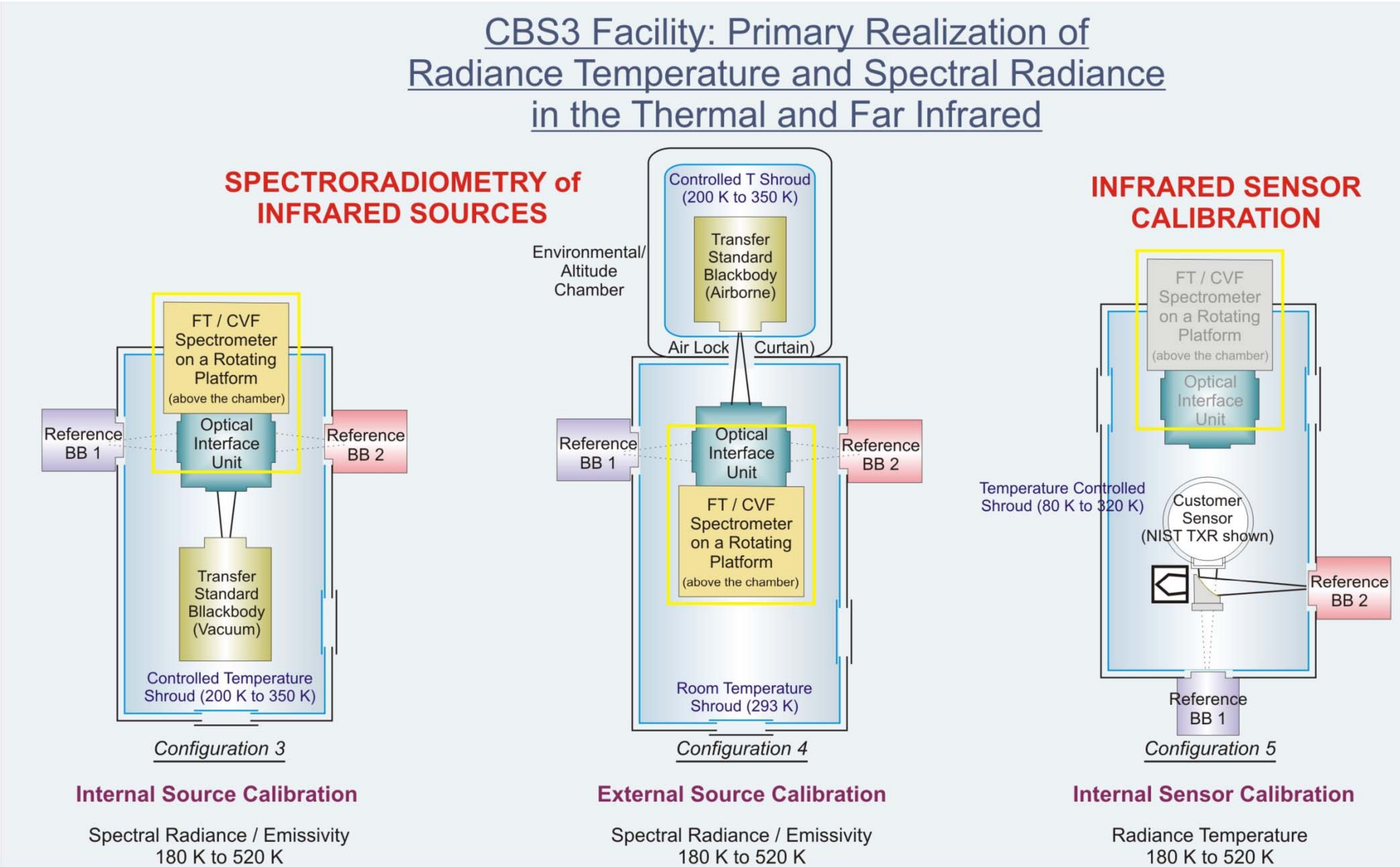
- Limitations: calibrated in the ambient air and radiation background

Multifunctional Modular IR Testbed Concept - Design Principles

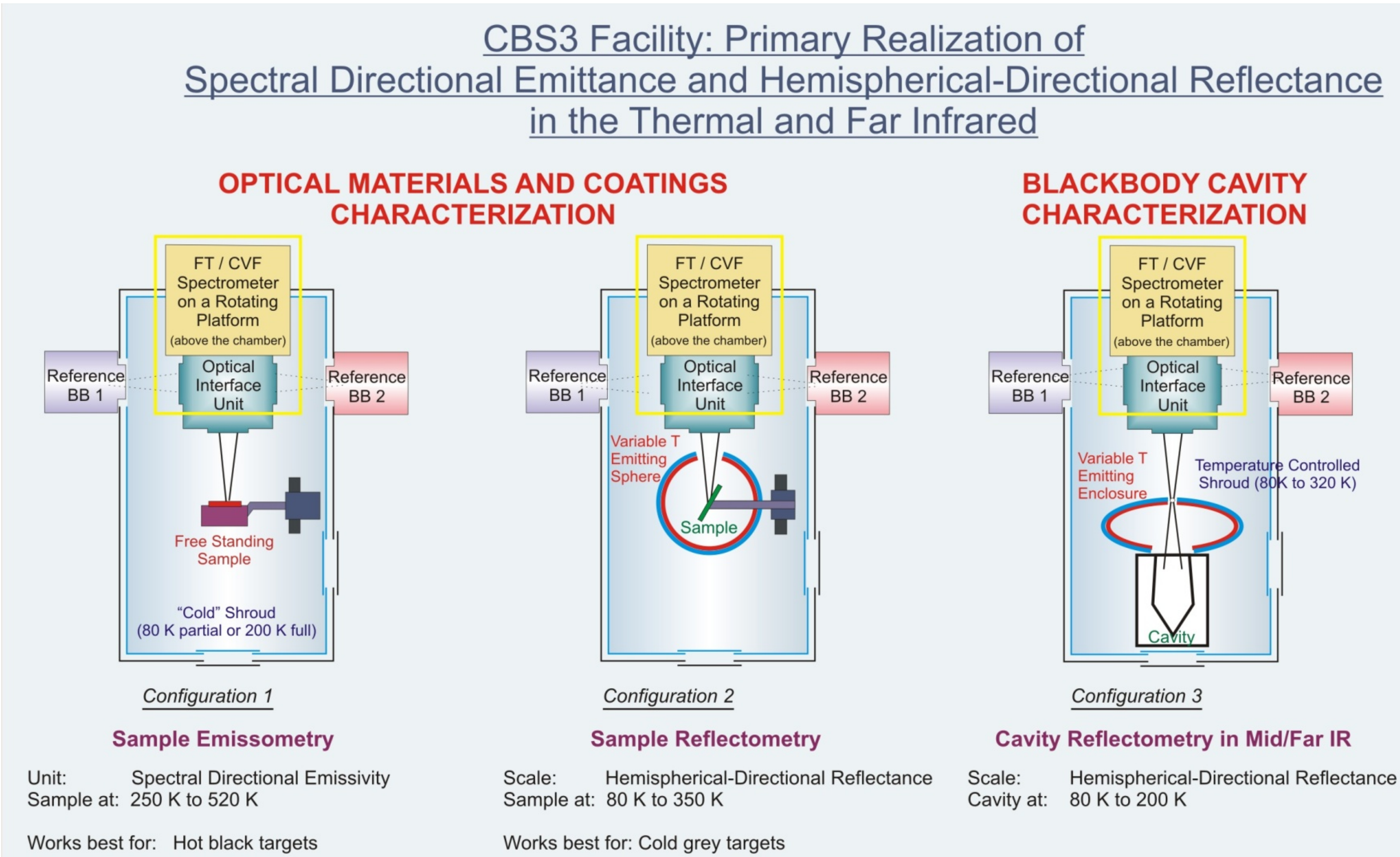
- After analysis of emerging requirements in metrology of thermal emission sources and optical materials and components, and evaluation of several existing IR calibration facilities, a Controlled Background Spectroradiometry and Spectrophotometry System (CBS3) concept was developed;

- 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

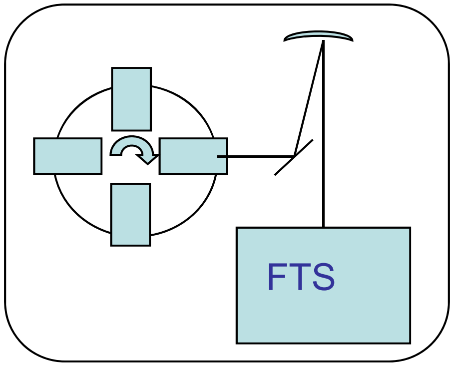
Radiance Temperature Modes of CBS3



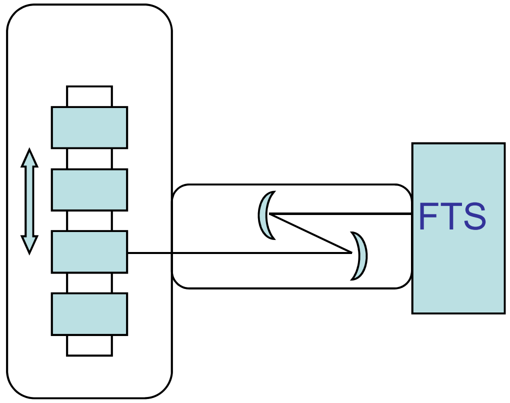
Optical Property Metrology Modes of CBS3



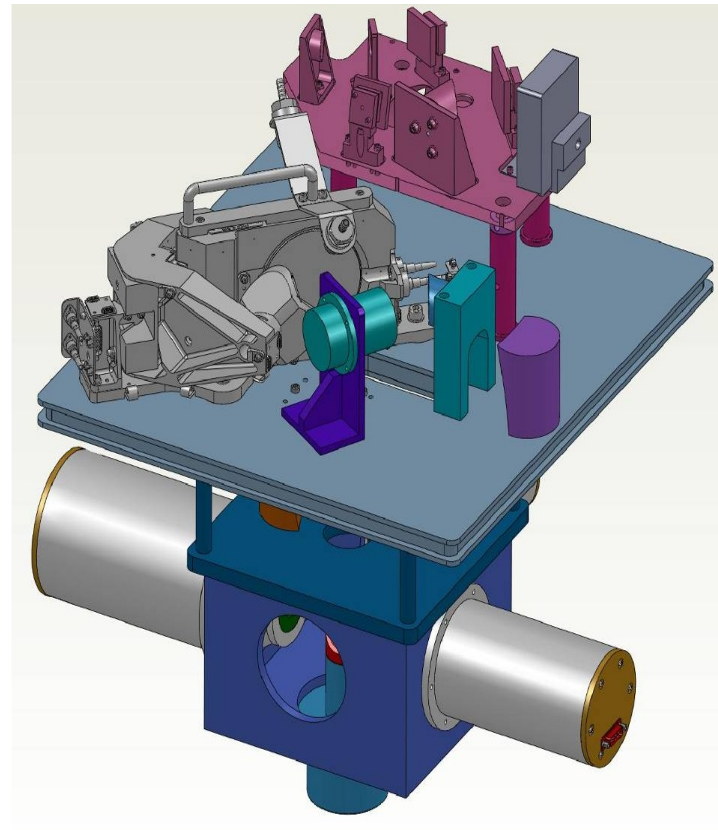
Vacuum Radiance Comparator Arrangements



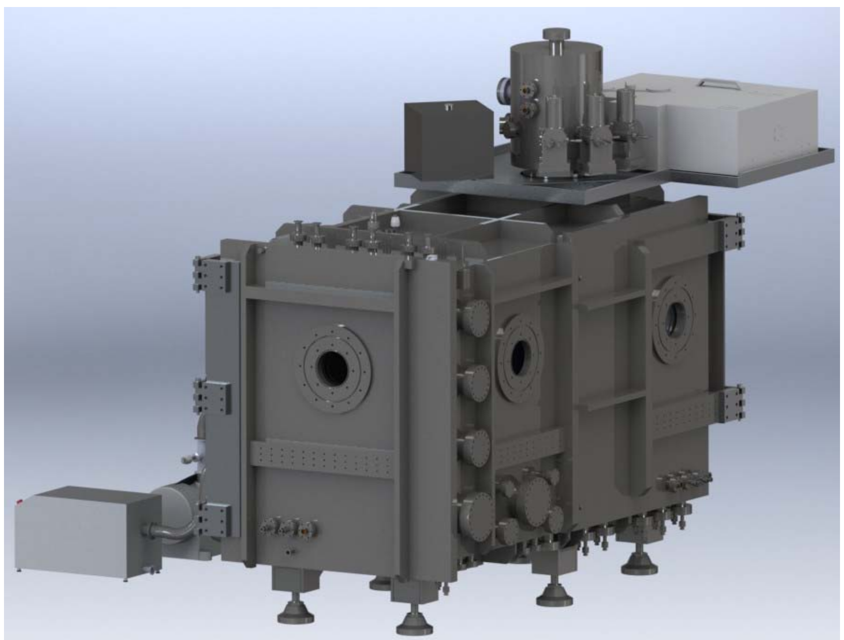
Harvard U. Chamber



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

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)

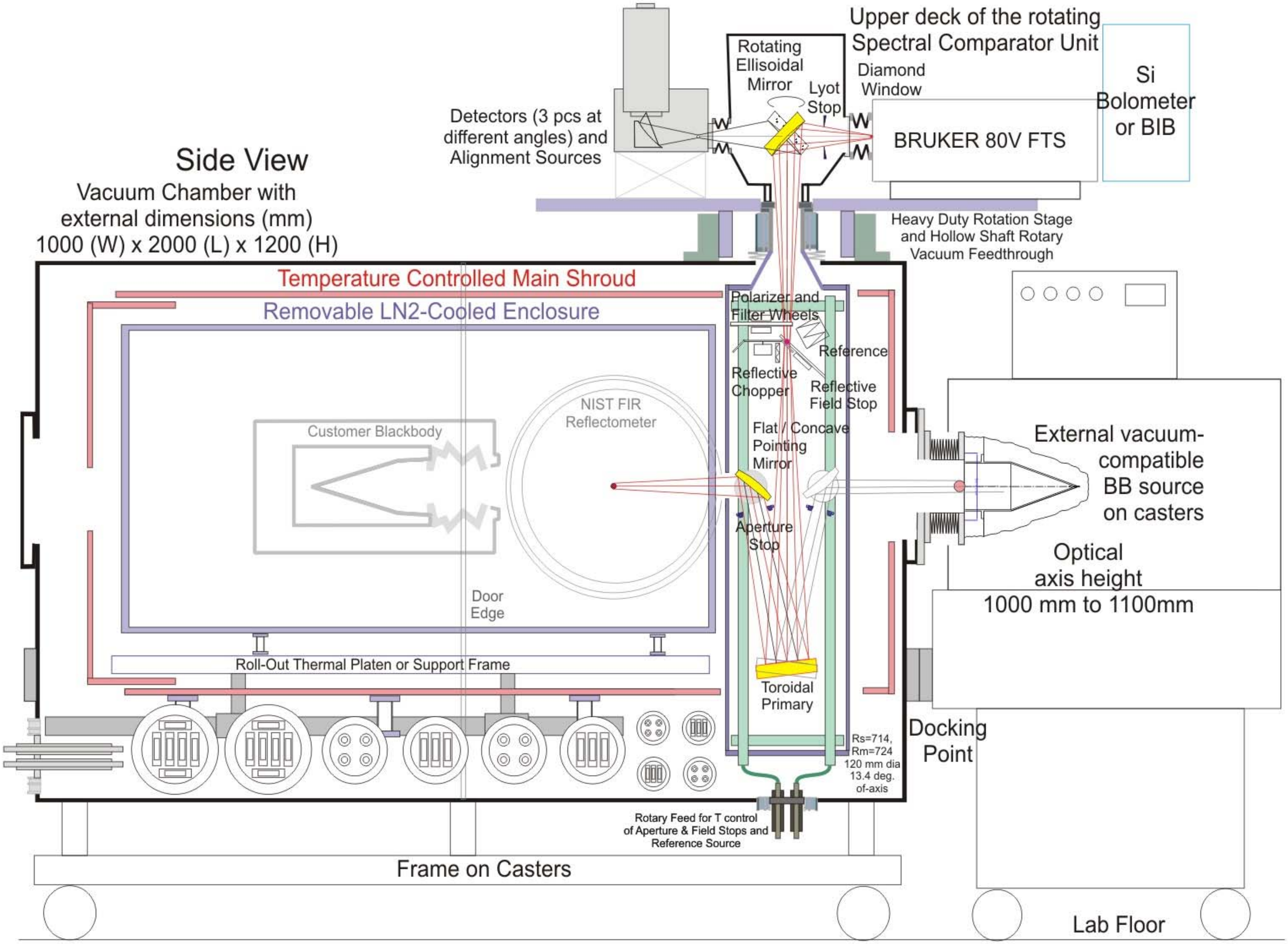
Remaining activities in this area include:

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

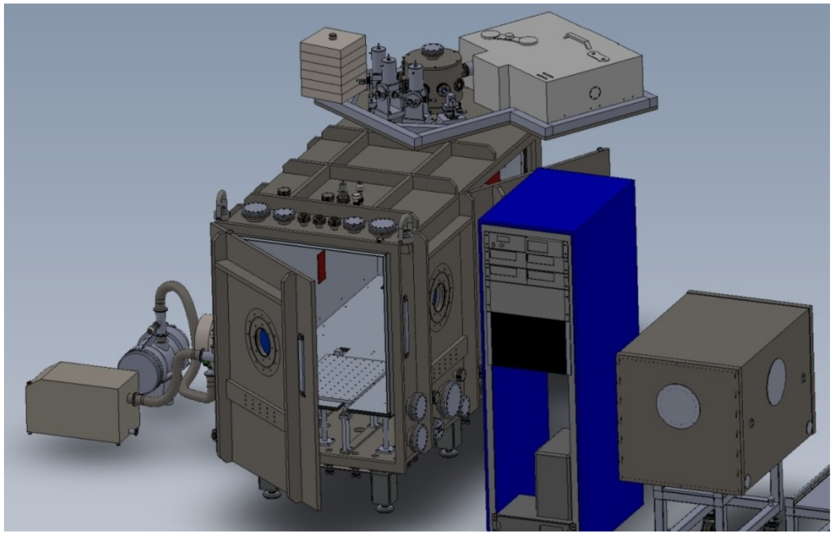
Results of the design effort:

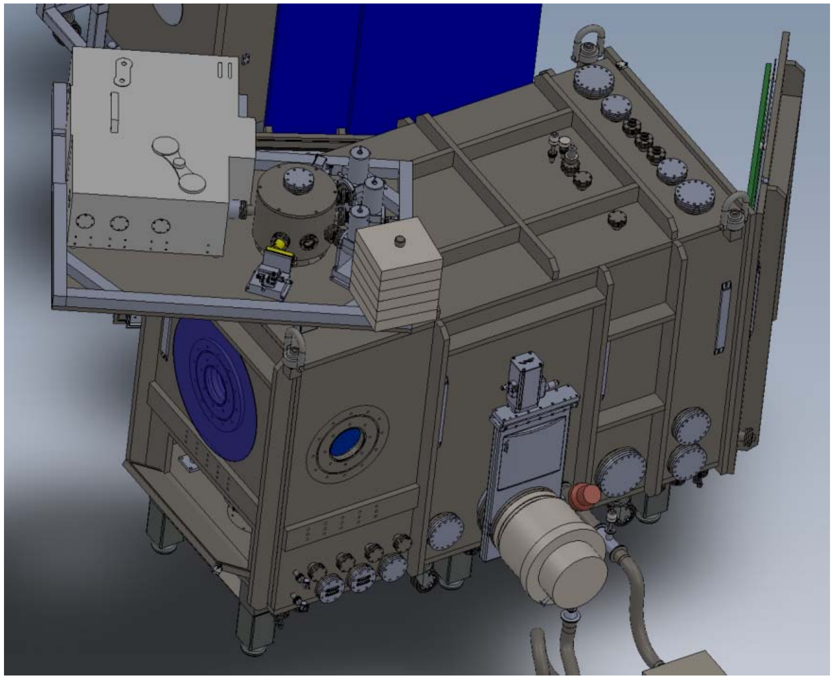
- Machine-ready design for the vacuum chamber and spectral comparator
- Advanced stage of the primary BB sources design
- Conceptual design stage for reflectometry components

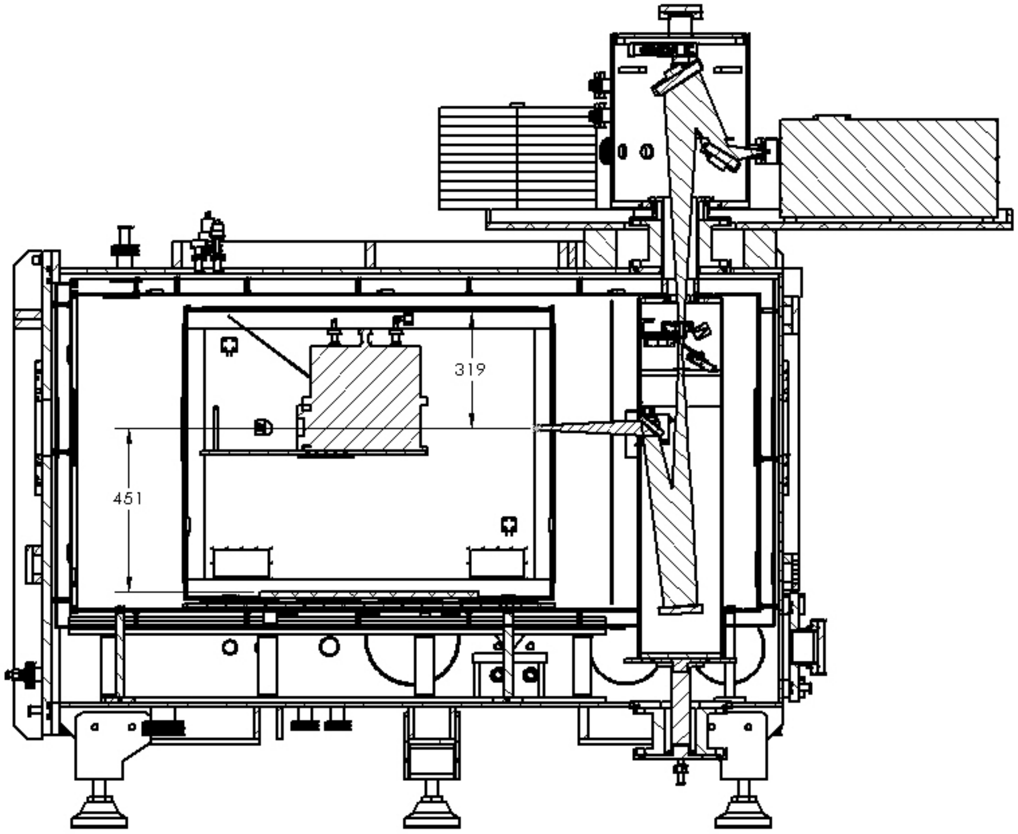
Schematic Cross-Section of the CBS3 Concept



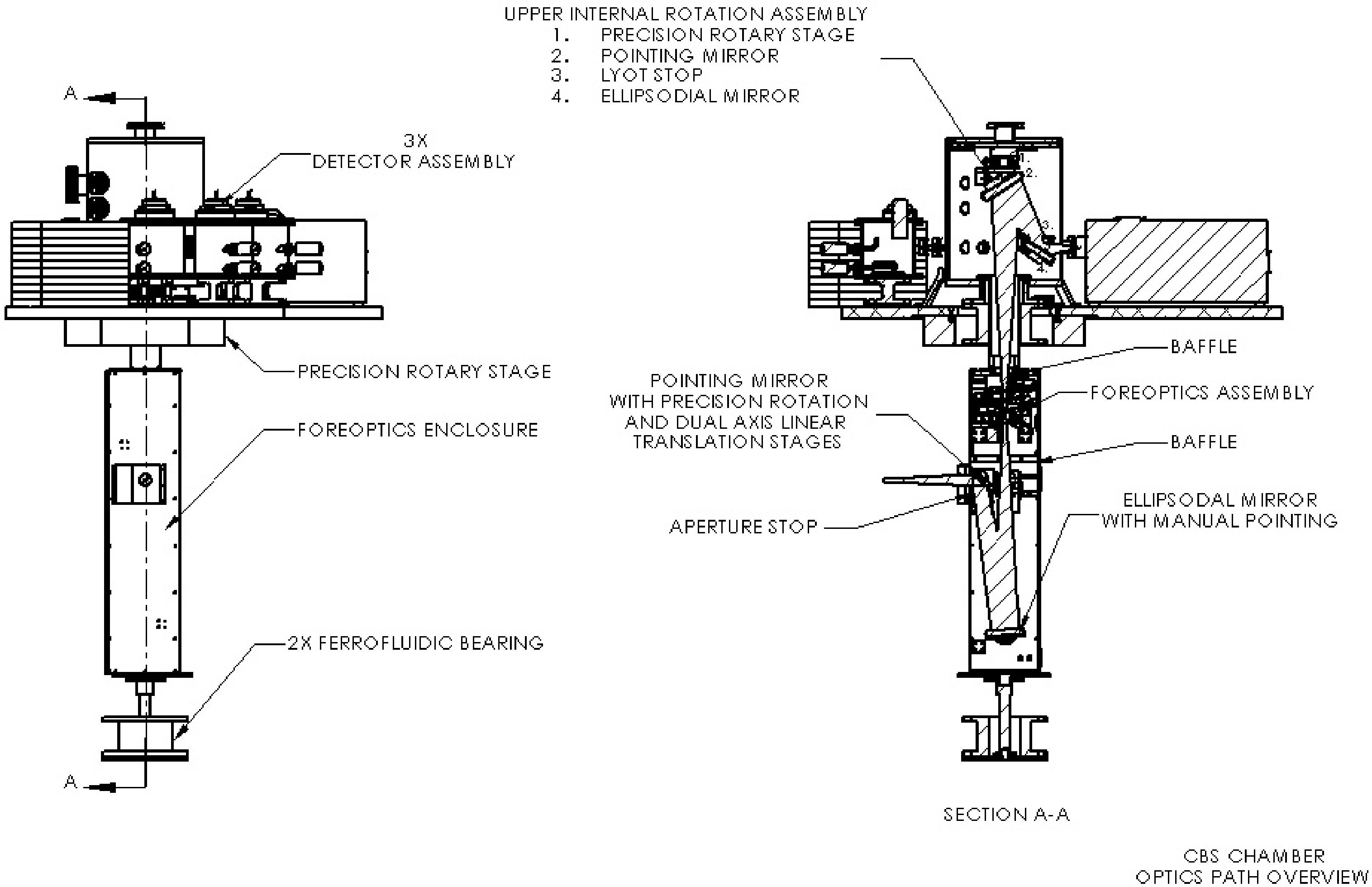
CBS3 3D Model Views (with TXR in the right figure)



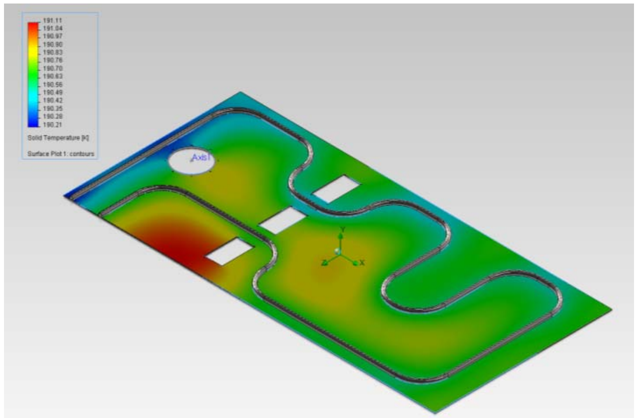




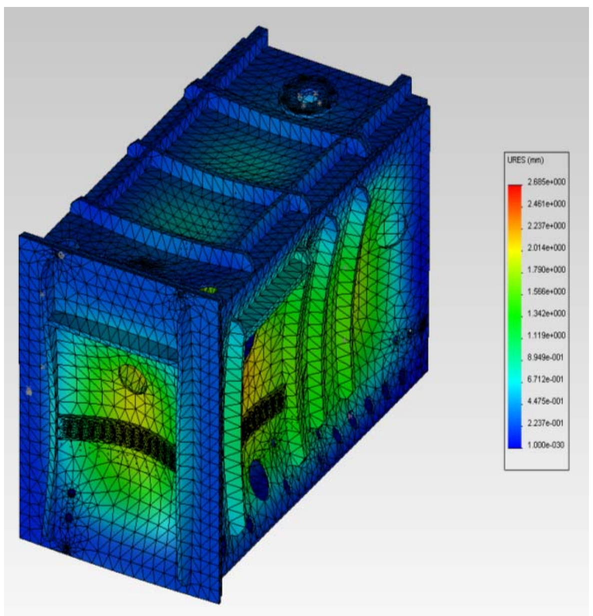
Foreoptics and Upper Chamber Assembly Design



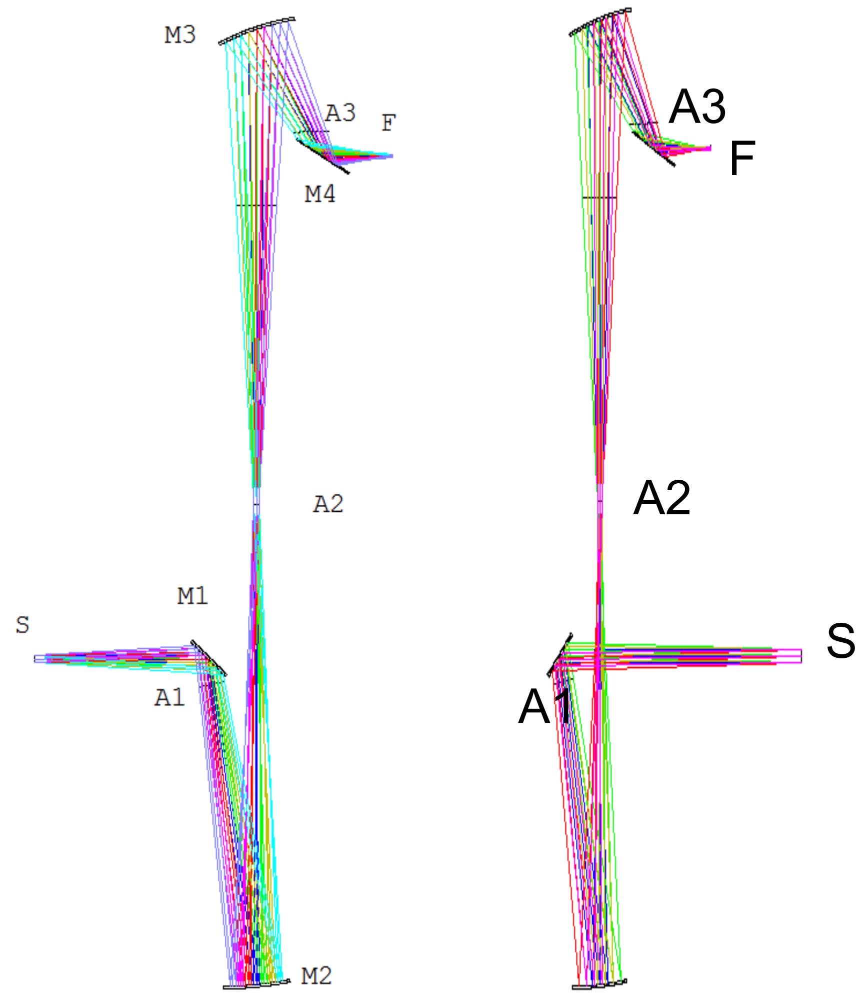
Modeling and Design Results (L-1)



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



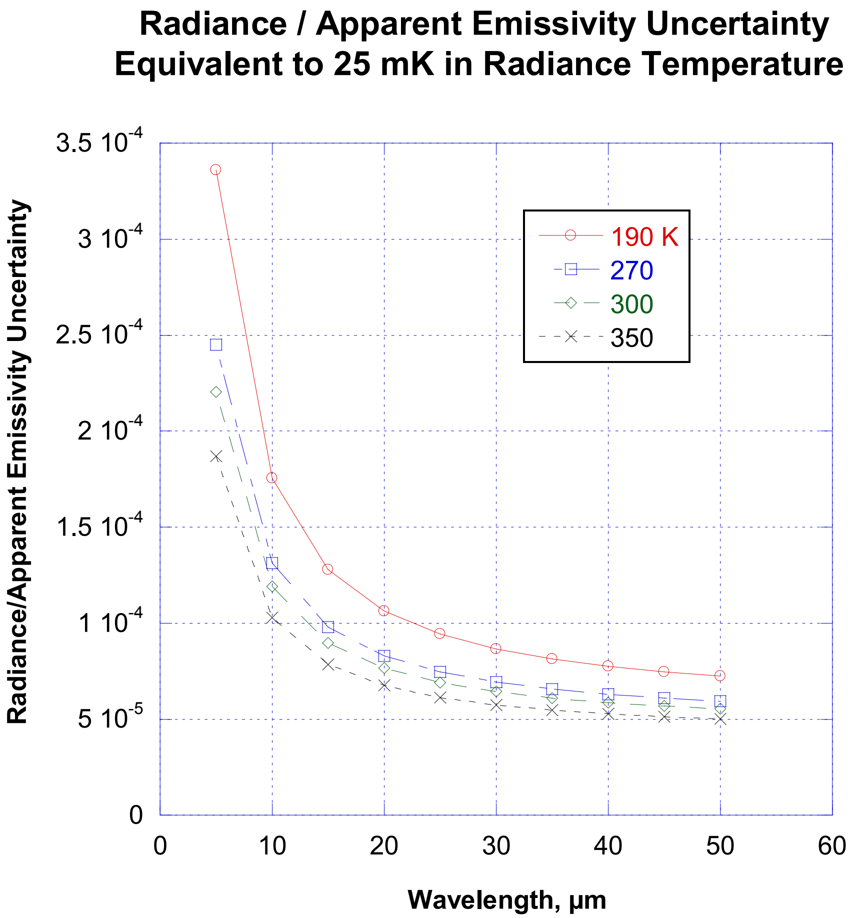
Isometric view of Stress Test, Trial 2 (12.7 mm plates).



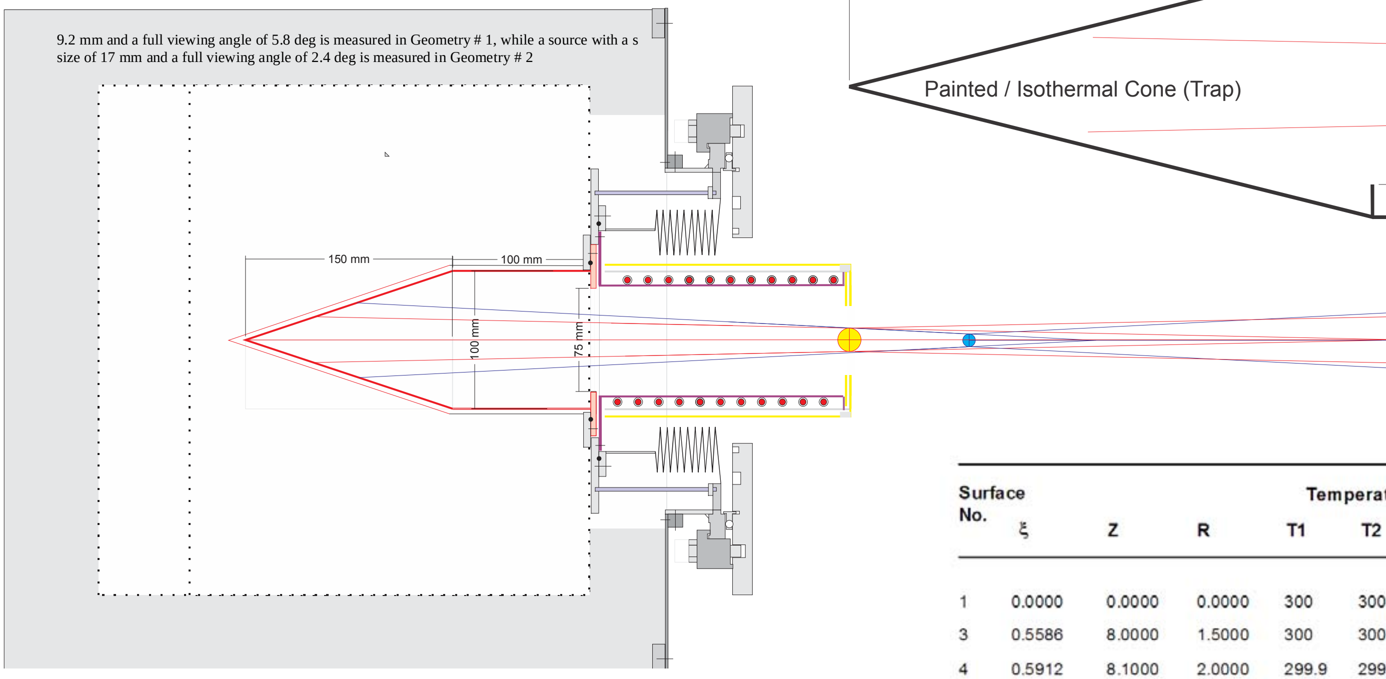
ZEMAX layout for tow geometries. The image at Lyot Stop using the image analysis tool in ZEMAX.

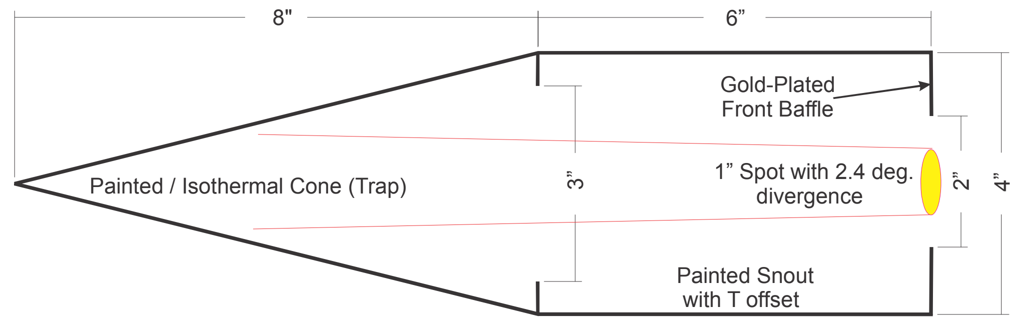
Blackbody Emissivity Requirements

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

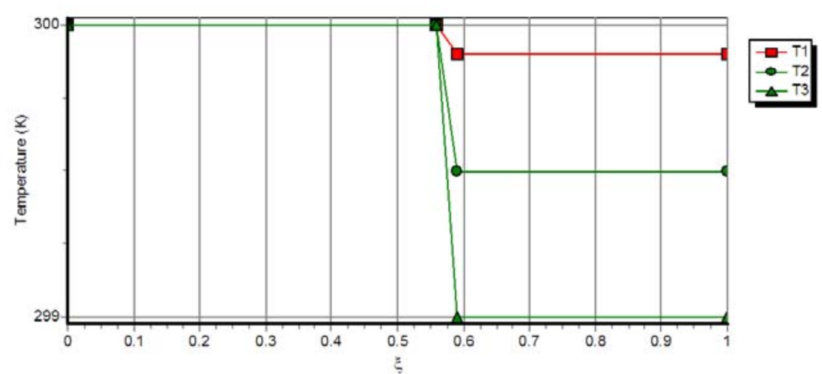


Fluid Bath-Based BB Cavity Absorptivity Modeling: Input Parameters





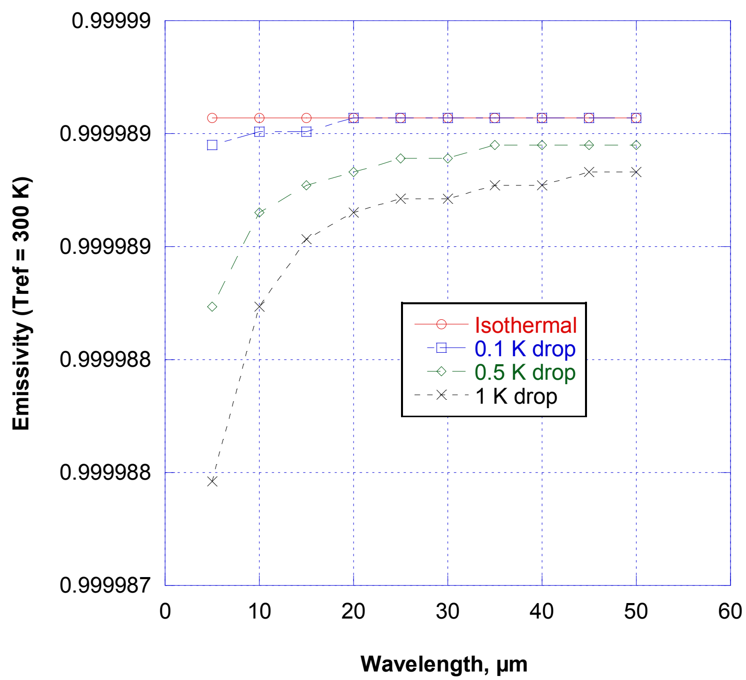
Surface No.				Temperature Distributions along Cavity Generatrix							
	ξ	Z	R	T1	T2	T3	T4	T5	T6	T7	T8
1	0.0000	0.0000	0.0000	300	300	300					
3	0.5586	8.0000	1.5000	300	300	300					
4	0.5912	8.1000	2.0000	299.9	299.5	299					
5	0.9991	14.0000	1.5144	299.9	299.5	299					



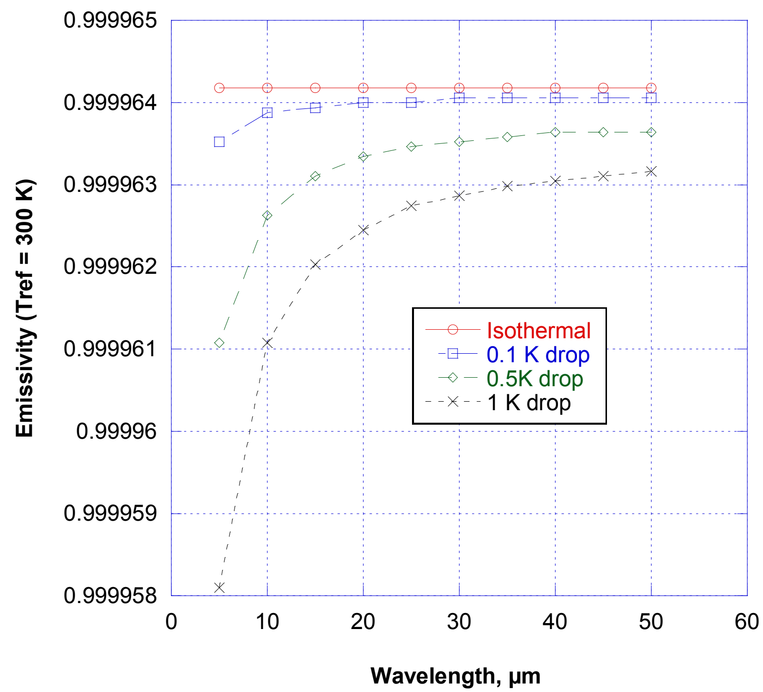
Results of Cavity Emissivity Modeling for Diffuse and Specular Paint Cases

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.

Specular Paint with Reflectance 10% and Specularity 98% (similar to PT-401)



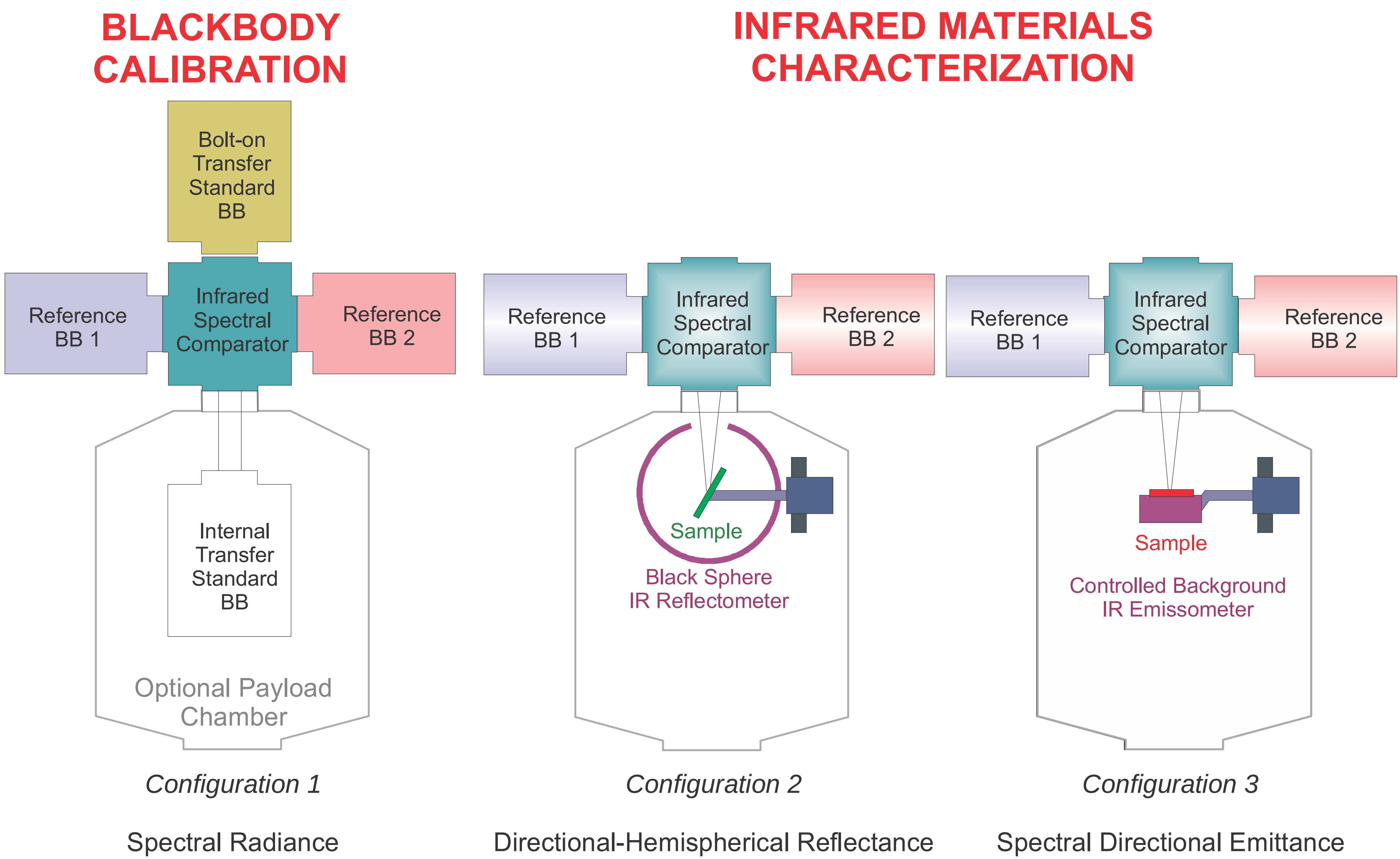
Specular Paint with Reflectance 20% and Specularity 98% (two times worse than PT-401)



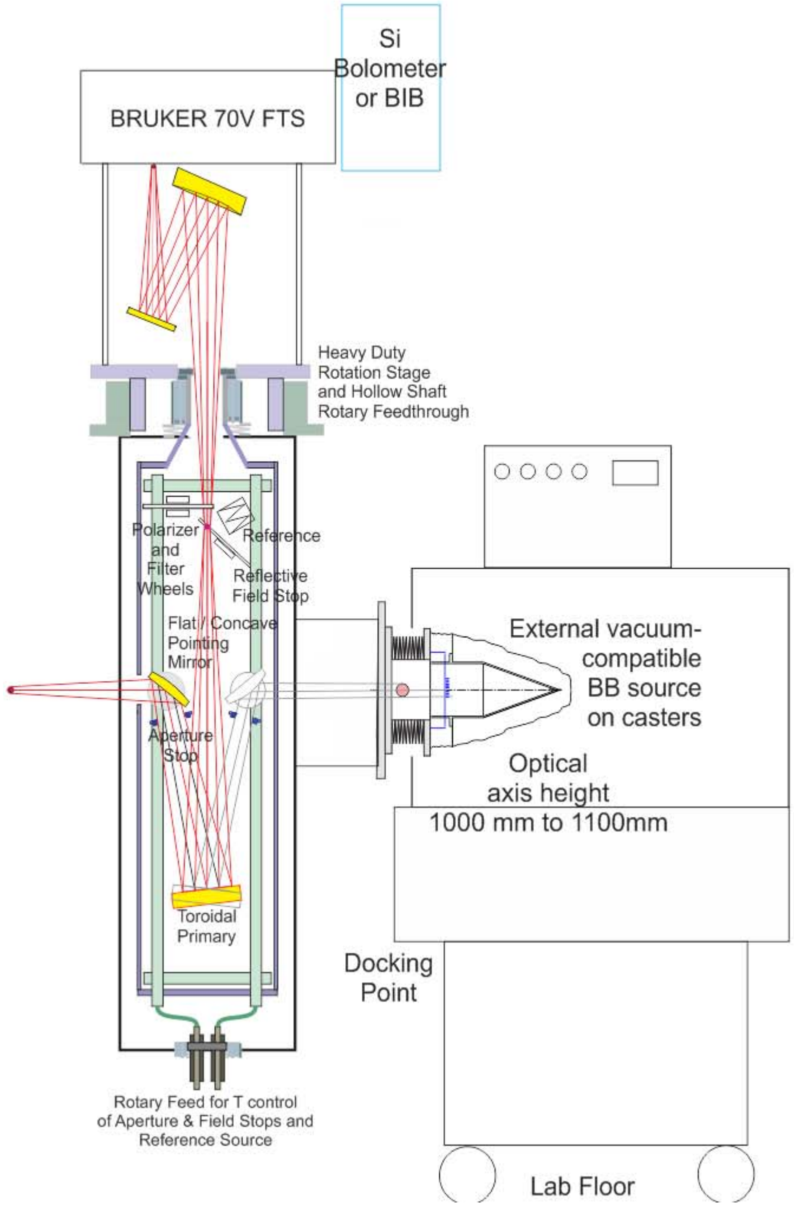
Primary Fixed Point BBs

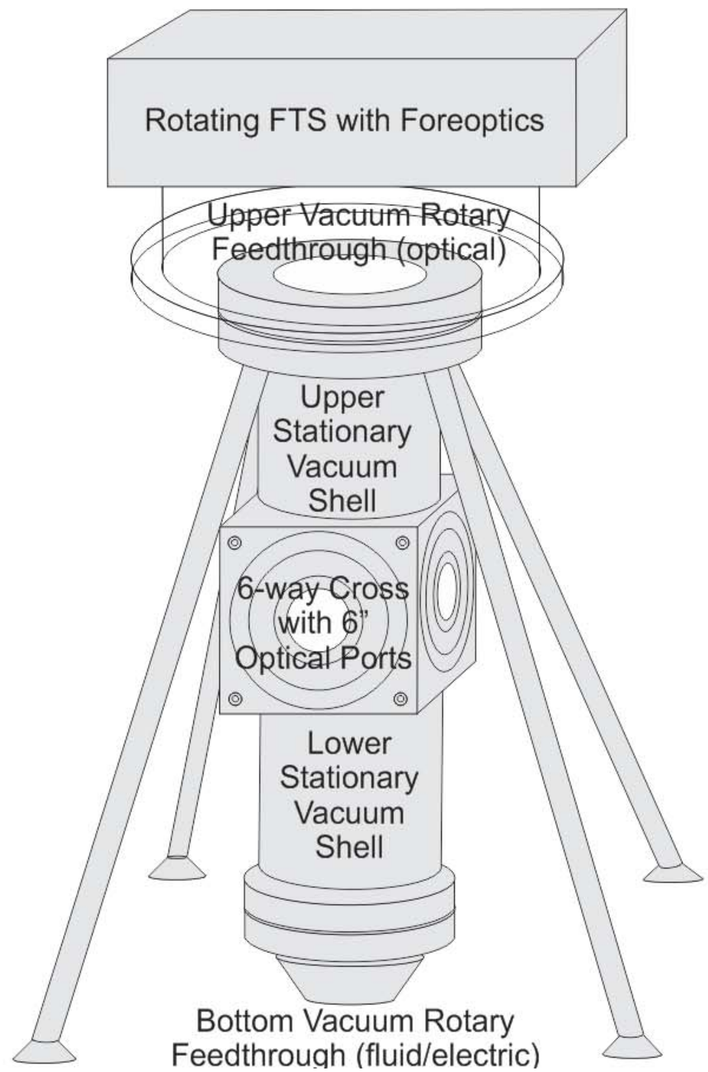
- For all three substances (water, mercury and gallium):
  - Common SS crucible design and coating
  - Common T control (Peltier elements)
  - Common housing and insulation
  - Common T sensors and read-outs
- LN2 source is also anticipated (0.1 K uncertainty)
- A vendor with unique experience in handling pure substances and making primary fixed points has expressed interest in fabrication (Pond Engineering), may participate in fabrication of VTBB also

Vacuum Spectral Comparator (VSC) Concept

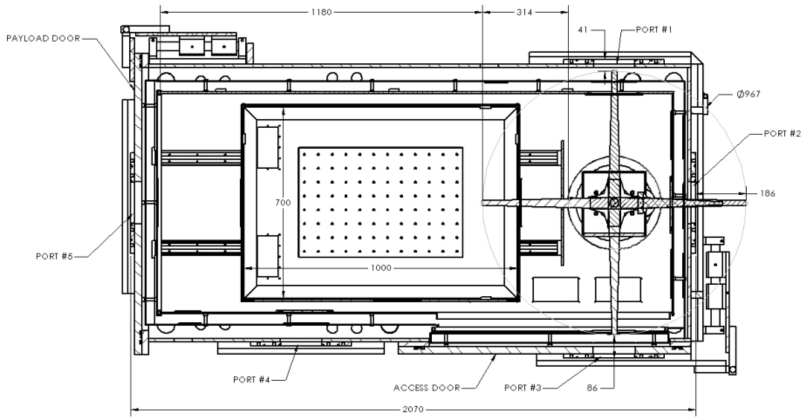


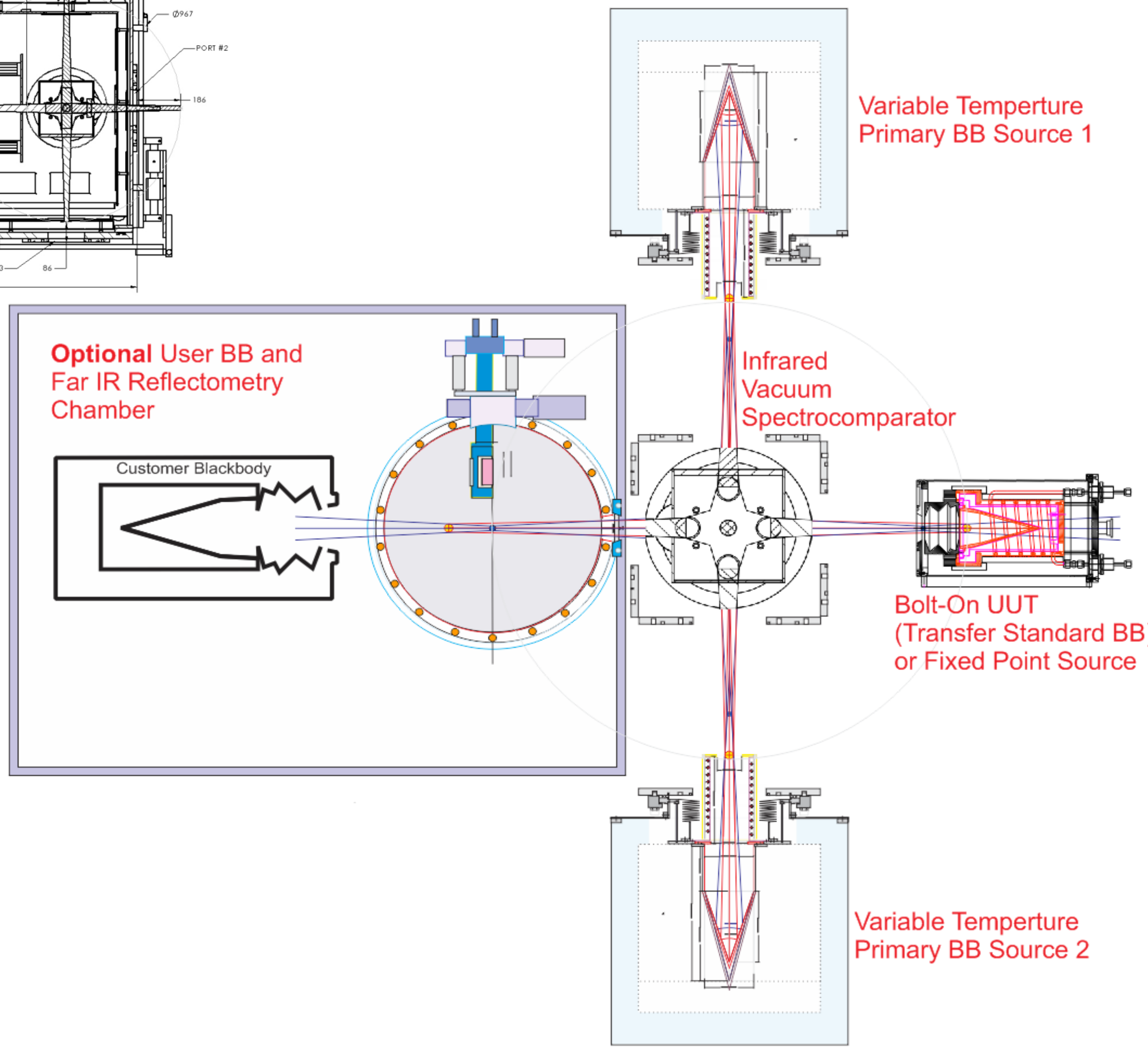
Stand-Alone Vacuum IR Spectral Comparator Concept





VSC with Primary and Transfer BB and Optional Chamber





Thermal and Far IR Radiance Support - Trade Study

Option	Functionality	Benefits	Risks / Drawbacks
Wait until full funding for original CBS3 concept becomes available	BB Spectral Radiance, DHR, Emittance, Cavity Reflectance	Comprehensive Far IR Coverage and Flexibility	1. Funding may never materialize 2. It may come too late for mission support
Build a stand-alone Infrared Spectral Comparator (ISC) + Bolt-On Primary BBs	BB Spectral Radiance (F/20 and F/7); includes spatial gradient assessment	Substantially reduced fabrication cost, weight and footrpint (compared with CBS3 concept)	1. If a bolt-on transfer standard BB is not sufficient for CLARREO successor and other missions, a UUT chamber is needed
Build Primary and Transfer Standard Sources, use PTB RBCF Facility for scale transfer	BB Spectral Radiance (F/8 geometry)	Save ISC Fabrication and Operation Costs	1. Wrong geometry and single stage optics 2. BB Compartment is extremely small 3. Overseas, potential issues with access
Build Transfer Standard Sources and use PTB RBCF Facility for scale realization and transfer	BB Spectral Radiance (F/8 geometry)	As above, plus save on primary BB fabrication and characterization	As above, plus - resident primary BBs (a) have 50 mK spec; (b) were not designed for Far IR, and (c) rely on modeling only
Rely on indirect characterization and modeling of a Transfer Standard BB Source	None directly related to spectral radiance	No hardware costs except cavity reflectometry support	No direct SI traceability

Middle Ground Scenario (Reduced but Significant Effort Level)

PRIMARY REALIZATION OF SPECTRAL RADIANCE AND RADIANCE TEMPERATURE IN THERMAL AND FAR IR for USER BLACKBODY AND SENSOR CALIBRATION SUPPORT IN A CRYO-VACUUM ENVIRONMENT

WBS	Tasks	FY2012				FY2013				FY2014				FY2015			
		O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S
1.1	**Establish Material Properties Metrology in Far IR**																
1.1.1	Establish a Transitional FIR DHR and Emittance Scales	■	■	■													
1.1.1.1	Add BIB detector to the DHR setup to extend spectral range																
1.1.1.2	Validate DHR and SDE scales using PTB, NPL and SOC data																
1.1.2	Characterize candidate FIR black coatings for BB sources		■	■	■												
1.1.2.2	Measure emittance/reflectance with S/D breakdown																
1.1.2.3	Evaluate outgassing/contamination																
1.2	**Establish Cavity Reflectance Metrology in Far IR**																
1.2.1	Upgrade NIST CHILR laser reflectometer	■	■	■	■	■											
1.2.1.1	Install FIR QCL Laser and FIR detector (PC or BIB) and filter																
1.2.1.3	Test/validate CHILR with QCL																
1.2.2	Build SFIRR to Achieve Continuous FIR Coverage			■	■	■	■	■	■								
1.2.2.1	Investigate/optimize FIR diffuse reflective coatings																
1.2.2.2	Design/Build a FIR integrating sphere reflectometer																
1.2.2.3	Steps to complete arrangements with PTB (MOU, SOW etc.)																
1.2.2.4	PTB upgrades MLS High Intensity FIR source																
1.2.2.5	Test SFIRR with MLS source, compare with TIR / 24 µm TStd																
1.3	**Build Primary Standard Blackbody Sources**																
1.3.1	Build Variable Temperature BBs (ethanol baths)			■	■	■	■	■	■								
1.3.1.1	Prepare conceptual design, select technologies																
1.3.1.2	Thermophysical and radiometric modeling of BB performance																
1.3.1.3	Build, paint and evaluate a prototype cavity, finalize design																
1.3.1.4	Build and test VT BBs																
1.3.2	Build Fixed Point BBs (water, mercury, LN2)							■	■	■	■	■	■				
1.4	**Build Infrared Spectral Comparator (ISC)**																
1.4.1	Build the IR Spectral Comparator				■	■	■	■	■	■	■	■	■				
1.4.1.1	Finalize a concept, develop a set of specifications																
1.4.1.2	Perform diffraction analysis and evaluation																
1.4.1.3	Design and Build the ISC																
1.4.1.4	Procure FTS (Bruker V70v)																
1.4.1.5	Install and test ISC																
1.4.2	Assemble, Align, Test and Operate ISC and BBs												■	■			
1.5	**Establish Far IR Spectral Radiance / RT Scales**																
1.5.1	Establish Uncertainty Budget of the Radiance Scale													■	■	■	■
1.5.1.1	Compare BBs with different exit apertures (SSE)																
1.5.1.2	Compare BBs at different BG (emissivity)																
1.5.1.3	Compare BBs at different set points (linearity)																
1.5.1.4	Evaluate individual components and calculate total uncertainty																

Conclusions

- Critical Supporting Technologies, Modeling and Concept Demonstration
  - Far IR Optical Properties of Materials / Preliminary Scales
    - *Achieved positive results for PT-401 paint, intercomparison and cross validation of capabilities is in progress (with PTB and SOC); NPL participation likely will enable resolution of discrepancies;*
  - Far IR Optical Properties of BB Cavities
    - *NIST has adequate capability for Thermal IR performance evaluation. Prior to SFIRR development, we can rely on extrapolation of the Far IR portion, using new coating data and developed software;*
    - *Ongoing experiment with QCL, BIB, IR sphere, and far IR filter to evaluate adequacy of PTB MLS for cavity reflectance;*
    - *SFIRR design and implementation, in cooperation with PTB, can then be continued; identification/development of diffuse coating at 50 µm is a major element;*
- Realization and Transfer of Spectral Radiance for Thermo-Vacuum Environment
  - Primary and transfer standard FIR BB sources
    - *Design and prototyping to continue (with possible cooperation with PTB Facility), if required modest resources are available;*
  - Spectral Comparator Facility
    - *Multipurpose full scale facility is completely designed and ready for construction;*
    - *The ISC concept leaves CBS3 core features and could be constructed immediately, with at least a 50% cost reduction and shorter production time*
- Realization of Far IR Spectral Emittance and Reflectance
    - *In case of further delay with CBS3 / ISC funding, such effort can be undertaken independently of the high accuracy radiance facility, as these applications do not has as challenging requirements to the uncertainty. For example, an available legacy IFS 66v can be employed.*