Principles for Robust, On-orbit Uncertainties Traceable to the SI

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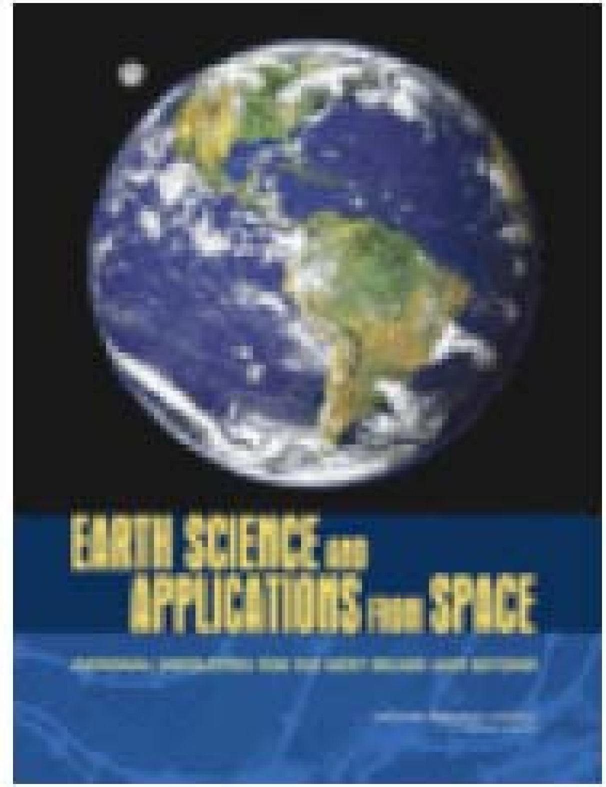
Talk Plan:

- **Setting the Stage—Challenges in Accurate Measurements**
- **The SI and the role for National Measurement Institute (NMIs)**
- **NIST Capabilities, by lab**
  - POWR
  - SIRCUS
  - AAMM
  - HIP
  - CBS3
- **International Inter-comparisons and Challenges**
- **Closing Remarks**

Motivation:

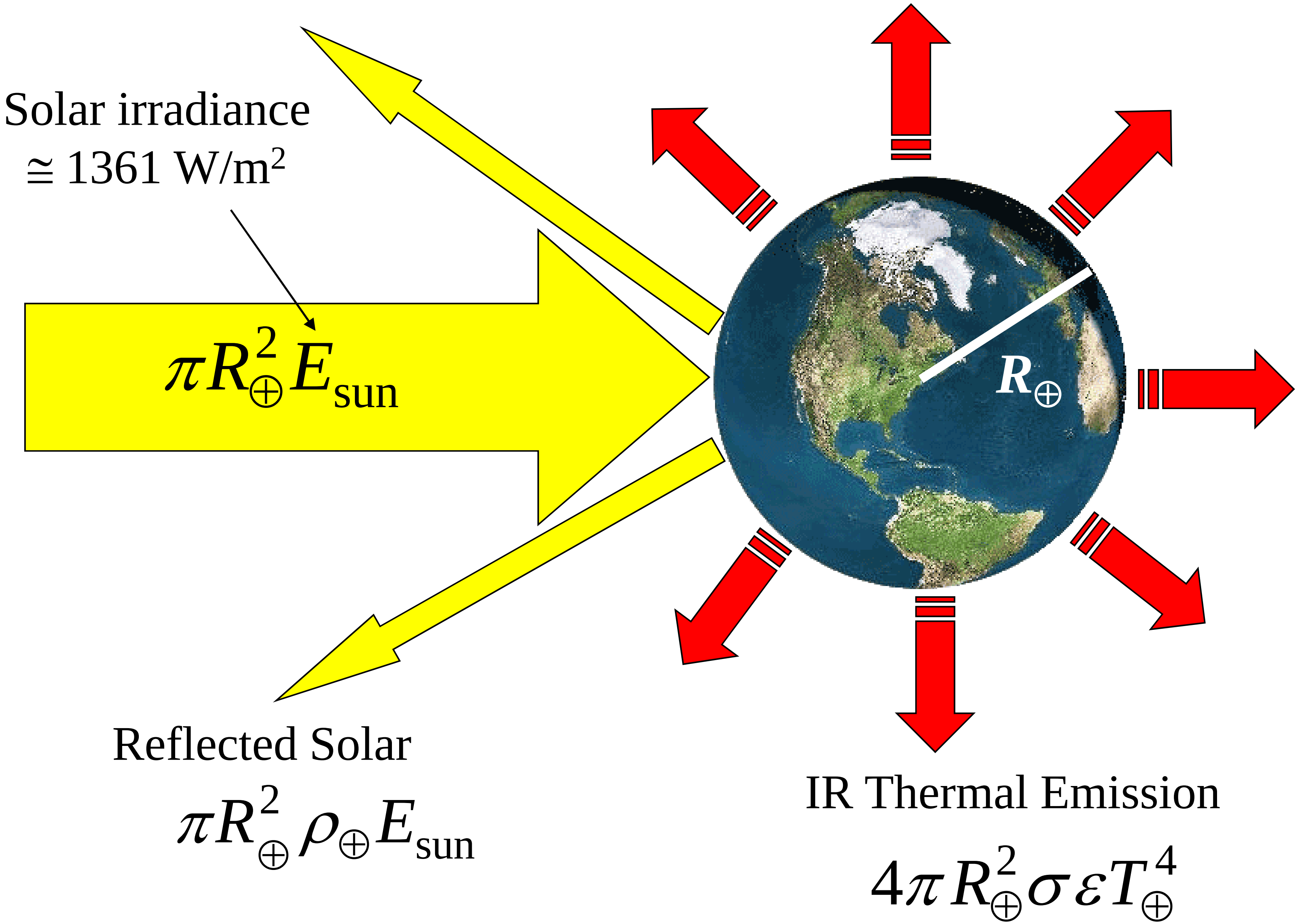
Stemming, say, from the NRC Decadal Survey Report



A VISION FOR THE FUTURE

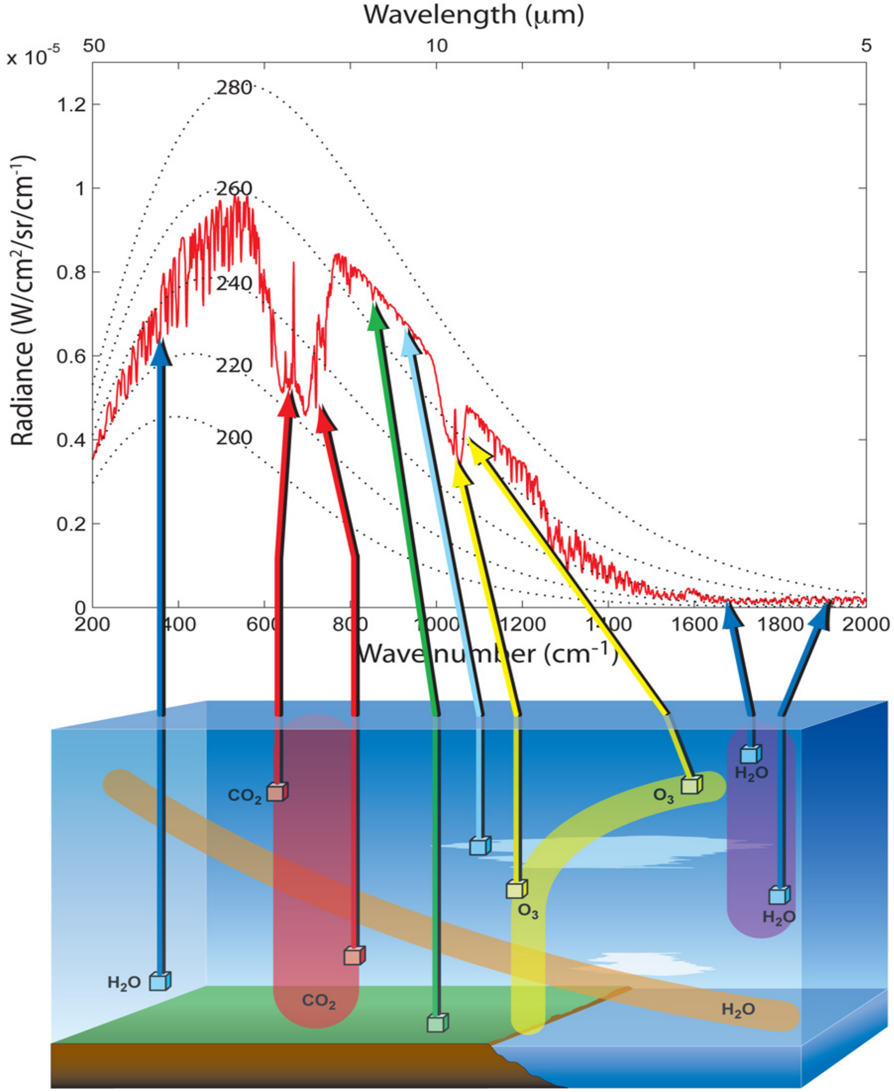
Understanding the complex, changing planet on which we live, how it supports life, and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity. It is also one of the most important challenges for society as it seeks to achieve prosperity, health, and sustainability.

Earth Radiation Budget:

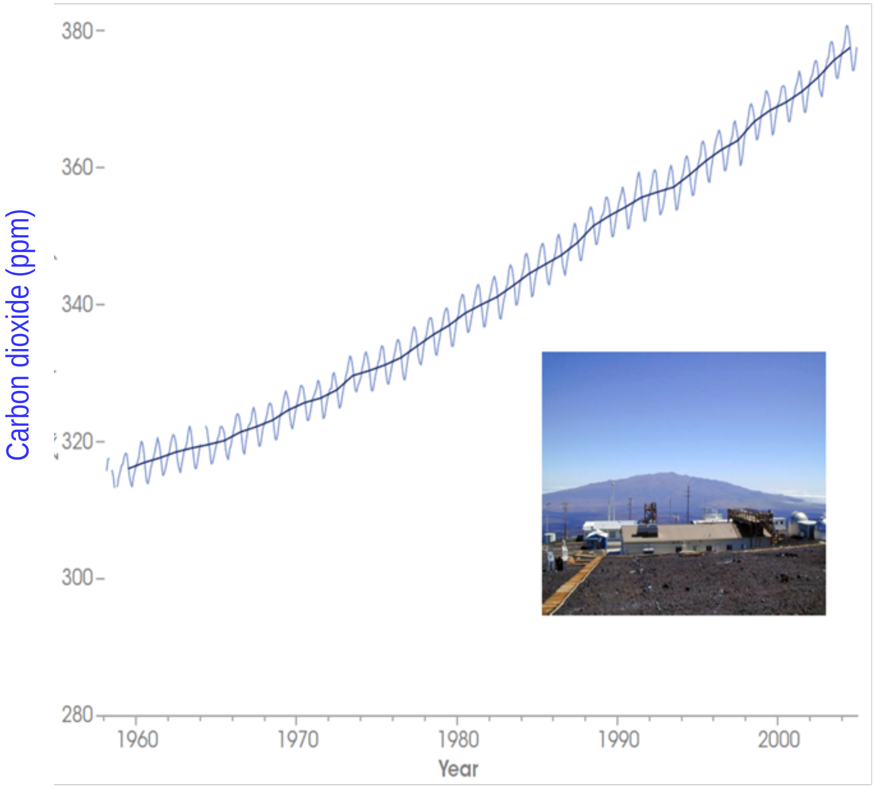


Earth Radiation Budget: affected by

- Atmospheric constituents
- Earth's albedo

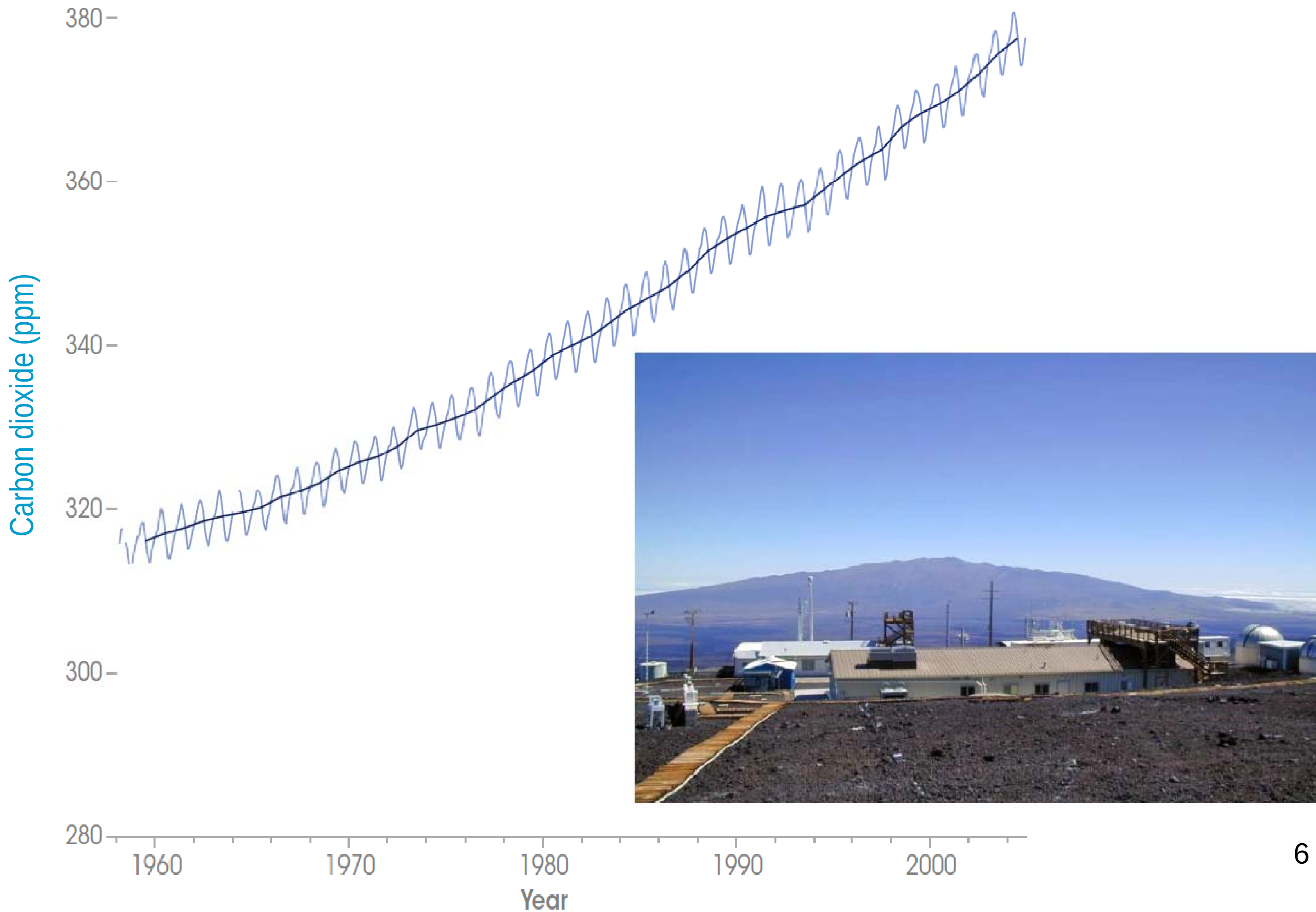


Keeling curve (atmospheric carbon dioxide fraction):



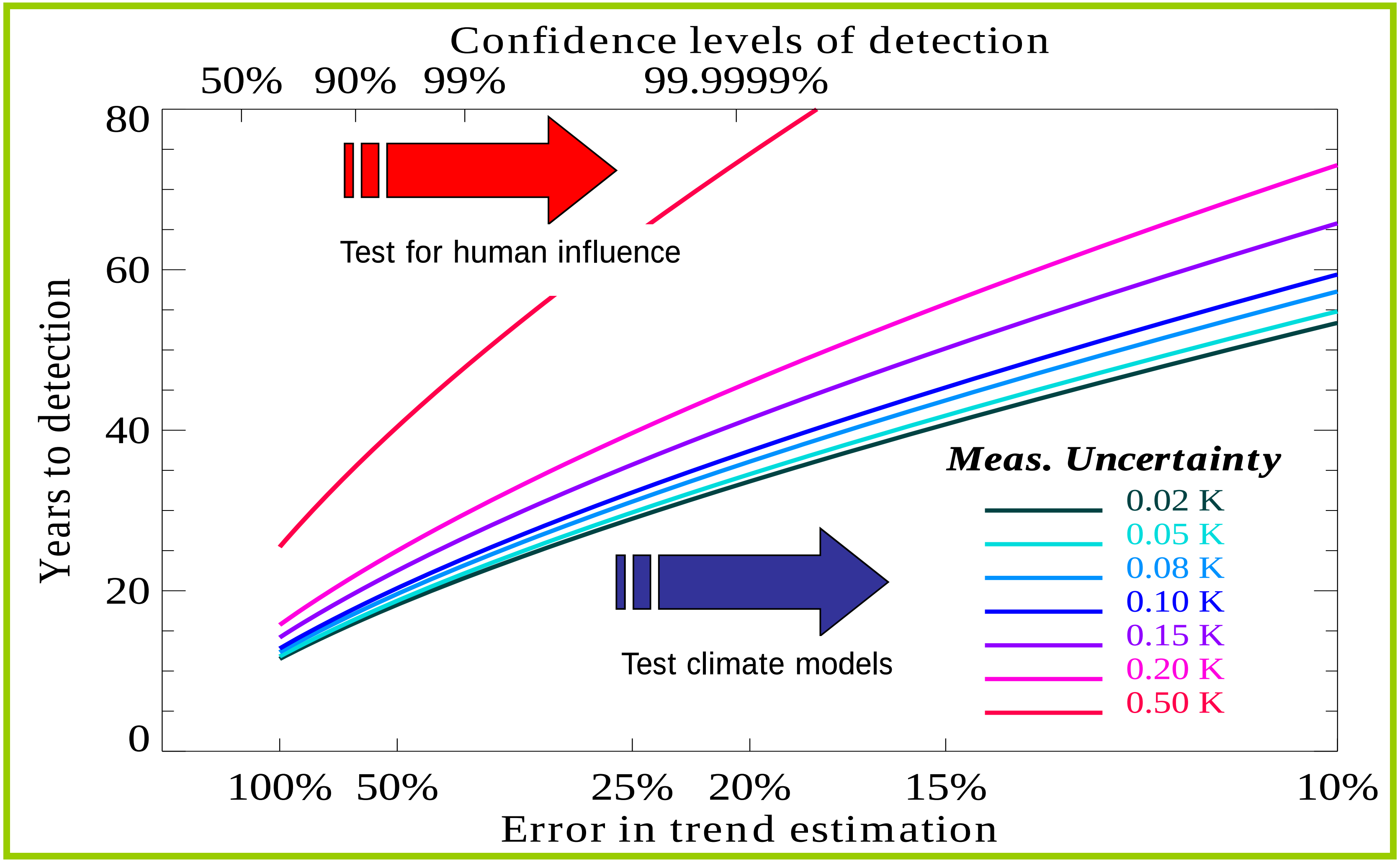
What do good measurements get us?

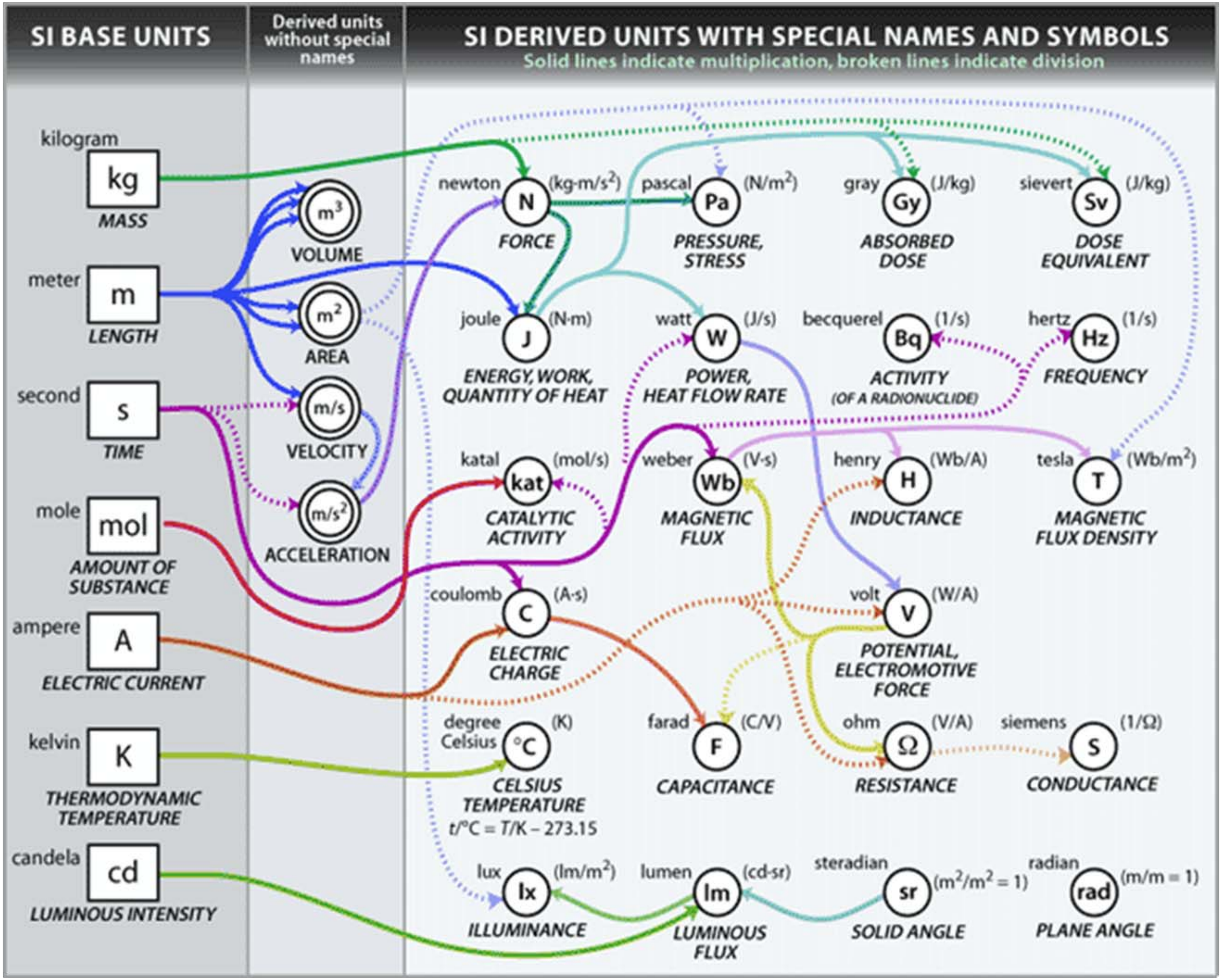
Keeling curve as an example– more sure tracking of changes.



What do good measurements get us?

Faster time to characterization of climate change, forcings, causes, etc.




SI BASE UNITS
Derived units without special names
SI DERIVED UNITS WITH SPECIAL NAMES AND SYMBOLS
Solid lines indicate multiplication, broken lines indicate division
kilogram
kg
MASS
meter
m
LENGTH
second
s
TIME
mole
mol
AMOUNT OF SUBSTANCE
ampere
A
ELECTRIC CURRENT
kelvin
K
THERMODYNAMIC TEMPERATURE
candela
cd
LUMINOUS INTENSITY
m³
VOLUME
m²
AREA
m/s
VELOCITY
m/s²
ACCELERATION
newton N (kg·m/s²) FORCE
pascal Pa (N/m²) PRESSURE, STRESS
gray Gy (J/kg) ABSORBED DOSE
sievert Sv (J/kg) DOSE EQUIVALENT
joule J (N·m) ENERGY, WORK, QUANTITY OF HEAT
watt W (J/s) POWER, HEAT FLOW RATE
becquerel Bq (1/s) ACTIVITY (OF A RADIONUCLIDE)
hertz Hz (1/s) FREQUENCY
katal kat (mol/s) CATALYTIC ACTIVITY
weber Wb (V·s) MAGNETIC FLUX
henry H (Wb/A) INDUCTANCE
tesla T (Wb/m²) MAGNETIC FLUX DENSITY
coulomb C (A·s) ELECTRIC CHARGE
volt V (W/A) POTENTIAL, ELECTROMOTIVE FORCE
degree Celsius °C (K) CELSIUS TEMPERATURE
t/°C = T/K – 273.15
farad F (C/V) CAPACITANCE
ohm Ω (V/A) RESISTANCE
siemens S (1/Ω) CONDUCTANCE
lux lx (lm/m²) ILLUMINANCE
lumen lm (cd·sr) LUMINOUS FLUX
steradian sr (m²/m² = 1) SOLID ANGLE
radian rad (m/m = 1) PLANE ANGLE

Traceability—Foundation for Accurate Measurements

Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties (VIM, 6.10)

and defensible!

Based on the "SI"
International System of Units

NIST facilities/capabilities

Presented:

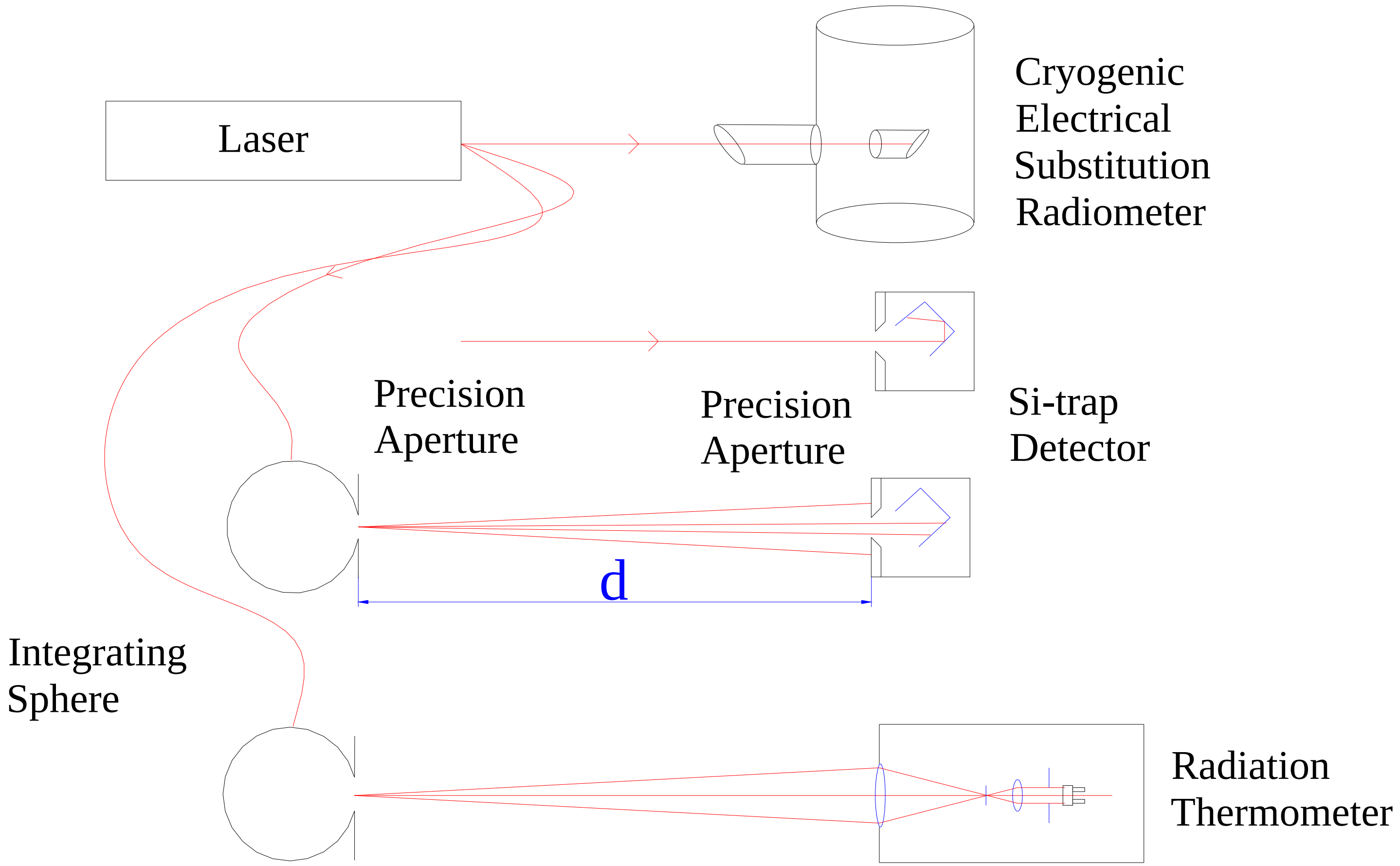
POWR	Primary Optical Watt Radiometer
SIRCUS	Spectral Irradiance & Radiance Calibration using Uniform Sources
AAMM	Aperture Area Measuring Machine
HIP	Hyperspectral Imaging Projector
CBS3	Controlled-Background System for Spectroradiometry and Spectrophotometry

Not presented:

LBIR	Low-Background Infrared Radiometry
RSL	Remote-Sensing Laboratory
R2T	Radiance & Radiance Temp., replacing FASCAL, FASCAL2, Heat Flux Facility
STARR	BRDF facility
IR BRDF	Infrared BRDF Facility
CHILR	For measuring IR reflectance
TXR	Thermal transfer radiometer

Example of a short traceability chain:

Detector-based temperature realization in SIRCUS

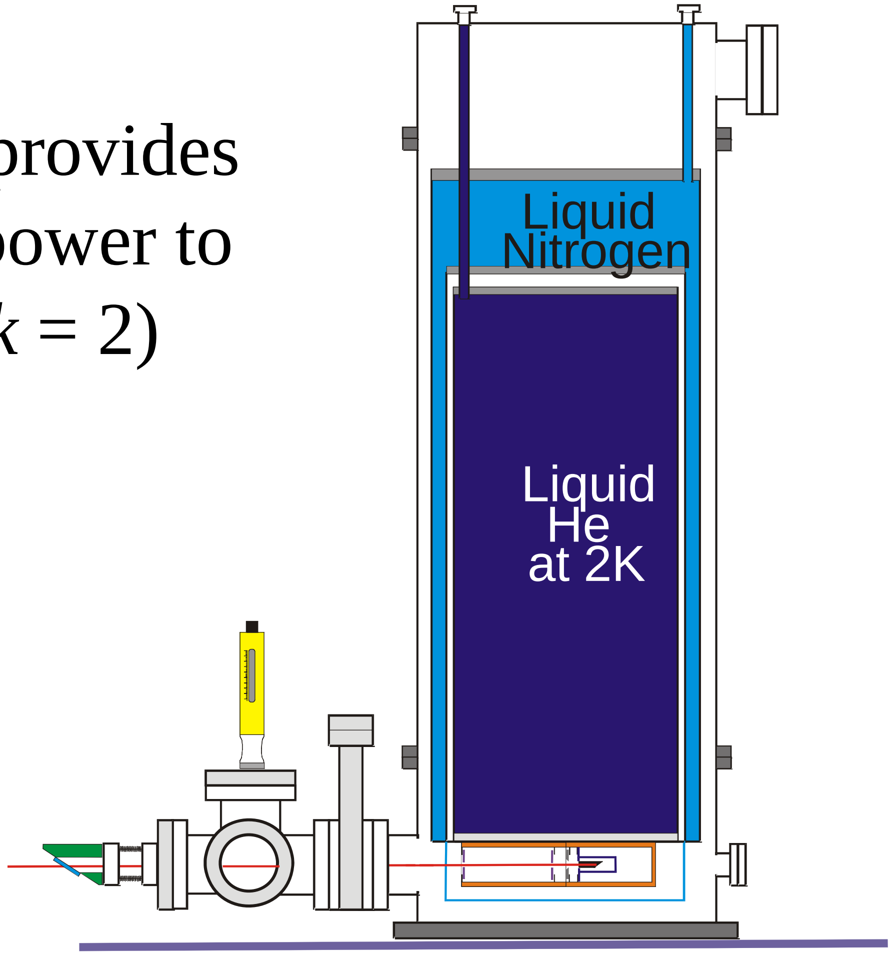


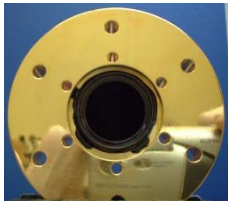
$$L(\lambda,T)=\frac{c_{1L}}{n^2\lambda^5\left(\exp\left(\frac{hc}{n\lambda kT}\right)-1\right)}$$

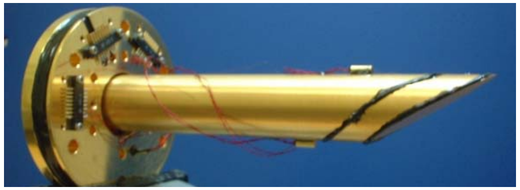
→ Realization, dissemination of temperature scales above Ag freezing point

NIST Optical Measurements are Traceable to the Electrical Watt through the Primary Optical Watt Radiometer (POWR)

- POWR provides optical power to 0.01% ($k = 2$)

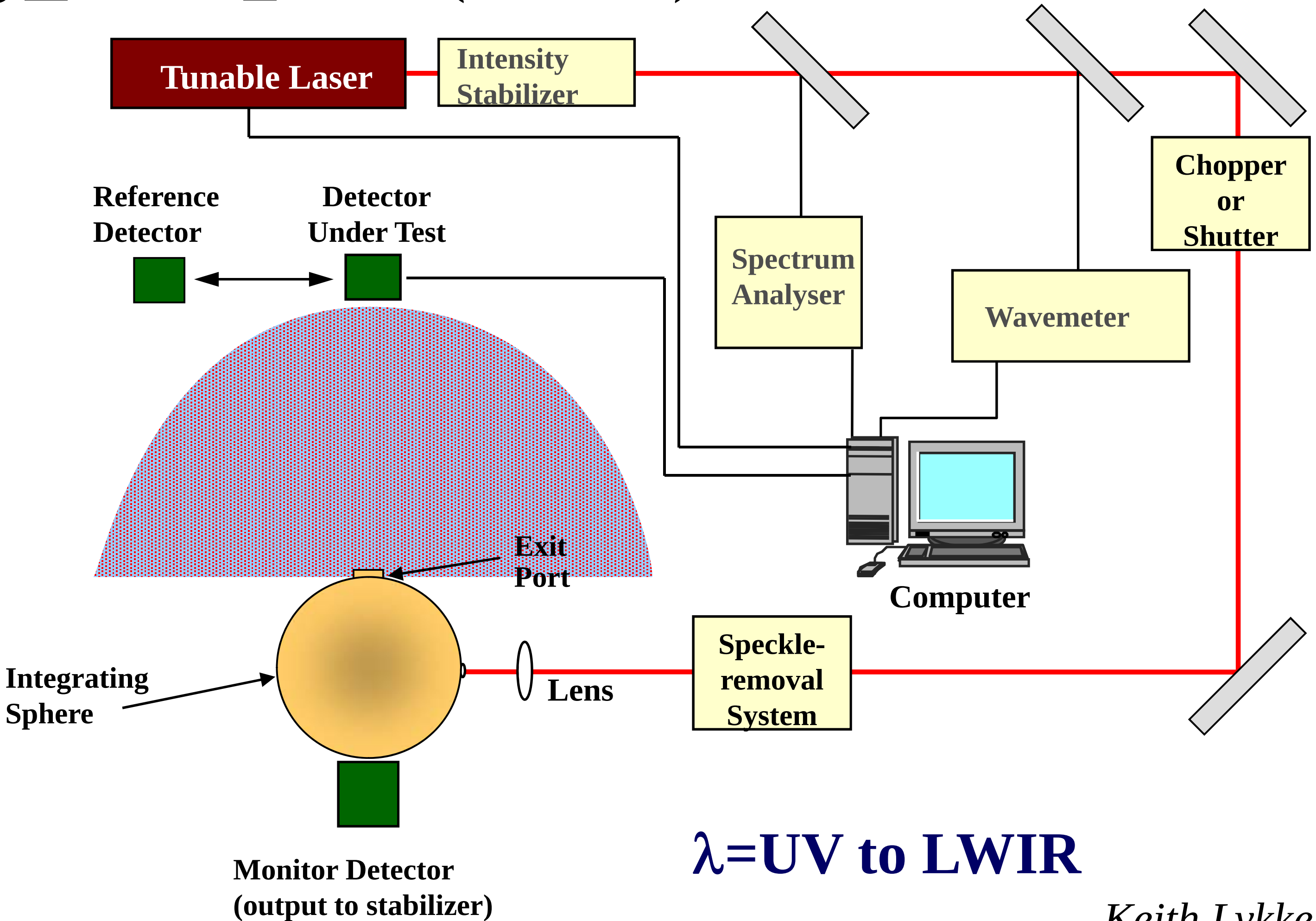






Jeanne Houston
Joe Rice

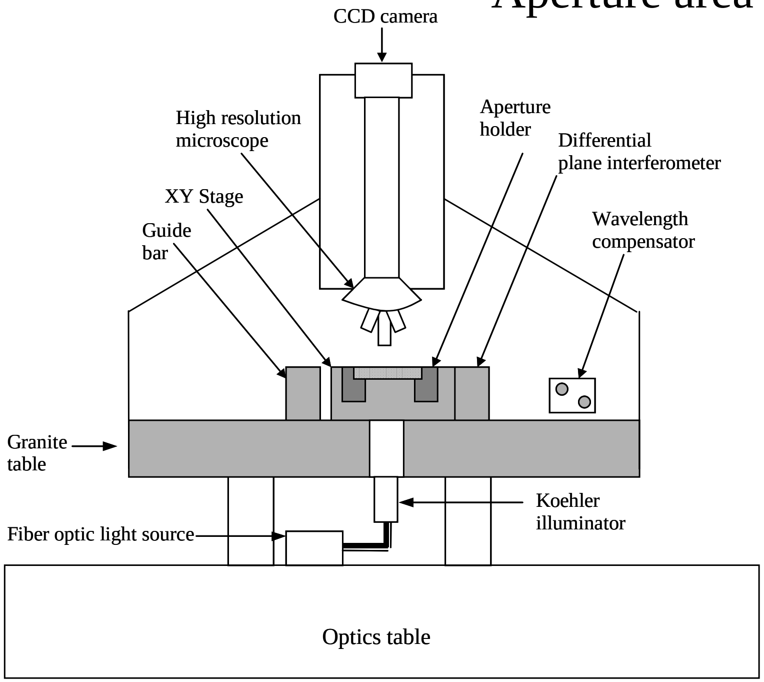
Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS)



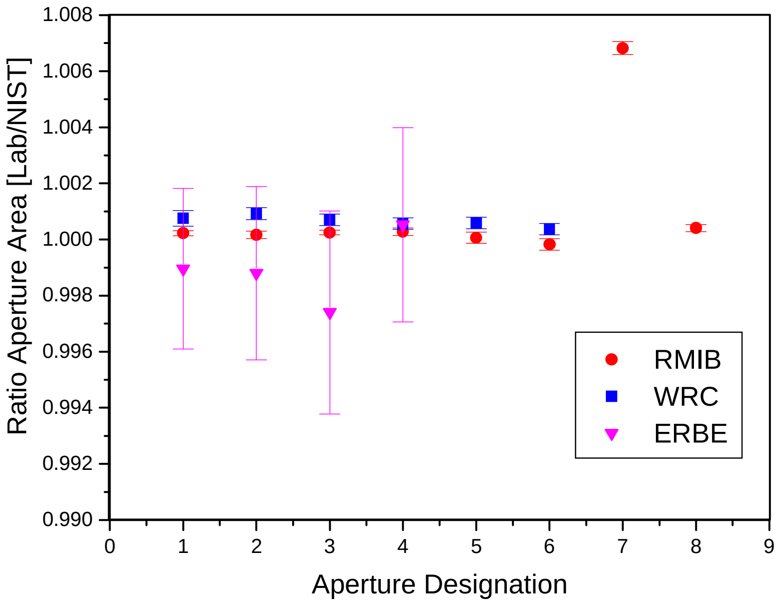
λ=UV to LWIR

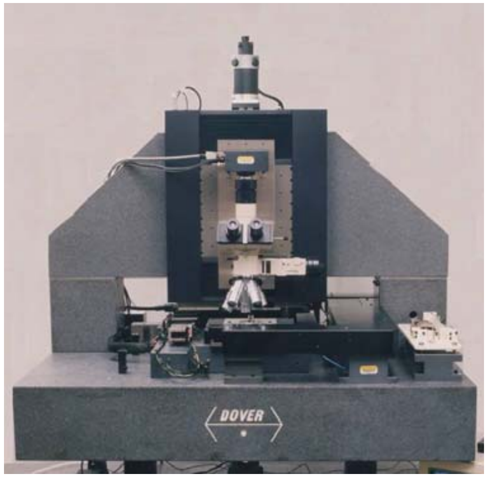
Keith Lykke
Steve Brown
George Eppeldauer

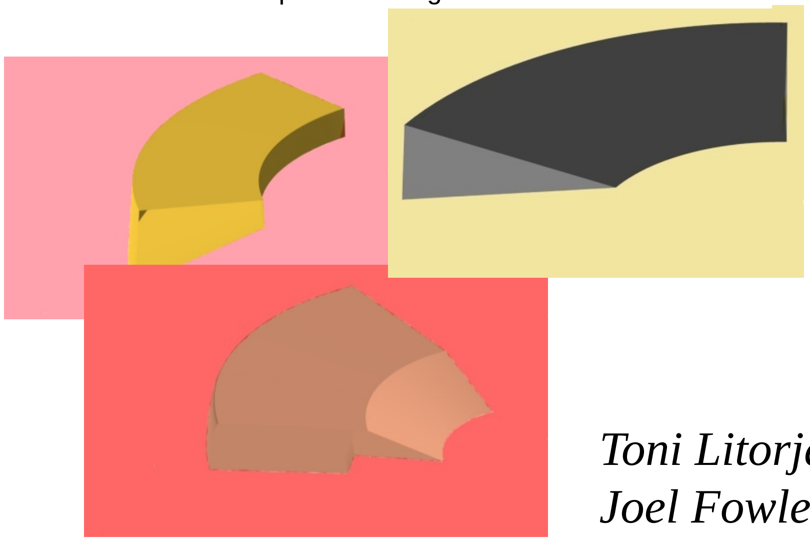
…and to the Meter through Aperture Area Measurements Performed by the Absolute Aperture Area Measurement Machine…



Aperture area to better than 0.01%



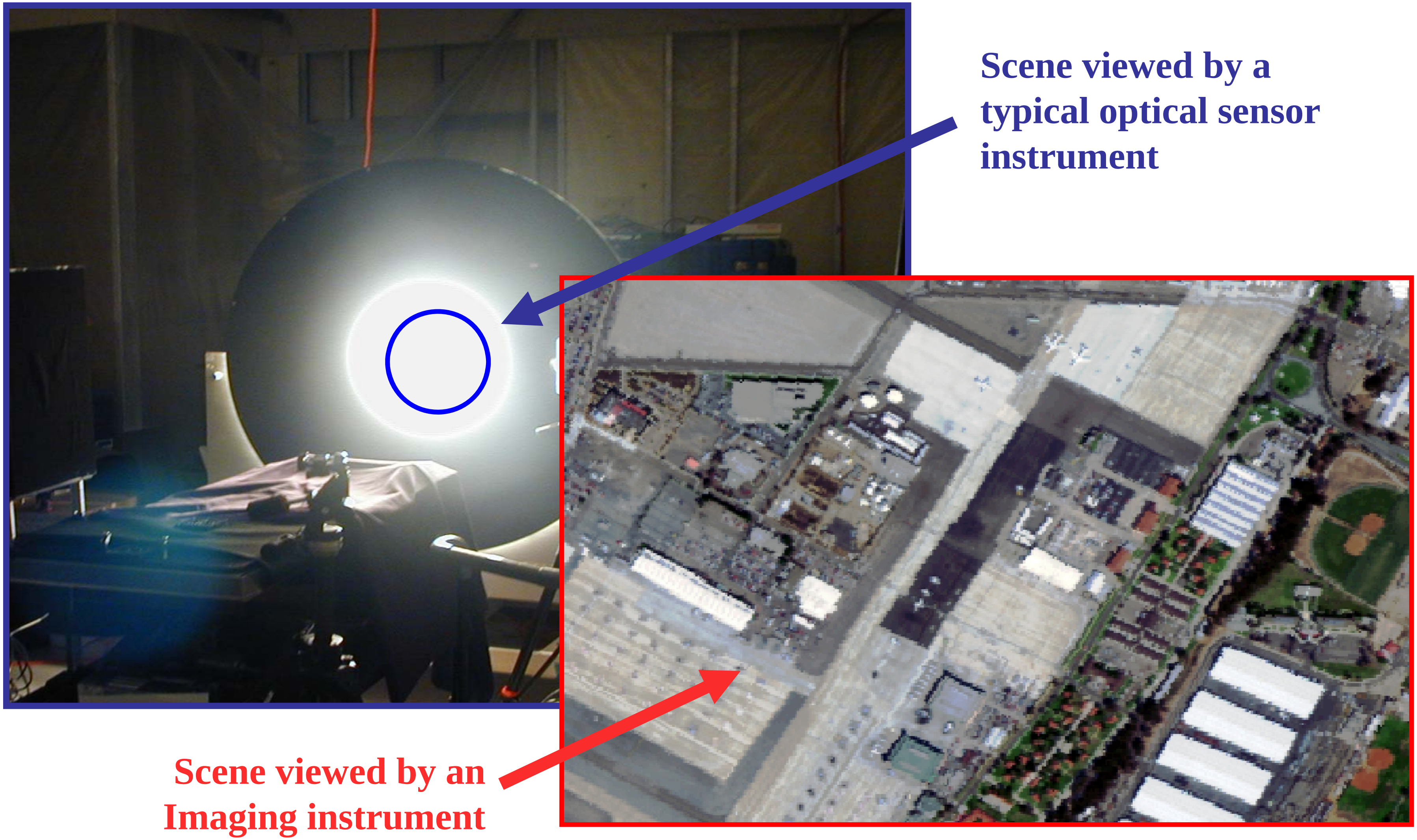




Toni Litorja
Joel Fowler

Hyperspectral Imaging Projector (HIP)

Consider the complexity of real-world scenes:

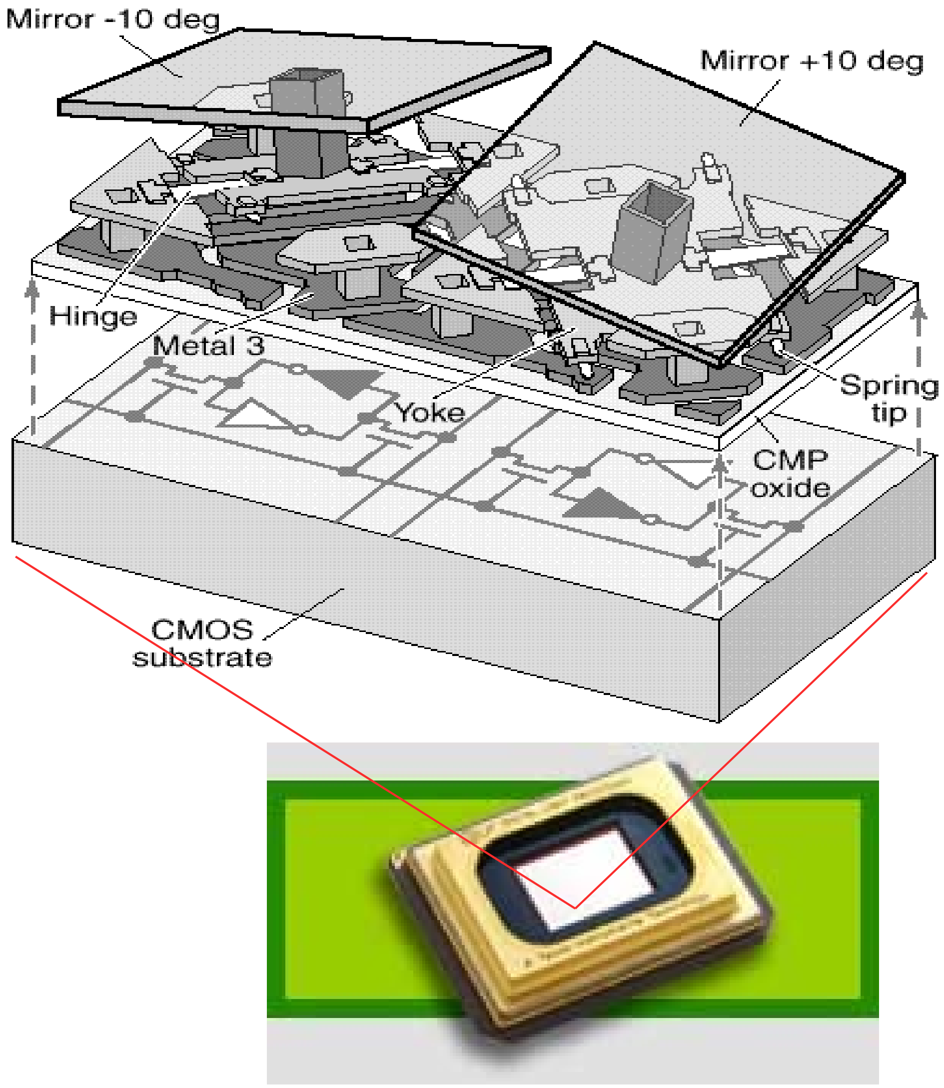


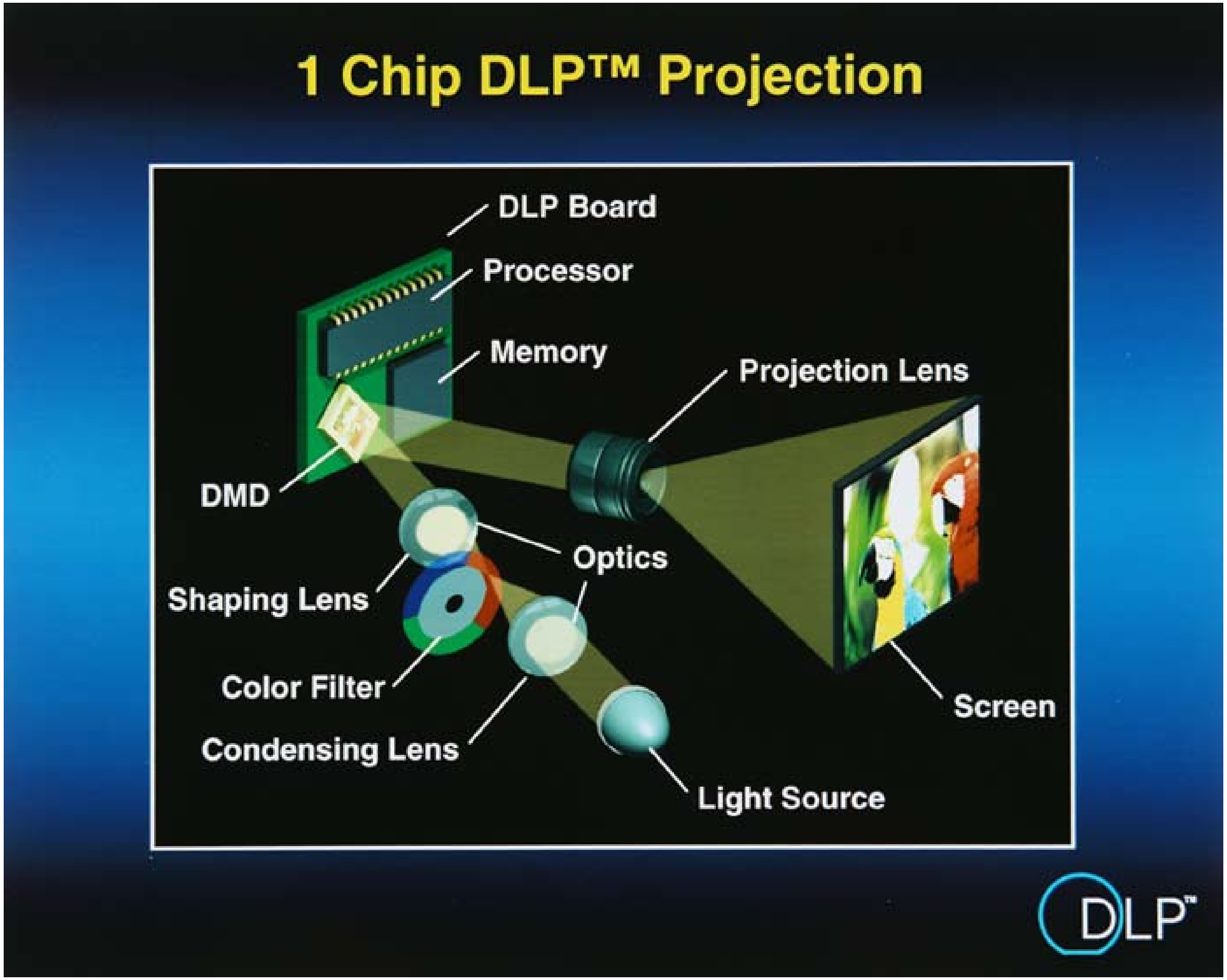
Scene viewed by a typical optical sensor instrument

Scene viewed by an Imaging instrument In practice

Digital Micromirror Device (DMD)

- **An array of MEMS micromirror elements**
- **Commercially available:**
  - 1024 x 768 elements
  - Aluminum mirrors
  - 13.7 micron pitch
- **For visible to 2500 nm applications:**
  commercially available hardware
- **For longer wavelength infrared developments we are using DMDs where the glass window is replaced by a ZnSe window.**
- **Control algorithms are being written using everyday control software for everyday hardware interfaces and operating systems.**




1 Chip DLP™ Projection
DLP Board
Processor
Memory
Projection Lens
DMD
Optics
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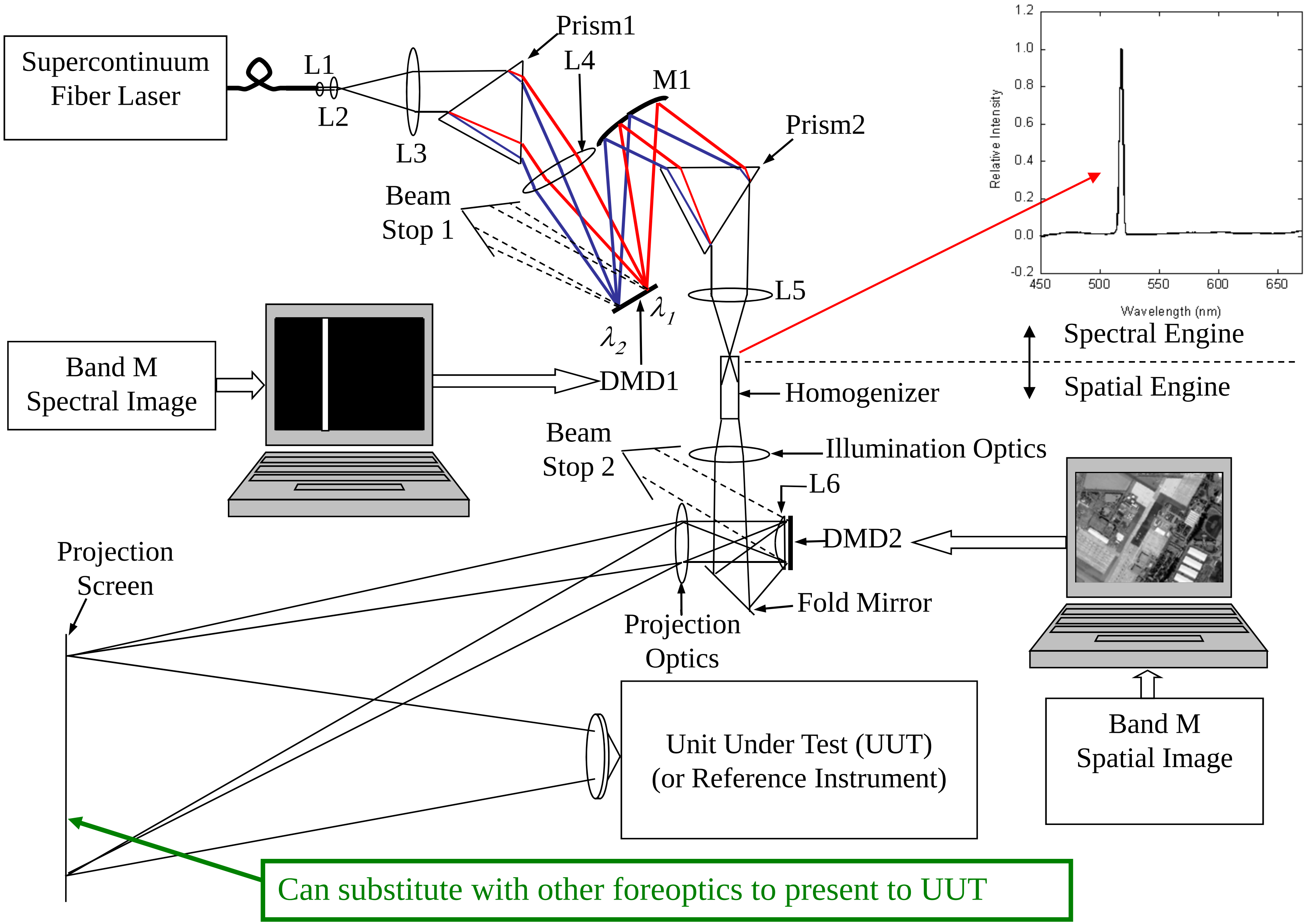
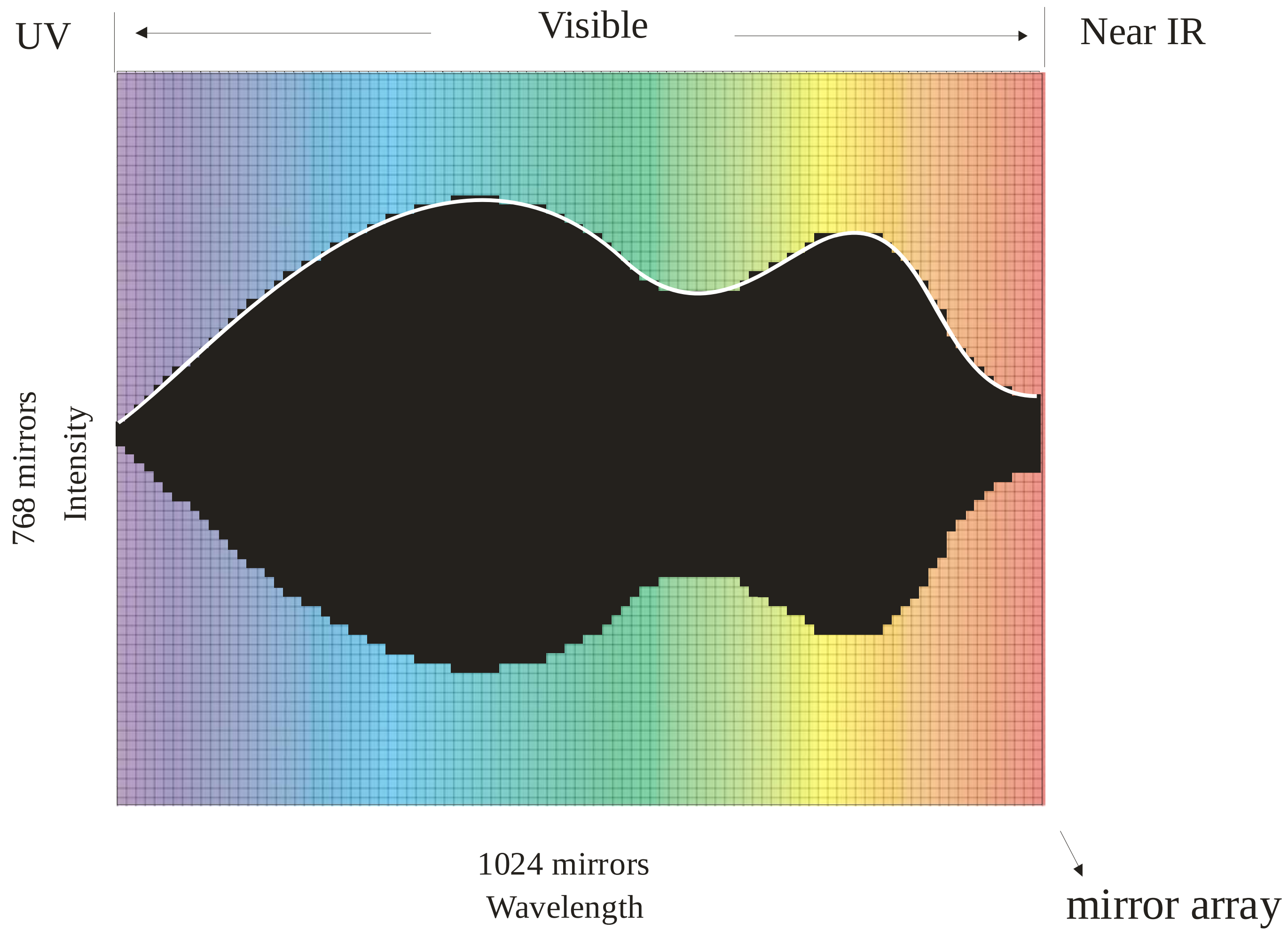
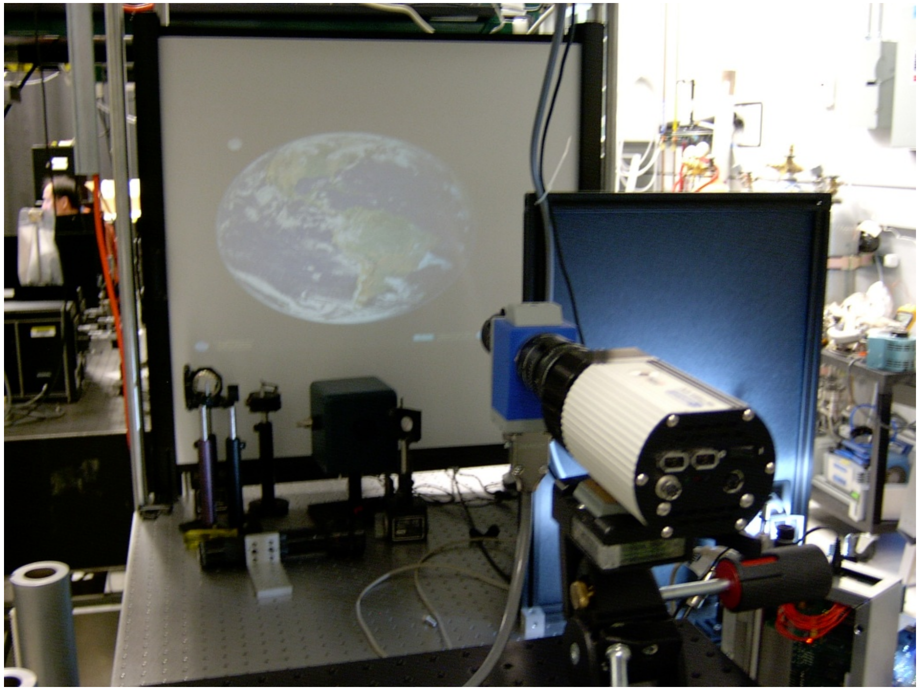


Supercontinuum Fiber Laser
L1
L2
L3
Prism1
L4
M1
Prism2
Beam Stop 1
λ1
λ2
DMD1
L5
Band M Spectral Image
Relative Intensity
Wavelength (nm)
Spectral Engine
Spatial Engine
Homogenizer
Beam Stop 2
Illumination Optics
L6
DMD2
Fold Mirror
Projection Optics
Projection Screen
Unit Under Test (UUT) (or Reference Instrument)
Band M Spatial Image
Can substitute with other foreoptics to present to UUT

How the DMD is used to create an arbitrarily programmable spectrum



Example image as projected by the prototype HIP onto a white screen and taken using a digital camera



Relation of Different Components of the Effort Aimed at Establishing of the Thermal and Far IR Spectral Radiance Scales

Thermal and Far IR Spectral Radiance Scale Realization and Validation

CAVITY EMISSIVITY MEASUREMENT VIA REFLECTOMETRY

Assumptions:
- T distribution is uniform
- Measurement geometry identical to the use

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

CAVITY EMISSIVITY MONTE - CARLO MODELING

Assumptions:
- T distribution is uniform or known
- Coating is uniform

Software	*Input Property Required*	*Facility*	*Method:*
STEEP3.15	Paint Emittance	NIST Emittance PTB Emittance	Direct (above 100 C only)
		NIST FIRES PTB RBCF	Black sphere reflectometer
Future Code (to be written)	Paint BRDF	NIST CHILR (24 um) PTB (FIR)	IR Gonio Synchrotron

Step 1. Realization

Effective Emissivity **Temperature**

Planck Equation

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

THERMOMETRY

Assumptions:
- Temperature distribution across the cavity is uniform or well known
- Thermowell (or crucible) temperature is equal to that of a cavity surface, or an offset can be calculated

Facility	*Implementation:*
CBS3	- PRT sensors - Surrounding or embedded phase transition cells

Step 2. 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)	- Comparison via Transfer Standard Blackbody Source

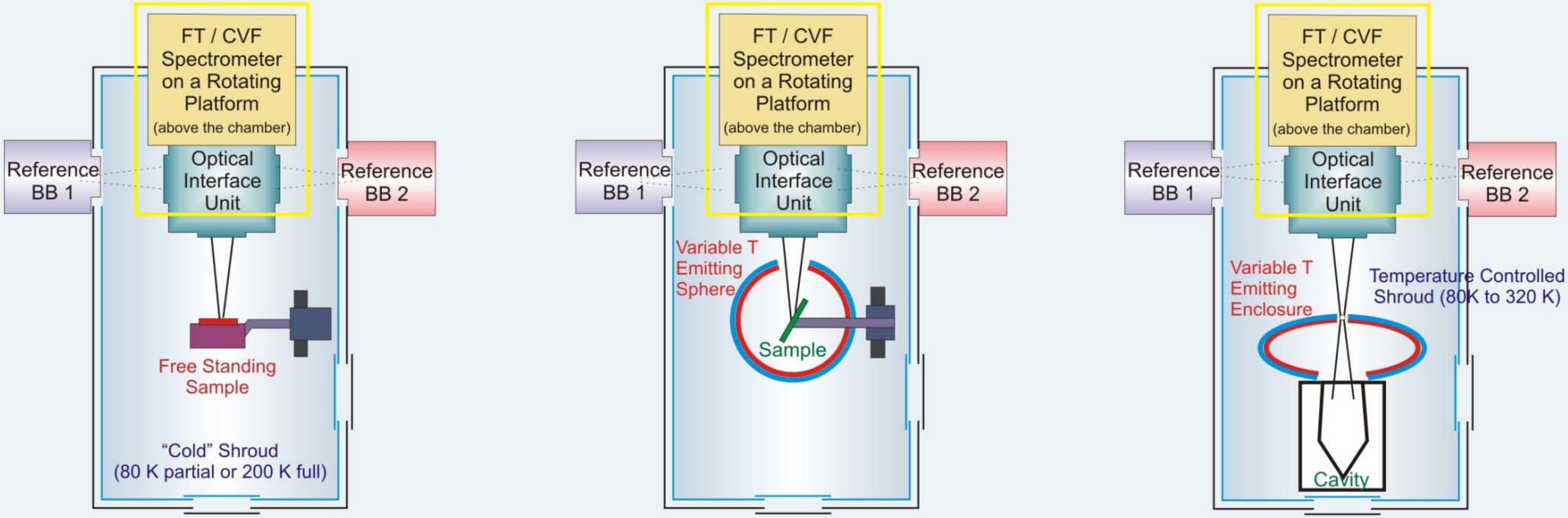
Support includes Spectral Radiance Realization (1), Validation (2) , and Transfer (3) Steps. The Transfer Step (not shown) includes calibration of the CLARREO Transfer Standard BB

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

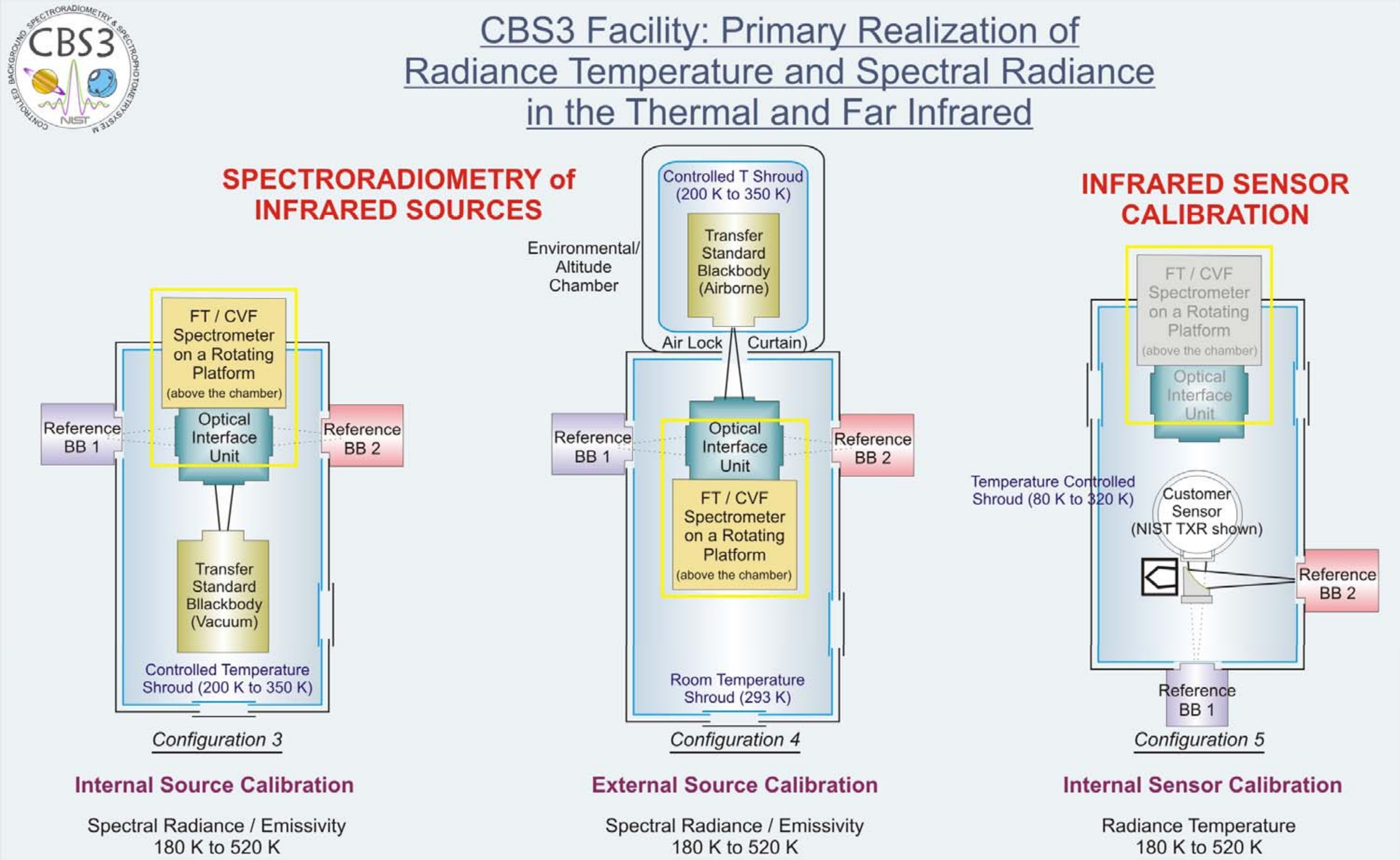
Works best for: Cold grey targets

Configuration 3

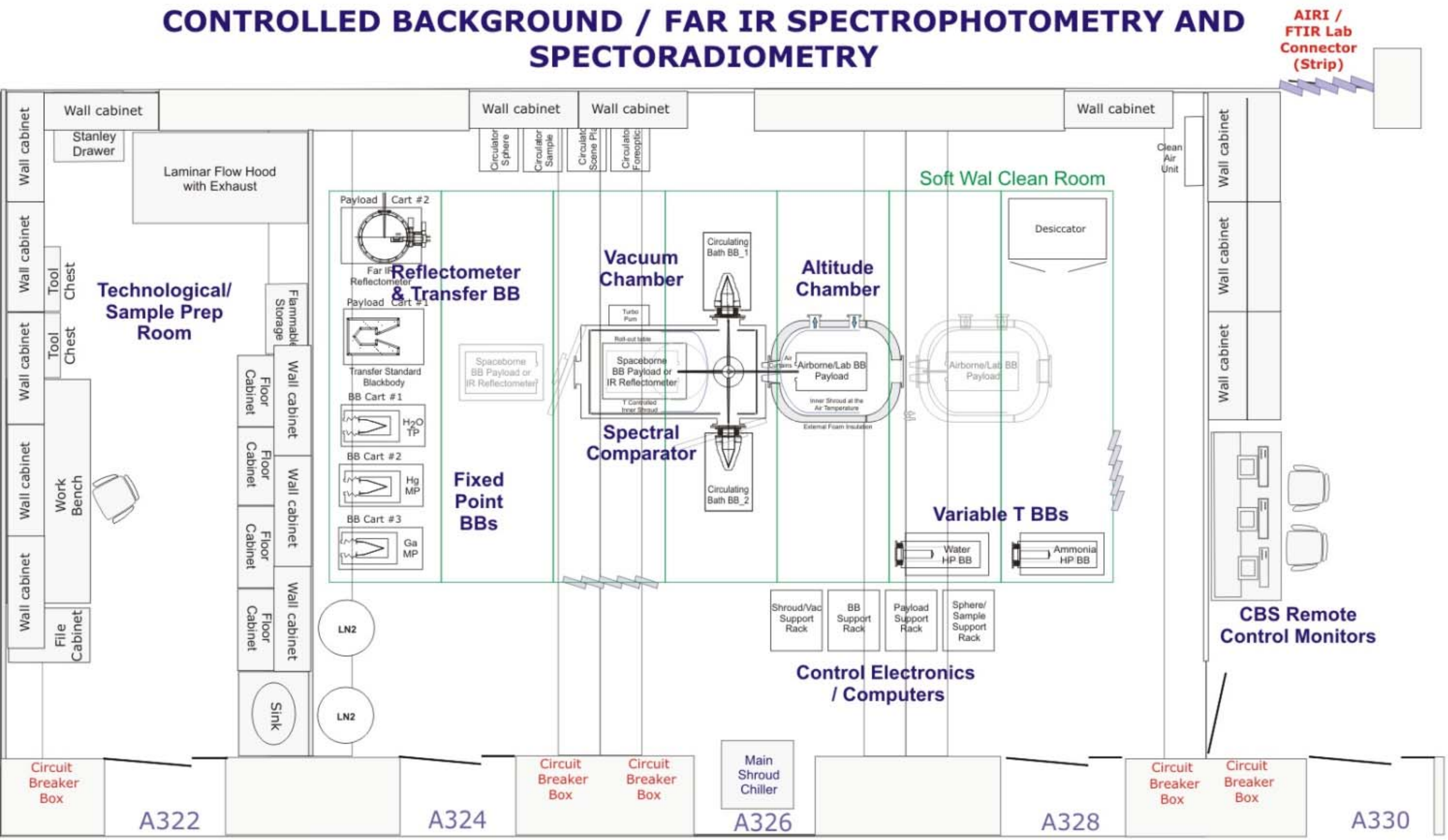
Cavity Reflectometry in Mid/Far IR

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

Radiance Temperature Modes of CBS3

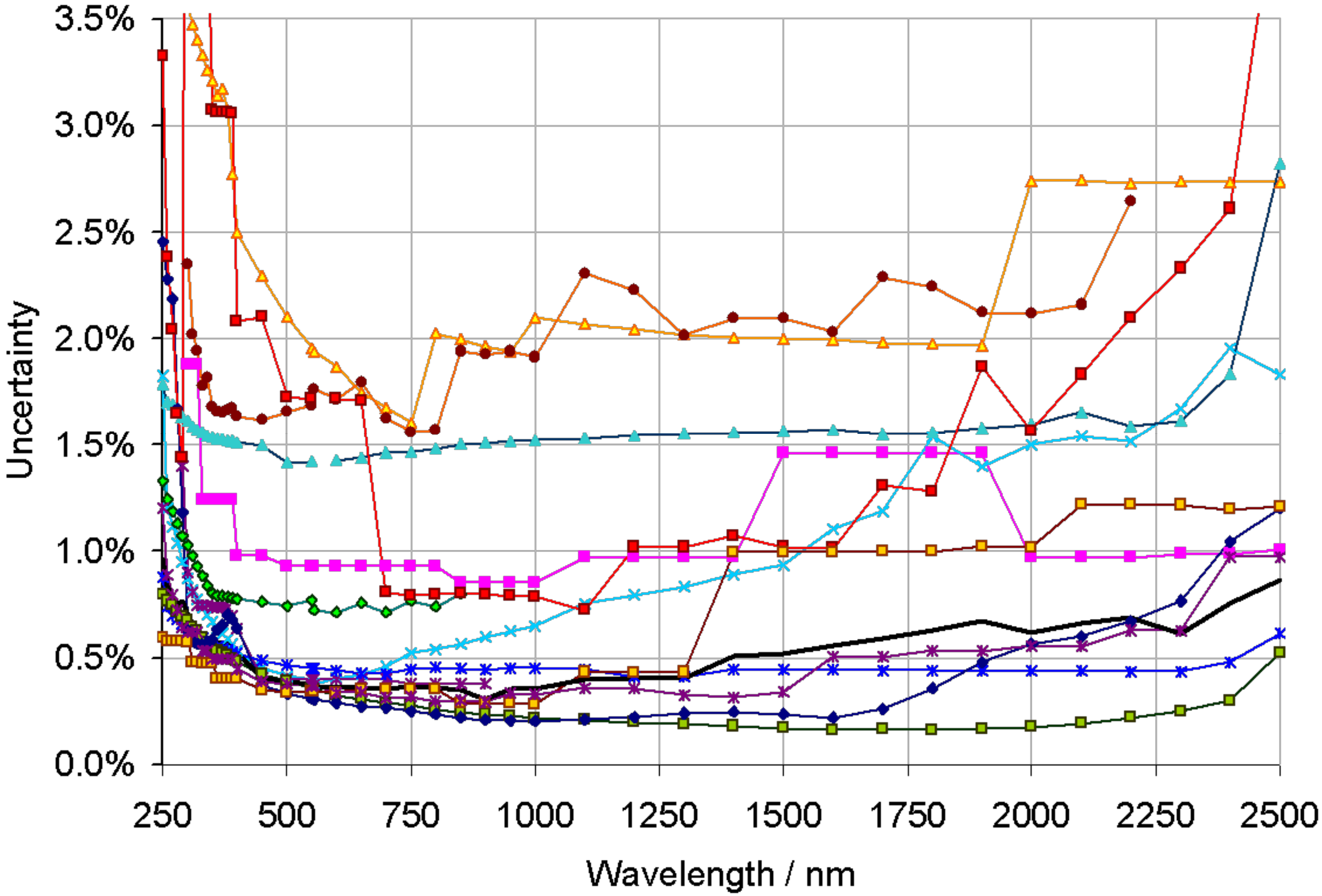


CBS3 System Lab Space



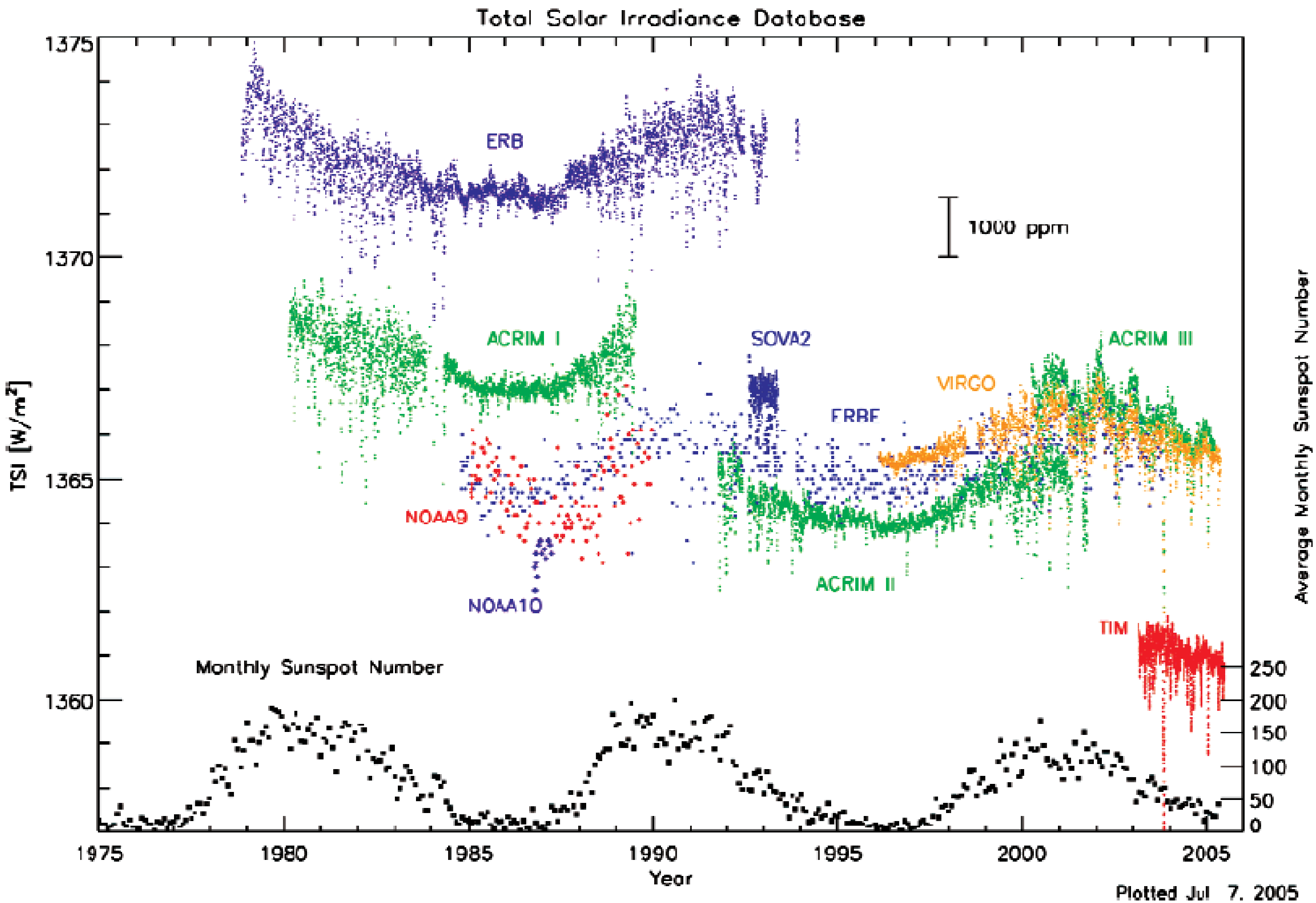
Validity of NMI measurements: uncertainties stem from

- Intercomparisons between NMIs (and other entities)
- NMI participation in the open scientific literature



Are we *there* yet?

No, but we are getting closer (e.g., it is desirable to be able to measure a 200 ppm decadal variability of TSI).



Closing Remarks

Robust Uncertainties

- Documented
- Defending measurements' validity
- Assigning quantitative significances to measurements
- In principle, helpful for inter-calibration analysis
- Can be amended in retrospect (if documented!)

For On-orbit Measurements

- On-board calibration systems
- Multiple & redundant methods of indefinite instrument calibration, validation
- "Self-calibrating instruments" concept

NIST is willing to work, along with the wider scientific community, to support measurements relevant to climate.