Passive Microwave Radiometric Calibration: Design and Hardware Issues

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Preamble

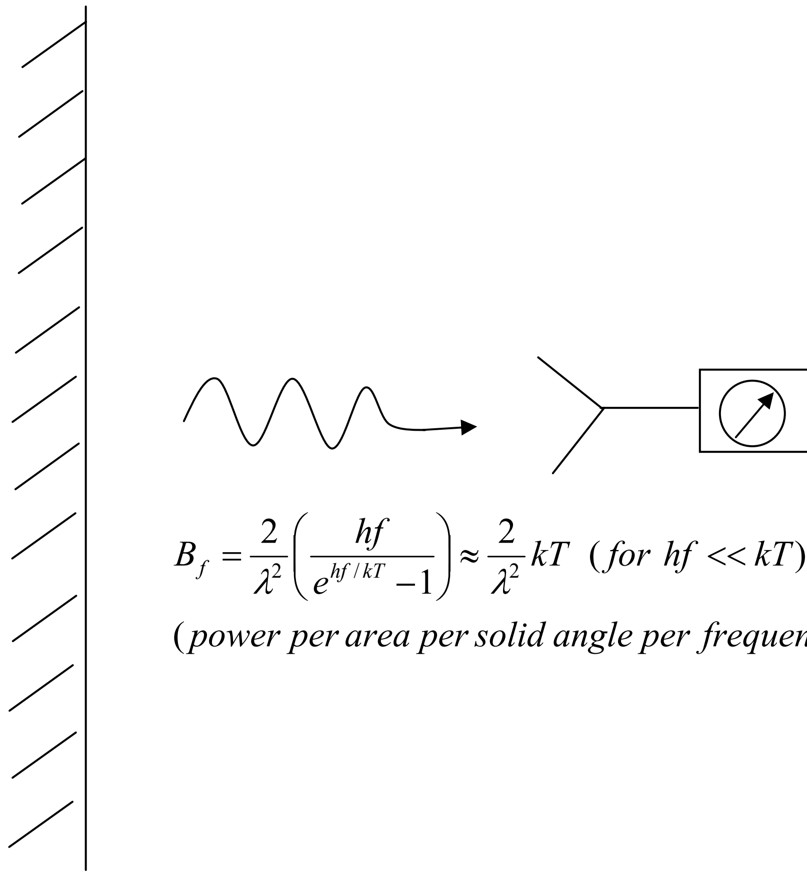
- NIST researchers: Jim Randa, Amanda Cox, Rob Billinger, George Free, Katie MacReynolds, Jeff Guerreri, Ron Whitmann
- MSU-specific issues difficult to quantify due to lack of design/test information, so this talk is generic for passive microwave radiometers (MSU-like instruments)

Motivation

- ASIC^3 summary emphasizes need for stds.
- SI Traceability (BIPM, 1998; CGPM, 1995)
- No national standards exist for μW T_B at NIST or any other NMI (China close, though)
  - "traceability" usually established thru calibrated PRT's in a non-ambient μW calibration target
- …in contrast to Vis/IR
  - NIST Physics Lab (& other institutions)

- Microwave remote sensing, ideal case:

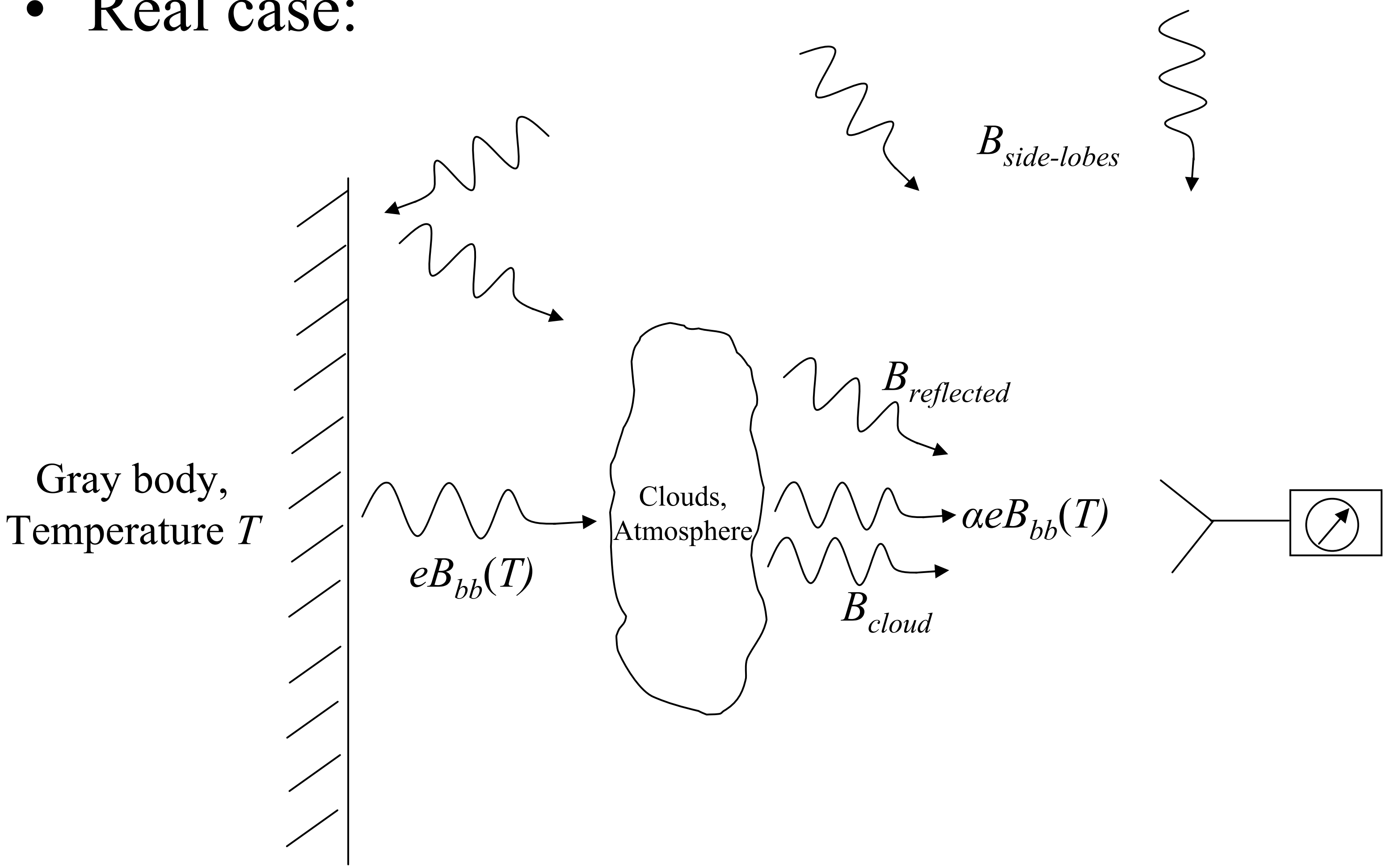
Black body,
Temperature *T*



$$B_f = \frac{2}{\lambda^2}\left(\frac{hf}{e^{hf/kT}-1}\right) \approx \frac{2}{\lambda^2}kT \quad (for\ hf << kT)$$

(*power per area per solid angle per frequency*)

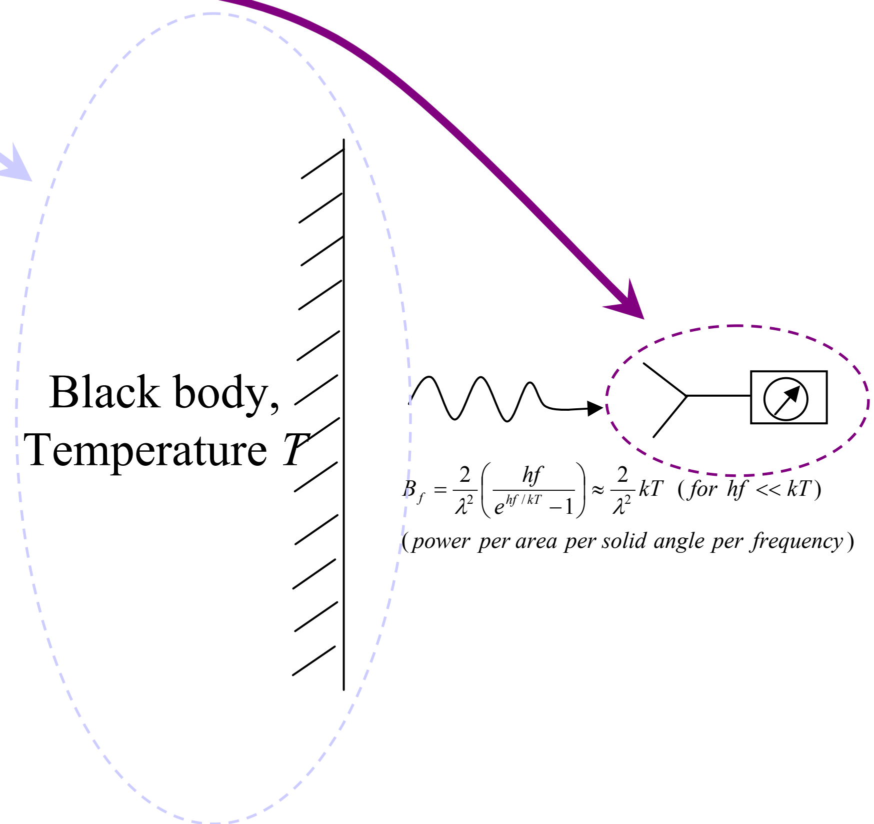
- Real case:



$B_{side\text{-}lobes}$
$B_{reflected}$
Gray body,
Temperature T
Clouds,
Atmosphere
$eB_{bb}(T)$
$\alpha eB_{bb}(T)$
B_{cloud}

- Calibration
  - linear radiometers $\Rightarrow$ need ($\geq$) two standards for calibration
  - need independent cal of targets, comparison to other radiometers, traceability
- Develop (& transfer) a standard for microwave brightness temperature
- Still in early stages, but some progress made

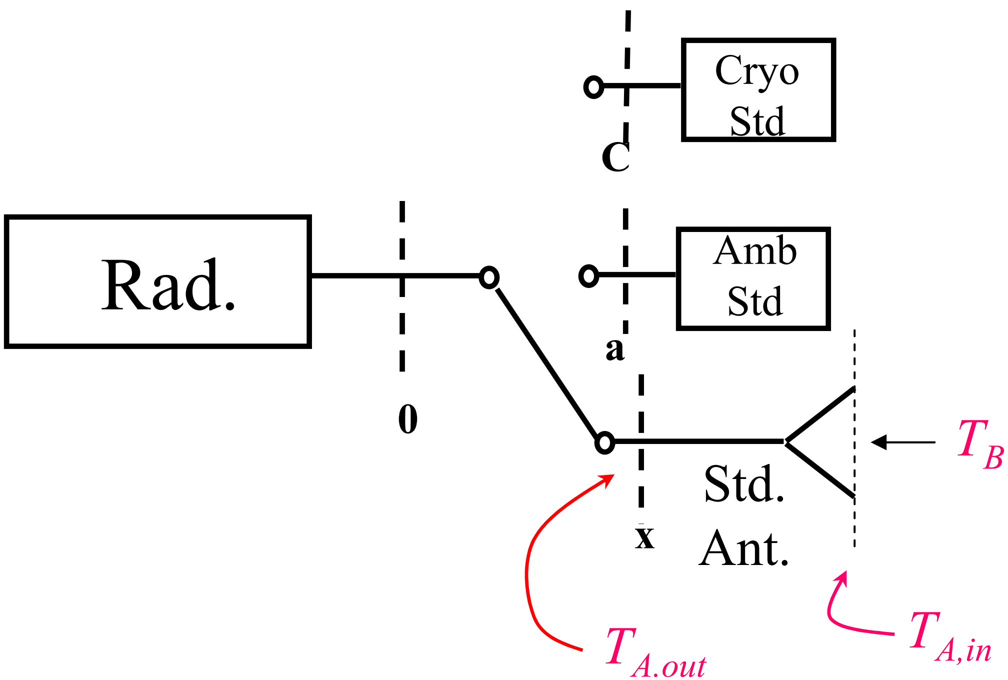
- Two approaches to brightness-temperature standard:
  - Standard radiometer
  - Standard target



- We have worked on both approaches.

Standard Radiometer

- Radiometer measures $T_{A,out}$; want to determine T_B (assume far field conditions)



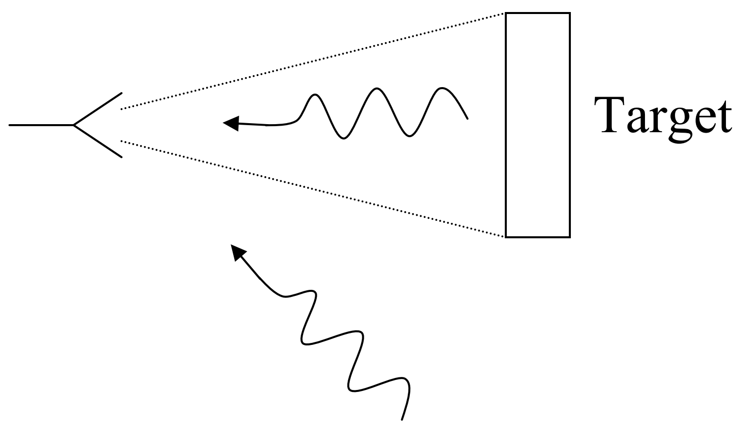
$$T_{A,out} = \alpha T_{A,in} + (1-\alpha)T_a$$

$$T_B(\theta,\phi) \equiv \frac{\lambda^2 B_f(\theta,\phi)}{2k}$$

$$T_{A,in} = \frac{\int_{4\pi} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\Omega_p}$$

$$\Omega_p = \int_{4\pi} F_n(\theta,\phi) d\Omega$$

- Break up $T_{A,in}$:



$$\overline{T_T} = \frac{\int_{\text{target}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\int_{\text{target}} F_n(\theta,\phi) d\Omega}$$

$$\overline{T_{BG}} = \frac{\int_{\text{other}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\int_{\text{other}} F_n(\theta,\phi) d\Omega} \quad .$$

$$\eta_{AT} \equiv \frac{\int_{\text{target}} F_n(\theta,\phi) d\Omega}{\Omega_p}$$

$$T_{A,in} = \eta_{AT} \overline{T_T} + (1-\eta_{AT}) \overline{T_{BG}}$$

- So,

$$T_{A,out} = \alpha\eta_{AT}\overline{T}_T + \alpha(1-\eta_{AT})\overline{T}_{BG} + (1-\alpha)T_a$$

- Control the background, $\overline{T}_{BG} = T_a$
- Then

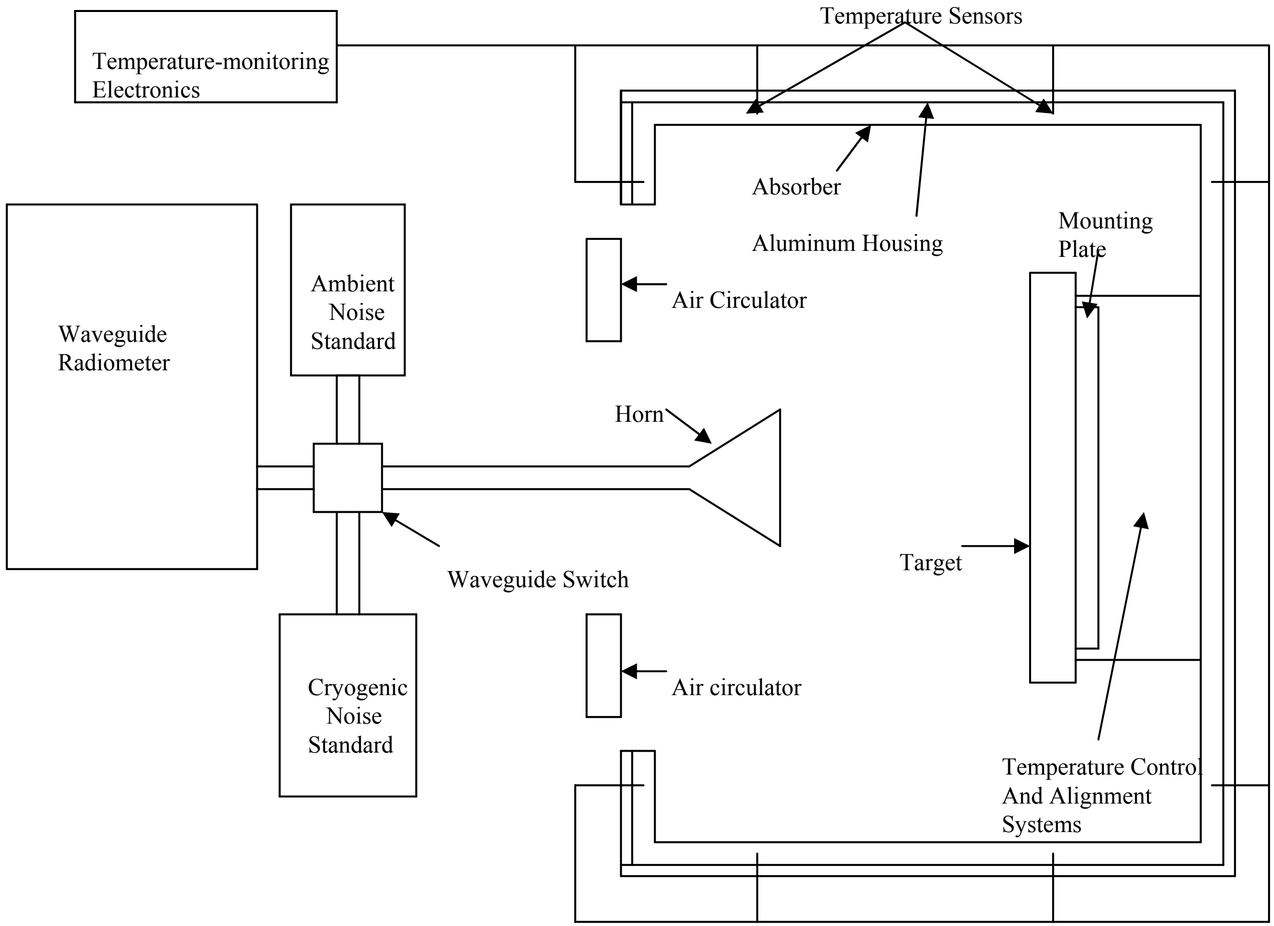
$$\overline{T_T} = T_a + \frac{1}{\alpha\eta_{AT}}\left(T_{A,out} - T_a\right)$$

- So we need $\alpha \approx 1/L$ and η_{AT}

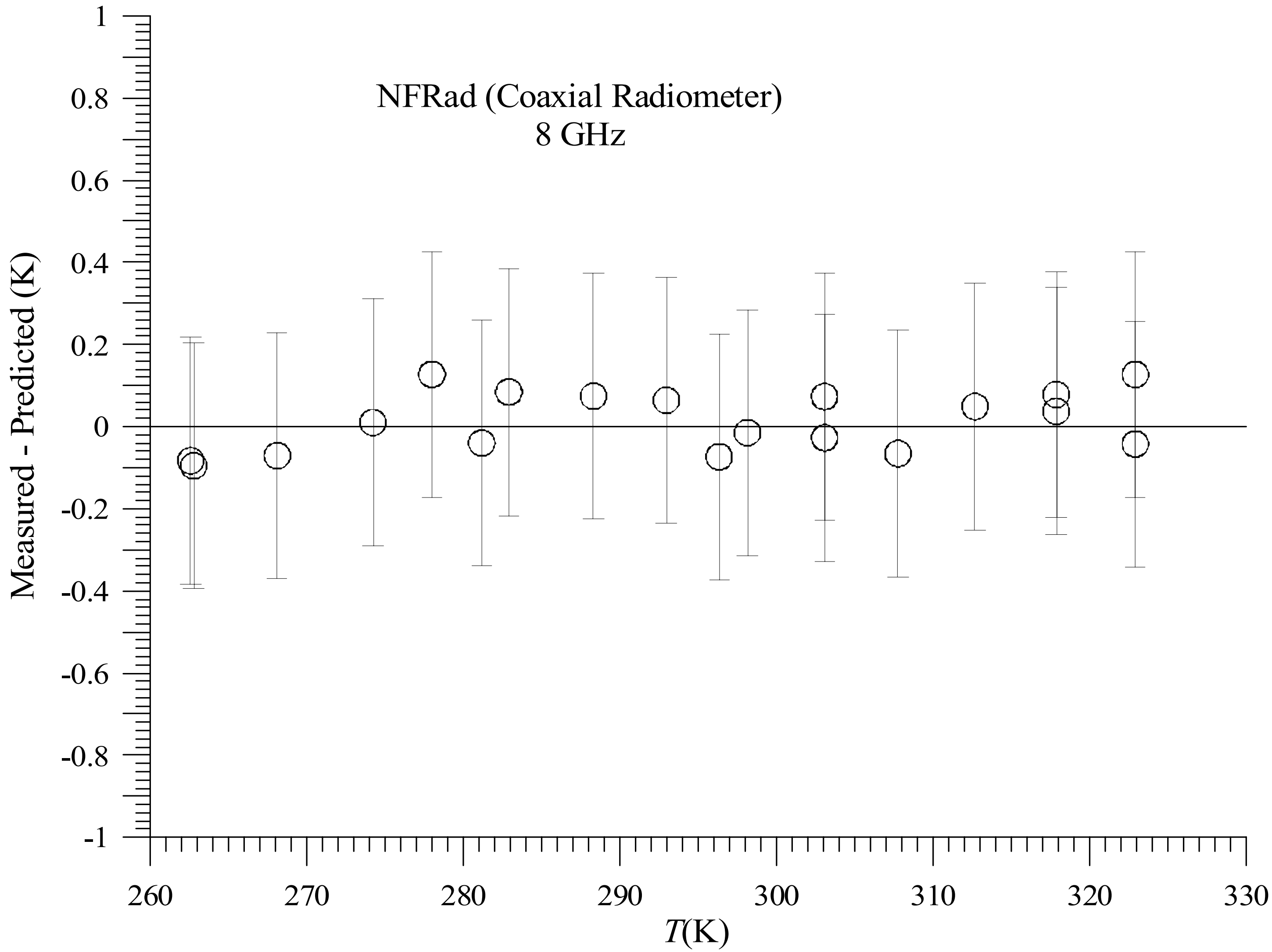
$$\eta_{AT} \equiv \frac{\int_{\text{target}} F_n(\theta,\phi)d\Omega}{\Omega_p}$$

- Environment
  - not thermal-vac
  - must control $$\overline{T_{SL}} = \frac{\int_{other} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\int_{other} F_n(\theta,\phi) d\Omega} \quad .$$
  - Do so by controlling/knowing T_B in the side lobes.

- Will need a chamber to control background



Noise measurements near ambient



- Approximate achievable uncertainties:

$$u^2(\overline{T}_T) = \left(1 - \frac{1}{\alpha\eta_{AT}}\right)^2 u^2(T_a) + \left(\frac{1}{\alpha\eta_{AT}}\right)^2 u^2(T_{A,out}) + (\overline{T}_T - T_a)^2 \left(\frac{u^2(\eta_{AT})}{\eta_{AT}^2} + \frac{u^2(\alpha)}{\alpha^2}\right)$$

$u(T_a) \approx 0.2$ K
$u(T_{A,out}) \approx 0.3 - 0.5$ K (for $T_{A,out} = 200$ to 300 K, 18 – 26.5 GHz)
$u(\eta_{AT}) \approx 0.003$
$u(\alpha) \approx 0.005$

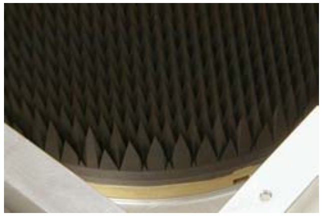
- So should be able to get

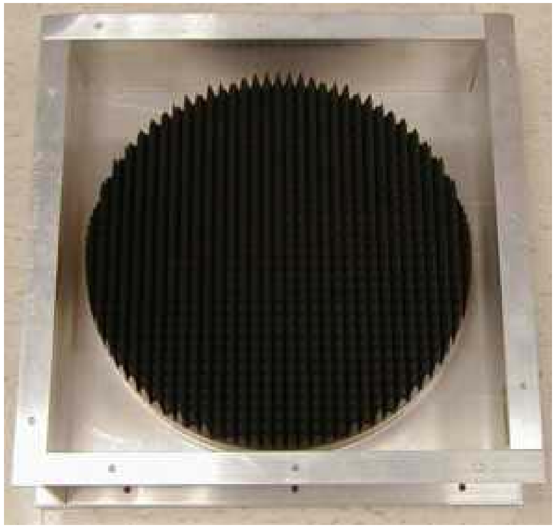
$$u(\overline{T}_T) \approx 0.3 \text{ K to } 0.7 \text{ K}$$

for $T_{A,out} = 200$ to 300 K, 18 – 26.5 GHz

Standard Target & Hybrid Standard

- Most microwave remote sensing programs use a standard target, a blackbody radiator.



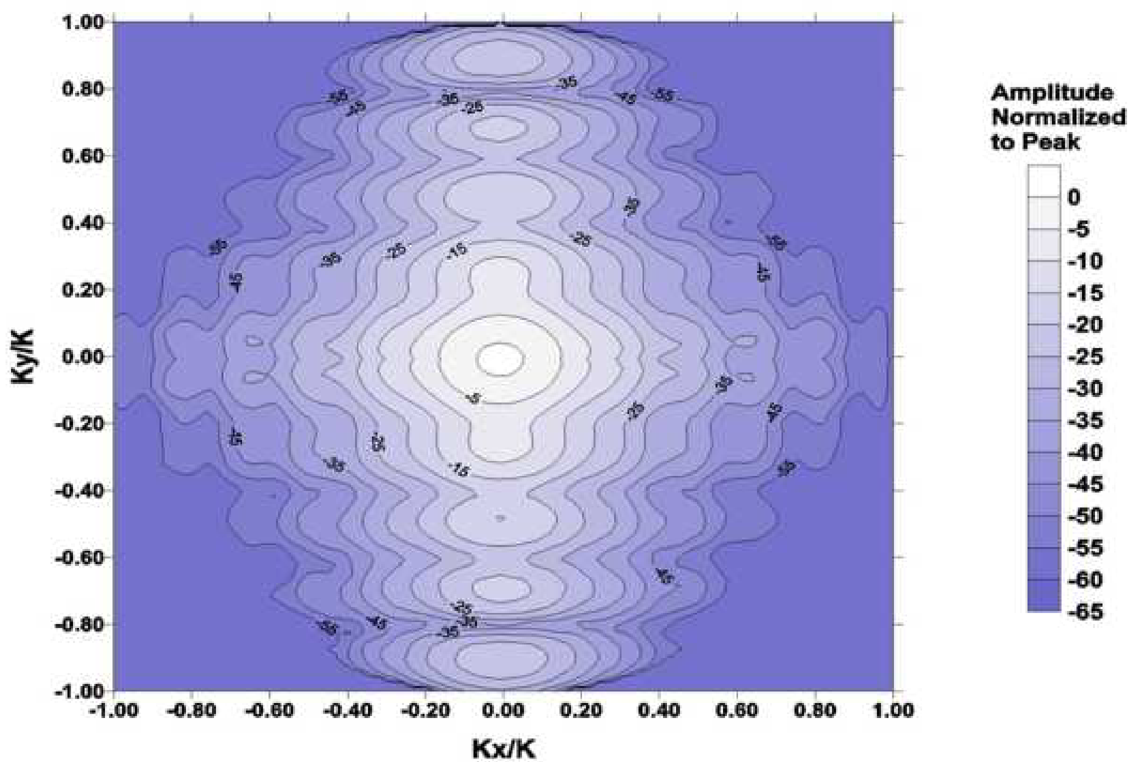


- Need to know
  - surface temperature and uniformity (thermometers embedded at a few locations in *back* of target)
  - emissivity (no generally accepted standard measurement method)
  - pattern (or near-field effects)

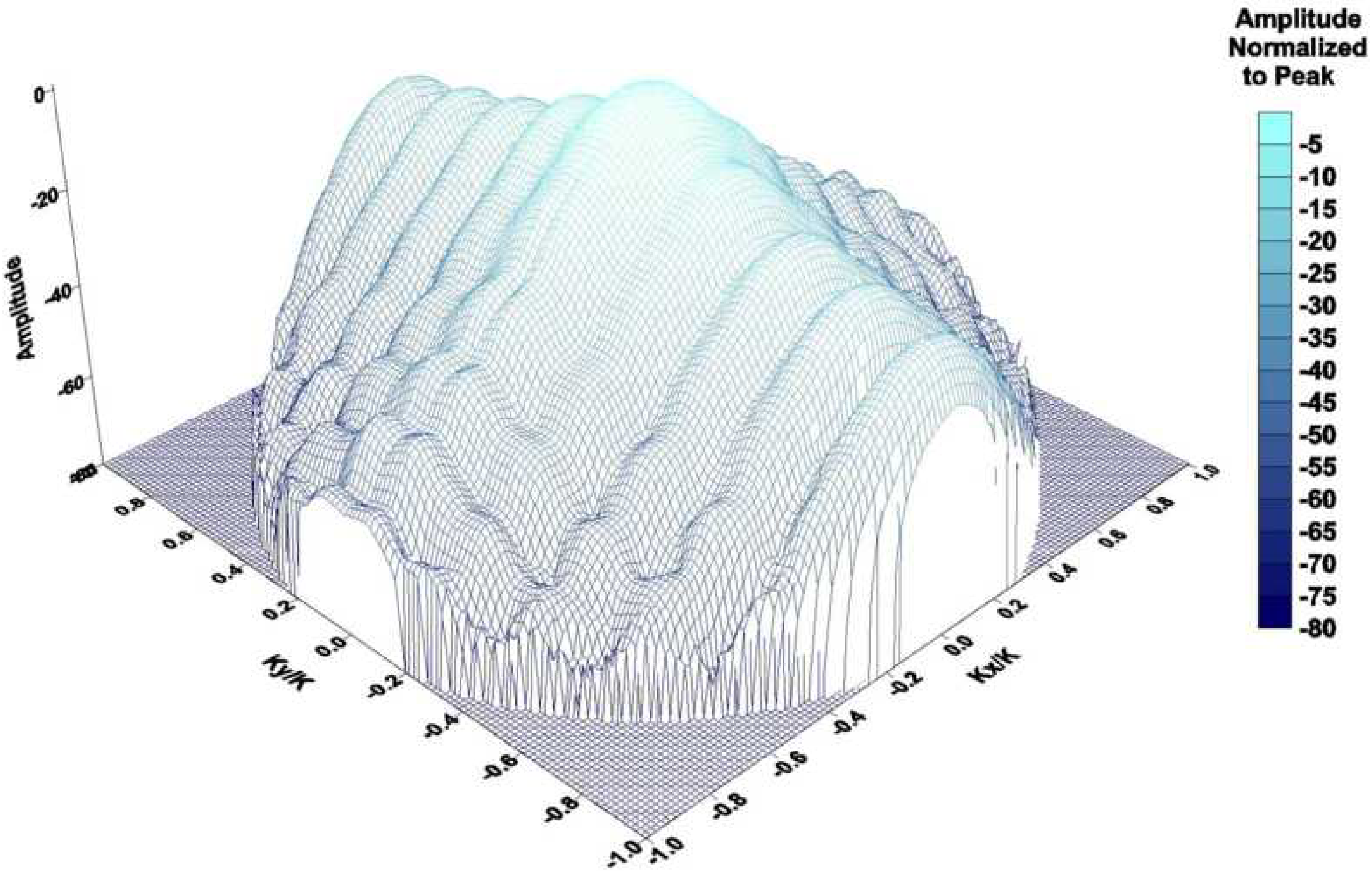
Demonstration Measurements

- Measured antenna pattern for a standard-gain horn (SGH) on the near-field range

Far-field at K-Band Standard Gain Horn at 26 GHz

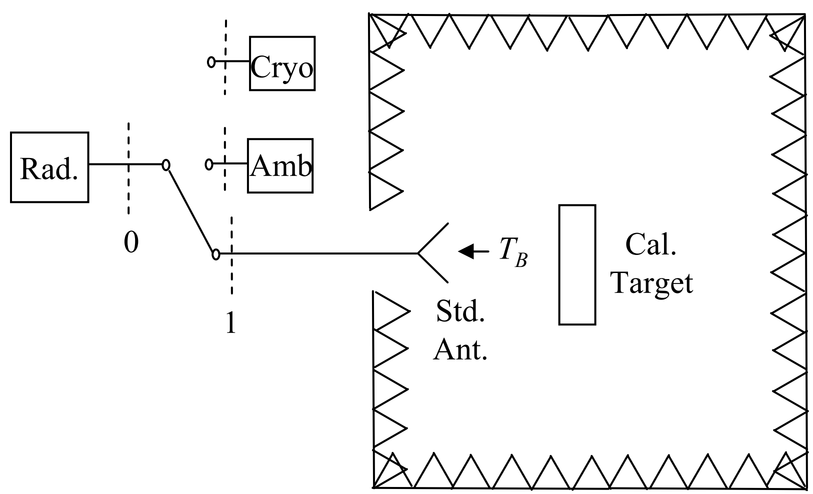


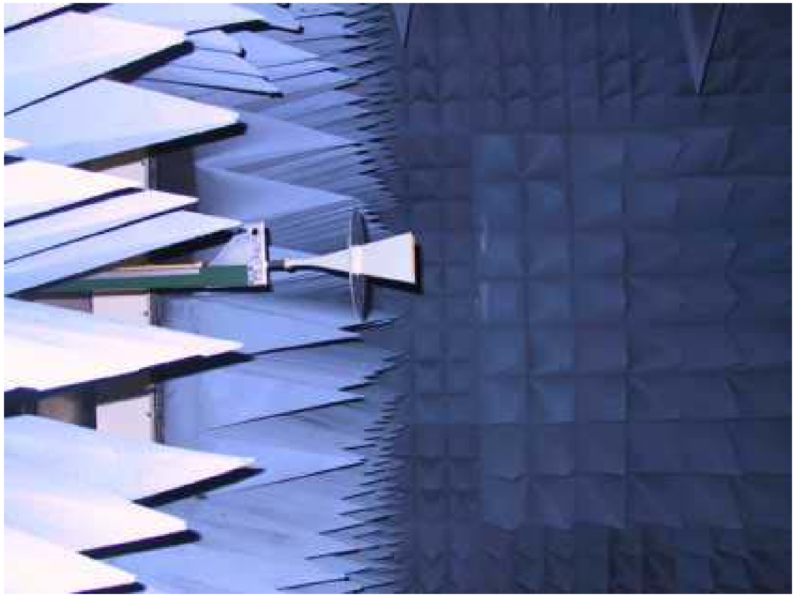
Far-field at K-Band Standard Gain Horn at 26 GHz

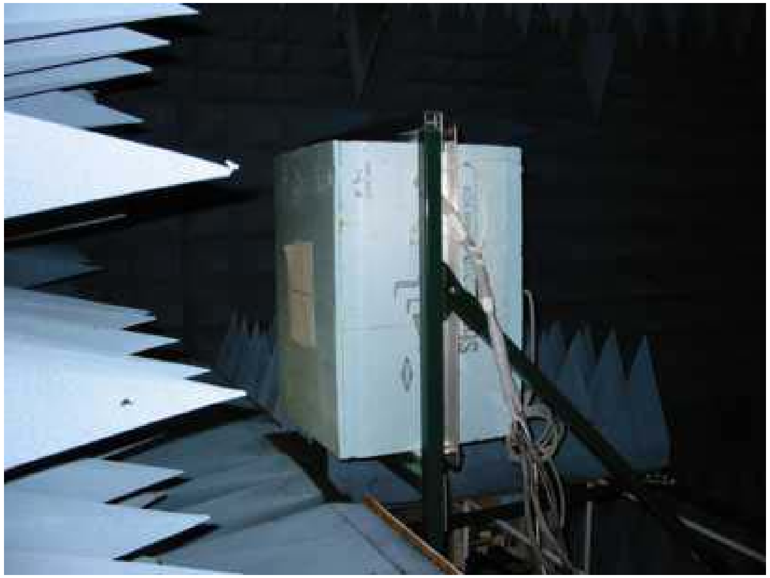


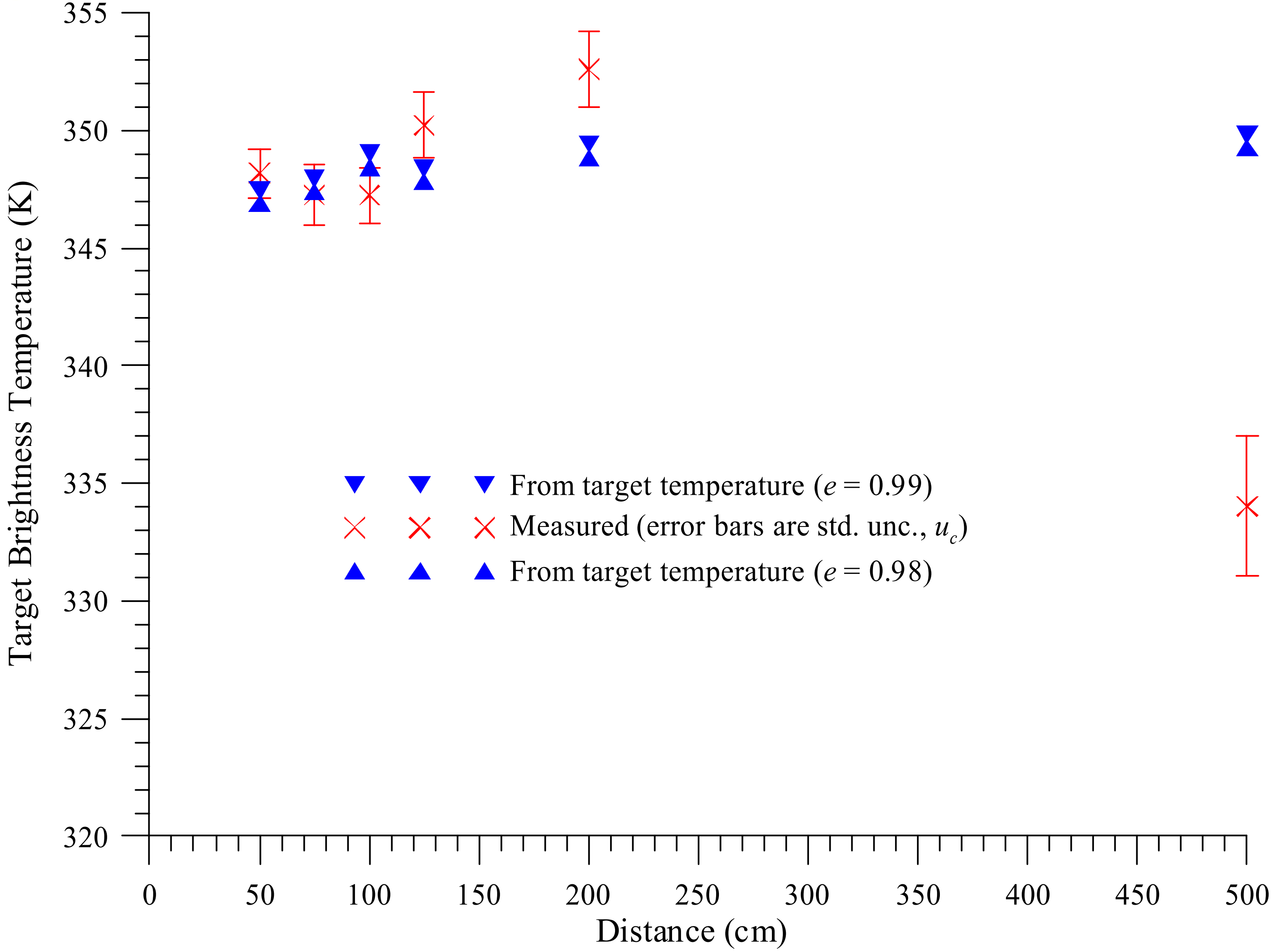
- Integrate pattern to get η_{AT}; value depends on frequency & distance. At 26 GHz, $\eta_{AT} = 0.980$ at 50 cm, $\eta_{AT} = 0.301$ at 5 m
- Compute α from conductivity. $\alpha = 0.9954 \pm 0.0023$ at 26 GHz
- Connected SGH to the DUT plane of the WR-42 (18 – 26.5 GHz) waveguide radiometer

- Borrowed hot calibration targets from NOAA GSR (Al Gasiewski & Marian Klein, NOAA ETL) and NASA Goddard (Paul Racette)
- Measured it in the NIST anechoic chamber at 18, 22, & 26 GHz for several distances



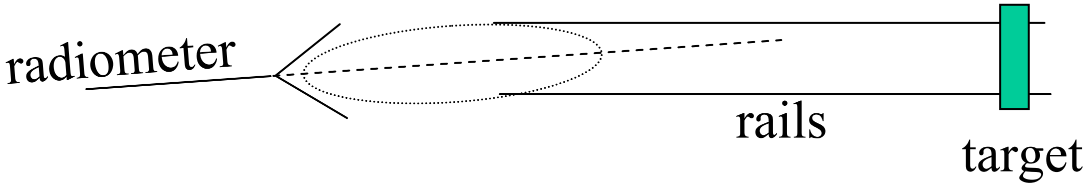




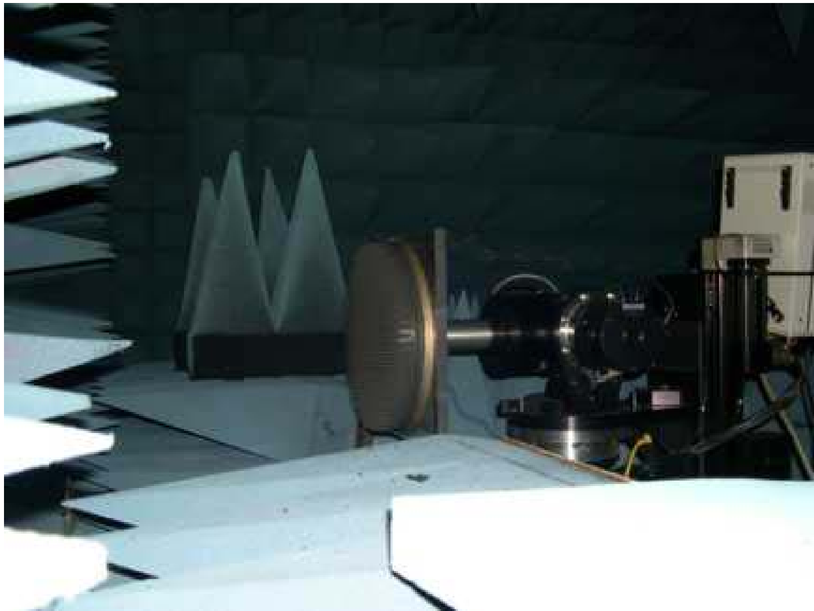


Target Brightness Temperature (K)
355
350
345
340
335
330
325
320
0
50
100
150
200
250
300
350
400
450
500
Distance (cm)
From target temperature (e = 0.99)
Measured (error bars are std. unc., u_c)
From target temperature (e = 0.98)

- 5 m results discrepancy probably just due to (mis)alignment



- Uncertainty large due to large $u(\eta_{AT}) = 0.0153$. Would be $u(\eta_{AT}) \approx 0.003$ if we knew target location better.



- Summary (standard radiometer)
  - Have developed framework and performed preliminary measurements
  - Expect uncertainties of about 0.5 – 0.7 K for T_B = 200 to 300 K, f = 18 – 26 GHz (Larger uncerts for higher/lower temperatures and/or higher frequencies)
  - Connection to thermal-vac testing must still be established.

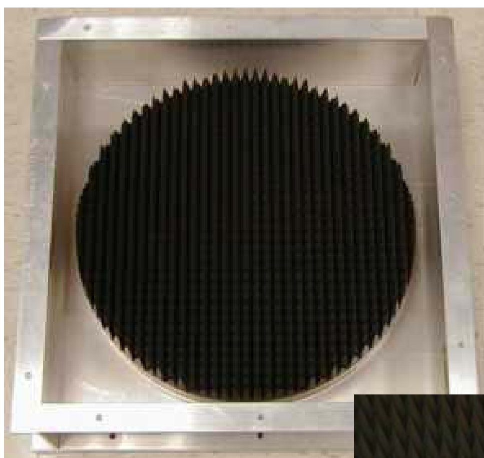
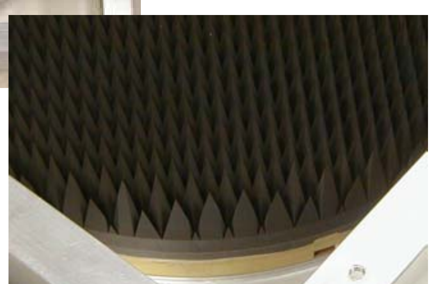
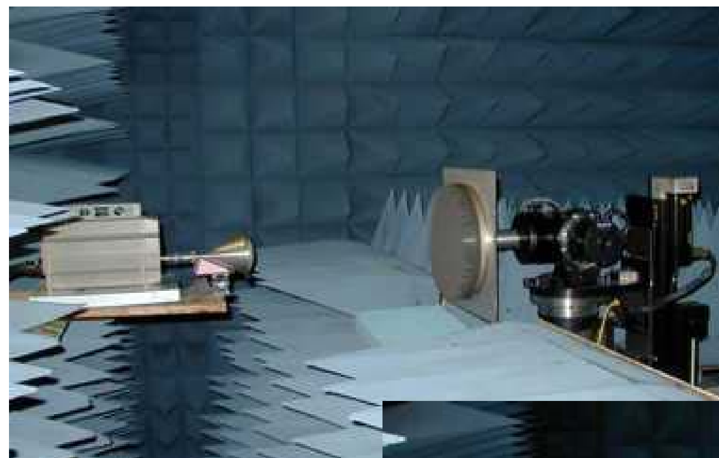
- Have also investigated
  - Material properties measurements
  - Antenna near-field effect (preliminary)
  - Detector nonlinearity
- Suggest a “hybrid” standard, which would consist of a standard radiometer + a standard target
  - Independent realizations of T_B
  - Would reduce uncertainties somewhat
  - Greater flexibility
  - More robust (and credible)
- Transfering the T_B standard would involve either:
  - A second (portable) target calibrated with the full standard
  - Measuring a customer’s target or radiometer at NIST with the full standard

- Calibration targets close to the sensing antenna:
  - linear radiometers need ≥ two standards for calibration.
  - satellites: cold sky, if possible (far-field)
  - otherwise: hot & cold targets (near-field)
  - Scene is always far-field
- Near-field targets introduce two general types of error in a total-power radiometer:
  - Antenna+target affects antenna pattern, directivity (ignore)
  - $\Delta\Gamma$ at antenna output due to non-ideal target (this work):
    - Difference in M (mismatch factor) for target, scene
    - Difference in system F and G_{av} “ “ “

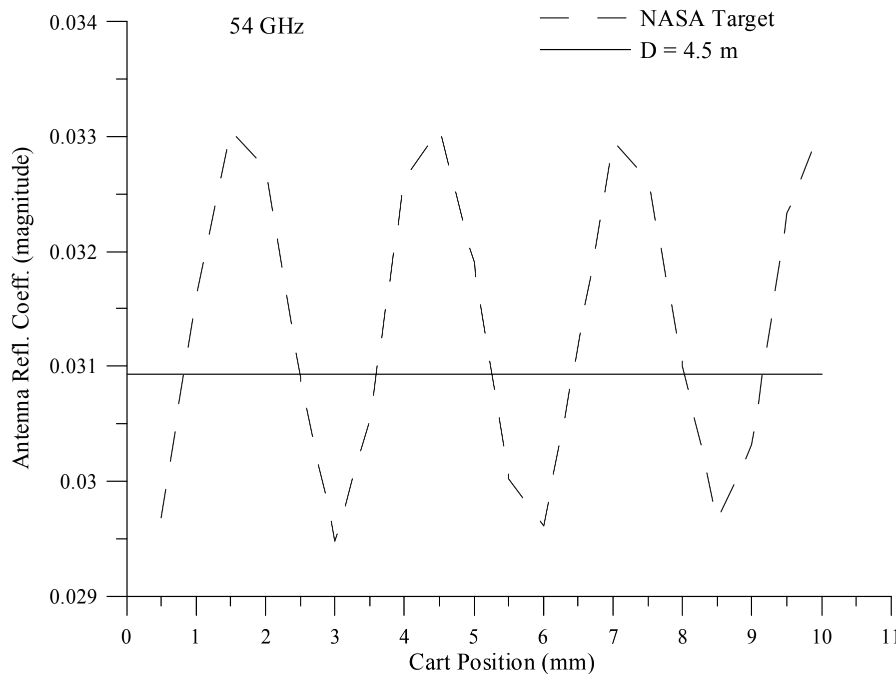
III. MEASUREMENTS

- Measured Γ_c, Γ_∞ (thus $\Delta\Gamma$) with ANA for several combinations of antenna and target.

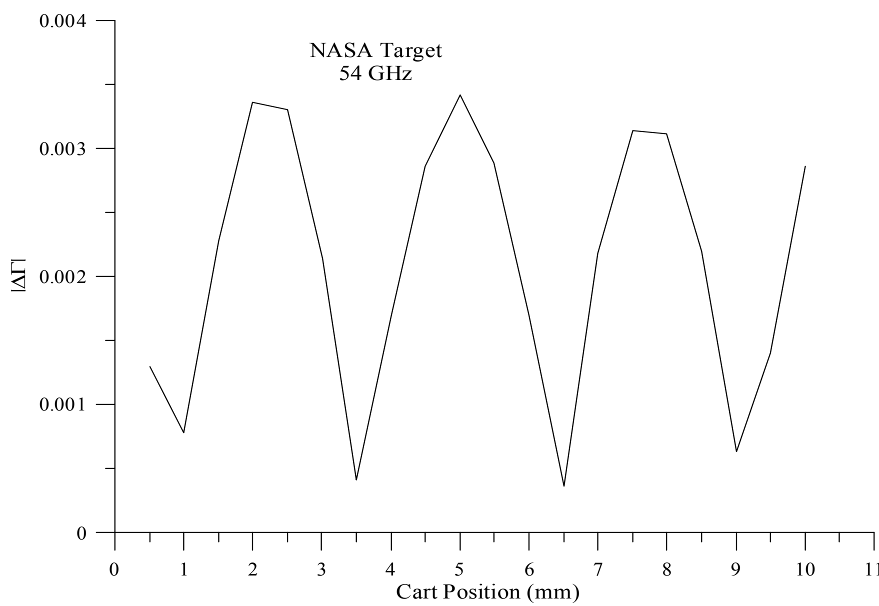
NASA target and NOAA antenna

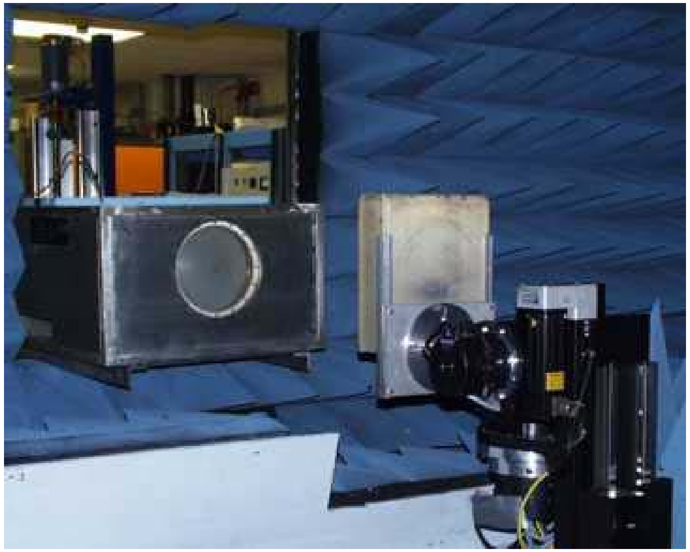

NASA target, NOAA antenna
Γ_c , Γ_∞

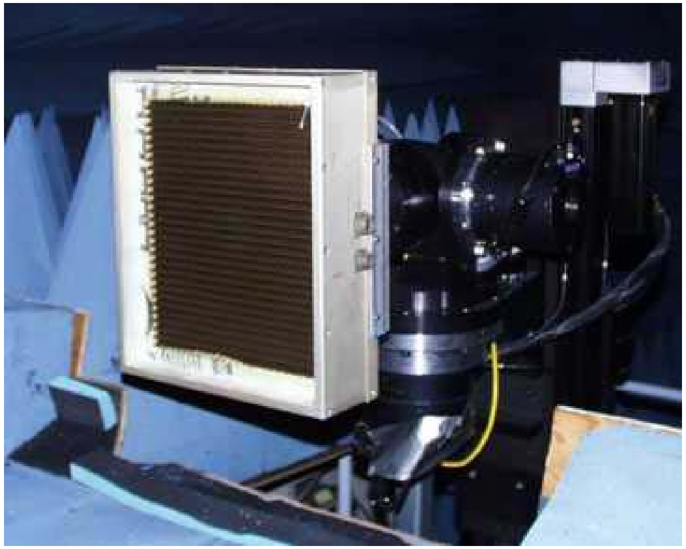


$$\Delta\Gamma = \Gamma_c - \Gamma_\infty$$



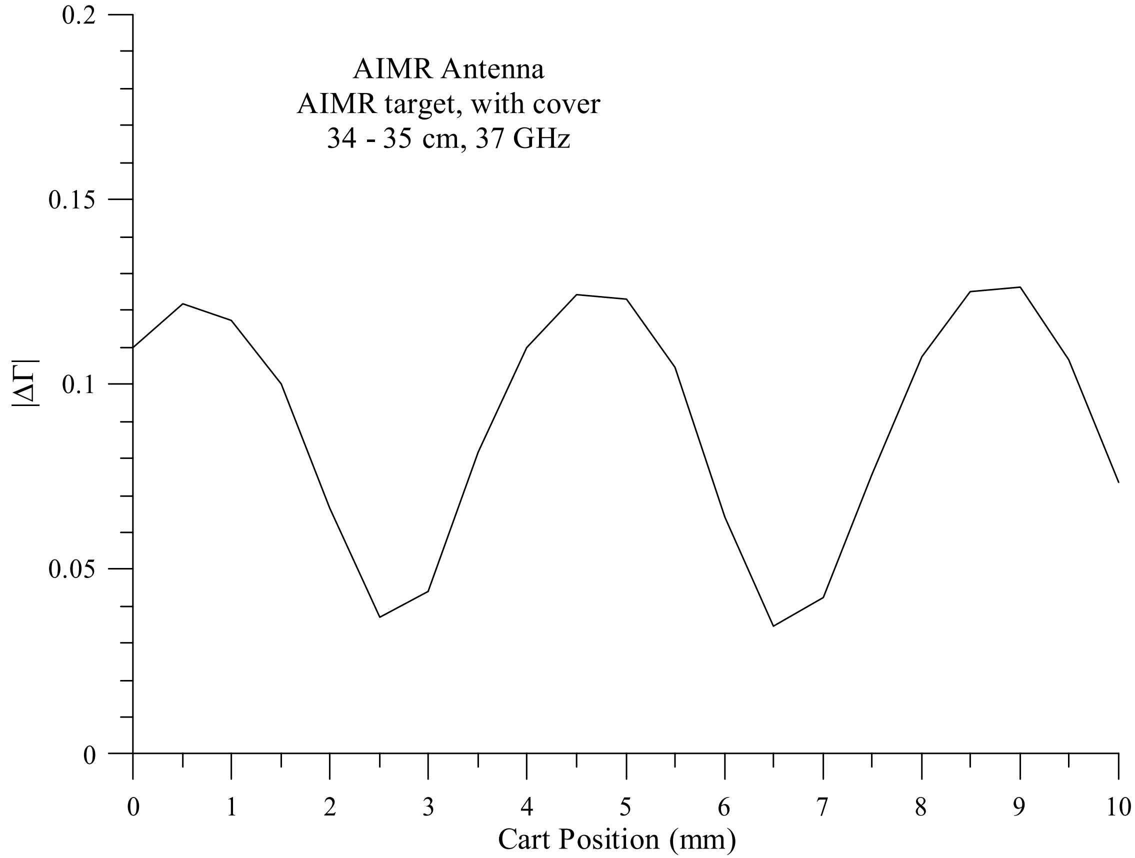
AIMR Antenna & Target





AIMR target and antenna

$\Delta\Gamma = \Gamma_c - \Gamma_\infty$



Uncertainties

- AIMR antenna & target, $T_{x,0}$ from 200 K to 300 K:

$$u_{tot}^{(0)} \approx \sqrt{2}\,|X_{12}|\,|\Delta\Gamma|_{RMS} \approx 5.2\,K$$

- Prior AIMR cal checks show agreement to within ~2 K
  - $|X_{12}|$ may be overestimated due to meas. time span
  - Spare feedhorn w/o reflector may differ from actual components
  - RMS value is an average; actual instrument is just one position

- Add input isolator with $|S_{11}|$=0.025; for $|T_{x,0} - T_a| \leq$50 K

$$u_{tot}^{(0)} \approx 1\,K$$

Uncertainties

- NOAA ant., NASA target, $T_{x,0}$ from 200 K-300 K:

$$u_{tot}^{(0)} \approx 0.0033 \left|X_{12}\right|$$

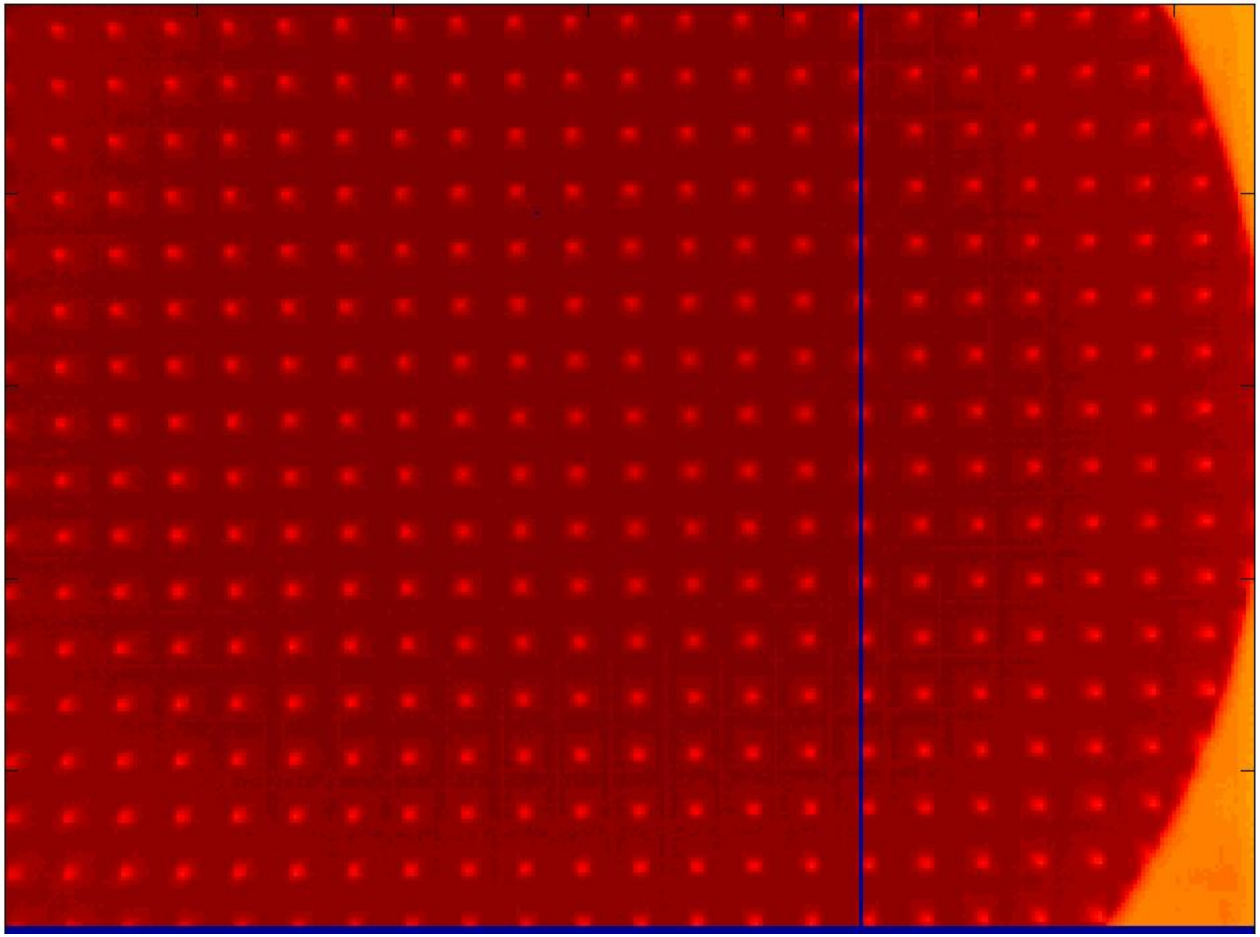
- $|X_{12}|$ could be 100 K or more, so uncertainty could be ≥ 0.3 K
  - Significant for some radiometers to be deployed in the next decade

- With an input isolator:

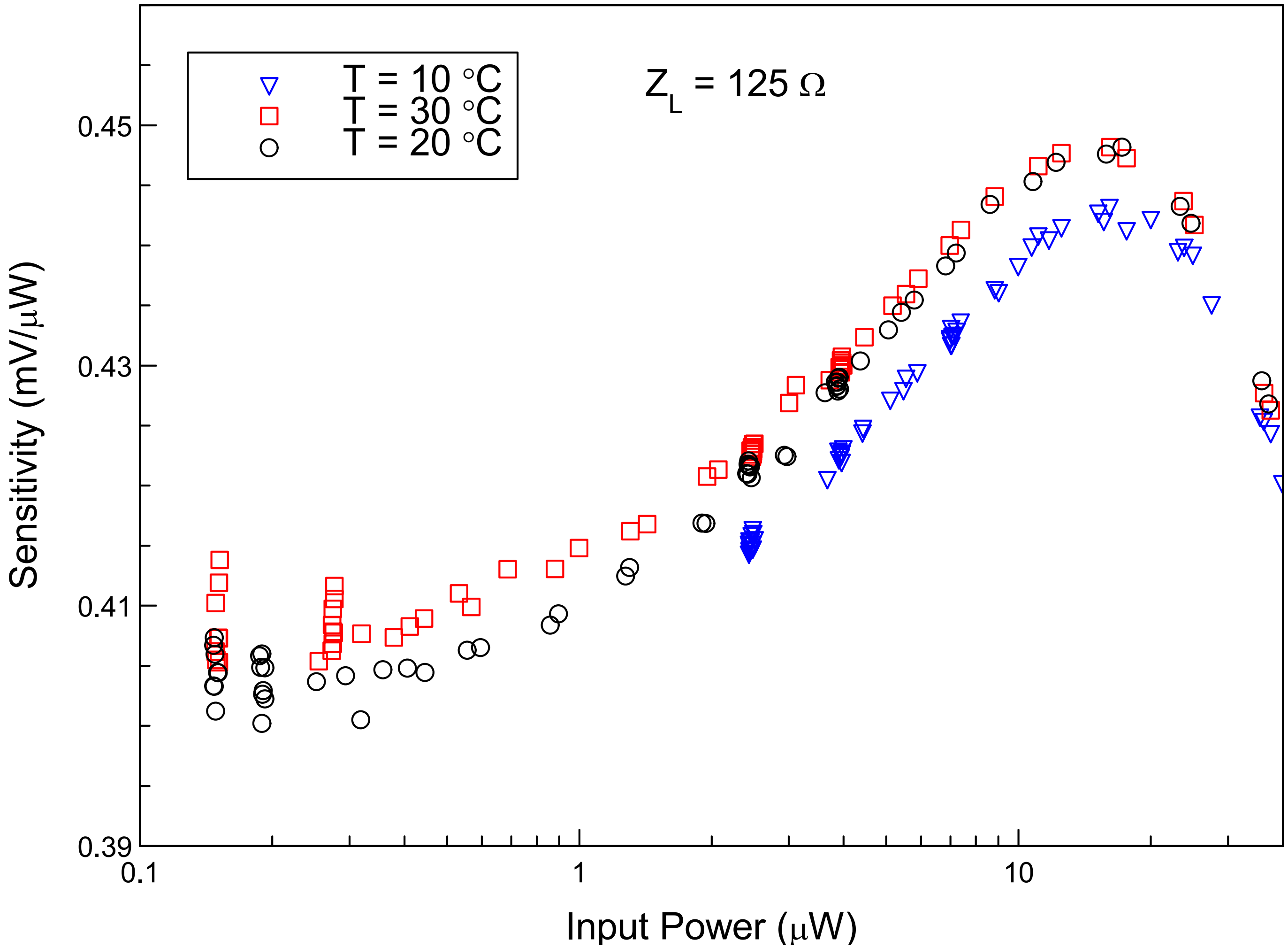
$$u_{tot}^{(0)} \approx 0.95\ K \times \left|S_{11}^{I}\right|$$

$$u_{tot}^{(0)} \leq 0.1\,K$$

IR Thermal Image of Target



Detector nonlinearity study



Standard terminology for microwave radiometry

- Developed in cooperation with CEOS WGCV
- Link at:

http://boulder.nist.gov/div818/81801/Noise/index.html

V. SUMMARY

- µW T_B traceable to fundamental physical quantities requires either a radiometer, a target, or both, referenced to primary (SI-based) standards
- NIST advocates developing a combined standard
- Noise radiometers at NIST available to cover 1-65 GHz presently (higher possible).
- Significant progress on both approaches (and related calibration issues) at NIST; more R&D needed
- National/int'l commitment is needed to implement a µW T_B standard.