PART III.

OPERATION, TESTING, AND UNCERTAINTIES

Part III. Outline

Operation
Software
Testing
Uncertainties
Measurements through Adapters

Operation [15]

Setup:

<Connect receiver unit to common port of front-end switch.

<Charge (Liquid Nitrogen) cryogenic standard & connect to port 2.

<System power left on at all times.

<Connect DUT and check standard to test ports; turn on their power supplies; allow to equilibrate (if necessary).

<Program’s initial screen shows default values for setup. Change if desired.

Initial Ports

<1: ambient standard

<2: cryogenic standard

<5: check standard

<6: DUT

Initial Program Steps

<Initializes all instrumentation, switches, etc.

<Looks up all relevant reflection coefficients and S-parameters.

<Turns IF off, selects channel A or B, sets IF BW, sets 127 dB variable attenuator to 6 dB, switches 3 dB attenuator out.

<Switches on LO; sets to first frequency.

Measurement

- Initial measurements:
  - Read ambient temp from 3 thermistors
  - Read atmospheric pressure from lab barometer
- System performs 25 measurement cycles with 3 dB attenuator out of IF path and 25 cycles with attenuator in path.

- Each cycle consists of
  - Power-off reading (no IF power to card)
  - Power from ambient standard
  - Power from cryogenic standard
  - Power from check standard
  - Power from DUT
  - Power from ambient standard.
- Each reading is done at all frequencies; *i.e.*, the frequency loop is the innermost loop.
- Time for one reading is 1/6 s.

- Noise temperatures computed for each cycle.
- DUT noise temps for 3 dB in and out must agree within ±0.2%.
- Compute average and std dev. for DUT & check standard noise temperatures.
- Read to output file.
- Change ports for DUT and check standard and measure again. Each measured on three different ports (typically).

Output files

- Raw file: all power & temperature readings and computed noise temperatures for a single "measurement" (*i.e.*, 50 readings)
- Measurement file: summary of results and uncertainty analysis for one measurement.
- Calibration file: combines 3 (typically) measurement files to obtain final calibration results for customer, including type-A uncertainty analysis.

Software

- Written in HP Basic for Windows.
- Major Subroutines:
  - Init_instr: Sets all equipment to known, default state.
  - Disable_atten: Resets 127-dB variable attenuator to known state.
  - Setup_meas: Defines DUT & parameters for measurement.

- Major Subroutines (cont'd)
  - Select_devices: Reads files & information for chosen radiometer, switch head, adaptors, check standards and DUT.
  - Mm_and_eta: Computes mismatch factors and looks up path asymmetries.
  - Interface: Sets all equipment (synthesizer, multimeters, switches, attenuators, ...) to measurement configuration.
  - Measurement: Measures powers, calculates noise temperatures, & stores results in raw data file.

Major Subroutines (cont'd)

<Unc_analysis: Computes measurement uncertainties.

<Save_unc_file: Saves measurement information.

<Typea_unc: Computes the Type-A uncertainties.

<Save_cal_file: Saves information reported to customer.

Testing [15]

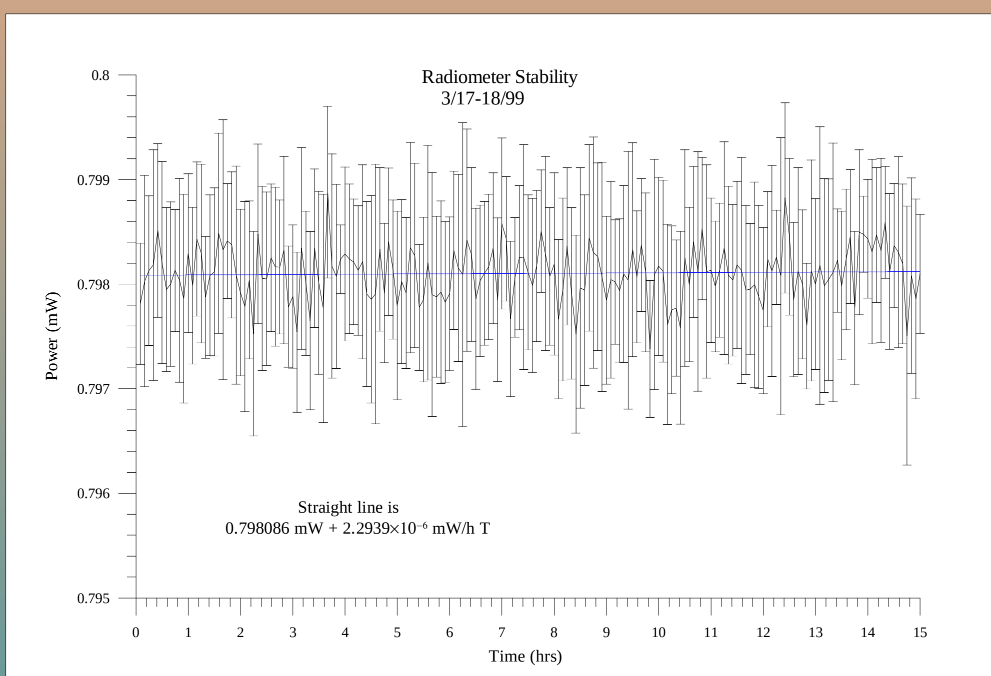
Need to test the assumptions behind the radiometer equation and all the variables used in it:

<Isolation
<Stability
<Primary standards
<Linearity
<Spurious signals
<Mismatch factors, asymmetry
<Repeatability/time dependence
<Comparison to results on old system.

Isolation: measured isolators on VNA; isolation greater than 60 dB across band.

Stability: recorded measured power from ambient standard at five-minute intervals for 12–24 hours. Drift # 0.001 % per hour.

Typical Stability



Primary Standards

<Cryogenic standard [18]: same as was used on old system. Software tested by comparing computation results to [18] and to results of an independent program.

<Ambient standard: checked that it is about 296 K; compared results for standard in receiver with those for standard in switch head.

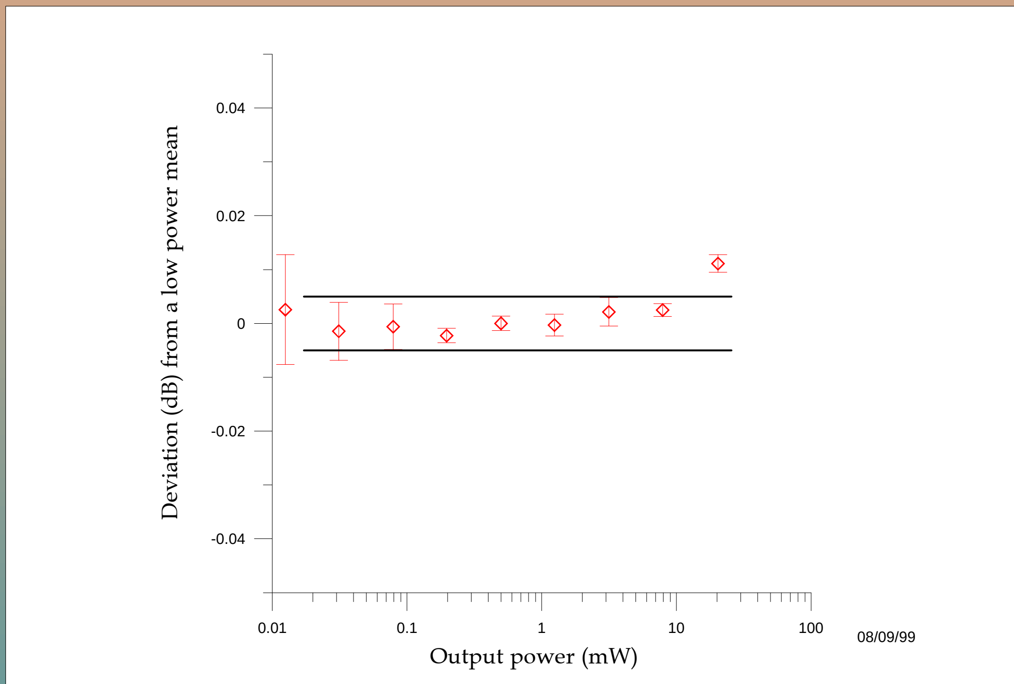
IF linearity

<IF amplifiers handle the greatest power, most likely to saturate.

<For a given setting of the 127 dB variable attenuator in IF section, measure output power with the 3 dB attenuator in and then out, and take ratio of two powers. Repeat for a range of variable attenuator settings.

<Plot ratio as a function of output power; if IF section linear, the result should be a constant (equal to the attenuation, . 3 dB).

<IF linearity results



Mixer linearity

<Measure noise temperature of noise source.

<Reduce LO power to mixer by about 3 dB and remeasure same noise source.

<Two results agreed within 0.06 %.

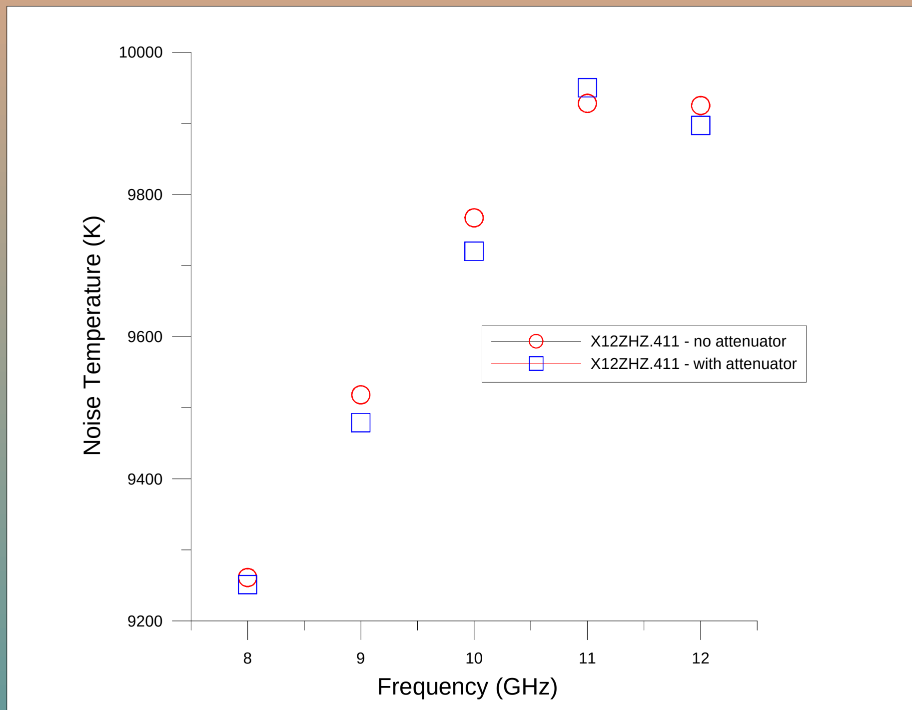
Full system linearity

<Measure noise temperature of noise source.

<Measure same noise source with characterized “3 dB” attenuator.

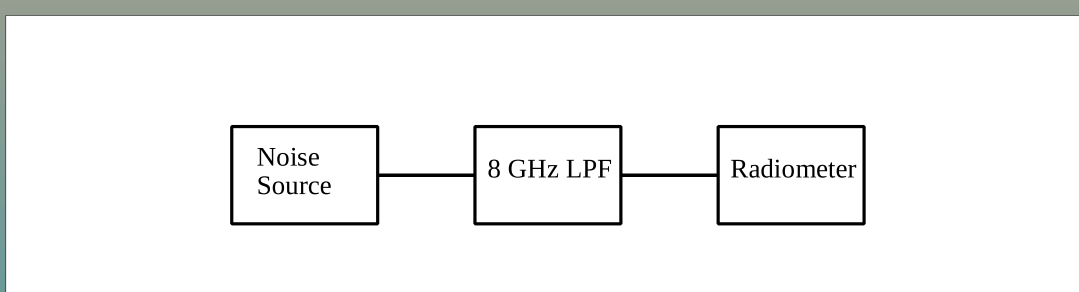
<After correcting for attenuator, two results should agree within uncertainty of attenuator characterization.

<Full system linearity results

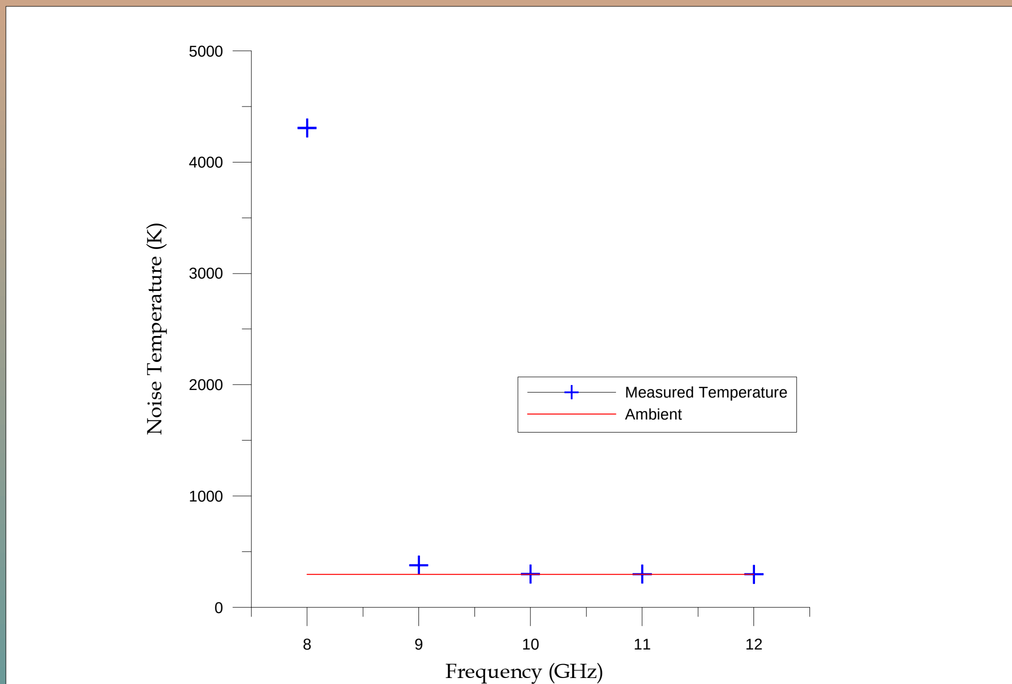


Spurious signals

<Use 8 GHz LPF to remove desired signal (*i.e.* noise from noise source); measured noise temperature should then be ambient temperature. Harmonics of lower frequencies will cause departure from ambient.



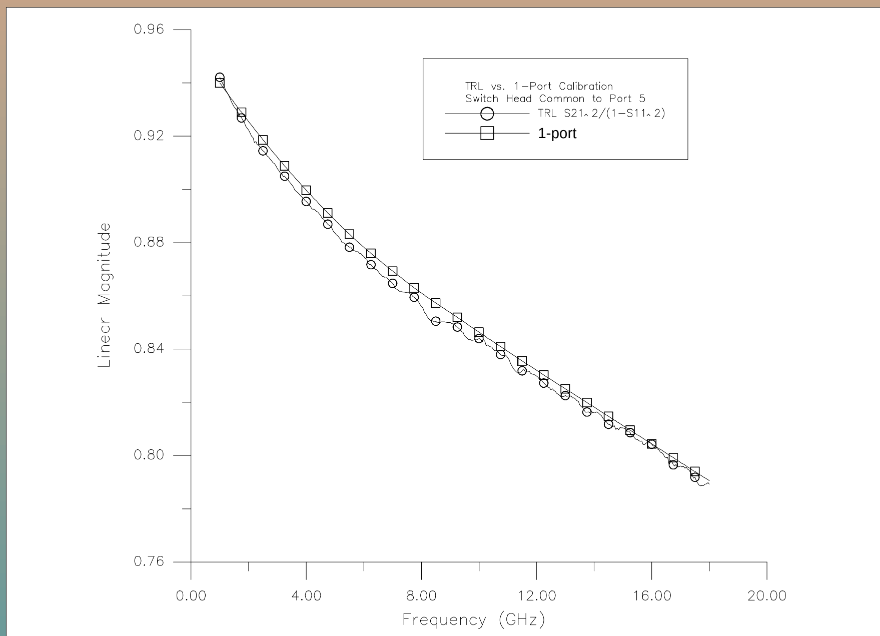
<Results of spurious signal test



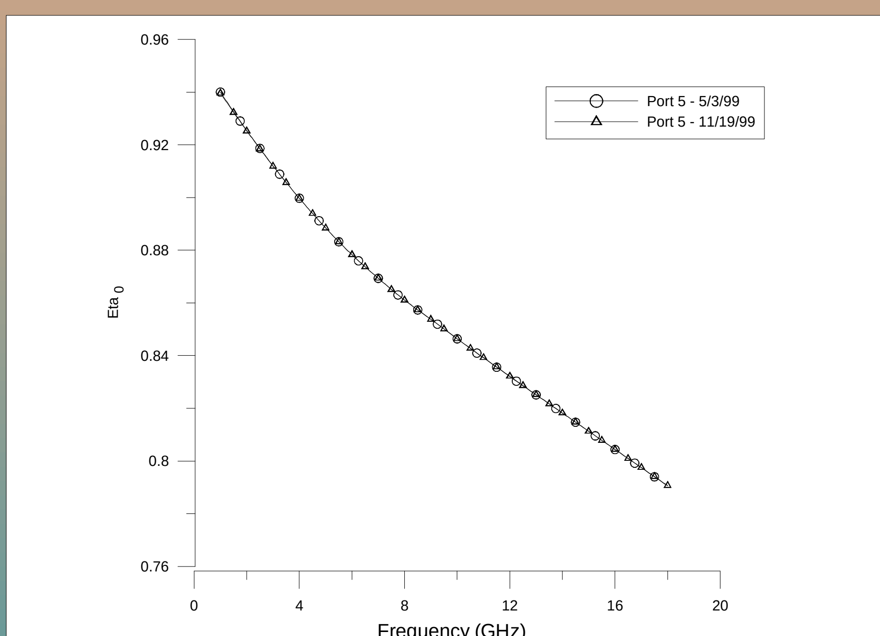
Mismatch factors & asymmetry

- <Measured efficiencies two different ways and compared. (Fig.)
- <Measured efficiencies 6 months apart and compared. (Fig.)
- <Compared efficiencies of different ports (should be about the same).
- <Compared ' measured for switch + radiometer to result from cascading *S* of switch with ' of radiometer.
- <Computed a few mismatch factors manually (Mathcad) and compared to program result.

<Comparison of efficiency measured with two different methods

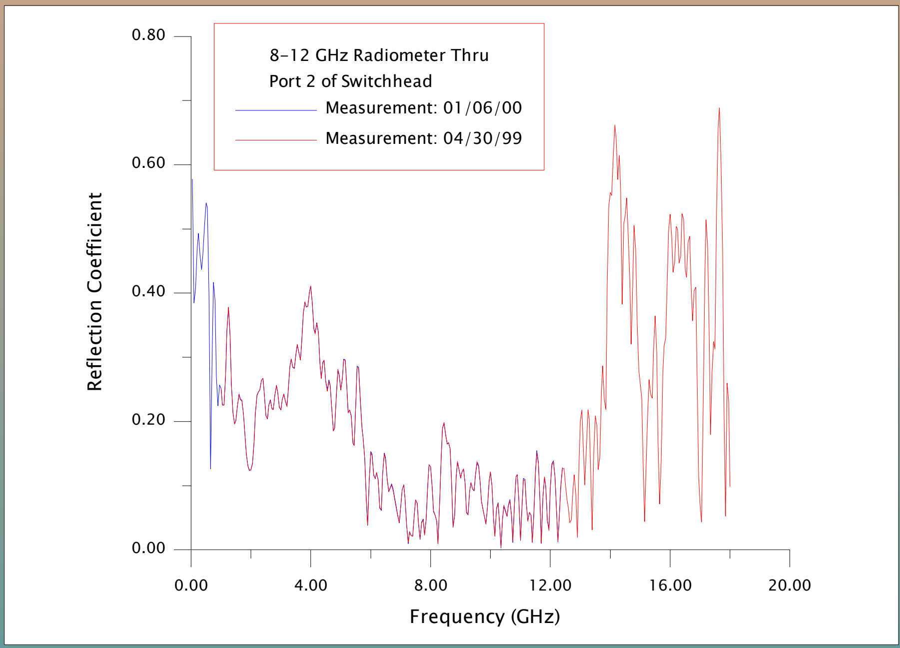


<Comparison of efficiency measurements 6 months apart.

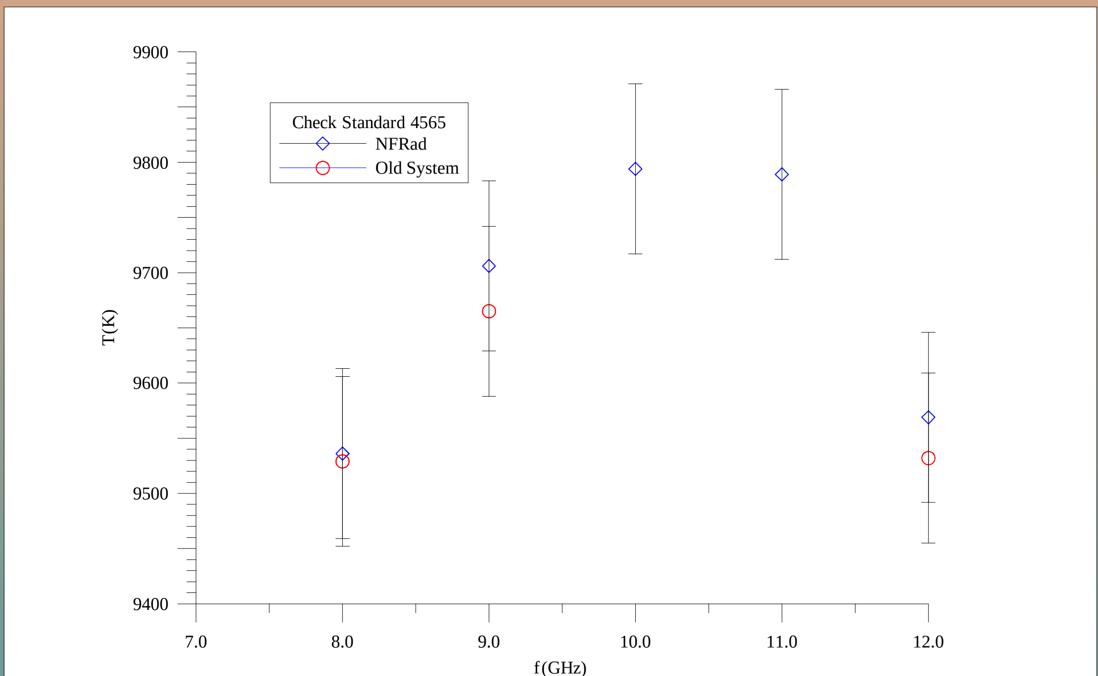


Repeatability & time dependence

< "Typical" results

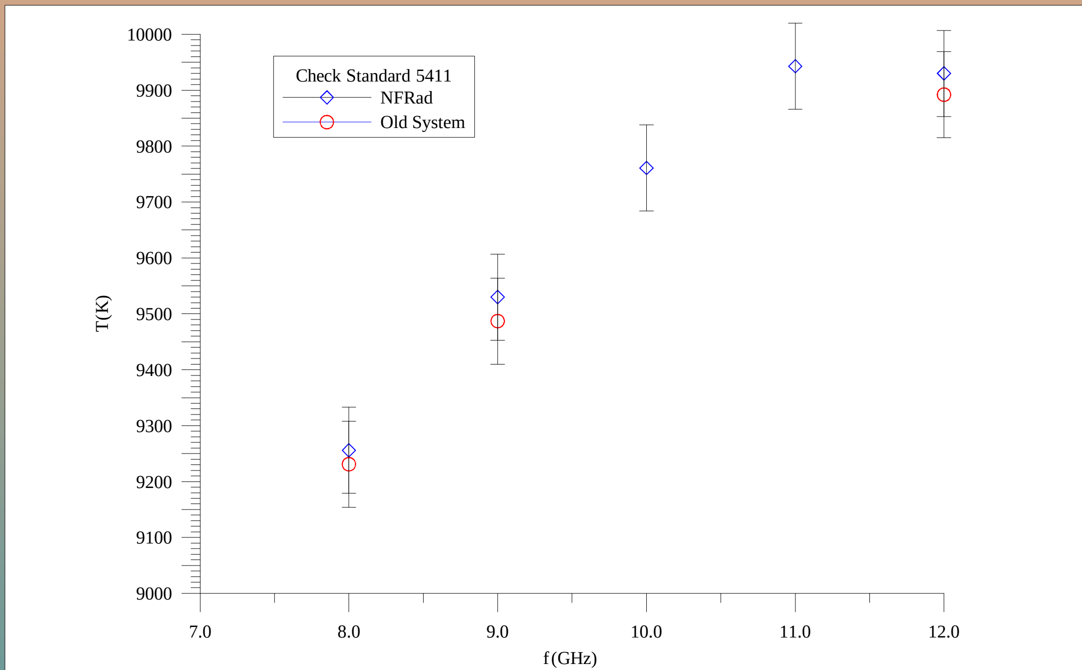


Comparison to results on old system



Uncerts are approximate (2 sigma) and do not include contribution of cryogenic standard (common to both).

Comparison to old results (cont'd)



Uncerts are approximate (2 sigma) and do not include contribution of cryogenic standard (common to both).

Uncertainties [15,21]

Background and Notation [19–21]

<Type-A (evaluated statistically) & Type-B (any other way) uncertainties [20,21].

<Mostly Type-B; Type-A at end of section.

<Notation:

@ *u* is used for standard (1F) uncertainty.

@ *U* is used for expanded (2F) uncertainty.

@ õ represents fractional standard uncertainty.

@) is used for nonstandard uncertainties (*e.g.*, worst case).

@ * is used to denote arbitrary (small) variations in a parameter.

Background and Notation (cont'd)

< u_z^2 = <**z*^{2}>, where average is over typical variations occuring in that parameter in a (very large) set of independent measurements.

<Radiometer equation

$$T_x \; ' \; T_a \, \% \, \frac{M_s 0_s}{M_x 0_x} \frac{(Y_x \, \& \, 1)}{(Y_s \, \& \, 1)} (T_s \, \& \, T_a)$$

<Uncertainties in T_x arise from uncertainties in determination of quantities in radiometer equation and from departures from perfect isolation and linearity.

Background & notation (cont'd)

<Propagation of uncertainty computed in usual manner, *e.g.*,

$$*T_x(Cry) \; ' \; \frac{MT_x}{MT_S} *T_S \; ' \; \frac{M_S 0_S \, (Y_x \, \& \, 1)}{M_x 0_x \, (Y_S \, \& \, 1)} *T_S$$

$$' \left(1 \, \& \, \frac{T_a}{T_x}\right) \frac{T_x}{T_S \, \& \, T_a} *T_S ,$$

and thus

$$\frac{u_{T_x}(Cry)}{T_x} \; ' \; \left|1 \, \& \, \frac{T_a}{T_x}\right| \left|\frac{T_S}{T_a \, \& \, T_S}\right| \frac{u_{Cry}}{T_S} .$$

Cryogenic Standard

< $$\frac{u_{T_x}(Cry)}{T_x} \; ' \; \left|1 \;\&\; \frac{T_a}{T_x}\right| \left|\frac{T_S}{T_a \;\&\; T_S}\right| \; õ_{Cry} \, .$$

<Nice feature: $T_S/(T_a\ !\ T_S)$. 0.4

<Equation for $õ_{Cry}$, approx $õ_{Cry}$. 0.8 %. major component is uncertainty in VNA measurement of the transmission line loss.

<So u_{TS} . 0.6 K; u_{Tx}/T_x . 0.22 % for typical hot source; -20 K for T_x - 10 000 K.

Ambient Standard

< $$\frac{u_{T_x}(amb)}{T_x} \; ' \; \left|\frac{T_x \;\&\; T_s}{T_a \;\&\; T_s}\right| \frac{T_a}{T_x} \; õ_{T_a} \, .$$

<u_{Ta} = 0.1 K ; $õ_{Ta}$ = 0.034 % .

<u_{Tx}/T_x - 0.05 % for typical hot source; negligible.

Mismatch Factors

- $$\frac{u_{T_x}(M/M)}{T_x} = \left|1 - \frac{T_a}{T_x}\right| \delta_{M/M} \approx \left|1 - \frac{T_a}{T_x}\right| u_{M/M}.$$

- Ratio of mismatch factors given by

$$\frac{M_S}{M_x} = \frac{(1-|\Gamma_S|^2)(1-|\Gamma_{r,S}|^2)}{|1-\Gamma_S\Gamma_{r,S}|^2}\,\frac{|1-\Gamma_x\Gamma_{r,x}|^2}{(1-|\Gamma_x|^2)(1-|\Gamma_{r,x}|^2)}$$

- Variation in *M/M* due to small variation in Γ's:

$$\delta\left(\frac{M_S}{M_x}\right) \approx -2(x_S - x_{r,S})(\delta x_S - \delta x_{r,S}) - 2(y_S + y_{r,S})(\delta y_S + \delta y_{r,S}) + 2(x_x - x_{r,x})(\delta x_x - \delta x_{r,x}) + 2(y_x + y_{r,x})(\delta y_x + \delta y_{r,x}),$$

- Correlations very important.

- If all δ's perfectly correlated, then

$$u_{M/M}(cor.) = 4\,u_{Im\Gamma}\,|y_S + y_{r,S} - y_x - y_{r,x}|.$$

- If all δ's are uncorrelated, then

$$u_{M/M}(uncor.) = 2\sqrt{2}\,u_{Re\Gamma}\,[(x_S - x_{r,S})^2 + (y_S + y_{r,S})^2 + (x_x - x_{r,x})^2 + (y_x + y_{r,x})^2]^{\frac{1}{2}},$$

where *x* & *y* refer to real & imaginary parts, and we have taken $u_{Re\Gamma} = u_{Im\Gamma}$.

<We expect correlation, but not perfect correlation. To be safe, we use the maximum of *u(cor)* and *u(uncor)*.

<We use $u_{Re'} = u_{Im'} = 0.025$. (Manufacturer says 0.0007.)

<Our value includes possible changes in system over time and connector nonrepeatability.

<Typical contribution to standard (1F) uncertainty in T_x is about 0.1% to 0.2%.

Asymmetry

< $$\frac{u_{T_x}(0/0)}{T_x} = \left|1 - \frac{T_a}{T_x}\right| u_{0/0}$$

<Several possible ways to measure asymmetry. We use Daywitt technique [23–25] to measure the two efficiencies & take ratio.

<Method and uncertainties discussed under adapter section below.

< $u_{0/0}$ = 0.0034 for 2–12.4 GHz,
0.0042 for 1–2 or 12.4–18 GHz.

Power Ratios

<Let $Y = (Y_x ! 1)/(Y_S ! 1)$

< $$\frac{u_{T_x}(Y)}{T_x} \;' \left|\frac{T_s \,\&\, T_a}{T_x}\right| u_Y$$

<Model effective efficiency of thermistor mount as $0_e = 0_{e0} + kp$, then

$$u_Y \;' \; 0_{e0} \left|\frac{Y_x \,\&\, 1}{1 \,\&\, Y_s}\right| \frac{*p_x \,\&\, p_S*}{(0_{e0} \,\&\, k\,p_a)^2}\, u_k$$

<And $$\frac{u_{T_x}(Y)}{T_x} \;' \; \frac{0_{e0}}{(0_{e0} \,\&\, k\,p_a)^2} \left|1 \,\&\, \frac{T_a}{T_x}\right| *p_x \,\&\, p_s*\; u_k$$

<From NIST Power Project, u_k < 0.02%/ mW. Also, 0_{e0} . 1, kp_a << 1, p_x & p_a # 2 mW.

< Then $$\frac{u_{T_x}(Y)}{T_x} \;\#\; \left|1 \,\&\, \frac{T_a}{T_x}\right| \times 0.04\%$$

<Negligible unless T_x # $T_a/3$.

Nonlinearity

<Check IF linearity in each measurement by taking 25 readings with 3 dB in path and 25 with it out. Must agree to within 0.2%.

<Take that as expanded (*k* = 2) uncertainty, so

$$\frac{u_{T_x}(lin)}{T_x} \text{ ' } 0.10\ \%$$

Other Type-B Uncertainties

<Imperfect isolation: #0.01%, negligible.

<Broadband mismatch: due to fact that measure ' ’s at “single” frequency, but noise measurement bandwidth is 10 MHz.   ' ’s (especially phase) can vary across noise measurement bandwidth. Systems designed so that resulting uncertainty is negligible.

Type-A Uncertainties

- Measure each DUT on three different ports, and have 50 readings on each port.
- Notation: let T_{ij} be value of a single reading. i denotes number of the measurement, 1 to N_M (3). j denotes number of reading, 1 to N_R (50). Let T_i and σ_i refer to average & sample standard deviation of the 50 readings in measurement i,

$$T_i = \frac{1}{N_R} \sum_{j=1}^{N_R} T_{ij}$$

$$\sigma_i^2 = \frac{1}{(N_R - 1)} \sum_{j=1}^{N_R} (T_i - T_{ij})^2$$

- And let T and σ refer to the avg & s.d. of the N_M measurements,

$$T = \frac{1}{N_M} \sum_{i=1}^{N_M} T_i$$

$$\sigma^2 = \frac{1}{(N_M - 1)} \sum_{i=1}^{N_M} (T_i - T)^2$$

- Model T_{ij} as $T_{ij} = \tau + M_i + R_{ij}$ [22]
- Then τ is the "true" value of the variable T,

$$\tau \approx T \equiv \frac{1}{N_M N_R} \sum_{i=1}^{N_M} \sum_{j=1}^{N_R} T_{ij}$$

- Variances of the random variables,

$$\langle M_i^2 \rangle = v_M, \qquad \frac{1}{N_M(N_R - 1)} \sum_{i,j} (T_{ij} - T_i)^2 \approx v_R,$$

$$\langle R_{ij}^2 \rangle = v_R, \qquad \frac{1}{(N_M - 1)} \sum_i (T_i - T)^2 \approx v_M + \frac{v_R}{N_R}.$$

$$v_R = \langle \sigma_i^2 \rangle,$$

$$v_M = \sigma^2 - \frac{v_R}{N_R}$$

- Then u_A is sqrt of variance in T,

$$u_A \approx \sqrt{\frac{v_M}{N_M} + \frac{v_R}{N_M N_R}}.$$

Combined Uncertainty

- Type-B

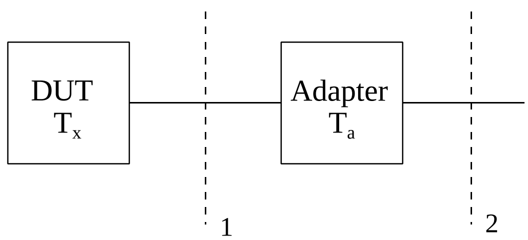
$$u_B = [u_{T_x}^2(Cry) + u_{T_x}^2(amb) + u_{T_x}^2(Y) + u_{T_x}^2(M/M) + u_{T_x}^2(0/0)$$
$$+ u_{T_x}^2(isol) + u_{T_x}^2(BBMM) + u_{T_x}^2(lin)]^{\frac{1}{2}}$$

- Expanded combined uncertainty:

$$U_{T_x} = 2\sqrt{u_A^2 + u_B^2}.$$

- Typically, $U \approx 1\%$.

Measurements Through Adapters [23–25]



$$T_2 = T_{x+a} = \eta_{21} T_x + (1 - \eta_{21}) T_a$$

$$T_x = \frac{T_{x+a} - (1 - \eta_{21}) T_a}{\eta_{21}}$$

- Measure T_{x+a}, compute T_a.
- Must know η for adapter.

- Use Daywitt technique for η:
  - First use $\eta_{21} = \eta_{12}$
  - Daywitt showed $\eta_{12} \approx \eta_{12}^{0} [1 + 2\mathrm{Re}(\rho \Gamma_G)]$, where ρ and Γ_G are both small, so $\eta_{12} \approx \eta_{12}^{0}$
  - To measure η_{12}^{0}, put reflective termination on port 1 and measure Γ_2. Daywitt showed that $|\Gamma_2| \approx \eta_{12}^{0} |\Gamma_{rt}| - |\rho| \cos\phi$, where Γ_{rt} is reflection coefficient of termination (≈ 1), and ϕ varies rapidly (relative to η_{12}^{0}) with frequency.

- So measure *'$_{2}$*, smooth to get 0$_{120}$ *'$_{rt}$*, divide by *'$_{rt}$* to correct for loss in termination.
- Size of ripples determines *P *, which is used in uncertainty analysis.
- Use two different reflective terminations, (short & offset short) differing in phase by B, to improve smoothing.
- Example:

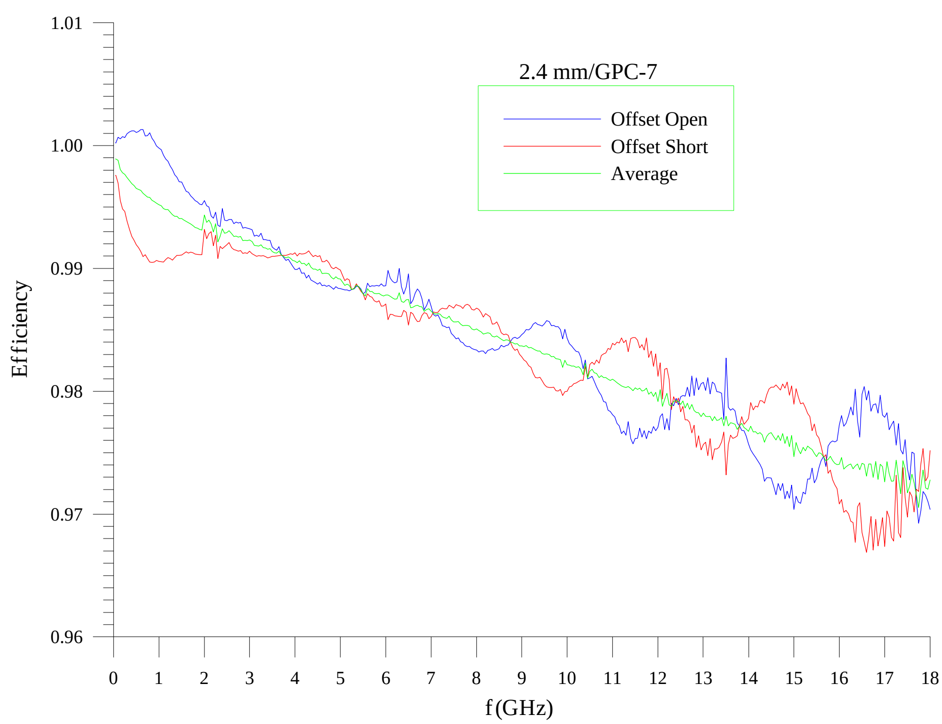


Figure 2. Efficiency (solid line) as determined in the reflective termination technique.

- Uncertainty in " [19]:
  - Determination of 0_{120} from graph
  - VNA uncertainty in measuring $'_2$
  - 0_{12} . 0_{120}
  - Connector repeatability
  - Combined, typically $u_{"}$. 0.003 to 0.005
- Contribution to u_{Tx} :

$$* T_x \ ' \ \frac{1}{"} * T_{x\%a} \ ! \ \left(\frac{1}{"} \ ! \ 1\right) * T_a \ \% \ (T_x \ ! \ T_a) \frac{*"}{"}$$

$$u_x \ ' \ \sqrt{\frac{u^2_{x\%a}}{"^2} \ \% \ (T_x \ ! \ T_a)^2 \frac{u^2_{"}}{"^2}}$$

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