NFRAD – REVIEW OF THE NEW NIST NOISE MEASUREMENT SYSTEM*

C.A. Grosvenor, J. Randa, and R.L. Billinger

National Institute of Standards and Technology
325 Broadway, Mail Stop 813.01, Boulder, CO 80303
Tel.: (303) 497-5958 \ Fax: (303) 497-3970 \ e-mail: chriss@boulder.nist.gov

Abstract - The National Institute of Standards and Technology (NIST) has completed design and testing of a new noise measurement system. The new system is capable of measuring noise temperature at multiple frequencies about ten times faster than previous NIST systems. This system will also be used to measure the noise parameters of amplifiers. Required reflection coefficients used to calculate mismatch and asymmetry are no longer measured by a six-port reflectometer in each noise measurement. Instead, they are measured with a vector network analyzer and stored in lookup tables. We have tested radiometers in the frequency ranges 4–8 GHz, 8–12 GHz, and 12–18 GHz. The system tests will be discussed as well as measurements and uncertainty analysis.

1. INTRODUCTION

The new noise measurement system was designed to measure both noise temperature and noise figure; hence its name Noise Figure Radiometer (NFRad). It is described in detail in [1]. The heart of the system is a set of five isolated, total-power radiometers, which together cover the frequency range 1–18 GHz. The results given here are primarily for the 4–8 GHz and 8–12 GHz units (NFRad4-8 and NFRad8-12, respectively).

NFRad is mechanically and electronically more stable than previous NIST radiometers. This has eliminated the need for an internal six-port reflectometer to measure reflection coefficients, mismatches, and asymmetries. Instead these quantities are measured with a vector network analyzer (VNA) and stored in lookup tables. This improvement, and the fact that the switch allows measurement of several devices under test (DUTs) at one time, allows us to make noise measurements much faster than was possible previous radiometers. The increased speed and order-of-magnitude increase in stability are also essential for future noise parameter measurements. Previous NIST coaxial systems required one full day for calibration and measurement of a noise source at one frequency. The new system can make the necessary measurements at 5 frequencies in one half-day. Measurements of relevant reflection coefficients will be repeated every few months to ensure that system parameters remain unchanged.

This paper provides a system overview in Section 2, documents the system tests for the 8-12 GHz radiometer in section 3, and presents typical uncertainties in Section 4. A brief summary is included in Section 5.

---

*U.S. Government work, not protected by U.S. copyright.

2. SYSTEM OVERVIEW

The system measures the noise power from various standards and a DUT. The measured powers are then used to calculate the noise temperature of the DUT. The power from each DUT is of the order of 10^{-12} W in our 5 MHz measurement bandwidth. Because there are no detectors currently available to measure these low powers, the signal is amplified and refined in various stages until it can be measured by a thermistor. The system as whole has about 100 dB of gain. A block diagram of the system is shown in Figure 1.

There are three main stages of the measurement system. The first is the switch head and radiometer or radio-frequency (RF) stage which includes the isolation, the first amplifier and the mixer. The second stage is the intermediate-frequency (IF) section which filters and amplifies the signal up to a level that can be measured. The last stage contains the equipment used to measure the signal, including a digital multimeter, a synthesizer, two switch control units, a circuitry section, and a unit housing power supplies.

The equipment is assembled as follows. The switch head has 6 measurement ports and one common port. The radiometer is attached to the common port, and the primary standards, check standards and the DUTs are connected to the other ports. This allows us to conveniently switch between ports without disconnecting devices. The first port is reserved for the ambient standard and is located internal to the housing. Port 2 is on the bottom of the assembly and is reserved for the cryogenic standard, which must remain vertical when filled with liquid nitrogen. In the RF section, the signal passes through two isolators that provide about 60 dB of isolation. After the isolators, the signal is amplified and then filtered using a 12.4 GHz low-pass filter. The RF signal and local oscillator (LO) signal from the synthesizer are then mixed using a double-

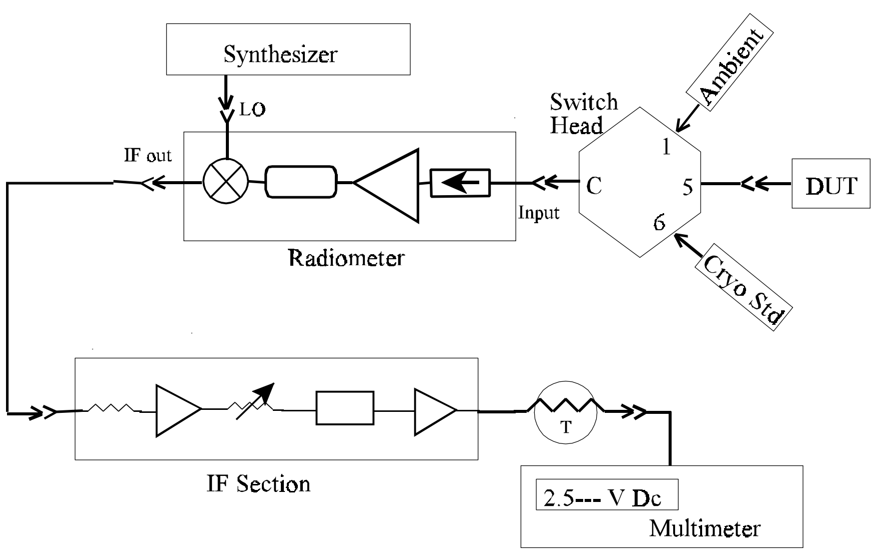

Figure 1. System block diagram

balanced mixer. After mixing, the IF signal is fed into the IF section containing a 3-dB attenuator used to test the IF linearity in each measurement and several amplifiers which amplify the signal into the 1-10 mW range. At this point, the multimeter is used to measure the voltages from the thermistor using a Type IV power meter card [2]. These voltages are converted to powers using a DC-power substitution equation [2].

For a typical measurement, a power measurement with no IF supplied to card is taken first, the ambient standard second, the cryogenic standard third, the check standard fourth, the DUT fifth, and then the ambient standard is measured again. This whole sequence takes approximately 30 seconds. During this sequence, temperature stability must be maintained. This is achieved using a series of water channels throughout the stainless steel switch assembly. Stainless steel maintains temperature equilibrium and mechanical rigidity. The RF and IF sections sit on water plates and water is also circulated throughout the system. Thermistors measure the ambient temperatures in the radiometer, in the switch head and prior to the cryogenic standard.

3. TESTING

Before using the system for everyday measurements, several tests must be performed to verify that the system is operating correctly. These tests are based on two assumptions. First, the network responds linearly to our signal (no power compression), and second, the radiometer is sufficiently isolated from the source impedance. If these assumptions are valid, then we can derive an expression for the output noise temperature of the DUT. This is the system's radiometer equation [1],

$$T_x = T_a + (T_s - T_a)\frac{(Y_x - 1)}{(Y_s - 1)}\frac{M_s\,\eta_s}{M_x\,\eta_x}, \tag{1}$$

where T_a is the noise temperature of the ambient standard, T_s is the noise temperature of the cryogenic standard, and T_x is the noise temperature of the DUT. The power ratio Y_x is defined as the delivered power spectral density of the unknown p_x divided by the delivered power spectral density of the ambient p_a. The power ratio Y_s is defined as the delivered power spectral density of the cryogenic standard p_s divided by p_a. The quantities M_s and M_x are the mismatch factors at the cryogenic port and the DUT port, respectively, η_s is the efficiency or ratio of delivered powers between the radiometer and cryogenic port, η_x is the efficiency or ratio of delivered powers between the radiometer and DUT port. Other tests include verifying the calculated values for the primary standards, mismatch factors, and path asymmetries and their repeatability with time. The tests described below are for the NFRad8–12.

The cryogenic standard is the same one used with the previous NIST coaxial radiometer [3]. It consists of a matched load immersed in liquid nitrogen, connected to the output connector by a precision coaxial transmission line. Corrections are made for the small losses and reflections in the line and for the variation of temperature with depth in the liquid nitrogen. The ambient standard consists of a coaxial load maintained at a temperature near room temperature, around

296 K. A calibrated thermistor located within the switch assembly is used to determine the exact temperature. The multimeter measures the resistance of the thermistor, which is then converted to a temperature.

It is important to know the stability of the radiometer during a measurement of a customer's device. To test the stability of the radiometer, we track the power and temperature of the ambient standard over a certain period of time. For the most recent test we measured the ambient standard over a fifteen-hour period. The results of this test are shown in Figure 2. For each measurement or data point on the plot, the ambient was read 100 times. Between every two measurements there is a delay of 5 minutes. This sequence is repeated until the end of the set time period. A linear fit was imposed on the data and the following characteristics were obtained. The slope was 8.639 x 10^{-6} mW per hour and the y-intercept was 0.79911 mW. The slope shows that any measurement drift is of the order of 0.001% per hour.

There are three potential sources of nonlinearity, with the most likely source being from the IF section. The powers entering the IF section have already been amplified, and further amplification of the signal could drive the amplifiers into the nonlinear region. The other two potential sources of nonlinearity are the RF section and the mixer. The mixer linearity test ensures that a small change in the LO power does not appreciably affect the measured temperature. The test procedure is as follows. The noise temperature of the standards is measured for an output synthesizer power of 10 dBm. The output power of the synthesizer is decreased by approximately 3 dBm and the noise temperatures are measured again. These should agree to within 2σ.

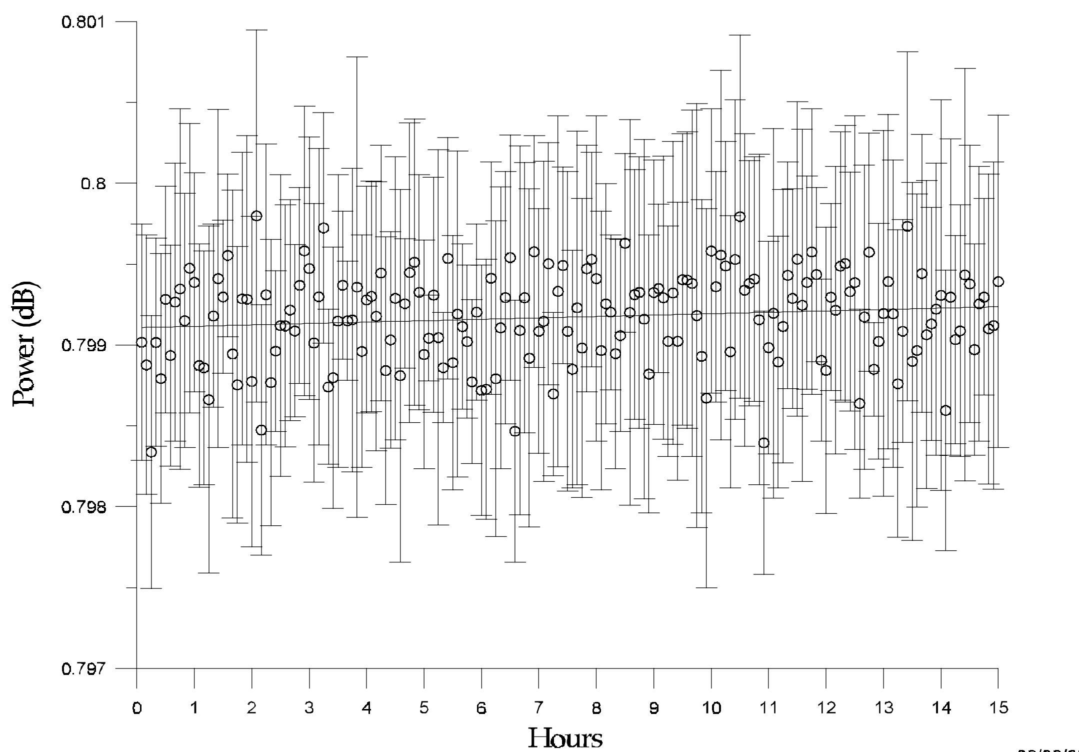

Figure 2. 8-12 GHz radiometer stability test. Circles represent the measured values and the bars are computed standard deviations for that measurement.

The IF linearity test determines the linear operating range of the IF section for various output powers. The IF linearity test is conducted as follows. A variable 127-dB attenuator in the IF section is varied from 0 dB to approximately 32 dB. At each setting, a 3-dB attenuator is switched into and out of the IF path and voltage measurements are taken. A mean power is calculated as a ratio of the power with the 3 dB attenuator out to the power with the 3 dB attenuator in. A low power mean is determined and subtracted from the values calculated above. This ratio of powers is plotted in Figure 3 versus output power with the 3 dB attenuator switched in. The IF system is considered linear when the ratio of these powers is constant to within 0.1 percent or ± 0.005 dB. In Figure 3, the solid black lines represent quoted uncertainties. For output powers between 0.02 and 10 mW we are within these uncertainties.

The RF linearity measurement tests the linearity of the RF amplifier at the front end of the radiometer path as well as everything behind this amplifier. Two check standards are measured and their noise temperatures recorded. A 3-dB attenuator is then inserted between the switch port and one of the check standards. After correcting for the attenuator, the measured noise temperature of the check standard should be the same in either case.

One of the assumptions made in deriving eq. (2) was that the output from the radiometer is not dependent on the source impedance. In the construction of the radiometer, two isolators are inserted at the input of the radiometer to isolate the radiometer from the source. To test this isolation, we measured the value of the two isolators using a VNA. Since isolators are band-limited, we measure them in the frequency band of interest. For NFRad8–12, the total input isolation measured approximately 60 dB across the band.

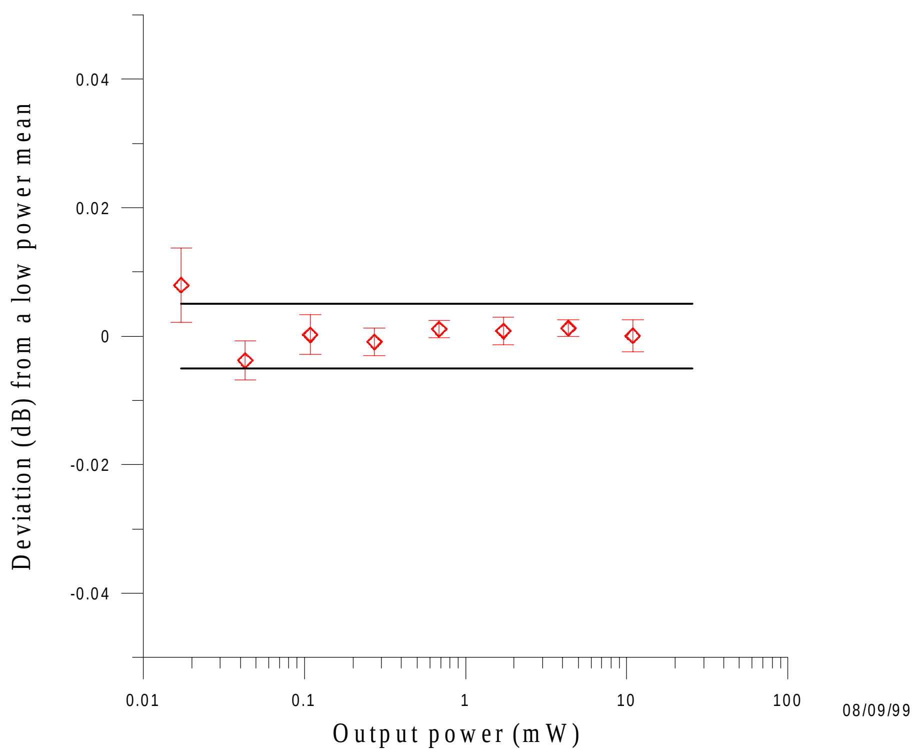

Figure 3. IF linearity test at 8 GHz.

Mismatch factors are defined as the ratio of delivered power to available power across an interface. Asymmetry is a ratio of the efficiency in one path compared to the efficiency in another path. The efficiency is a measure of the path loss. In previous systems, the mismatch was measured with a six-port reflectometer, and the asymmetry was determined from measurements of the same sources on two different ports [4, 5]. In the present system, the mismatch factors are calculated from measured reflection coefficients and the efficiencies are measured directly on the VNA [6, 7]. The asymmetry is just the ratio of the efficiency of the cryogenic path over the efficiency of the DUT path. To ensure that the mismatch factor and efficiencies are computed correctly we made sure it is similar in magnitude to previous values and manually check the program computations.

Since the reflection coefficients are no longer measured for each noise-temperature measurement, change over small time scales will be unaccounted for in the new system. It is therefore imperative that we check the repeatability and time dependence of the reflection coefficients measured on the VNA every few months. The radiometer plus switch head combination was measured in May, 1999 and again in November, 1999. Results for port 2 are shown in Figure 4. The maximum difference between the two sets of results is 0.00063, well within our calculated uncertainty in efficiency, which is 0.0034 from 2-12.4 GHz. This repeatability is typical of the other efficiency and reflection coefficient measurements as well.

As a final check of the new system, we can compare the noise temperatures measured on NFRad to those measured by the older coaxial systems. The results of this test for check standard

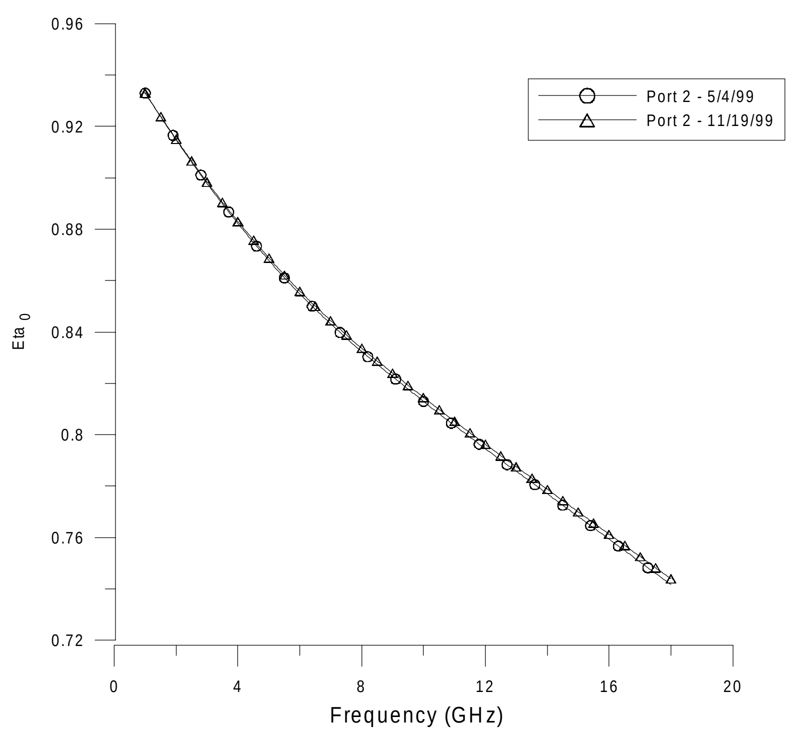

Figure 4. Time dependence of efficiency measurements on port 2.

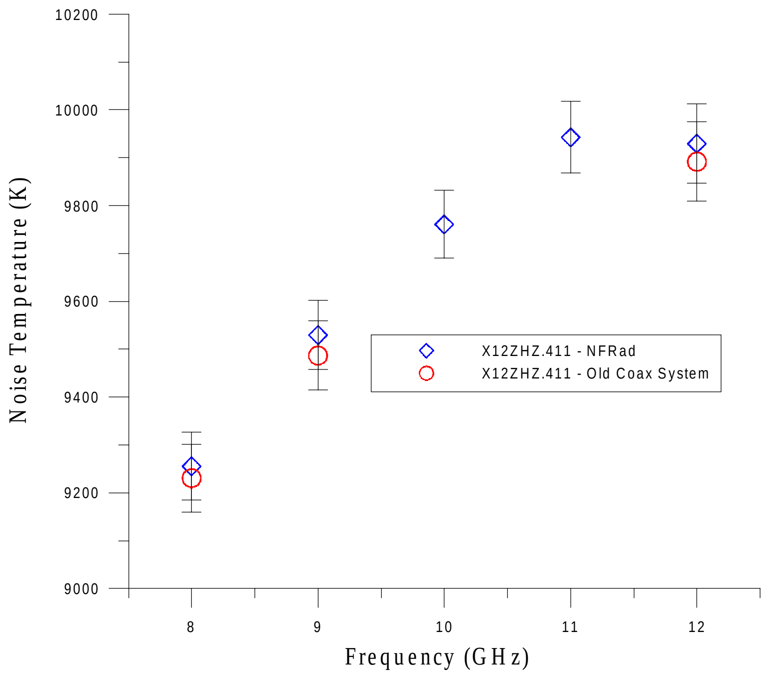

Figure 5. Measurement comparison between old coax system and NFRad for X12ZHZ.411.

X12ZHZ.411 are shown in Figure 5. The NFRad measurement shown is an average value for 12 independent measurements on different ports. The historical measurement shown is an average value for all measurements taken on the old coaxial system. No 7 mm check standard measurements were ever taken at 10 or 11 GHz on the older system. The error bars correspond to expanded (k=2) combined (dominantly type-B) uncertainties, excluding the cryogenic standard uncertainty. The average noise temperatures between the two systems agree to within 45 K, which is well within estimated uncertainties. As mentioned previously, we have tested NFRad4–8 and have partially tested NFRad12–18. Figure 6 shows the results of these tests along with those of the NFRad8–12 from 4–14 GHz. The error bars are statistical only. The type-B uncertainties are about 90 K for each point. However, the type-B uncertainties on different systems are correlated, and therefore they would be misleading in comparing results on different systems. Consequently they are not shown. The measurements agree very well at the 8 GHz band edge, but the difference at 12 GHz is about 50 K. This is barely acceptable, but it reflects only one measurement on NFRad12-18, and testing on that system is not complete. We expect additional measurements and the remaining tests to resolve the discrepancy.

4. UNCERTAINTY ANALYSIS

The uncertainty analysis closely follows that for the other NIST total-power radiometers [2, 8]. Uncertainties in T_x arise due to departures from perfect isolation and linearity and to contributions in T_x from the cryogenic standard, the ambient standard, the mismatch factors, the

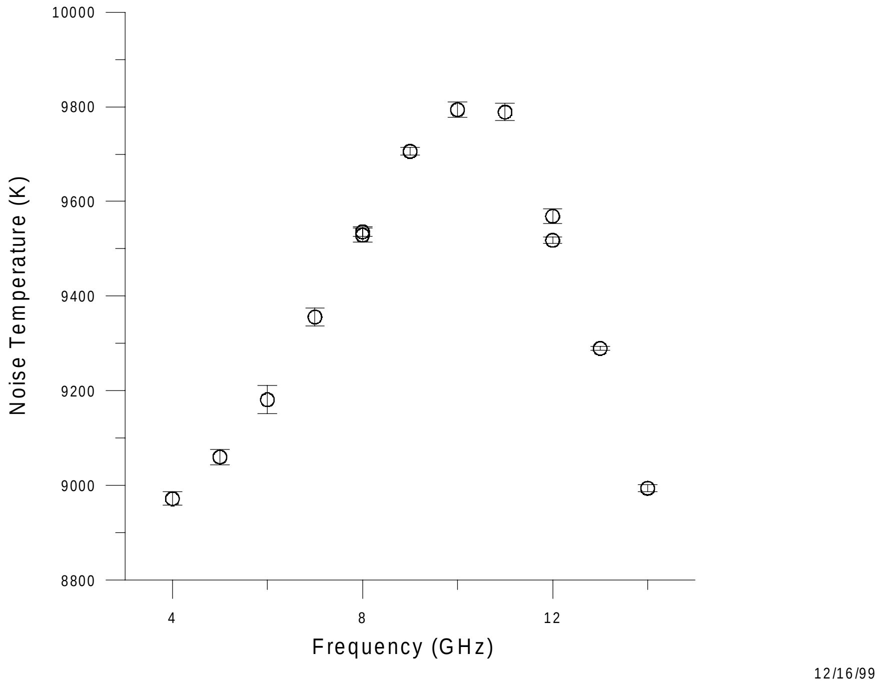

Figure 6. Measurements of X12ZHZ.565 using 3 separate radiometers from 4–14 GHz.

asymmetry, broadband mismatch effects, the power ratio measurements, and connector repeatability. We will deal first with the major and minor contributions to the Type-B uncertainties and secondly with the Type-A uncertainties [9, 10].

The cryogenic standard is a major contributor to the uncertainty in T_x. The fractional uncertainty is around 0.8 percent over the frequency range of operation for Standard C (1–12 GHz), which corresponds to an uncertainty of about 0.3 percent in T_x for a typical hot (9000 K) noise source. The contribution of the uncertainty in the ambient standard temperature is about 0.1K or 0.047 percent. The mismatch uncertainty depends strongly on the poorly known correlation between uncertainties in the measurements of different reflection coefficients, and so we use the maximum of the uncertainties obtained by assuming either complete correlation or no correlation whatsoever. In NFRad the reflection coefficients are measured with a commercial VNA. The VNA manufacturer's specifications for measurements of small reflection coefficients are uncomfortably small so we still use the larger values from the old radiometer analysis, which leads to an uncertainty in T_x for mismatch of approximately 0.01% . The asymmetry is defined as the ratio of efficiencies η_s/η_x appearing in the radiometer equation. With NFRad, the efficiencies are typically measured with a reflective-termination technique [6, 7]. The uncertainty analysis for this method [7, 8] was applied to the measurements made on the various switch paths (common to ports 3-6). It resulted in an uncertainty in T_x due to the asymmetry that is typically on the order of 0.3 percent.

The uncertainty in connector variability is included in the mismatch and asymmetry uncertainties. It is also included (roughly) in the type-A uncertainty computed from multiple measurements with the sources disconnected between measurement. The measured powers enter the radiometer equation through the ratios $Y_x \equiv p_x/p_a$ and $Y_s \equiv p_s/p_a$ in the factor $Y = (Y_x - 1)/(Y_s - 1)$. The powers are measured in the same manner in NFRad as in the previous NIST systems, and the uncertainty is the same. It is negligible unless $T_a \geq 3\,T_x$. The uncertainty due to imperfect isolation was given in [8] for 40 dB, 45 dB, and 50 dB isolation. NFRad8-12 has 60 dB of isolation across its bandwidth, and the uncertainty due to imperfect isolation is about 0.01 percent. The uncertainty due to frequency offset and broadband mismatch is of the same form as in reference [8]. Like other NIST radiometers, NFRad was designed so that the broadband mismatch uncertainty is negligible. The linearity of the system is better than 0.2 percent, which leads to a fractional uncertainty (1σ) of 0.10%.

In noise-temperature calibrations using NFRad, we repeat measurements on two different levels. Typically we do three separate measurements of the noise temperature, one on each of three different ports. For each of these separate measurements we do 50 readings (25 each with and without the 3-dB attenuator in the IF section). Evaluation of type-A uncertainties was addressed in Section 3.10 of reference [8], and that same treatment is followed here. The type-A standard uncertainties are typically of order 0.05%, much smaller than the type-B uncertainties.

The type-B standard uncertainty for a single noise temperature measurement is obtained by forming the square root of the sum of the squares of the individual contributions as given above. The expanded (k=2) combined uncertainty is computed as

$$U_{T_x} = 2\sqrt{u_A^2 + u_B^2}\,. \qquad \textbf{(2)}$$

The expanded uncertainty varies with the device being tested, the frequency, and the method of measuring the asymmetry. A typical value for a GPC-7 source with high noise temperature (above a few thousand kelvins) is about 1 percent.

5. SUMMARY

We have completed testing of NFRad8-12 and have performed most of the tests on NFRad4-8 and NFRad12-18. Measurement results for a typical diode source on all three units are shown in fig. 6, which demonstrates the consistency of the different units at the band edges (8 GHz and 12 GHz) All tests proved satisfactory, and all measurements agree to within 50 K of noise temperatures taken with our old coaxial systems. For measurements on any of the new radiometers we can measure a DUT at five frequencies on three separate ports within four hours. On the old coaxial system, a good calibration and measurement, at one frequency, would require eight hours. Measurements and tests on the 12 -18 GHz radiometer are not fully complete, and the other two radiometers (NFRad1-2 and NFRad2-4) are in the final stages of construction.

ACKNOWLEDGMENTS

J.W. Allen, D.F. Wait and J. Rice were responsible for the original design and the initial testing of the system. We are grateful for these contributions and for additional suggestions and assistance. This work was supported to a large extent by the Air Force Metrology Calibration Group.

6. REFERENCES

[1] Grosvenor, C.A., Randa, J., and Billinger, R.L. Design and testing of NFRad—A new noise measurement system. Natl. Inst. Stand. Technol. Tech. Note; in review, 2000.

[2] Larsen, N.T. A New Self-Balancing DC-Substitution RF Power Meter. IEEE Trans. IM-25(4): 343-347; 1976 December.

[3] Daywitt, W.C. A coaxial noise standard for the 1 GHz to 12.4 GHz frequency range. Natl. Inst. Stand. Technol. Tech. Note 1074; 1984 March.

[4] Daywitt, W.C. Radiometer equation and analysis of systematic errors for the NIST automated radiometers. Natl. Inst. Stand. Technol. Tech. Note 1327; 1989 March.

[5] Randa, J.R.,Terrell, L.A. Noise temperature measurement system for the WR-28 band. Natl. Inst. Stand. Technol. Tech. Note 1395; 1997 August.

[6] Daywitt, W.C. Determining Adaptor efficiency by envelope averaging swept frequency reflection data. IEEE Trans. MTT-38(11): 1748-1752; 1990 November.

[7] Pucic, S.P., and Daywitt, W.C. Single-port technique for adapter efficiency evaluation. 45th ARFTG Conference Digest, Orlando, FL, pp. 113-118; 1995 May.

[8] Randa, J. Uncertainties in NIST noise-temperature measurements. Natl. Inst. Stand. Technol. Tech. Note 1502; 1998 March.

[9] ISO Guide to the Expression of Uncertainty in Measurement. International Organization for Standardization; Geneva, Switzerland; 1993.

[10] Taylor, B.N.; Kuyatt, C.E. Guidelines for evaluating and expressing the uncertainty of NIST measurement results. Natl. Inst. Stand. Technol. Tech. Note 1297, 1994 edition; 1994 September.