

Experimental Measurement of Noise Figure and Radiation Efficiency With the Antenna Y-Factor Method at X-Band

David Buck^{ID}, Mitchell C. Burnett^{ID}, and Karl F. Warnick^{ID}, *Fellow, IEEE*

Abstract—To optimize the design of a high-sensitivity receiver, it is valuable to be able to assign noise budget contributions to various parts of the system. The system noise and aperture efficiency can be characterized using the antenna Y-factor method, which has been added recently to the IEEE Recommended Practice for Antenna Measurements, Std 149-2021. We extend the antenna Y-factor method by showing that it can be used to measure the noise figure of an active antenna and receiver system. With an additional measurement of the receiver noise, the antenna radiation efficiency can be determined. We demonstrate the extended antenna Y-factor method experimentally at X-band for antennas under test, including a horn with near 100% efficiency, microstrip patch antenna with efficiency near 80%, and a patch antenna array with 40% nominal efficiency.

Index Terms—Antenna Y factor, noise figure, radiation efficiency.

I. INTRODUCTION

WHEN designing and optimizing high sensitivity receivers for radio astronomy, remote sensing, satellite communications, and other applications, careful attention must be given to minimize noise due to losses in the antenna and impedance mismatch between the antenna and receiver electronics in the system front end. Methods for characterizing the noise performance of the system are required.

One approach to measure the noise properties of an active antenna and receiver system experimentally is the antenna Y-factor method [1], [2], [3], [4]. This method extends the hot and cold load benchtop measurement technique to antennas. Typically, the sky is used as a cold load, and a microwave absorber is used as a hot load to determine the noise properties of an active antenna and receiver system. Other types of hot and cold loads can also be used [5], [6]. The antenna Y-factor method has been in use for many years [7], particularly for astronomical receivers [8], [9], [10]. The method was recently systematized and included in the IEEE Recommended Practice For Antenna Measurements [11].

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The authors are with the Department of Electrical and Computer Engineering, Brigham Young University, Provo, UT 84602 USA (e-mail: warnick@byu.edu).

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In the antenna Y-factor method, the noise power ratio at the system output with external hot and cold loads is determined. From the Y factor, the antenna and receiver equivalent sky noise temperature [12]

$$T_{\text{eq}} = \frac{T_{\text{hot}} - Y T_{\text{cold}}}{Y - 1} \quad (1)$$

can be computed. From the Y factor, the external part of the isotropic noise response can be determined. The isotropic noise response is used to compute active antenna figures of merit [13]. With an additional signal power measurement, the aperture efficiency can be found [11]. The antenna and receiver equivalent sky noise temperature (1) is related to the antenna and receiver system noise figure [14].

The antenna Y-factor method is limited in that it cannot be used directly to determine the radiation efficiency of an antenna under test (AUT). Antenna radiation efficiency is critical in receiver systems, as it affects the overall system performance and SNR more strongly than other efficiency parameters [15]. Estimating or measuring the radiation efficiency of a highly efficient antenna is challenging. The existing techniques include the Wheeler cap method [16], a well-calibrated antenna range [17], [18], a reverberation chamber [19], or numerical simulations with a high-quality material loss model [8]. These methods have drawbacks with respect to the cost and complexity of the measurement setup and the accuracy of the measured radiation efficiency, particularly for the highly efficient antennas used in astronomical receivers. Commercial electromagnetic simulation tools can, in some cases, yield reasonable results for the efficiency of low-loss antennas, but since radiation efficiency is computed from the difference between input power and radiated power, small errors in the numerical solution can lead to inaccurate results or computed efficiencies greater than 100%.

With additional information about the system, the antenna Y factor can be used to measure antenna radiation efficiency. This was first proposed by Ashkenazy et al. [20] and later compared with other methods for measuring radiation efficiency [16]. That work compared the radiation efficiency of an AUT to a horn antenna that was assumed to have a radiation efficiency of essentially 100%. By combining a measurement of the receiver noise temperature associated with the front end electronics with the antenna Y-factor method, the radiation efficiency of the antenna can be determined directly [21]. In simple terms, the antenna Y-factor method determines the noise performance

of the antenna and receiver system, and by subtracting the receiver noise, the contribution from antenna losses to the system noise and the corresponding radiation efficiency can be determined.

In [21], the antenna Y-factor method was used to measure the radiation efficiency of an L-band antenna at ambient temperature and extrapolated to cryogenic temperature using a loss over temperature model. In this article, we use the antenna Y-factor method to measure the radiation efficiency of several antennas under test at X-band, including a horn antenna, microstrip patch antenna, and a patch array antenna. Horn antennas have very high radiation efficiency and provide a convenient benchmark case with which to compare less efficient microstrip antennas. Since the antenna Y-factor radiation efficiency method involves subtracting receiver noise from a combined antenna and receiver noise measurement, a high-efficiency benchmark antenna, such as the horn antenna, is important in validating the proposed technique.

II. ANTENNA Y-FACTOR MEASUREMENT TECHNIQUE

In the antenna Y-factor method, the response of the system with two different external noise temperatures is measured. The antenna is immersed in spatially isotropic thermal noise with two brightness temperatures T_{cold} and T_{hot} , typically using cold sky and ambient temperature microwave absorber foam, respectively, and with a conductive shield to block ground noise. The system output powers P_{hot} and P_{cold} are measured to find the Y factor $P_{\text{hot}}/P_{\text{cold}}$.

The noise performance of a receiver system can be characterized by the active antenna noise figure [14]. The active antenna and receiver noise figure is

$$F = 1 + \frac{T_{\text{eq}}}{T_0} \quad (2)$$

where T_{eq} is the equivalent temperature (1). This figure of merit characterizes the noise added by antenna losses and receiver electronics, considering including noise sources external to the antenna to be the input noise.

With an additional receiver noise measurement, the antenna the radiation efficiency can be found using

$$\eta_{\text{rad}} = \frac{(T_p + T_{\text{rec}})(Y - 1)}{T_{\text{hot}} - T_p + Y(T_p - T_{\text{cold}})} \quad (3)$$

where T_p is the physical temperature of the antenna, and T_{rec} is the equivalent receiver noise temperature. For a single antenna system, the receiver noise temperature can be measured using the standard benchtop Y-factor method. In essence, the antenna Y-factor method determines the combined antenna and receiver noise, and if the receiver noise is known, the antenna radiation efficiency can be computed using (3). Losses in connectors and cables between the antenna and the receiver input are considered to be part of the antenna and reduce the measured antenna radiation efficiency.

A. Application to Phased Array Antennas

One important feature of the antenna Y-factor method is that it can be directly applied to multielement array antennas and phased array systems of arbitrary complexity, including digitally beamformed arrays. For antenna array receiver systems

that include nonreciprocal components, the radiation efficiency is replaced by the receiving efficiency [13]. Noise powers for the hot and cold loads can be measured individually for formed beams, or for digitally sampled systems, the array output noise correlation matrix can be computed, from which antenna parameters can be found for any formed beam. For an array antenna, the receiver noise is influenced by beam-dependent active impedances [22] and is more difficult to measure. Since the array noise response depends on beamformer coefficients, the receiving efficiency, noise figure, and receiver noise are scan angle-dependent.

B. Sensitivity Analysis

Several factors contribute to uncertainty in the measured radiation efficiency. These include radio frequency interference (RFI), antenna impedance mismatch, uncertainty in the cold sky temperature, and errors in the measured Y factors. For the basic antenna Y-factor method, a comprehensive accuracy analysis has been given [9], including random and systematic errors caused by RFI and uncertainty in the cold and hot power measurements, sky temperature, and the absorber physical temperature and illumination efficiency.

As the accuracy of the antenna Y-factor method has been analyzed in the literature, we are concerned here with errors that affect the measured radiation efficiency. The main sources of inaccuracy in the radiation efficiency measurement are RFI, impedance mismatch, error in the antenna and receiver Y factor, and uncertainty in the cold temperature T_{cold} . RFI was minimized by performing the measurement in a remote location, although at X-band, a semi-urban environment can be quiet enough to perform the measurement.

If the antenna is imperfectly matched to its feeding transmission line, the antenna Y-factor method leads to an underestimate of the radiation efficiency. The connectorized noise source used to measure the receiver noise figure is typically well matched. Due to antenna mismatch, the receiver adds more noise in the antenna and receiver Y-factor measurement than in the receiver only Y-factor measurement, which biases the receiving efficiency toward a lower value. As the impedance mismatch can lead to poor performance of the receiver and would be minimized separately in addition to designing for low loss and high radiation efficiency, error in the measured radiation efficiency due to impedance mismatch is not critical in our applications of interest and can be readily assessed by measuring the antenna input impedance.

The accuracy of the radiation efficiency measurement is influenced by error in the receiver Y factor and the antenna and receiver Y factor measured using external sky and absorber loads. The receiver Y-factor measurement is a standard benchtop technique using a connectorized source and is normally more accurate than the antenna and receiver Y-factor measurement. Therefore, we focus here on error in the antenna and receiver Y factor. From (3), the sensitivity of the computed radiation efficiency to error in the measured Y factor is

$$\Delta\eta_{\text{rad}} \simeq \Delta Y \frac{1 + T_{\text{rec}}/T_h}{Y^2}. \quad (4)$$

For high sensitivity receivers with low receiver noise and a large Y factor approaching $T_{\text{hot}}/T_{\text{sys}}$, which is typically much greater than unity, the measured radiation efficiency with the proposed method is remarkably insensitive to error in the Y factor, as the scale factor between uncertainty in the Y factor and error in the radiation efficiency in (4) can be less than unity. For the parameter values in the experimental results in Section III, the scale factor in (4) relating Y-factor error and radiation efficiency error is 0.9. The Y factor can be measured in a typical experimental setup to within 0.2 dB. This leads to an absolute error in the radiation efficiency due to measurement uncertainty in the Y factor of ± 0.06 .

Another source of error is uncertainty in the value of T_{cold} . This is caused by leakage of ground noise into the ground screen aperture and variations in the sky temperature near the horizon and dependence of sky noise on humidity and atmospheric conditions. The relative sensitivity of the radiation efficiency to error in the cold load temperature is

$$\frac{\Delta \eta_{\text{rad}}}{\eta_{\text{rad}}} \simeq \frac{\Delta T_{\text{cold}}}{T_{\text{hot}}}. \quad (5)$$

The typical variability of the sky temperature at X-band is roughly ± 5 K. This translates to a relative error of ± 0.02 in the measured radiation efficiency, which is smaller than the expected error caused by uncertainty in the Y-factor measurement. Combining the errors due to uncertainty in the Y factor and the relative error due to uncertainty in the cold load temperature leads to an overall worst case estimated error bar on the radiation efficiency for the X-band measurements reported in Section III of ± 0.08 .

III. EXPERIMENTAL RESULTS

The procedure described in Section II was used to experimentally measure the active antenna and receiver noise figure and antenna radiation efficiency and validate the proposed technique for several X-band antennas. These experiments were conducted at a remote location away from transmitters to provide a noise environment with as little in-band RFI as possible.

Fig. 1 shows the setup at the remote site. A stand with conductive ground shield was used to support the AUT. The base of the shield has a copper ground plane and a funnel shape with 16 mesh copper walls. The opening was directed vertically to the sky for cold load output power measurements. For hot load measurements, a large rigid panel with microwave absorber was placed over the opening of the shield making contact with the inner wall to ensure that the brightness temperature distribution observed by the antenna was as close to uniform as possible. The AUT is mounted on the flat plate at the bottom of the inside the ground shield.

The antenna Y-factor measurement technique was applied to several test antennas selected to have a range of radiation efficiencies from relatively low to efficiency near 100%. The high-efficiency antenna was a rectangular horn. With no dielectrics in the radiating aperture, losses are limited to the conductivity of the metallic walls of the antenna. A standard microstrip patch antenna fabricated on printed circuit board tuned to the X-band frequency range provided a mid-efficiency



Fig. 1. Equipment at the remote measurement site with the conductive ground shield setup for a hot load antenna measurement for the Y-factor method.

test antenna. An AUT with relatively low efficiency was realized using a Dolph-Chebyshev microstrip patch antenna. This antenna consisted of seven patches of varying widths arrayed in a line and connected with microstrip lines. Both the Dolph-Chebyshev and patch antennas were manufactured using Rogers 4003C, 60 mil substrate and were driven by through-hole SMA coaxial connectors. The operating frequency range of all AUTs was 10–10.5 GHz.

The receiver was a baseband receiver that outputs narrowband downconverted snapshots at tunable RF frequencies. The mixer output of the receiver was sampled at a rate of 1.625 Ms/s, yielding a Nyquist bandwidth of 812.5 kHz. The ADC output samples from the receiver were channelized using a 1024-point FFT with power averaged over 4000 frames. Outliers caused by RFI were removed, and samples at the lower end of the baseband output were discarded to avoid the stopband of a dc blocking filter that lowers the receiver noise figure. The mean of the remaining narrowband FFT samples provided an estimate of the system output power at a given tunable RF frequency point.

The Y factor was computed as the ratio of the system output powers obtained with the hot and cold loads at each RF frequency. Measured Y factors for the three antennas under test are shown in Fig. 2. The horn and Chebyshev array antennas had a relatively stable Y factor across the band, whereas the patch antenna Y factor was more erratic. The active antenna and receiver system noise figure computed from the Y factor using (1) and (2) is shown in Fig. 3 for each of the three antenna cases. The qualitative impact of loss on the system noise figure is apparent in the noise figure results. In the next section, we give quantitative results for the radiation efficiency of each of the antennas.

A. Radiation Efficiency Measurements

Determining the radiation efficiency of an antenna essentially requires a subtraction of the receiver noise contribution from the antenna and receiver noise using the antenna Y-factor method. Two separate Y-factor noise measurements

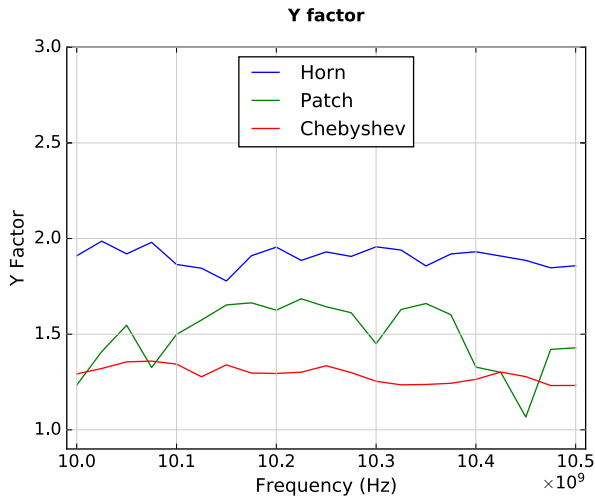


Fig. 2. Y-factor measurement for three antennas showing the power ratio between the absorber foam (hot) and sky (cold) sources.

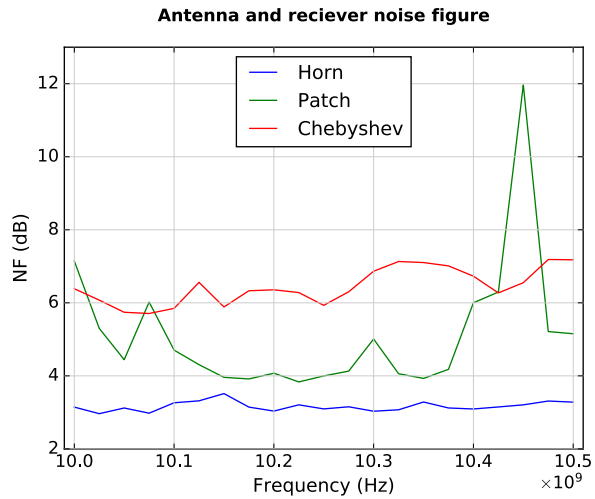


Fig. 3. Active antenna and receiver system noise figure calculated from the Y factor using (1) and (2), showing the expected strong impact of antenna losses on the noise figure.

are needed: one to obtain the equivalent noise temperature of the receiver, T_{rec} , using a connectorized noise source, and the other for the antenna and receiver system using microwave absorber and sky as the hot and cold loads. To reduce error due to temperature drift over time, the two measurements were done in the same location with as few disturbances as possible to the receiver equipment. To facilitate this, the funnel of the ground shield was removable from the base in order to expose the receiver input port. The same receiver was used for all measurements.

For the radiation efficiency measurements, we assumed that the antenna and the absorber (hot load) are the same temperature as the outdoor ambient environment. This simplifies (3) to

$$\eta_{\text{rad}} = \frac{(T_p + T_{\text{rec}})(Y - 1)}{Y(T_p - T_{\text{cold}})}. \quad (6)$$

Measured radiation efficiencies for the horn, patch, and Chebyshev array antennas are shown in Fig. 4. Values for the independent variables in (6) include the X-band sky

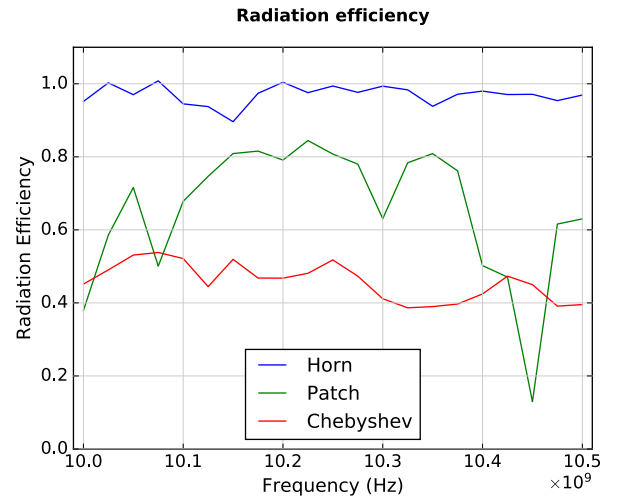


Fig. 4. Radiation efficiency calculated for three antennas at several snapshots in the ISM 10–10.5-GHz band. From the sensitivity analysis in Section II-B, the worst case error bar on these measurements is roughly ± 0.08 .

temperature T_{cold} of 5.5 K [23], and the ambient temperature T_p was 289 K (60 °F).

The horn antenna was the most efficient of the three X-band antennas with radiation efficiency near 100%. The radiation efficiency measurement technique requires absolute accuracy for both noise measurements, the antenna Y-factor method for the antenna and receiver system, and the connectorized noise source measurement for the receiver without antenna. Obtaining a radiation efficiency from the method close to 100% for the horn antenna provides an excellent validation for the proposed method. The patch antenna had a measured efficiency near 80%, and the microstrip antenna was the least efficient, with a radiation efficiency of 45% near the antenna center frequency.

IV. CONCLUSION

Measuring the radiation efficiency for low-loss antennas is challenging. Numerical methods can be inaccurate when modeling losses in highly efficient antennas. The direct method for determining radiation efficiency requires a well-calibrated antenna range and radiation pattern measurements over a full sphere, which can be time-consuming and costly. Other methods, such as the Wheeler cap method, are difficult to apply due to the complexities of the circuit models that are assumed with this approach. The proposed method, based on the antenna Y-factor method, has been shown to work well and provides results that agree with expected relative efficiencies for the X-band antenna examples considered in this article. This provides an alternative approach for characterizing antennas used in high-sensitivity receivers for astronomical instruments, remote sensing, radar, and other applications.

In future work, it would be valuable to use antenna range measurements and numerical simulations to benchmark the proposed measurement technique. In view of the limitations on the accuracy of simulated or directly measured radiation efficiency for low-loss antennas, validating the proposed method by comparison to other techniques may more challenging than it might seem. This could be done with a well-calibrated

antenna range, reverberation chamber, or numerical algorithms specially developed for low-loss antenna models [8] and careful attention to sources of inaccuracy in loss measurements for high-efficiency antennas.

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David Buck, photograph and biography not available at the time of publication.



Mitchell C. Burnett received the B.S. and M.S. degrees in electrical engineering from BYU, Provo, UT, USA, in 2015 and 2017, respectively.

He was a Co-Founder and a Lead Engineer of Smart Home Technology Startup Linq Home. After graduation, he worked with Rincon Research Corporation, Tucson, AZ, USA, developing high-performance DSP systems and algorithms for the U.S. Defense and Intelligence communities. He currently serves as a Research Engineer with BYU Radio Astronomy Systems Research Group,

developing a new cryogenic phased array feed and high-performance digital back end processing system.



Karl F. Warnick (Fellow, IEEE) received the B.S. degree in electrical engineering and mathematics and the Ph.D. degree in electrical engineering from Brigham Young University (BYU), Provo, UT, USA in 1994 and 1997, respectively.

From 1998 to 2000, he was a Post-Doctoral Research Associate and a Visiting Assistant Professor with the Center for Computational Electromagnetics, University of Illinois at Urbana-Champaign, Champaign, IL, USA. Since 2000, he has been a Faculty Member with the Department of Electrical

and Computer Engineering, BYU, where he is currently a Professor. He has published many books, scientific articles, and conference papers on electromagnetic theory, numerical methods, antenna applications, and high sensitivity phased arrays for satellite communications and radio astronomy.