Implementation of a Technique for Computing Antenna System Noise Temperature Using Planar Near-Field Data

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Abstract—This paper presents the second phase of the development of a new measurement technique to determine antenna system noise temperature using data acquired from a planar near-field measurement. In the first phase, it was shown that the noise temperature can be obtained using the plane-wave spectrum of the planar near-field data and focusing on the portion of the spectrum in the evanescent region or “imaginary space”. Actual evanescent modes are highly attenuated in the latter region and therefore the spectrum in this region must be produced by “errors” in the measured data. Some error sources such as multiple reflections will produce distinct localized lobes in the evanescent region and these are recognized and correctly identified by using a data point spacing of less than \( \lambda/2 \) to avoid aliasing errors in the far-field pattern. It has been observed that the plane wave spectrum beyond these localized lobes becomes random with a uniform average power. This region of the spectrum must be produced by random noise in the near-field data that is produced by all sources of thermal noise in the electronics and radiated noise sources received by the antenna. By analysing and calibrating this portion of the spectrum in the evanescent region the near-field noise power can be deduced and the corresponding noise temperature determined. In the current phase of tests, planar near-field data has been acquired on a measurement system and the analysis applied to determine the system noise parameters. Measurements have been performed with terminations inserted at three different locations in the RF receiving path: the IF input to the receiver, the input to the mixer and the input to the probe that is transmitting to a centre-fed reflector antenna. The terminations consist of either a load that serves as the “cold” noise source or a noise source with a known noise output for the “hot” noise source.

Keywords—Planar Near-Field, Noise Temperature, G/T Figure-of-Merit Measurements, Simulation, Plane Wave Spectrum.

I. INTRODUCTION

A receiving antenna system can be modeled as shown in Figure 1, by the antenna with a gain of \( G \), an ohmic loss of \( \alpha \), an amplifier with a gain denoted by \( A \) and the noise factor of the amplifier denoted as \( F \). A frequently used figure of merit for the receiving system is the ratio of the antenna’s gain, \( G \) to the effective noise temperature of the antenna and amplifier \( T_e \).

The effective noise temperature of the system is due to the noise produced by the antenna’s ohmic loss that is directly related to the radiation efficiency \( \eta \) and the amplifier noise.

This figure of merit is usually measured by alternately directing the antenna towards a hot noise source such as the sun, moon or radio star and then towards a “cold” region of space that is free of noise sources other than the cosmic background radiation. From the measured change in the received noise of the antenna system and knowledge of the noise temperature of the hot and cold noise sources, the ratio of \( G/T_e \) can be determined. A large disadvantage of this technique for a satellite antenna system is the need to transport and place the satellite in an outdoor environment where it can be directed towards the hot and cold radiation sources. Since the satellite with all of its antennas and electronic systems has been assembled and tested in a controlled clean environment, exposure to an outdoor range could cause damage or contamination of sensitive components.

Near-field measurement techniques have been developed, proven and are routinely used for the accurate measurement of antenna pattern, gain, directivity,
polarization, EIRP and Saturating Flux Density [1]. Work is currently underway to develop and implement near-field measurements to determine system group delay and End-to-End testing of satellite communication systems. With these developments and the successful implementation of the measurement of satellite system noise that will be described in this paper, all of the communication satellite testing could be performed on a near-field range without the need to move to a far-field or compact range. This would greatly reduce the time, cost and complexity of the testing process and avoid potential problems associated with the transportation and hazards of changing measurement environments.

II. PROPOSED MEASUREMENT AND ANALYSIS

The measurement and analysis technique for determining antenna noise and the ratio of gain to noise temperature that will be described in the following sections is very different than traditional approaches. The first difference is that the antenna gain and noise temperature are determined separately rather than as a ratio. The gain is determined from planar near-field measurements and the noise temperature or noise figure is determined from a separate measurement. The second difference is that the noise temperature is determined from a spectrum analysis processing that gives much better resolution and also removes the effect of leakage signals that can cause large errors in the measurement of low noise signals.

The determination of gain from planar near-field measurements is a standard process that is well established [1] and will not be reviewed in this paper. The uncertainty in antenna gain will depend on the gain standard and the measurement process and is typically on the order of ±0.1 to ±0.5 dB.

The originally proposed method for determining the system noise temperature [2] was to use the evanescent portion of the plane-wave spectrum derived from the regular near-field measurement on the antenna and receiver system where the signal transmitted by the probe was from a coherent source. Initial tests using this method identified some problems using the data from a coherent source. The evanescent spectrum from these measurements did contain the noise spectrum from the antenna loss and receiver noise, but it also included noise associated with the coherent source. The latter noise could not be separated from the receiver system noise and this caused errors in the final determination of receiver system noise properties. Another problem was that the proposed method using only one measurement of receiver noise power required a knowledge of the gain and bandwidth of the system to determine noise figure.

Because of these problems, the approach was modified to use a two-measurement Y-factor approach [3] and still use the spectrum analysis technique to give high resolution and discrimination of leakage effects. In the first measurement, a “cold” noise source is connected to the input port and the noise output of the system is determined using the spectrum analysis technique. A “hot” noise source is then connected to the input port and the noise power determined with the same analysis. The Y-factor equation is then used to determine the noise figure of the system. Since the Y-factor uses the ratio of the two noise powers, knowledge of the gain and bandwidth are not required. To develop the details of the measurement and analysis technique, real and simulated data was generated and analyzed for four different combinations of the components of a receiver system. The measurement system used for these initial tests was the Panther 9000 (P9K) receiver system since it is the receiver on the planar near-field range. It is not a satellite receiver system, but it can be used to validate the measurement and processing techniques. The four system combinations were:

1) Simulation of data to test the software.
2) The IF amplifier and detectors of the receiver.
3) The mixer, IF amplifier and detector combination.
4) The complete system including a radiating probe, receiving test antenna and the complete receiver.

In the first phase of tests simulated noise data with a known power level was produced and used to develop the processing scripts and verify that the dynamic range and resolution of the software was able to accurately process noise powers in the range between -40 and -180 dBm. The results of the tests using the simulated data were reported in the 2017 AMTA paper [2] and showed that the software was adequate and that the proposed analysis approach was sound.

Recently, measurements have been performed on subsystems of the receiver system and the noise power data generated was analyzed to produce noise figure results on these subsystems. The details of the measurement and analysis process are described in the following sections.

III. NOISE FIGURE MEASUREMENTS ON IF AMPLIFIER

The next phase of the measurement process used a noise source at the input to the 20 MHz IF amplifier of the P9K receiver as shown in Figure 2.

![Figure 2. Receiver system schematic with the noise source connected to the input of the IF amplifier.](image)

The cold source for these measurements was a 50-ohm load and the hot source was a commercial Noise Source (NS) with
an Excess Noise Ratio (ENR) of 21.5 dB. Analysis of the data with these two noise sources will produce the noise figure of the IF amplifier. Since there was no probe or antenna involved in these measurements, the measured amplitude and phase values were not actually planar near-field data obtained as a function of X and Y positions on a plane. However, to make use of the data recording, numerical processing, graphics and script analysis available in the NSI2000 software [4], the ratioed noise signal at the output of the receiver was recorded as if it was a planar near-field data file.

The position controlling software was operated in a simulation mode where there was no probe motion, and measurements of the amplitude and phase were acquired at the maximum speed of the receiver. In a typical measurement consisting of 251 “scans” in the y-direction with 251 points in each scan the total measurement took about 28 minutes. The amplitude for a typical measurement is illustrated in Figures 3 and 4. Phase was also measured. The labels of the X and Y axes are in meters since the data is recorded using the planar software, but the actual independent variables are time. The time for a “scan” in the y-dimension is 7 seconds and the time in the x-direction is 28 minutes. In the following discussion when the term “near-field” data is used, it will refer to recorded data as a function of time. The amplitude is recorded as the ratio of the noise output of the measurement channel to the coherent reference channel. For the data in Figures 3 and 4, the reference level was -41.6 dB and so the average noise power level was approximately -142 dBm.

The first step in the processing to determine the average noise power produced by the combination of the load and the internal noise of the receiver is the computation of a 2D Fourier transform to calculate the spectrum of the measured data. The spectrum for the data shown in Figures 3-4 can be seen in Figure 5. The axes are labeled Kx and Ky since the normal input data is from a planar near-field measurement. Since the measurement variables are time, the spectrum variable is actually frequency, but this does not cause a problem in the analysis. As expected for a noise signal the spectrum is nearly uniform, but there is a peak at (0,0) and higher amplitudes along the centerlines. These features are caused by leakage between the reference and measurement channels and if not accounted for will cause an error in the calculation of average noise power, especially for the cold source where the system noise is near the leakage level.

To determine the average noise power of the measured data and exclude the effect of the leakage signal, the power of the spectrum within a part of the spectrum area that does not have the leakage is first computed. The power of the spectrum within this partial region of k-space is

\[
P_{S_P} = \frac{\Delta k_x \Delta k_y}{4\pi^2} \sum_{k_{x, \text{min}}}^{k_{x, \text{max}}} \sum_{k_{y, \text{min}}}^{k_{y, \text{max}}} |D_T(k_x, k_y)|^2
\]

Figure 3. Noise amplitude for load termination on IF input.

Figure 4. Noise amplitude X-cut from 2D data array.

Figure 5. Spectrum of measured data showing the partial region used to compute the total power.
The thermal noise spectrum extends uniformly over all k-space but near (0,0) the leakage spectrum dominates. Since the noise spectrum is uniform over all k-space, its total power can be determined from the total power within the selected region defined by the rectangular boundaries in Figure 5 and a span correction. The span correction is the ratio of the total number of data points over all calculated k-space to the number of points within the selected region.

\[ \text{Span Correction} = \frac{NT_x NT_y}{NS_x NS_y} \]  

In Equation (2), \( NT_x \) and \( NT_y \) are respectively the total number of spectral points in calculated K-space; \( NS_x \) and \( NS_y \) are respectively the number of spectral points in the selected subsection of k-space. The total power over all calculated k-space is then

\[ PS_T = PS_p \times \text{Span Correction}. \]  

Using Parseval's theorem [5], the total power in the spectral domain is equal to the total power in the near-field measured data and therefore, the total and average power of the thermal noise in the measured data are respectively

\[ PNF_T = PS_T \quad PNF_A = \frac{PNF_T}{N_x N_y}. \]  

\( N_x \) and \( N_y \) are respectively the number of data points in the near-field data array.

To prove that the spectrum processing just described eliminates the effect of leakage, a series of simulated data files were produced with known levels of noise and leakage powers. Figure 6 shows the result for an extreme case where the input noise level was -120 dBm, the leakage level was -110 dBm and the processed result was -120.1 dBm. If the measured data is simply averaged, the results would have an error of 11 dB. This is an extreme case, but in the actual measurements, the observed leakages would have caused errors of 3-5 dB if not properly accounted for.

To complete the Y-factor measurement, the load termination at the input to the IF amplifier is replaced by a noise source with a known output noise power determined from its Excess Noise Ratio (ENR). The measurement and recording of a 2D data set is repeated and processed in the same way that the cold source power was analyzed. If possible, the hot noise source should produce an increase in the output noise power of at least 10 dB but it must not cause clipping or non-linearity in the system response. From the two processed average noise powers the Y-factor is computed.

\[ Y = \frac{PNF_A(\text{Hot})}{PNF_A(\text{Cold})} \]

The noise factor of the device under test, in this case the IF amplifier is then

\[ Y = \frac{PNF_A(\text{Hot})}{PNF_A(\text{Cold})} = kBG(T_h + T_c) = (T_h + T_c) \]

\[ T_c = \frac{T_h - YT_c}{Y - 1} \quad F = 1 + \frac{T_c}{T_0} \]

In the above, \( k \) is Boltzmann's constant, \( B \) the system bandwidth, \( G \) the system gain, \( T_h \) the effective noise temperature of the amplifier, \( T_c \) the noise temperature of the hot source, \( T_c \) the noise temperature of the cold source and \( T_0 = 290K \). Finally, \( F \) is the noise factor of the device under test.

The IF amplifier within the P9K is operated in a high and low gain mode with different noise figures for each mode. A number of measurements were performed for each mode with three different bandwidths differing by factors of ten. The results of these measurements along with comparison to the estimated noise figure from analysis of the circuit elements are summarized in Table I.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Measured</th>
<th>Standard Deviation</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>8.5 dB</td>
<td>0.1 dB</td>
<td>4.0 dB</td>
</tr>
<tr>
<td>Low</td>
<td>20.0 dB</td>
<td>0.4 dB</td>
<td>20.0 dB</td>
</tr>
</tbody>
</table>
The comparisons between the measured noise figures and those estimated by analysis are not close enough for all cases to verify the accuracy of the technique. However, the uncertainty in the analysis estimates have not been established. Additional comparisons and other analysis will be used to estimate the uncertainty in the measurement technique.

IV. MEASUREMENTS AT THE MIXER INPUT

In the next series of measurements, the hot noise source along with the amplifier and attenuator is connected to the input of the mixer as shown in Figure 7.

Noise data files were produced and analyzed as described in the last section, but in this case, the frequency of the coherent reference signal and the local oscillator were varied during the measurement to produce noise figure results over a range of frequencies. Nine frequencies were used between 8.2 and 12.2 GHz with 0.5 GHz steps. Since the mixer had a higher noise figure than the IF amplifier, a hot source with a larger effective noise temperature was required to produce a Y-factor of at least 10 dB. The NS with and ENR of 21.5 dB was combined with an Auxiliary Amplifier (AA) and a 10 dB Attenuator (ATT) to produce an ENR of 44.3 dB. The amplifier gain was 32.7 dB and its noise figure was specified as 5 dB. The resulting hot noise power was determined from the spectrum processing of the measured data and is show in Figure 8. The cold source power was measured with the load termination on the mixer input and that result is also shown in Figure 8.

Using the hot and cold noise powers, the ENR of the cascaded NS/AA/ATT combination and Equation (6) the noise figure of the mixer over the frequency range was obtained as shown in Figure 9, for two different attenuators.

The AA amplifier that is placed between the noise source and the attenuator in Figure 7, has a noise figure of approximately 5 dB and it should have a smaller variation with frequency than the mixer. Measurement of its noise figure should be a better test of the measurement and processing than the mixer. When hot source noise power measurements are made with the cascaded NS/AA/ATT as shown in Figure 7, the resulting hot power data can be used to determine the noise figure of the mixer, the AA or the cascaded AA/ATT/Mixer combination as the Device Under Test (DUT). The DUT is specified by defining which components constitute the noise source and therefore the

![Figure 7. Schematic of receiver with cascaded noise source input to the mixer.](image1)

![Figure 8. Hot and cold noise power results for input to the mixer.](image2)

![Figure 9. Noise Figure results for the mixer.](image3)
ENR of the hot source and by selection of the input terminal for the cold source load. The different options are summarized in Table II.

**TABLE II. HOT SOURCE COMPONENTS AND COLD SOURCE INPUT LOCATION FOR DIFFERENT DEFINITIONS OF THE DEVICE UNDER TEST.**

<table>
<thead>
<tr>
<th>DUT</th>
<th>Hot Source Components</th>
<th>Cold Source Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixer</td>
<td>NS/AA/ATT</td>
<td>Mixer Input</td>
</tr>
<tr>
<td>ATT/Mixer</td>
<td>NS/AA</td>
<td>Attenuator</td>
</tr>
<tr>
<td>AA/ATT/Mixer</td>
<td>NS</td>
<td>AA Input</td>
</tr>
<tr>
<td>AA Amplifier</td>
<td>NS</td>
<td>AA Input</td>
</tr>
</tbody>
</table>

To obtain the noise figure of the amplifier, the noise figure results for the Attenuator/Mixer combination must be used to remove the contribution of these components from the cascaded noise figure of the AA/ATT/Mixer results using the equation,

\[ F_C = F_{AA} + \frac{F_{M/ATT}}{G_{AA}} \]  

(7)

In Equation (7) \( F_C \) is the noise factor for the cascaded combination of the amplifier, the attenuator and the mixer. \( F_{AA} \) is the noise factor for the amplifier. \( F_{M/ATT} \) is the noise factor of the attenuator and mixer combination and \( G_{AA} \) is the gain of the amplifier. The noise figure results for the amplifier are tabulated in Table III.

**TABLE III. NOISE FIGURE RESULTS FOR AMPLIFIER**

<table>
<thead>
<tr>
<th>Freq (GHz)</th>
<th>8.2</th>
<th>8.7</th>
<th>9.2</th>
<th>9.7</th>
<th>10.2</th>
<th>10.7</th>
<th>11.1</th>
<th>11.7</th>
<th>12.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Fig (dB)</td>
<td>6.1</td>
<td>6.2</td>
<td>6.2</td>
<td>5.6</td>
<td>4.8</td>
<td>5.6</td>
<td>6.2</td>
<td>5.3</td>
<td>5.9</td>
</tr>
</tbody>
</table>

The comparison of the specified noise figure of 5 dB and the measured results are the best indication of the uncertainty in the measurement and analysis process. Assuming that the manufacturer’s specifications have an uncertainty of 0.5 dB, the measurement uncertainty is approximately the same. A better estimate of the uncertainty will be derived by a careful evaluation of each part of the measurement and analysis process. This will be done in the near future.

V. FUTURE MEASUREMENTS

To complete the development of the process to measure the noise figure of the antenna and receiver combination, measurements on an antenna placed on the planar near-field range must be performed and the measurement details and analysis for the total system developed. This is likely a complex and challenging task and will require the same kind of tests and verification that have been used to develop the technique thus far. Some of the analysis has been developed and measurements are planned in the near future.

VI. CONCLUSIONS

A new technique for measuring antenna noise and G/T has been described, illustrated and verified with measurements on the receiver system at three locations in the amplifier, mixer, and IF amplifier chain. The technique uses a spectrum analysis process that eliminates the effect of leakage signals in the receiver mixer and amplifier stages. Guidelines have been developed to specify the ENR of the noise sources to use to achieve the best accuracy and avoid clipping and non-linearity in the receiver amplifier and detection system.

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