Deep Space Network Receiving Systems' Operating Noise Temperature Measurements

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The operating noise temperature (T_{op}) of radio frequency (RF) receiving systems can be calculated using measured power ratios obtained when switching between calibration loads at different temperatures. One method uses the Rayleigh–Jeans (R-J) approximation to determine the noise temperature of the calibration loads [4–6]. An exact calculation uses Planck's radiation law [4–6]. We show that small receiver (T_e) and antenna (T_i) noise temperature errors resulting from the use of the R-J approximation are self-compensating, and the simpler approximation can be used with an insignificant T_{op} error. The accuracy of T_{op}, consisting of the sum of the calibrated antenna noise temperature and the receiver noise temperature, is adequate using the simplified R-J approximation (physical temperature) at frequencies as high as 100 GHz.

I. Introduction

The Deep Space Network (DSN) requires accurate system operating noise temperature calibrations [1,2] for validating the low-noise performance needed for receiving weak signals from distant spacecraft. A receiving system's operating noise temperature in kelvins is given at a specified frequency by [3, p. 766]

$$T_{op} = \frac{N_o}{kG_s} \tag{1}$$

where

$N_o =$ output noise power spectral density, W/Hz

$k =$ Boltzmann's constant $= 1.38065 \times 10^{-23}$, J/K

$G_s =$ delivered output power/input available signal power, ratio

and at a defined reference plane. T_{op} is the sum of the source input and the receiver effective noise temperatures:

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[1] IND Technology Program Office.

[2] Spacecraft Telecommunications Equipment Section.

[3] Communications Ground Systems Section.

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$$T_{op} = T_i + T_e \tag{2}$$

where

$T_i =$ input source (includes matched termination, load or antenna) noise temperature, K

$T_e =$ (receiver) effective input noise temperature, K

T_i and T_e are defined at the same reference plane as T_{op}. T_e is generally measured using two loads [2], replacing T_i in Eq. (2) with loads of known noise temperatures, as shown in Fig. 1(a). If the sky temperature is known, one of the loads can be replaced with an antenna feed horn, usually pointed at zenith. In this manner, T_e can be calibrated using a single calibration load, usually an ambient aperture load, as shown in Fig. 1(b); the antenna feed horn and sky serve as a cold calibration load. Also, in principle, T_e could be determined from knowledge of the receiver's components and design. Knowing T_e,

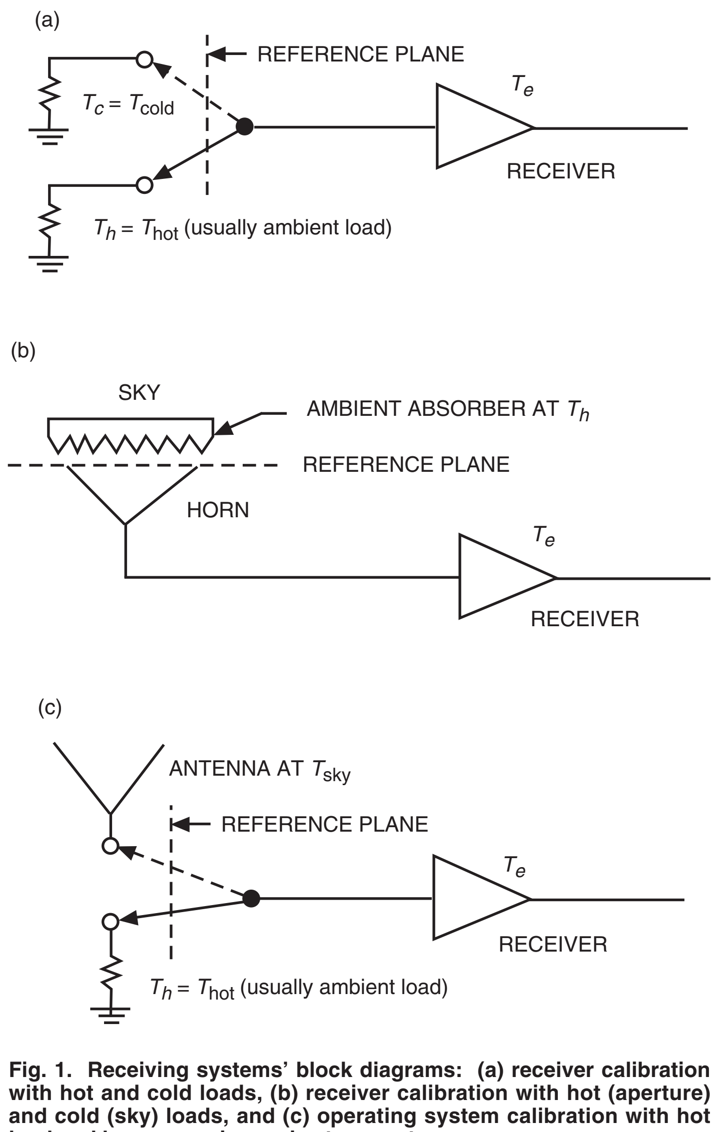

Fig. 1. Receiving systems' block diagrams: (a) receiver calibration with hot and cold loads, (b) receiver calibration with hot (aperture) and cold (sky) loads, and (c) operating system calibration with hot load and known receiver noise temperature.

T_{op} can be evaluated by switching [1] between the sky and the hot load (usually an ambient load), as shown in Fig. 1(c). DSN considerations and procedures for determining T_i, T_e, and T_{op} are as follows:

(1) The calibration load noise temperature is obtained assuming the Rayleigh–Jeans (R-J) low-frequency approximation [4–6] and is equal to its physical (*phy*) temperature,

$$T \sim T_n^{\text{R-J}} = T_{phy} \tag{3}$$

The noise power, in watts, in terms of the effective physical temperature is given by

$$P_n = N_o B = kTB \tag{4}$$

where $B =$ bandwidth, Hz.

(2) The calibration load noise temperature is corrected in terms of the physical temperature, T, by Planck's law [4–6] at higher frequencies:

$$T_n^{\text{Planck}} = \frac{\dfrac{hf}{k}}{\exp\left(\dfrac{hf}{kT}\right) - 1} \tag{5}$$

where

$h =$ Planck's constant, 6.62607×10^{-34}, J-s

$f =$ frequency, Hz

Figure 2 shows Planck's law noise-temperature 'falloff' as a function of frequency and temperature. For a load at a physical temperature of 10 K, the noise temperature reduction is 0.24 K at 10 GHz and 2.21 K at 100 GHz. This suggests a possible need to apply Planck's law with DSN microwave systems' calibration loads.

(3) Noise corrections with frequency using Eq. (5) are incorporated into the format of Eq. (4) for fixed-frequency computations. The available thermal noise power from a load is calculated using Eq. (4) with this high-frequency corrected noise temperature replacing the physical temperature.

(4) T_i, T_e, and T_{op} are calculated with the measured power ratios (Y-factors) resulting from switching between the hot (T_h) and cold (T_c) calibrated loads and the system temperature on the sky (T_{op}), using for the noise temperatures of the calibrated loads either the R-J low-frequency approximation, Eq. (3), or the more precise Planck corrected temperature, Eq. (5).

We propose that the DSN use only the physical temperatures of the calibrated loads, not corrected with Planck's law for DSN operating frequencies. This simplified approach provides very accurate solutions for T_{op} with present and anticipated future DSN microwave frequencies and calibration loads.

The analysis of the accuracy of using the physical temperatures of the calibration loads without Planck's law correction assumes matched systems with linear receivers. Errors due to receiver and calibration load mismatches and to receiver non-linearity are not addressed.

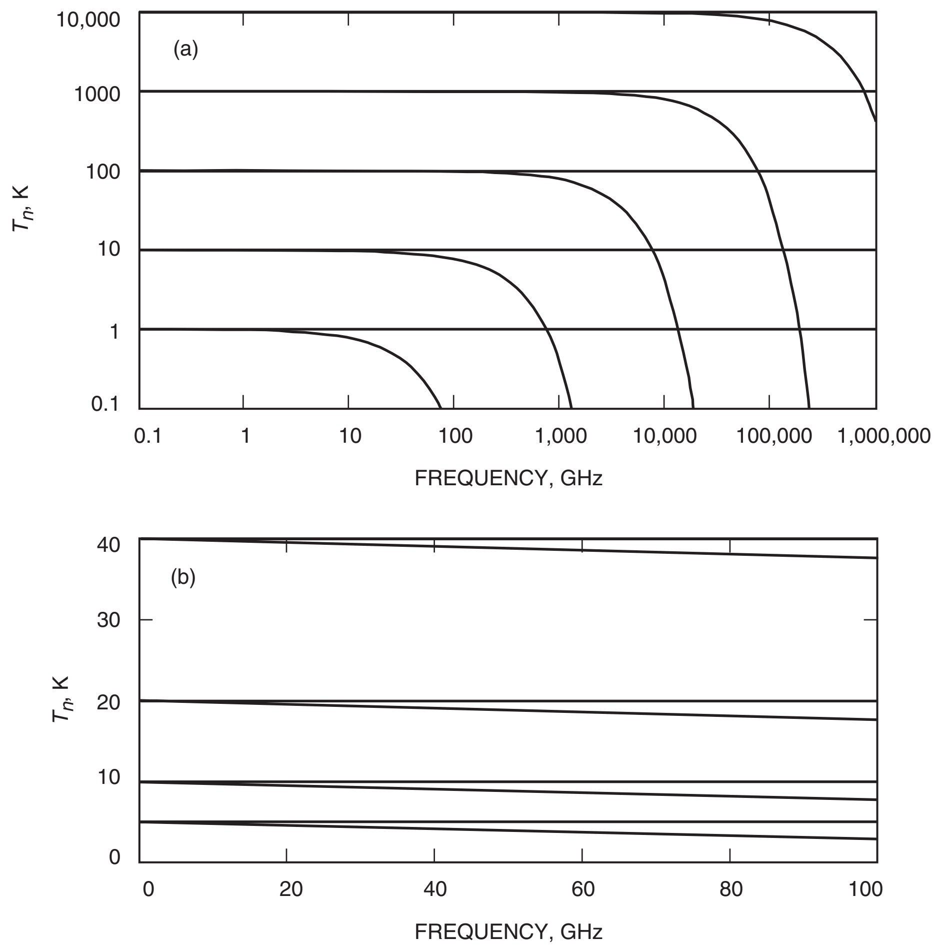

Fig. 2. Calibration load noise (T_n) temperatures, showing the R-J (physical temperature) low-frequency (horizontal lines) approximation and Planck's law reduced output as functions of frequency for (a) a broad range of frequencies and (b) the frequency range of more interest to the DSN.

II. Analysis of Measurements

The key equations for determining T_e, T_{op}, and T_{ant} (T_i switched to the antenna) using calibrated loads' noise temperatures [1] are [see Fig. 1(a)]

$$T_e = \frac{T_h - Y_e T_c}{Y_e - 1} \tag{6}$$

and [see Fig. 1(c)]

$$T_{op} = \frac{T_h + T_e}{Y_a} \tag{7}$$

where

$Y_e =$ Y-factor power-ratio measurement switching the receiver input between the hot and cold loads

$Y_a =$ Y-factor power-ratio measurement switching the receiver input between the hot load and the antenna

and, with Eq. (2),

$$T_{ant} = T_{op} - T_e \tag{8}$$

Combining Eqs. (6) and (7),

$$T_{op} = (T_h - T_c)\frac{Y_e}{Y_a(Y_e - 1)} = (T_h - T_c)Y \tag{9}$$

where $Y = Y_e/[Y_a(Y_e - 1)]$.

Equation (9) can be analyzed with T_h and T_c defined by either uncorrected (phy) or corrected values using Planck's law. The difference between the R-J (phy) and Planck solutions is

$$\Delta T_{op} = T_{op}^{phy} - T_{op}^{\text{Planck}} \tag{10}$$

so that

$$\Delta T_{op}, \% = 100\left[1 - \frac{T_h^{\text{Planck}} - T_c^{\text{Planck}}}{T_h^{phy} - T_c^{phy}}\right] \tag{11}$$

For the case with T_e determined by the configuration shown in Fig. 1(b), where sky temperature is known, Eqs. (6) and (11) are valid, with the horn plus sky serving as the cold load.

III. Comparison

A plot of ΔT_{op}, percent, is shown in Fig. 3, obtained with Eq. (11), assuming $T_h^{phy} = 290$ K, with values of T_c^{phy} of 4, 10, and 80 K, as a function of frequency, up to 100 GHz. The biggest difference for this range of values occurs at 100 GHz with a 4-K cold load, i.e., with the highest frequencies and the lowest calibration load temperatures (lowest value for $T_h^{phy} \times T_c^{phy}$). Table 1 also shows these differences, assuming $T_h^{phy} = 290$ K and $T_c^{phy} = 10$ K for DSN present frequency values of 8.5 GHz, 32 GHz, and beyond this at 100 GHz. The small values for ΔT_{op}, percent, at these frequencies are not significant for DSN system error budgets.

The difference in the antenna temperature solution T_{ant} using the physical versus the Planck noise temperatures is an increase of 0.24 K at 10 GHz. The corresponding value calculated for T_e is decreased by almost this same amount, about $hf/2k$. This results in only a very small difference for T_{op}, the sum of the antenna and receiver noise temperatures. The important key parameter is T_{op}, which determines the signal-to-noise ratio for signal reception from the spacecraft missions. The differences in T_{ant} and T_e are secondary to the real objective of determining T_{op}.

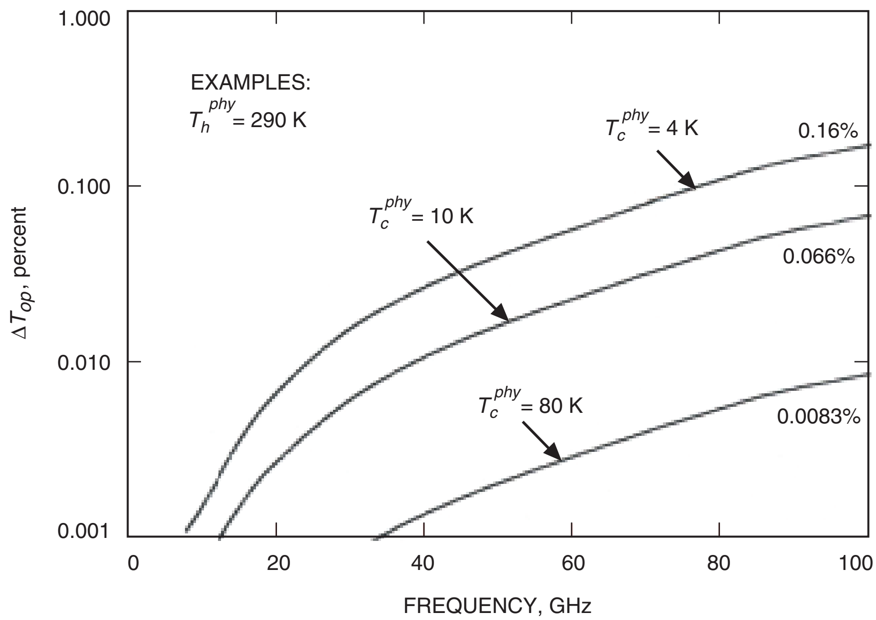

Fig. 3. Plot of the ΔT_{op}, percent, determinations using calibration load physical temperatures uncorrected (T_{phy}) or corrected (T_{Planck}) for a range of frequencies and load temperatures.

Table 1. Difference in T_{op}, percent, using calibration loads at 290 and 10 K with both loads' noise temperatures determined by their physical temperature (R-J) or corrected with Planck's law.

ΔT_{op}, %	Frequency, GHz		
	8.5	32	100
ΔT_{op}, %	4.8×10^{-4}	6.8×10^{-3}	6.6×10^{-2}

IV. Summary

Using the physical temperatures for the calibration loads without Planck's law correction is simple and accurate, as indicated in the above examples.

This simplified procedure using only the physical temperature (R-J) noise approximation is recommended for evaluating DSN operational microwave low-noise system operating noise temperatures. This includes S-band (2.4 GHz) and X-band (8.5 GHz), as well as the upgrade to Ka-band (32 GHz) for deep-space missions ground communications support.

References

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