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Correction of High-Frequency Noise-Temperature Inaccuracies

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Deep-space mission data rates to Earth are limited by the system operating noise-temperature (T_{op}) *performance of the DSN. This article addresses some of the techniques and definitions used for measuring and reporting the effective noise temperature of receivers* (Te) *and* T_{op} *of the DSN's ground receiving systems. Calibration loads are used to measure* T_{op} *of the DSN antennas. At 32 GHz, a calibration load cooled to 2-K physical temperature requires a correction of 0.67 K to determine the noise temperature. Using corrected noise temperature for the calibration loads results in the correct values for* T_{op} *such that the total system noise power can be defined by* $Pn = kT_{op} B$, *as required for DSN telecommunications design control tables.* T_{op} *and* Te *should not be converted to equivalent physical temperatures.*

I. Introduction

System operating noise temperature (T_{op}) is very important to the DSN; deep-space mission data rates to Earth are limited by the DSN's T_{op} performance. The DSN uses design control tables to document parameters of the spacecraft-to-ground end-to-end telecommunications system. A key parameter affecting the data quality is the signal-to-noise ratio (SNR) of the signal received by the DSN. The received SNR is proportional to DSN antenna gain divided by the system operating noise temperature (G/T_{op}).

This article addresses some of the techniques and definitions used for measuring and reporting the effective noise temperature of receivers (Te) and T_{op} of the DSN's ground receiving systems. Proper evaluation of the noise-temperature performance of high-frequency, low-noise amplifiers (LNA's), such as Ka-band (32-GHz) masers currently under development in the DSN Advanced Systems Program, requires the use of frequency-dependent corrections for the noise power available from the calibration loads. At 32 GHz, a calibration load cooled to 2 K has an available noise power equivalent to 1.33 K; a correction of 0.67 K is needed.

An analysis for optimizing the testing configuration for LNA noise temperature is provided in [1]; frequency-dependent corrections are not used. Frequency-dependent

[4] can give large errors. Using Eq. (2) with the equivalent corrected noise temperature results in

$$Pn = kTnB \tag{4}$$

Use of the corrected equivalent noise temperature is appropriate for telecommunications design control tables, such as used in the DSN [5].

Calibration of the corrected equivalent noise temperature of an LNA using a load with physical T and a noise source (usually a noise diode connected to the LNA through a directional coupler between the LNA and the load) with temperature TND, all referred to the amplifier input, requires solution of

$$Te = \frac{TND}{Y - 1} - Tn \tag{5}$$

where

$Y =$ power ratio at the output of follow-up amplifiers with the noise source turned on and off

$TND =$ noise source excess noise at amplifier input, K

$Tn =$ equivalent noise temperature of source at physical temperature T, K

Measurement configurations using cooled attenuators located between the load and the LNA are evaluated using Eq. (5) by analyzing an equivalent TND and Tn defined at the LNA input. Similarly, using two calibration loads and a cooled attenuator requires the evaluation of corrected equivalent noise temperatures $T1$ and $T2$ for the loads, defined at the LNA input, and the solution of

$$Te = \frac{T2 - T1Y}{Y - 1} \tag{6}$$

where $Y =$ power ratio obtained at output of follow-up amplifiers switching between $T1$ and $T2$.

The value Te, as measured with Eqs. (5) and (6), contains the follow-up amplifier noise temperature Tf. The LNA noise temperature, $TLNA$, requires the correction

$$TLNA = Te - Tf \tag{7}$$

For most system applications, especially when the first amplifier has more than a 30-dB gain, Tf is small compared with Te. For system applications, Te is the significant parameter.

III. Results

Equations (5) and (6) have been programmed in Supercalc 4. Assuming the load and noise source are separated from the amplifier by an attenuator with loss L at physical temperature Tp, Figs. 1 and 2 show the solutions using Eq. (5). Using Eq. (6), Figs. 3 and 4 assume the loads are separated from the amplifier by the attenuator. The values TND, L, Tp, $T1$, $T2$, and Y are considered known. Equation (3) is used to correct $T1$, $T2$, and TL for frequency. The equation $TL = Tp\ (1 - 1/L)$ represents the attenuator noise-temperature contribution. The Eq. (3) correction is applied to Tp, not TL.

For the purposes of this article, $f = 0.001$ GHz is used as the dc ($f = 0$) case. The results shown in Fig. 1, at dc, assume $Y = 2.1136$, appropriate for $Te = 4.0$ K and the other input parameters assumed and used in [2]. Figure 2 shows the result of operating at $f = 32$ GHz with all other inputs unchanged. The errors in Te due to various parameter changes are virtually unchanged with frequency and also agree with [2] (Fig. 3 for $L = 20$ dB). However, Te increases from 4.00 to 4.67 K at $f = 32$ GHz relative to dc. Figures 3 and 4 have similar results, with Te increasing from 4.00 K at dc to 4.68 K at 32 GHz.

IV. Conclusion

Using loads with corrected equivalent noise temperatures results in the proper value for the amplifier noise temperature, Te. The value Te in this case is the equivalent noise temperature, not the physical temperature. From Eq. (3), the physical temperature is given by

$$T = \frac{hf/k}{ln((hf/kTn) + 1)} \tag{8}$$

Equation (8) is useful for converting a measured noise temperature, Tn, to a physical temperature, T. An example of this is using T, the physical or thermodynamic temperature, for reporting the cosmic background radiation temperature. The cosmic physical or thermodynamic temperature obtained with Eq. (8) after measuring the noise temperature is independent of frequency.

The physical or thermodynamic temperature is not appropriate for reporting measurements of amplifier noise temperature, Te, for such purposes as the DSN telecommunications-link design tables. In addition, quantum noise is inherent to low-noise amplifiers and is included in

at S- and X-bands presently used in the DSN (T reduced by 0.2 K at 8.4 GHz for a 300-K load) but is important for future Ka-band operation (T reduced by 0.77 K at 32 GHz

Table 1. Examples of errors in treating *Tc* as a constant with changes of frequency, *f*, and the calibration load physical temperature, *T*.

f, GHz	T, K	Tc, K	Error in Tc, K due to 10-percent change in T
8	2	0.19	0.0006
8	80	0.19	<0.0001
8	300	0.19	<0.0001
32	2	0.67	0.0087
32	80	0.77	0.0002
32	300	0.77	<0.0001

INPUT --

T=	300	TND=	1000	Tp=	2	f,GHz=	.001
DT=	.1	DTND=	50	DTp=	.1	Y=	2.1136
DYLDB,A=	.01	DLDB,A=	.01	B,MHZ=	50	DYG=	.01
DYLDB,B=	.01	DLDB,B=	.03	T,SEC=	1	L=	100

RESULTS -------------"Te error (DTe)----------------------

DL	.78622	DTp	.09900	DYG	.328408
DT	.00100	DYL	.16455	SUM	1.83299
DTND	.44899	DYN	.00482	RMS	.982087

CALCULATIONS ---

L,DB= 20 Y,DB= 3.2502 DYN= .00014 hf/k= .000048

NOMINAL		DELTA CALCULATIONS ---------------		
		L+DL,DB=	T+DT=	TN+DTN
		20.61	300.1	1050
		L+DL=		
		115.08		
TL=	1.98	1.9826	1.98	1.98
TLn=	1.9800	1.9826	1.9800	1.97998
TnR=	3.0000	2.6069	3.0010	3.00000
T=	4.9800	4.5895	4.9810	4.97998
TND=	10	8.6896	10	10.5
Te=	3.9999	3.2137	3.9989	4.44890

DELTA CALCULATIONS,CONT --------------------------------

	Tp+DTp=	Y+DYL,DB=	Y(1+2*DYN)=	Y(1+2*DYG)=
	2.1	3.2927	2.1142	2.15587
		Y+DY=		
		2.1344		
TL=	2.079	1.98	1.98	1.98
TLn=	2.0790	1.9800	1.9800	1.97998
TnR=	3.0000	3.0000	3.0000	3.00000
T=	5.0790	4.9800	4.9800	4.97998
TND=	10	10	10	10
Te=	3.9009	3.8354	3.9951	3.67150

DEFINITIONS

Te=LNA NOISE TEMP	Tp=PHY TEMP OF L
L=ATTEN LOSS	DTp=DELTA Tp
DL=DELTA L	TND=NOISE DIODE
TL=TEMP CONTR OF L	DTND=DELTA NOISE DIODE
Y=Y FACTOR	T=LOAD TEMP
DYL=DELTA Y FACTOR,LINEARITY	DT=DELTA T
DYN=DELTA Y, RADIOMETER NOISE (T,B)	Tn=T CORRECTED FOR FREQ
DYG=DELTA Y, RADIOMETER GAIN DELTA G	TnR=Tn AT REF

Fig. 1. Supercalc 4 computer program NOISE2ND printout of the measured noise temperature and errors of a low-noise amplifier using a load, noise diode, and cooled attenuator at 0.001 GHz (dc).

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INPUT   ----------------------------------------------------
        T=     300      TND=    1000     Tp=       2   f,GHz=       32
       DT=      .1     DTND=      50    DTp=      .1      Y=    2.1136
DYLDB,A=       .01  DLDB,A=     .01  B,MHZ=      50    DYG=       .01
DYLDB,B=       .01  DLDB,B=     .03  T,SEC=       1      L=       100

RESULTS  --------"Te error (DTe) ---------------------------
       DL .78635              DTp .10794                DYG .328408
       DT .00100              DYL .16455                SUM 1.84206
     DTND .44899              DYN .00482                RMS .983130

CALCULATIONS  ---------------------------------------------
   L,DB=      20     Y,DB= 3.2502   DYN= .00014   hf/k=   1.536
         NOMINAL         DELTA CALCULATIONS ---------------
                         L+DL,DB=         T+DT=           TN+DTN
                           20.61          300.1             1050
                          L+DL=
                          115.08
      Tpn= 1.3294         1.3294         1.3294          1.32935
      TLn= 1.3161         1.3178         1.3161          1.31606
      TnR= 2.9923         2.6002         2.9933          2.99233
        T= 4.3084         3.9180         4.3094          4.30838
      TND=     10         8.6896             10             10.5
       Te= 4.6715         3.8852         4.6705          5.12050

DELTA CALCULATIONS,CONT   ---------------------------------
          Tp+DTp=        Y+DYL,DB=    Y(1+2*DYN)=    Y(1+2*DYG)=
             2.1          3.2927         2.1142          2.15587
                           Y+DY=
                          2.1344
      Tpn= 1.4384         1.3294         1.3294          1.32935
      TLn= 1.4240         1.3161         1.3161          1.31606
      TnR= 2.9923         2.9923         2.9923          2.99233
        T= 4.4163         4.3084         4.3084          4.30838
      TND=     10             10             10               10
       Te= 4.5636         4.5070         4.6667          4.34309

DEFINITIONS                                  Tpn=Tp CORRECTED FOR FREQ
Te=LNA NOISE TEMP                            Tp=PHY TEMP OF L
L=ATTEN LOSS                                 DTp=DELTA Tp
DL=DELTA L                                   TND=NOISE DIODE
TL=TEMP CONTR OF L                           DTND=DELTA NOISE DIODE
Y=Y FACTOR                                   T=LOAD TEMP
DYL=DELTA Y FACTOR,LINEARITY                 DT=DELTA T
DYN=DELTA Y, RADIOMETER NOISE (T,B)          Tn=T CORRECTED FOR FREQ
DYG=DELTA Y, RADIOMETER GAIN DELTA G         TnR=Tn AT REF
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Fig. 2. Supercalc 4 computer program NOISE2ND printout of the measured noise temperature and errors of a low-noise amplifier using a load, noise diode, and cooled attenuator at 32 GHz.

INPUT --

T2=	300	T1=	80	Tp=	2	f,Ghz=	.001
DT2=	.1	DT1=	1	DTp=	.01	Y=	2.5942
DYLDB,A=	.01	DLDB,A=	.01	B,MHZ=	50	DYG=	.01
DYLDB,B=	.01	DLDB,B=	.03	T,SEC=	1	L=	10

RESULTS --------------- TE error (DTE) ---------------------

DL	.41335	DTP	.00900	DYG	.434972
DT2	.00627	DYL	.26228	SUM	1.29495
DT1	.16273	DYN	.00635	RMS	.674902

CALCULATIONS --

L,DB= 10 Y,DB= 4.1400 DYN= .00014 hf/k= .000048

NOMINAL	DELTA CALCULATIONS	---------------	
	L+DL,DB=	T2+DT2=	T1+DT1=
	10.31	300.1	81
	L+DL=		
	10.740		
TL= 1.8	1.8138	1.8	1.8
TLn= 1.8000	1.8138	1.8000	1.79998
T2nR= 30.000	27.933	30.010	30.0000
T2 31.800	29.747	31.810	31.8000
T1nR= 8.0000	7.4489	8.0000	8.10000
T1 9.8000	9.2626	9.8000	9.89997
Te= 4.0001	3.5867	4.0063	3.83732

DELTA CALCULATIONS,CONT ---------------------------------

Tp+DTp=	Y+DYL,DB=	Y(1+2*DYN)=	Y(1+2*DYG)=
2.01	4.1914	2.5949	2.64608
	Y+DY=		
	2.6251		
TL= 1.809	1.8	1.8	1.8
TLn= 1.8090	1.8000	1.8000	1.79998
T2nR= 30.000	30.000	30.000	30.0000
T2 31.809	31.800	31.800	31.8000
T1nR= 8.0000	8.0000	8.0000	8.00000
T1 9.8090	9.8000	9.8000	9.79997
Te= 3.9911	3.7378	3.9937	3.56508

DEFINITIONS

Te=LNA NOISE TEMP	Tp=PHY TEMP OF L
L=ATTEN LOSS	DTp=DELTA Tp
DL=DELTA L	T1=COLD LOAD TEMP
TL=TEMP CONTR OF L	DT1=DELTA T1
Y=Y FACTOR	T2=HOT LOAD TEMP
DYL=DELTA Y FACTOR,LINEARITY	DT2=DELTA T2
DYN=DELTA Y, RADIOMETER NOISE (T,B)	Tn=T CORRECTED FOR FREQ
DYG=DELTA Y, RADIOMETER GAIN DELTA G	TnR=Tn AT REF

Fig. 3. Supercalc 4 computer program NOISE2LD printout of the measured noise temperature and errors of a low-noise amplifier using two loads and a cooled attenuator at 0.001 GHz (dc).

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INPUT  ------------------------------------------------
    T2=    300      T1=      80    Tp=      2  f,Ghz=      32
   DT2=     .1     DT1=       1   DTp=    .01      Y=  2.5942
DYLDB,A=   .01  DLDB,A=     .01 B,MHZ=     50    DYG=     .01
DYLDB,B=   .01  DLDB,B=     .03 T,SEC=      1      L=      10

RESULTS ------------------ TE error (DTE) ------------------
      DL .41400            DTP .00857             DYG .434968
     DT2 .00627            DYL .26228             SUM 1.29516
     DT1 .16272            DYN .00635             RMS .675288

CALCULATIONS ----------------------------------------------
   L,DB=      10    Y,DB= 4.1400   DYN= .00014   hf/k=   1.536
         NOMINAL        DELTA CALCULATIONS ---------------
                        L+DL,DB=        T2+DT2=        T1+DT1=
                          10.31          300.1              81
                          L+DL=
                         10.740
     Tpn= 1.3294         1.3294         1.3294         1.32935
     TLn= 1.1964         1.2056         1.1964         1.19642
    T2nR= 29.923         27.862         29.933         29.9233
      T2= 31.120         29.067         31.130         31.1197
    T1nR= 7.9234         7.3776         7.9234         8.02344
      T1= 9.1199         8.5832         9.1199         9.21986
      Te= 4.6801         4.2660         4.6863         4.51733

DELTA CALCULATIONS,CONT   ---------------------------------
         Tp+DTp=        Y+DYL,DB=     Y(1+2*DYN)=    Y(1+2*DYG)=
            2.01         4.1914         2.5949         2.64608
                          Y+DY=
                         2.6251
     Tpn= 1.3389         1.3294         1.3294         1.32935
     TLn= 1.2050         1.1964         1.1964         1.19642
    T2nR= 29.923         29.923         29.923         29.9233
      T2= 31.128         31.120         31.120         31.1197
    T1nR= 7.9234         7.9234         7.9234         7.92345
      T1= 9.1284         9.1199         9.1199         9.11986
      Te= 4.6715         4.4178         4.6737         4.24508

DEFINITIONS                                  Tpn=Tp CORRECTED FOR FREQ
Te=LNA NOISE TEMP                            Tp=PHY TEMP OF L
L=ATTEN LOSS                                 DTp=DELTA Tp
DL=DELTA L                                   T1=COLD LOAD TEMP
TL=TEMP CONTR OF L                           DT1=DELTA T1
Y=Y FACTOR                                   T2=HOT LOAD TEMP
DYL=DELTA Y FACTOR,LINEARITY                 DT2=DELTA T2
DYN=DELTA Y, RADIOMETER NOISE (T,B)          Tn=T CORRECTED FOR FREQ
DYG=DELTA Y, RADIOMETER GAIN DELTA G         TnR=Tn AT REF
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Fig. 4. Supercalc 4 computer program NOISE2LD printout of the measured noise temperature and errors of a low-noise amplifier using two loads and a cooled attenuator at 32 GHz.