Minimizing Noise-Temperature Measurement Errors

C. T. Stelzried
TDA Technology Development Section

An analysis of noise-temperature measurement errors of low-noise amplifiers has been performed. Results of this analysis can be used to optimize measurement schemes for minimum errors. For the cases evaluated, the effective noise temperature (Te) of a Ka-band maser can be measured most accurately by switching between an ambient and a 2-K cooled load without an isolation attenuator. A measurement accuracy of 0.3 K was obtained for this example.

I. Introduction

An analysis of low-noise amplifier (LNA) noise-temperature measurement errors is performed based on the Y-factor (power ratio measurement) method [1]. The results provide a guide for selecting a measurement scheme based on minimizing errors. The individual error sources are identified.

Load (input source termination) high-frequency noise-temperature corrections [2,3] are not addressed in this article because the effect upon the error analysis is minimal. For example, at 32 GHz, the high-frequency noise-temperature correction effectively reduces the noise temperature of a load at 2-K physical temperature by 0.67 K. The effect of this on the noise-temperature measurement error for the optimum case analyzed in this article, case 4 in Table 1, with no attenuator loss, is 0.03 K. This is determined using the equations and computer program as described, with the load noise temperature reduced 0.67 K. This small error is acceptable for the purpose of this article.

The effects of microwave component mismatch errors and receiver nonlinearity are not analyzed in this article.

II. Analysis

Two noise-temperature measurement schemes, shown in Figs. 1 and 2, are analyzed. Figure 1 shows the Y factor measured with the noise source on and off. The scheme in Fig. 2 requires that the Y factor be measured while switching between two loads at different temperatures.

The following equations were used in a Supercalc 4 spreadsheet computer program to analyze the noise-temperature measurement errors as a function of attenuator setting L, in dB. The measurement errors are determined by differencing Te using nominal and perturbed parameter values. The amplifier noise-temperature differences (measurement errors) are shown as summed (worst-case) and rms.

Both the Y-factor measurement and the attenuator values are assigned errors of the form dB, A, and dB, B, where A represents a fixed error and B represents a fractional or percentage error per dB. The terms used in the program associated with Eqs. (1) and (2) are defined at the bottoms of Figs. 3, 5, 7, 9, and 11. (Figures 4, 6, 8, 10, and 12 plot the data presented in each preceding figure.) For Fig. 1, using the noise source,

$$Y = \frac{(T/L) + (Tn/L) + TL + Te}{(T/L) + TL + Te} \quad (1)$$

and

$$Te = \frac{Te}{L(Y-1)} - (T/L) - Tp(1 - 1/L) \quad (2)$$

For Fig. 2, using two loads at different temperatures,

$$Y = \frac{(T2/L) + TL + Te}{(T1/L) + TL + Te} \quad (3)$$

and

$$Te = \frac{T2 - T1Y}{L(Y-1)} - Tp(1 - 1/L) \quad (4)$$

where for both cases,

$$TL = Tp(1 - (1/L))$$

III. Results

Table 1 shows selected results for Eq. (2), Figs. 3 and 5 (cases 1 and 2), and Eq. (4), Figs. 7, 9, and 11 (cases 3, 4, and 5). Assumed parameter and error values are indicated in the figures. A 1-sec measurement integration time, 50-MHz amplifier bandwidth, designated amplifier gain change (the higher gain change due to a different load match effect for $L = 0$ dB), and 5-percent noise-source accuracy parameters are used. The noise source might be calibrated more accurately by a standards laboratory. The approximate value of L, dB, resulting in the minimum Te-rms measurement error, is indicated for each case, except case 5.

A comparison of cases 1 and 2 with cases 3, 4, and 5 shows that with the accuracies assumed, two loads are preferable to one load and a noise source. A comparison of cases 3 and 5 shows that the cold load should be as cold as possible. A comparison of cases 4 and 5 shows that reducing the amplifier gain change (DYG) obtained with an attenuator between the amplifier and loads does not result in a net advantage.

Case 4, Fig. 9, using an ambient and a 2-K cold load with no attenuator, provides the most accurate noise-temperature measurement result of 0.3-K rms.

Averaged measurements with several configurations, including different attenuations, $L = 10$ dB (case 5) for example, to reduce the amplifier gain change due to a different input load match, will reduce bias errors and indicate the magnitude of the error.

IV. Conclusion

For the schemes analyzed in this article with assumed parameter and measurement accuracies, it is preferable to use two loads as opposed to one load and a noise source. A fixed attenuator between the amplifier and input loads has no advantage except as a measurement consistency check. The most accurate case evaluated, with input loads at an ambient and a 2-K temperature and no attenuator, provides an LNA noise-temperature measurement accuracy result of 0.3-K rms.

Acknowledgments

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References

[1] C. Stelzried, *The Deep Space Network—Noise Temperature Concepts, Measurements, and Performance*, JPL Publication 82-33, Jet Propulsion Laboratory, Pasadena, California, September 15, 1982.

[2] C. Stelzried, R. Clauss, W. Rafferty, and S. Petty, "DSN G/T_{op} and Telecommunications System Performance," *TDA Progress Report 42-108*, vol. October–December 1991, Jet Propulsion Laboratory, Pasadena, California, pp. 271–278, February 15, 1991.

[3] C. Stelzried, "Corrections of High-Frequency Noise-Temperature Inaccuracies," *TDA Progress Report 42-111*, vol. July–September 1992, Jet Propulsion Laboratory, Pasadena, California, pp. 169–277, November 15, 1992.

Table 1. Summary of Supercalc 4 computer programs NOISE1ND and NOISE1LD analysis of an LNA noise-temperature measurement delta or error (*DTe*).

Case	Figure	Method	Configuration	L, dB	DTe (rms), K
1	3, 4	1 input load and noise source	$T = 300$ K $Tn = 1000$ K $DYG = 0.01$	20	1.0
2	5, 6	1 input load and noise source	$T = 300$ K $Tn = 60{,}000$ K $DYG = 0.02$	20	1.1
3	7, 8	2 input loads	$T1 = 80$ K $T2 = 300$ K $DYG = 0.01$	10	0.7
4	9, 10	2 input loads	$T1 = 2$ K $T2 = 300$ K $DYG = 0.02$	0	0.3
5	11, 12	2 input loads	$T1 = 2$ K $T2 = 300$ K $DYG = 0.01$	10	0.5

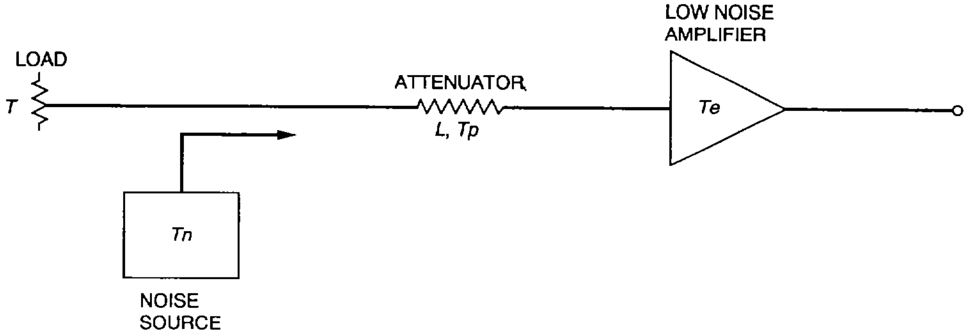


Fig. 1. Low-noise amplifier measurement scheme using a load at temperature T, a noise source, and a fixed attenuator.

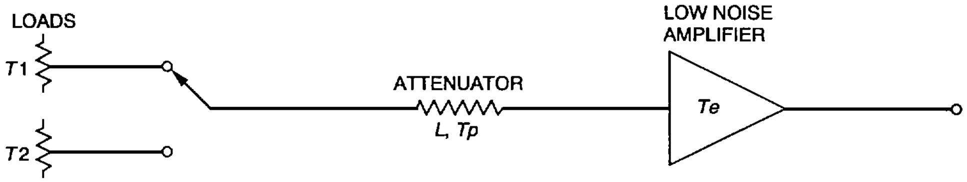
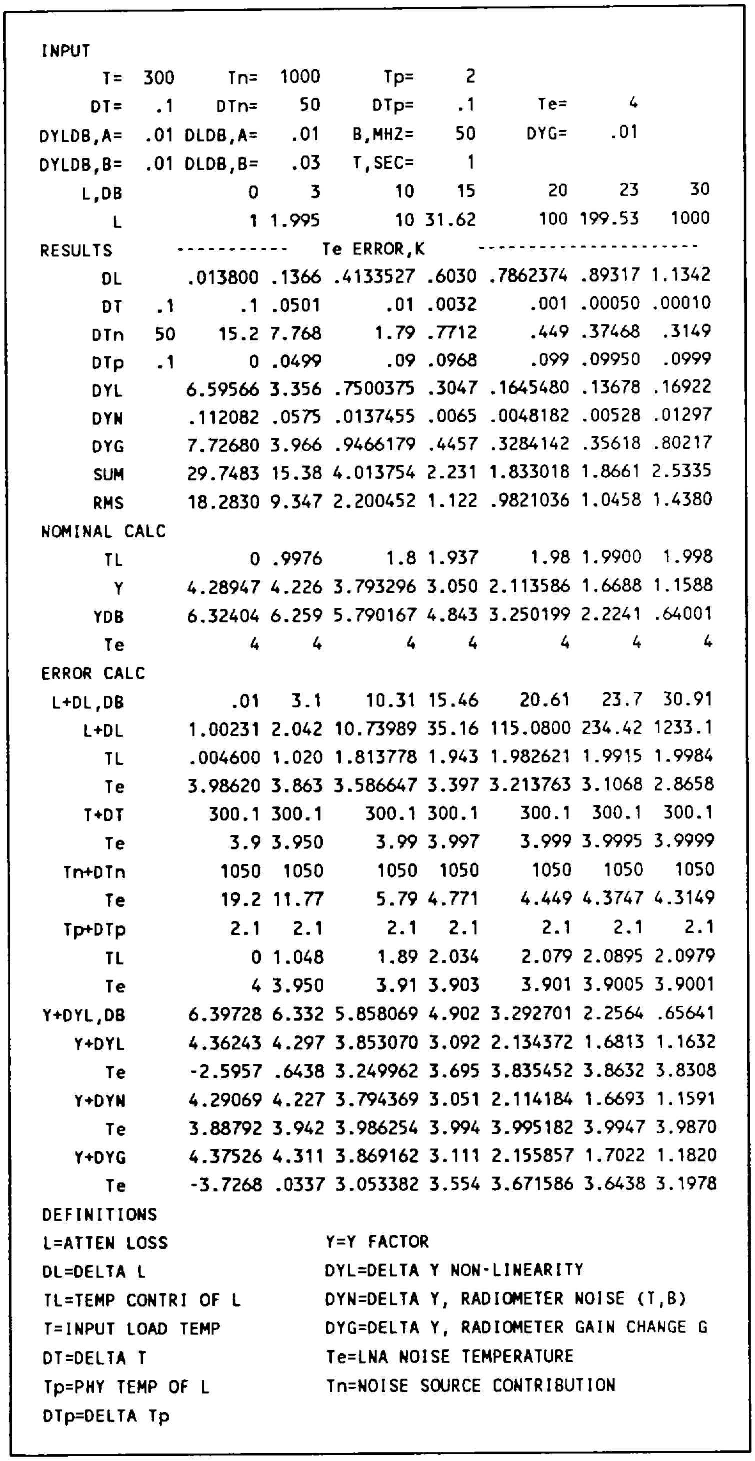


Fig. 2. Low-noise amplifier measurement scheme using two loads at temperatures $T1$ and $T2$ and a fixed attenuator.



```
INPUT
        T=  300      Tn=  1000       Tp=     2
       DT=   .1     DTn=    50      DTp=    .1      Te=      4
 DYLDB,A=  .01  DLDB,A=   .01    B,MHZ=    50     DYG=    .01
 DYLDB,B=  .01  DLDB,B=   .03    T,SEC=     1
     L,DB                0     3        10    15        20     23      30
        L                1 1.995        10 31.62       100 199.53    1000
RESULTS        -----------  Te ERROR,K    ---------------------
       DL          .013800 .1366  .4133527 .6030  .7862374 .89317  1.1342
       DT    .1         .1 .0501       .01 .0032      .001 .00050  .00010
      DTn    50       15.2 7.768      1.79 .7712      .449 .37468   .3149
      DTp    .1          0 .0499       .09 .0968      .099 .09950   .0999
      DYL          6.59566 3.356  .7500375 .3047  .1645480 .13678  .16922
      DYN          .112082 .0575  .0137455 .0065  .0048182 .00528  .01297
      DYG          7.72680 3.966  .9466179 .4457  .3284142 .35618  .80217
      SUM          29.7483 15.38  4.013754 2.231  1.833018 1.8661  2.5335
      RMS          18.2830 9.347  2.200452 1.122  .9821036 1.0458  1.4380
NOMINAL CALC
       TL                0 .9976       1.8 1.937      1.98 1.9900   1.998
        Y          4.28947 4.226  3.793296 3.050  2.113586 1.6688  1.1588
      YDB          6.32404 6.259  5.790167 4.843  3.250199 2.2241  .64001
       Te                4     4         4     4         4      4       4
ERROR CALC
  L+DL,DB              .01   3.1     10.31 15.46     20.61   23.7   30.91
     L+DL          1.00231 2.042  10.73989 35.16  115.0800 234.42  1233.1
       TL          .004600 1.020  1.813778 1.943  1.982621 1.9915  1.9984
       Te          3.98620 3.863  3.586647 3.397  3.213763 3.1068  2.8658
     T+DT            300.1 300.1     300.1 300.1     300.1  300.1   300.1
       Te              3.9 3.950      3.99 3.997     3.999 3.9995  3.9999
   Tn+DTn             1050  1050      1050  1050      1050   1050    1050
       Te             19.2 11.77      5.79 4.771     4.449 4.3747  4.3149
   Tp+DTp              2.1   2.1       2.1   2.1       2.1    2.1     2.1
       TL                0 1.048      1.89 2.034     2.079 2.0895  2.0979
       Te                4 3.950      3.91 3.903     3.901 3.9005  3.9001
 Y+DYL,DB          6.39728 6.332  5.858069 4.902  3.292701 2.2564  .65641
    Y+DYL          4.36243 4.297  3.853070 3.092  2.134372 1.6813  1.1632
       Te          -2.5957 .6438  3.249962 3.695  3.835452 3.8632  3.8308
    Y+DYN          4.29069 4.227  3.794369 3.051  2.114184 1.6693  1.1591
       Te          3.88792 3.942  3.986254 3.994  3.995182 3.9947  3.9870
    Y+DYG          4.37526 4.311  3.869162 3.111  2.155857 1.7022  1.1820
       Te          -3.7268 .0337  3.053382 3.554  3.671586 3.6438  3.1978
DEFINITIONS
L=ATTEN LOSS                 Y=Y FACTOR
DL=DELTA L                   DYL=DELTA Y NON-LINEARITY
TL=TEMP CONTRI OF L          DYN=DELTA Y, RADIOMETER NOISE (T,B)
T=INPUT LOAD TEMP            DYG=DELTA Y, RADIOMETER GAIN CHANGE G
DT=DELTA T                   Te=LNA NOISE TEMPERATURE
Tp=PHY TEMP OF L             Tn=NOISE SOURCE CONTRIBUTION
DTp=DELTA Tp
```

Fig. 3. Supercalc 4 computer program NOISE1ND printout of the analysis of Fig. 1, showing the measurement error as a function of attenuator loss *L*, dB, and assumed input parameter errors; noise source = 1000 K.

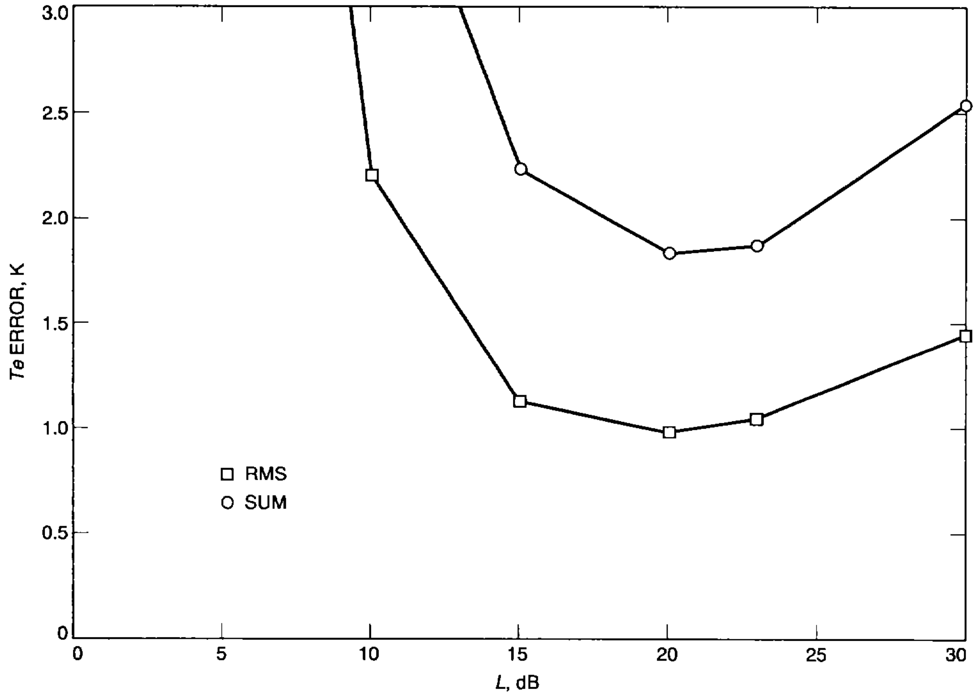


Fig. 4. Plot of the data in Fig. 3.

```
INPUT
        T=   300       Tn=  60000       Tp=      2
       DT=    .1      DTn=   3000      DTp=     .1       Te=       4
  DYLDB,A=   .01   DLDB,A=    .01    B,MHZ=     50      DYG=     .02
  DYLDB,B=   .01   DLDB,B=    .03    T,SEC=      1
      L,DB               0      3        10     15        20      23      30
         L               1  1.995        10  31.62       100  199.53    1000
RESULTS          ----------     Te ERROR,K      --------------------
        DL         .013800  .1366  .4133527  .6030  .7862374  .89317  1.1342
        DT    .1        .1  .0501       .01  .0032      .001  .00050  .00010
       DTn  3000      15.2  7.768      1.79  .7712      .449  .37468   .3149
       DTp    .1         0  .0499       .09  .0968      .099  .09950   .0999
       DYL         16.4054  8.356  1.878164  .7655  .3961832  .29695  .17706
       DYN         .086395  .0442  .0101833  .0044  .0025772  .00217  .00197
       DYG         11.7493  6.005  1.384821  .5979  .3503522  .29511  .26658
       SUM         43.5549  22.41  5.576521  2.842  2.084350  1.9621  1.9947
       RMS         25.2634  12.89  2.971278  1.382  1.053227  1.0599  1.2239
NOMINAL CALC
        TL               0  .9976       1.8  1.937      1.98  1.9900   1.998
         Y         198.368  194.6  168.5978  124.0  67.81514  41.130  10.527
       YDB         22.9747  22.89  22.26852  20.93  18.31327  16.142  10.223
        Te               4      4         4      4         4       4       4
ERROR CALC
   L+DL,DB             .01    3.1     10.31  15.46     20.61    23.7   30.91
      L+DL         1.00231  2.042  10.73989  35.16  115.0800  234.42  1233.1
        TL         .004600  1.020  1.813778  1.943  1.982621  1.9915  1.9984
        Te         3.98620  3.863  3.586647  3.397  3.213763  3.1068  2.8658
      T+DT           300.1  300.1     300.1  300.1     300.1   300.1   300.1
        Te             3.9  3.950      3.99  3.997     3.999  3.9995  3.9999
    Tn+DTn           63000  63000     63000  63000     63000   63000   63000
        Te            19.2  11.77      5.79  4.771     4.449  4.3747  4.3149
    Tp+DTp             2.1    2.1       2.1    2.1       2.1     2.1     2.1
        TL               0  1.048      1.89  2.034     2.079  2.0895  2.0979
        Te               4  3.950      3.91  3.903     3.901  3.9005  3.9001
  Y+DYL,DB         23.2145  23.13  22.50120  21.15  18.50640  16.313  10.335
     Y+DYL         209.627  205.6  177.8772  130.4  70.89898  42.785  10.802
        Te         -12.405  -4.36  2.121836  3.234  3.603817  3.7031  3.8229
     Y+DYN         198.425  194.6  168.6455  124.1  67.83433  41.141  10.530
        Te         3.91360  3.956  3.989817  3.996  3.997423  3.9978  3.9980
     Y+DYG         206.303  202.3  175.3417  129.0  70.52775  42.775  10.948
        Te         -7.7493  -2.00  2.615179  3.402  3.649648  3.7049  3.7334
DEFINITIONS
L=ATTEN LOSS                  Y=Y FACTOR
DL=DELTA L                    DYL=DELTA Y NON-LINEARITY
TL=TEMP CONTRI OF L           DYN=DELTA Y, RADIOMETER NOISE (T,B)
T=INPUT LOAD TEMP             DYG=DELTA Y, RADIOMETER GAIN CHANGE G
DT=DELTA T                    Te=LNA NOISE TEMPERATURE
Tp=PHY TEMP OF L              Tn=NOISE SOURCE CONTRIBUTION
DTp=DELTA Tp
```

Fig. 5. Supercalc 4 computer program NOISE1ND printout of the analysis of Fig. 1, showing the *measurement error* as a function of attenuator loss *L*, dB, and assumed input parameter errors; noise source = 60,000 K. The higher gain change (*DYG*) than that in Fig. 3 is appropriate for *L* = small attenuation.

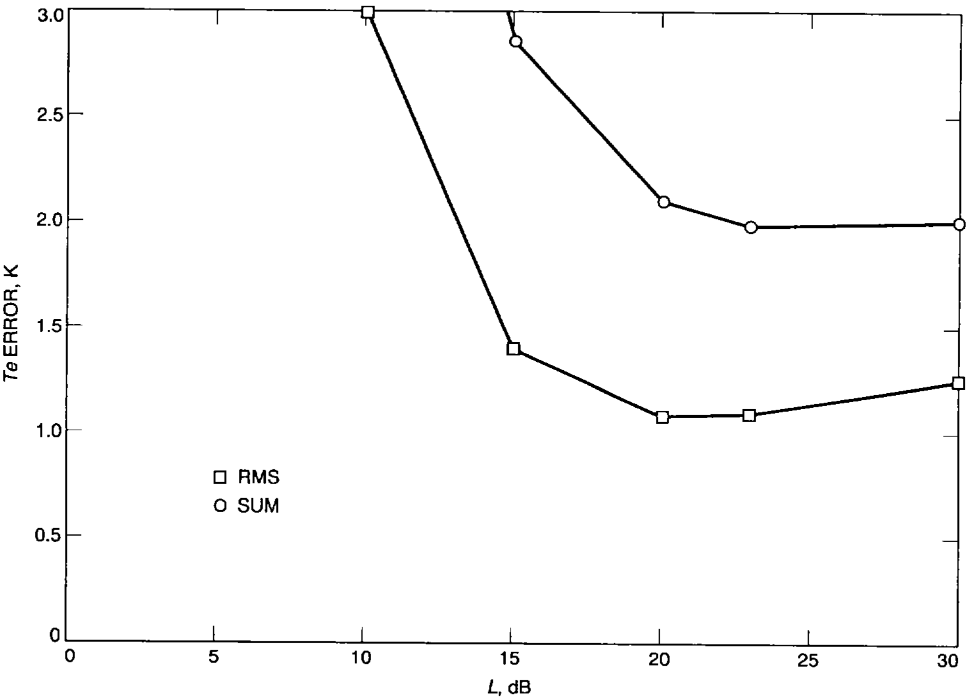
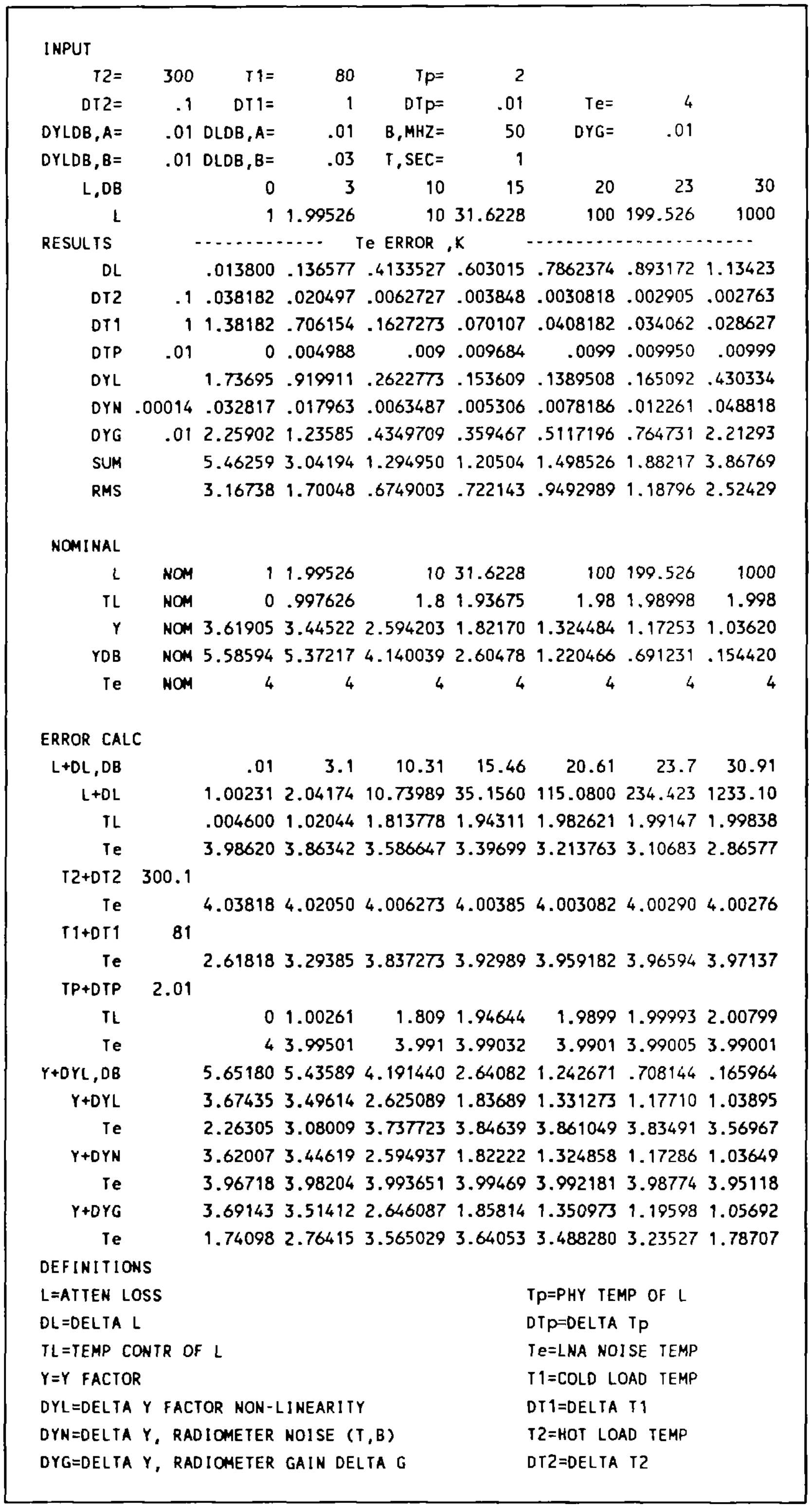


Fig. 6. Plot of the data in Fig. 5.



```
INPUT
       T2=    300      T1=       80      Tp=        2
      DT2=     .1     DT1=        1     DTp=      .01      Te=        4
  DYLDB,A=    .01  DLDB,A=      .01   B,MHZ=       50     DYG=      .01
  DYLDB,B=    .01  DLDB,B=      .03   T,SEC=        1
      L,DB                0        3       10       15       20       23       30
         L                1  1.99526       10  31.6228      100  199.526     1000
RESULTS          -------------   Te ERROR ,K      ----------------------
        DL          .013800  .136577 .4133527  .603015 .7862374  .893172  1.13423
       DT2     .1   .038182  .020497 .0062727  .003848 .0030818  .002905  .002763
       DT1      1   1.38182  .706154 .1627273  .070107 .0408182  .034062  .028627
       DTP    .01         0  .004988     .009  .009684    .0099  .009950   .00999
       DYL          1.73695  .919911 .2622773  .153609 .1389508  .165092  .430334
       DYN .00014   .032817  .017963 .0063487  .005306 .0078186  .012261  .048818
       DYG    .01   2.25902  1.23585 .4349709  .359467 .5117196  .764731  2.21293
       SUM          5.46259  3.04194 1.294950  1.20504 1.498526  1.88217  3.86769
       RMS          3.16738  1.70048 .6749003  .722143 .9492989  1.18796  2.52429

  NOMINAL
         L    NOM         1  1.99526       10  31.6228      100  199.526     1000
        TL    NOM         0  .997626      1.8  1.93675     1.98  1.98998    1.998
         Y    NOM   3.61905  3.44522 2.594203  1.82170 1.324484  1.17253  1.03620
       YDB    NOM   5.58594  5.37217 4.140039  2.60478 1.220466  .691231  .154420
        Te    NOM         4        4        4        4        4        4        4

ERROR CALC
   L+DL,DB              .01      3.1    10.31    15.46    20.61     23.7    30.91
      L+DL          1.00231  2.04174 10.73989  35.1560 115.0800  234.423  1233.10
        TL          .004600  1.02044 1.813778  1.94311 1.982621  1.99147  1.99838
        Te          3.98620  3.86342 3.586647  3.39699 3.213763  3.10683  2.86577
    T2+DT2  300.1
        Te          4.03818  4.02050 4.006273  4.00385 4.003082  4.00290  4.00276
    T1+DT1     81
        Te          2.61818  3.29385 3.837273  3.92989 3.959182  3.96594  3.97137
    TP+DTP   2.01
        TL                0  1.00261    1.809  1.94644   1.9899  1.99993  2.00799
        Te                4  3.99501    3.991  3.99032   3.9901  3.99005  3.99001
  Y+DYL,DB          5.65180  5.43589 4.191440  2.64082 1.242671  .708144  .165964
     Y+DYL          3.67435  3.49614 2.625089  1.83689 1.331273  1.17710  1.03895
        Te          2.26305  3.08009 3.737723  3.84639 3.861049  3.83491  3.56967
     Y+DYN          3.62007  3.44619 2.594937  1.82222 1.324858  1.17286  1.03649
        Te          3.96718  3.98204 3.993651  3.99469 3.992181  3.98774  3.95118
     Y+DYG          3.69143  3.51412 2.646087  1.85814 1.350973  1.19598  1.05692
        Te          1.74098  2.76415 3.565029  3.64053 3.488280  3.23527  1.78707
DEFINITIONS
L=ATTEN LOSS                                      Tp=PHY TEMP OF L
DL=DELTA L                                        DTp=DELTA Tp
TL=TEMP CONTR OF L                                Te=LNA NOISE TEMP
Y=Y FACTOR                                        T1=COLD LOAD TEMP
DYL=DELTA Y FACTOR NON-LINEARITY                  DT1=DELTA T1
DYN=DELTA Y, RADIOMETER NOISE (T,B)               T2=HOT LOAD TEMP
DYG=DELTA Y, RADIOMETER GAIN DELTA G              DT2=DELTA T2
```

Fig. 7. Supercalc 4 computer program NOISE1LD printout of the analysis of Fig. 2, showing the measurement error as a function of attenuator loss *L*, dB, and assumed input parameter errors; *T1* = 80 K and *T2* = 300 K.

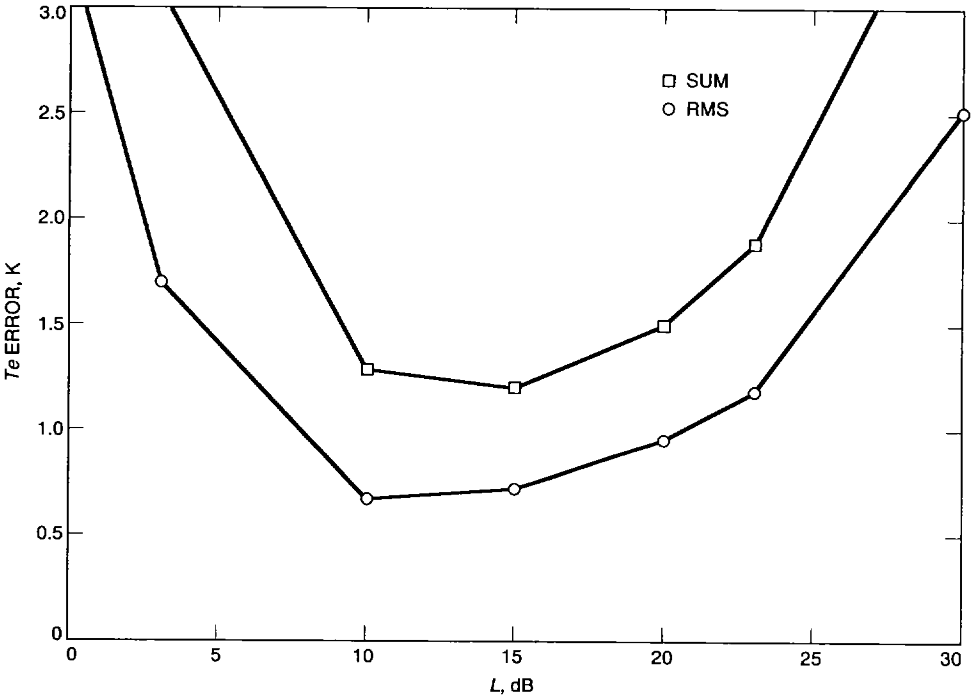


Fig. 8. Plot of the data in Fig. 7.

```
 INPUT
       T2=     300      T1=        2      Tp=        2
      DT2=      .1     DT1=      .01     DTp=      .01      Te=        4
 DYLDB,A=      .01  DLDB,A=      .01   B,MHZ=       50     DYG=      .02
 DYLDB,B=      .01  DLDB,B=      .03   T,SEC=        1
      L,DB                 0        3       10       15       20       23       30
         L                 1  1.99526       10  31.6228      100  199.526     1000
 RESULTS           -------------  Te ERROR ,K      ----------------------
        DL           .013800  .136577 .4133527  .603015 .7862374  .893172  1.13423
       DT2      .1   .002013  .002013 .0020134  .002013 .0020134  .002013  .002013
       DT1     .01   .010201  .005213 .0012013  .000518 .0003013  .000251  .000211
       DTP     .01         0  .004988     .009  .009684    .0099  .009950   .00999
       DYL           .248935  .213412 .1433149  .113808 .1127445  .133503  .334223
       DYN  .00014   .001731  .001765 .0020381  .002776 .0051096  .008503  .035653
       DYG     .02   .235233  .239670 .2751025  .368672 .6454241  1.00288  2.74862
       SUM           .511914  .603638 .8460230  1.10048 1.561730  2.05027  4.26494
       RMS           .342936  .348854 .5168865  .715963 1.023514  1.34964  2.99240

  NOMINAL
         L     NOM         1  1.99526       10  31.6228      100  199.526     1000
        TL     NOM         0  .997626      1.8  1.93675     1.98  1.98998    1.998
         Y     NOM   50.6667  25.8923 5.966667  2.57060 1.496667  1.24892  1.04967
       YDB     NOM   17.0472  14.1317 7.757318  4.10034 1.751251  .965357  .210514
        Te     NOM         4        4        4        4        4        4        4

 ERROR CALC
  L+DL,DB                .01      3.1    10.31    15.46    20.61     23.7    30.91
     L+DL            1.00231  2.04174 10.73989  35.1560 115.0800  234.423  1233.10
        TL           .004600  1.02044 1.813778  1.94311 1.982621  1.99147  1.99838
        Te           3.98620  3.86342 3.586647  3.39699 3.213763  3.10683  2.86577
   T2+DT2  300.1
        Te           4.00201  4.00201 4.002013  4.00201 4.002013  4.00201  4.00201
   T1+DT1   2.01
        Te           3.98980  3.99479 3.998799  3.99948 3.999699  3.99975  3.99979
   TP+DTP   2.01
        TL                 0  1.00261    1.809  1.94644   1.9899  1.99993  2.00799
        Te                 4  3.99501    3.991  3.99032   3.9901  3.99005  3.99001
 Y+DYL,DB            17.2277  14.2830 7.844891  4.15134 1.778763  .985010  .222619
    Y+DYL            52.8165  26.8103 6.088203  2.60096 1.506178  1.25459  1.05260
        Te           3.75106  3.78659 3.856685  3.88619 3.887256  3.86650  3.66578
    Y+DYN            50.6810  25.8996 5.968354  2.57132 1.497090  1.24928  1.04996
        Te           3.99827  3.99824 3.997962  3.99722 3.994890  3.99150  3.96435
    Y+DYG            52.6933  26.9280 6.205333  2.67342 1.556533  1.29888  1.09165
        Te           3.76477  3.76033 3.724898  3.63133 3.354576  2.99712  1.25138
 DEFINITIONS
 L=ATTEN LOSS                                        Tp=PHY TEMP OF L
 DL=DELTA L                                          DTp=DELTA Tp
 TL=TEMP CONTR OF L                                  Te=LNA NOISE TEMP
 Y=Y FACTOR                                          T1=COLD LOAD TEMP
 DYL=DELTA Y FACTOR NON-LINEARITY                    DT1=DELTA T1
 DYN=DELTA Y, RADIOMETER NOISE (T,B)                 T2=HOT LOAD TEMP
 DYG=DELTA Y, RADIOMETER GAIN DELTA G                DT2=DELTA T2
```

Fig. 9. Supercalc 4 computer program NOISE1LD printout of the analysis of Fig. 2, showing the measurement error as a function of attenuator loss L, dB, and assumed input parameter errors; $T1 = 2$ K and $T2 = 300$ K.

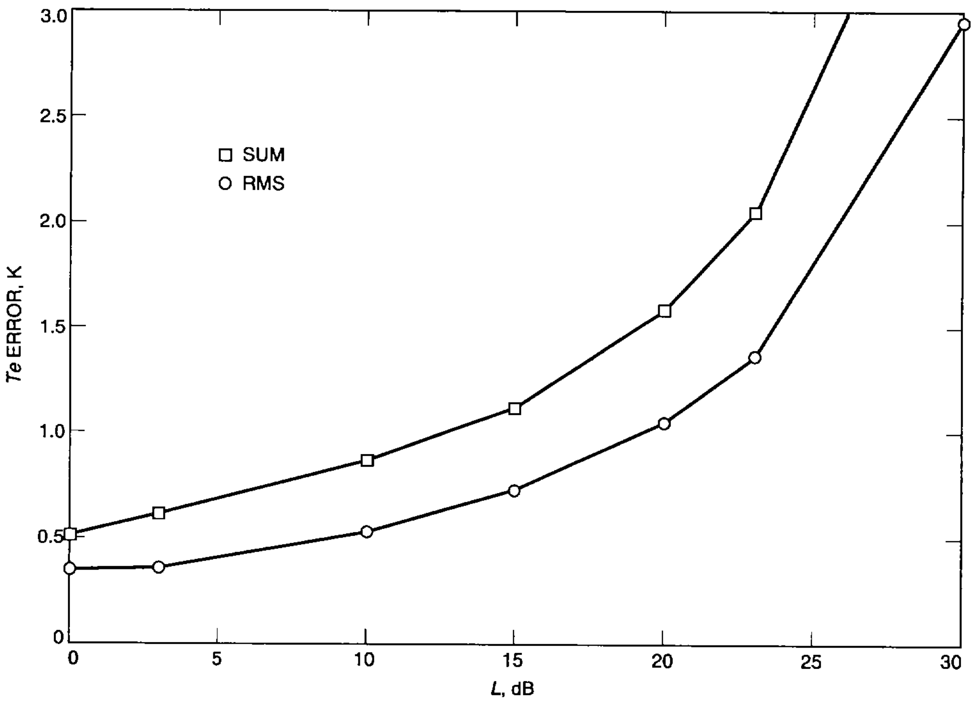
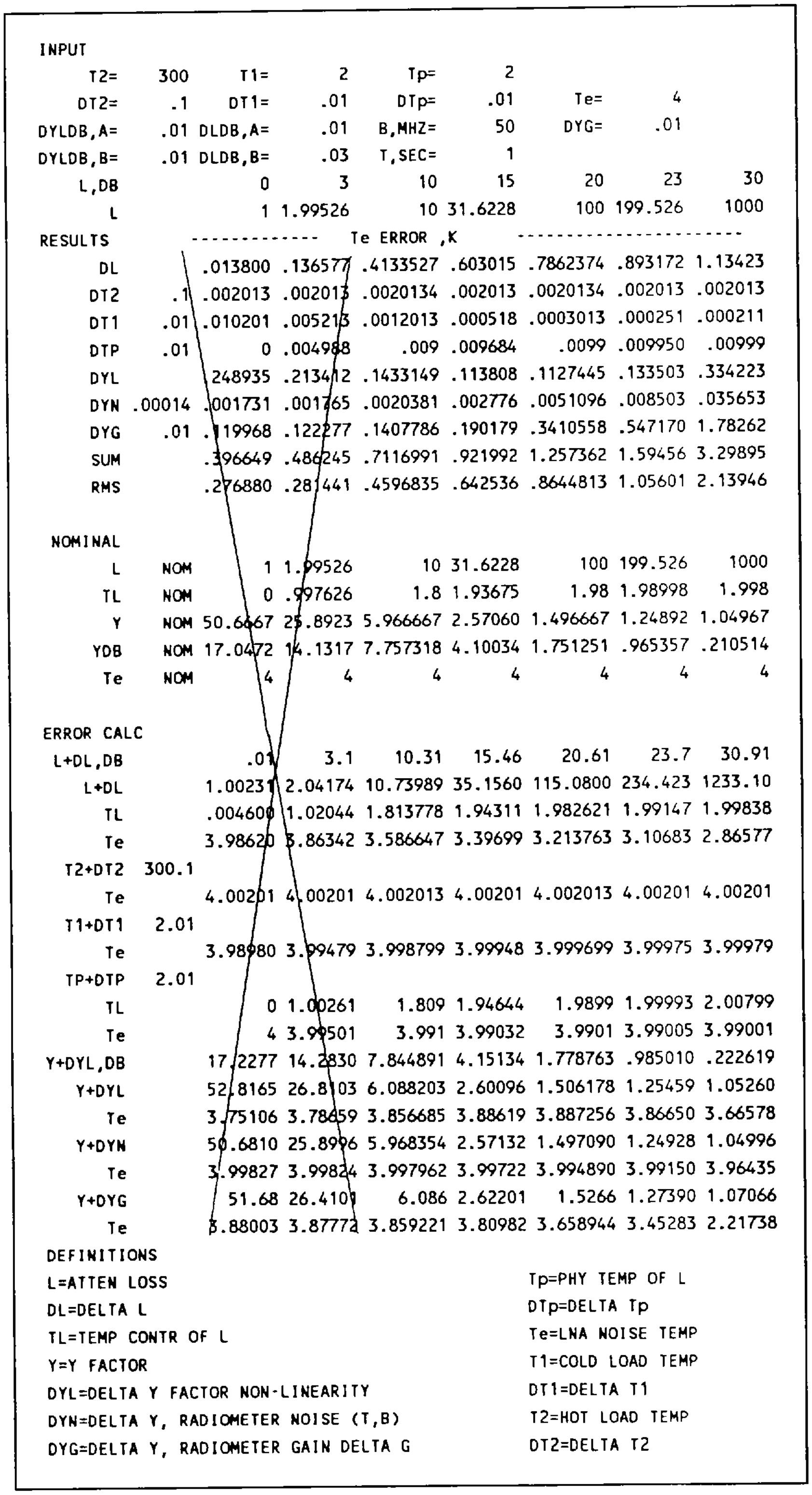


Fig. 10. Plot of the data in Fig. 9.



```
INPUT
      T2=     300     T1=        2      Tp=        2
     DT2=      .1    DT1=      .01     DTp=      .01      Te=        4
DYLDB,A=      .01 DLDB,A=      .01  B,MHZ=       50     DYG=      .01
DYLDB,B=      .01 DLDB,B=      .03  T,SEC=        1
     L,DB                0        3       10       15       20       23       30
        L                1  1.99526       10  31.6228      100  199.526     1000
RESULTS        -------------   Te ERROR ,K    -----------------------
       DL         .013800 .136577 .4133527 .603015 .7862374 .893172 1.13423
      DT2      .1 .002013 .002013 .0020134 .002013 .0020134 .002013 .002013
      DT1     .01 .010201 .005213 .0012013 .000518 .0003013 .000251 .000211
      DTP     .01       0 .004988     .009 .009684    .0099 .009950  .00999
      DYL         .248935 .213412 .1433149 .113808 .1127445 .133503 .334223
      DYN  .00014 .001731 .001765 .0020381 .002776 .0051096 .008503 .035653
      DYG     .01 .119968 .122277 .1407786 .190179 .3410558 .547170 1.78262
      SUM         .396649 .486245 .7116991 .921992 1.257362 1.59456 3.29895
      RMS         .276880 .281441 .4596835 .642536 .8644813 1.05601 2.13946

 NOMINAL
        L     NOM       1 1.99526       10 31.6228      100 199.526    1000
       TL     NOM       0 .997626      1.8 1.93675     1.98 1.98998   1.998
        Y     NOM 50.6667 25.8923 5.966667 2.57060 1.496667 1.24892 1.04967
      YDB     NOM 17.0472 14.1317 7.757318 4.10034 1.751251 .965357 .210514
       Te     NOM       4       4        4       4        4       4       4

ERROR CALC
 L+DL,DB              .01     3.1    10.31   15.46    20.61    23.7   30.91
     L+DL         1.00231 2.04174 10.73989 35.1560 115.0800 234.423 1233.10
       TL         .004600 1.02044 1.813778 1.94311 1.982621 1.99147 1.99838
       Te         3.98620 3.86342 3.586647 3.39699 3.213763 3.10683 2.86577
  T2+DT2  300.1
       Te         4.00201 4.00201 4.002013 4.00201 4.002013 4.00201 4.00201
  T1+DT1   2.01
       Te         3.98980 3.99479 3.998799 3.99948 3.999699 3.99975 3.99979
  TP+DTP   2.01
       TL               0 1.00261    1.809 1.94644   1.9899 1.99993 2.00799
       Te               4 3.99501    3.991 3.99032   3.9901 3.99005 3.99001
Y+DYL,DB          17.2277 14.2830 7.844891 4.15134 1.778763 .985010 .222619
    Y+DYL         52.8165 26.8103 6.088203 2.60096 1.506178 1.25459 1.05260
       Te         3.75106 3.78659 3.856685 3.88619 3.887256 3.86650 3.66578
    Y+DYN         50.6810 25.8996 5.968354 2.57132 1.497090 1.24928 1.04996
       Te         3.99827 3.99824 3.997962 3.99722 3.994890 3.99150 3.96435
    Y+DYG           51.68 26.4101    6.086 2.62201   1.5266 1.27390 1.07066
       Te         3.88003 3.87772 3.859221 3.80982 3.658944 3.45283 2.21738
DEFINITIONS
L=ATTEN LOSS                                         Tp=PHY TEMP OF L
DL=DELTA L                                           DTp=DELTA Tp
TL=TEMP CONTR OF L                                   Te=LNA NOISE TEMP
Y=Y FACTOR                                           T1=COLD LOAD TEMP
DYL=DELTA Y FACTOR NON-LINEARITY                     DT1=DELTA T1
DYN=DELTA Y, RADIOMETER NOISE (T,B)                  T2=HOT LOAD TEMP
DYG=DELTA Y, RADIOMETER GAIN DELTA G                 DT2=DELTA T2
```

Fig. 11. Supercalc 4 computer program NOISE1LD printout of the analysis of Fig. 2, showing the measurement error as a function of attenuator loss *L*, dB, and assumed input parameter errors; *T1* = 2 K and *T2* = 300 K. The lower gain change (*DYG*) than that in Fig. 9 is appropriate for case 5, *L* = 10 dB.

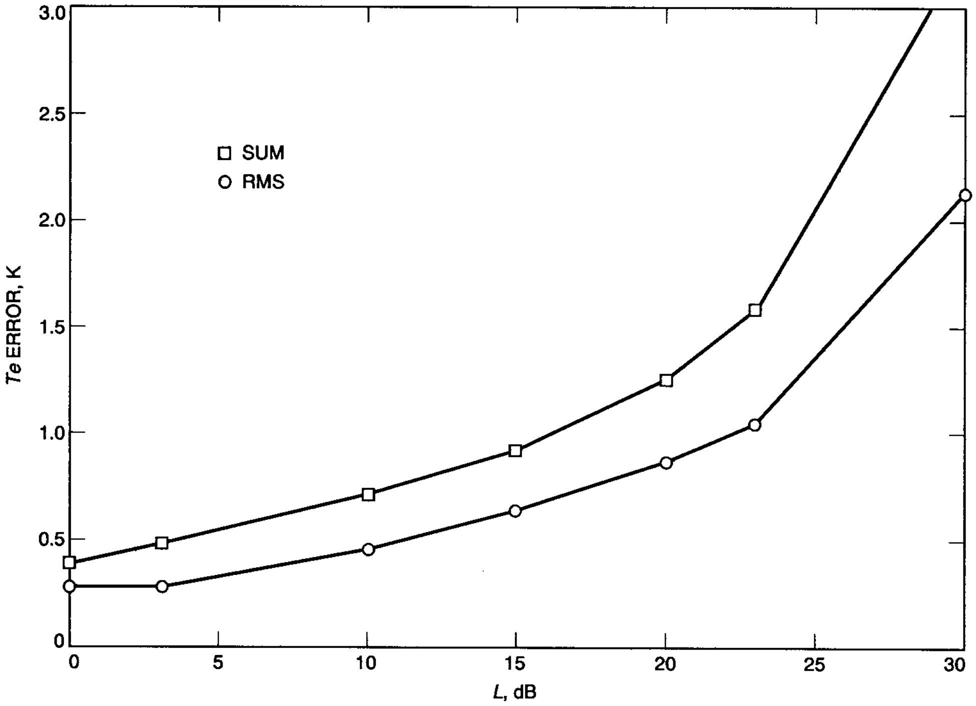


Fig. 12. Plot of the data in Fig. 11.