ANTENNA NOISE TEMPERATURE MEASUREMENT SYSTEM

Stephen A Rawson(1)**, Roberto Maddè**(2)

(1)Callisto
35 Grand Rue, F-11320 Labastide d'Anjou, France
Email: *steve.rawson@callisto-space.com*

(2)ESA/ESOC/TOS-GSS
Robert Bosch Str.5, D-64293 Darmstadt, Germany
Email: *rmadde@esoc.esa.de*

INTRODUCTION

The subject of the study was a method of measurement of the system noise temperature of a ground station reception chain. The system noise temperature is a fundamental parameter of performance of a ground station, which, together with the antenna receive gain, will ultimately determine the signal to noise ratio of downlink communications links. Traditional methods of measurement of system noise temperature normally rely on the measurement of noise power in a known bandwidth using a filter and a power detector. The method studied utilizes the effect of the noise on the bit error rate of a test signal, as a detector of the noise level. In this case the noise measurement bandwidth is defined by the bit rate of the test signal. In order to measure system noise temperature independent of the gain of the receive chain it is necessary to be able to inject a calibration signal into the receive chain at a reference point (LNA input). However, the calibration signal can cause degradation to any operational signals being simultaneously received. Conversely the presence of operational signals can interfere with the noise measurement system. These two factors make routine noise temperature measurements on operational ground station (i.e. whilst tracking satellites) difficult to implement. The method described in the study is specifically designed for use during operations. The use of a spread spectrum test signal for the measurement allows for the minimisation the mutual interference between any operational signals and the test signal.

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DESCRIPTION OF MEASUREMENT METHOD

The measurement configuration is shown in Fig. 1. An IF modulated test signal is generated by a test modem. This test signal is upconvertered to RF at a frequency within the RF receive band of the earth station downlink band. The modulation scheme employed is BPSK modulated data overlaid with a direct sequence spread spectrum code. The modulated RF test signal is coupled into the earth station receive chain by a directional coupler at the input to the LNA. This point of the receive chain is generally taken as the reference point of receive chain for the definition of G and T_{sys}. The test signal together with the receive chain system noise and any operational signals received by the antenna will then be amplified and downconvertered by the earth station receive chain (shown in blue on Fig. 1). A power divider at the output of the downconverter allows the test demodulator to be connected into the operational chain and thereby the test data is recovered from the combined downlink spectrum. The transmitted test data will be compared with the recovered test data and errors counted over a measurement time. The Bit Error Rate (BER) measurements are read by the test computer and used to evaluate the noise temperature as follows:

If the test signal level constant, then any change in the receive system noise will cause a change in the bit error rate. The change in BER is detected by the test processor, which responds by modifying the test date bit rate clock so as to return the BER to its original value. This servo loop action results in the data rate clock frequency being modified in response to any noise level change. It will be shown in the following section that this results in an inverse linear relationship between the data rate frequency and noise level. As the test signal is spread spectrum modulated there is a low level of mutual interference between the test signal and any operational signals present in the downlink spectrum. The constant of proportionality between data rate frequency and the noise level is determined by calibration using a noise diode, which is built into the measurement system.

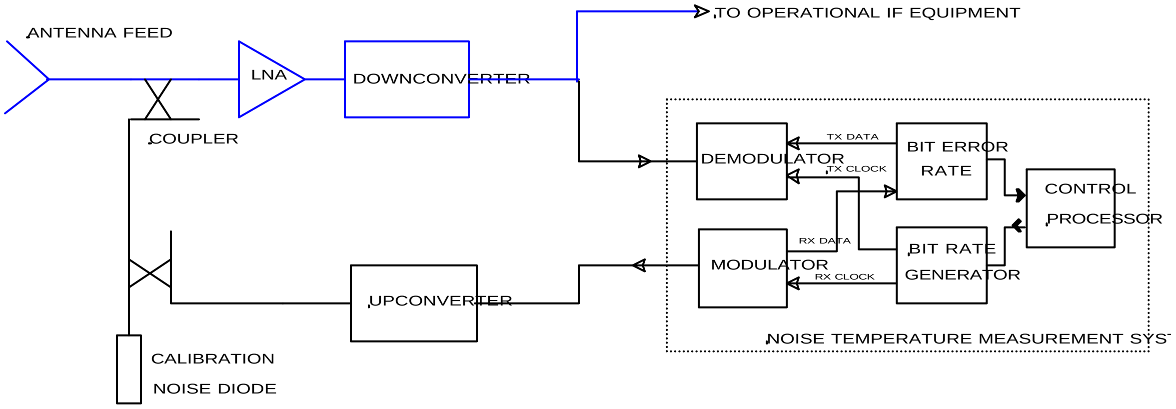

Figure 1

THEORETICAL ANALYSIS

Bit Error Probability and System Noise Temperature

For a BPSK modulated test signal the bit error probability (Pe) in the test loop will be:

$$Pe = \frac{1}{2} erfc \sqrt{EbNo.Dg} \qquad (1)$$

where: *EbNo* is the energy per bit to noise density ratio
Dg is a degradation factor due to the test modem and receive chain components.
erfc is the complementary error function.

At the input to the LNA(see Fig. 1):

$$EbNo = \frac{S_t}{f_b.k.T_{sys}} \qquad (2) \qquad \text{hence} \qquad Pe = \frac{1}{2} erfc \sqrt{\frac{S_t.Dg}{f_b.k.T_{sys}}} \quad (3)$$

where: S_t is the test signal level at the input to the LNA (W)
f_b is the test signal bit rate (bps).
k is Boltzman's constant (W/KHz).
T_{sys} is the earth station system noise temperature referred to the LNA input.

In order to maintain a constant error probability in the case of a variation in T_{sys} then a control loop is used, which can adjust the test signal bit rate so that any increase in Pe is countered by a decreased in f,$_b$ and visa versa. If the test signal is maintained at a constant level (S_t) and the degradation (Dg) remains constant, then there will be an inverse linear relationship between T_{sys} and f_b :

$$T_{sys} = \frac{K'}{f_b} \qquad (4) \quad \text{where } K' \text{ is a constant}$$

$$\text{so} \qquad \frac{dT_{sys}}{df_b} = -\frac{K'}{f_b^2} = -\frac{T_{sys}}{f_b} \qquad \text{or} \qquad \Delta f_b = \Delta T_s \frac{df_b}{dT_{sys}} = -\Delta T_s \frac{f_b}{T_{sys}} \qquad (5)$$

Equation 4 defines the relationship of the measurement parameters and equation 6 defines the measurement sensitivity. Thus using typical values of 10^2K for T_{sys} and 10^3bps for f_b , a change in system noise temperature of 1K will result in a change in bit rate of 10bps. Thus the sensitivity of the measurement technique will enable very small changes in T_{sys} to be detected if the modem bit clock can be synthesised with a resolution of better than 1 in 10^2 , which is perfectly feasible.

Measurement Resolution

In order to measure small variations in T_{sys} we must be able to reliably detect small variations in the bit error rate or the number of errors (N_e) counted in a defined measurement window. The measurement window can be defined in terms of number of bits (n) or by measurement time $t=n/f_b$. The variance due to statistical distribution of the error events will ultimately limit the measurement resolution and the size of the variance will be generally related to the measurement window length. The form of the statistical distribution of bit errors in digital communications is an equivalent case of a binomial distribution, therefore the uncertainty in Ne is found using the standard deviation of the binomial distribution, hence the uncertainty in T_{sys} due to uncertainty in Ne is:

$$\Delta T_{sys} = 2.T_{sys}.\sqrt{\frac{p.Pe.(1-Pe)}{n.EbNo}}.e^{EbNo} \qquad (6)$$

Measurement time and measurement uncertainty

Rearranging equation (6) to get n as a function of EbNo:

$$n = \frac{4.p.Pe.(1-Pe)}{(\Delta T_s/T_s)^2.EbNo}.e^{2EbNo} \qquad (7)$$

This expression has been evaluated for $\Delta T_S/T_S=1\%$ for a range of EbNo from -1dB to 8dB and has shown that the measurement window expressed as the number of bits n required for a 1% measurement resolution has a minimum at around EbNo = 1dB. For values of EbNo less than 4dB the measurement window required will be less than 10^5 bits. Therefore the preferred operating range in order to minimise the measurement time falls in the range of EbNo from -1dB to +4dB.

Effects of Operational signals on the test loop.

The test signal will be a spread spectrum signal so as to minimise the mutual interference between operational signals and the test loop. Thus any operational signal (level J) will been seen as noise after despreading in the test demodulator with equivalent noise density $Jo = J/W$, where W is the chip rate. General references on spread spectrum [2] demonstrate that the above is true equally for wide band interference signals as for narrow band interference signals.

This will result in a bias in the evaluation of the noise temperature. The bias component is a function of the signal to noise density ratio of the operational signal and of the chip rate (W). The bias terms is:

$$Bias = \frac{J}{No}.\frac{1}{W} \qquad (8)$$

When the operational signal to noise density is numerically equal to the chip rate, then the bias will be 100%.

Interference on Operational Signals due to the Test Signal.

The degradation on the operational signal due to the test signal of given EbNo is predicted by the following:

$$Deg = 1 + \frac{Eb_t}{No}.\frac{1}{Pg} \qquad (9)$$

Where Pg is the spread spectrum process gain in the test loop

With EbNo of 4dB in the test loop, the degradation on operational signals is < 0.1dB with a process gain greater than 110.

PROTOTYPE EVALUATION

A prototype noise temperature measurement system has been built to verify the theoretical predictions described above. The performance specifications for the prototype were as shown in table 1 and it was designed to operate in both S band and X band frequencies used for telemetry reception in ESA ground stations. The prototype system has been evaluated in a simulated ground station downlink chain comprising a horn antenna, an LNA and a downconverter. The horn antenna was pointed at clear sky (zenith) in order to provide a system noise temperature representative of a normal ground station.

Calibration Process and Overall Accuracy

The process control software for the prototype system was tested with three different methods of servo tracking of noise temperature changes. The first method was a simple stepping method in which the test signal bit rate was increased or decreased in discrete steps of 0.1dB, in response to a change in error rate. The second and third method was based on a polynomial approximation of the Pe versus EbNo curve. This allowed for bit rate adjustments in a continuous way in proportion to the size of the deviation of the Pe value from the null value. The difference between these two was that in the second method the correction was applied directly, while in the third the correction was applied via a second order tracking filter. The automatic calibration process involves switching on a noise diode, which injects a known level of noise into the reception chain. The response of the measurement system to the change on the known noise level is used for calibration of the coefficient of proportionality. In order to maximise the calibration accuracy, thus the eventual overall measurement accuracy, the calibration measurement can be automatically repeated a given number of cycles, and then the results are averaged to find a final calibration result. The three servo tracking methods described above have been evaluated to find the required number (N) of calibration cycles to produce a 2% error in the final average result. These results are shown in table 2.

Table 1

PROTOTYPE SPECIFICATIONS	
Noise Temperature Measurement Accuracy ($\Delta T_S/T_S$)	< 1%
Overall Noise Temperature Estimation Accuracy	< 5% (RSS)
Induced degradation on telemetry/ranging channels.	< 0.1dB
Range of system noise temperatures	20K to 300K
RF Measurement Bandwidth	100MHz in slices of 24 MHz
Chip rates	12 Mcps & 6 Mcps
Variable delay in test code for correlation	0 to 630ns in 10ns steps
Test signal Eb/No	~4dB
Basic Measurement Window (bits)	10^5
Basic Measurement Time (seconds)	3.3 to 10.5

Table 2

Tracking Method	Number of cycles for 2% mean error	Calibration uncertainty (%) for N=5
Step Tracking	N=27	3.63%
Polynomial prediction	N=8.6	2.35%
Polynomial prediction with filter	N=6.6	2.39%

Table 3

Source of Uncertainty	Error	Relative Error		
		Step Track	Polynomial	Poly +filter
Calibration uncertainty	measured data	3.63%	2.35%	2.39%
Test Signal stability	0.1dB	2.00%	2.00%	2.00%
Noise Diode Calibration	0.1dB	2.00%	2.00%	2.00%
Noise Diode Temp Stability	0.01dB/°C	2.00%	2.00%	2.00%
Coupling loss	0.1dB	2.00%	2.00%	2.00%
Step Attenuator	0.05dB	1.00%	1.00%	1.00%
WORST CASE		12.63%	11.35%	11.39%
RSS		5.49%	4.75%	4.77%

The uncertainty in calibration is also shown in table 2 for each of the tracking methods. These values were obtained by comparing results obtained by the noise temperature measurement system after a calibration of 5 cycles, with a measurement of noise temperature of the reception chain using the classical hot/cold load method. The overall measurement accuracy budget is shown in table 3 using the calibration uncertainty values derived from measurement data.

Measurement Sensitivity

The sensitivity is limited by the variance of the measurement process. This has been evaluated statistically by collecting measurement samples under constant noise conditions and calculating the standard devaition of the samples. The one-sigma variance has been shown to be 1.2% of the mean value, which a little worse that the design value for sensitivity which was 1%.

CONCLUSIONS

A noise temperature measurement method has been devised which uses the bit error rate induced on data transmitted in a test loop. The test loop signal may be spread spectrum modulated and so will have low interference with other signals in the system under test. This means the measurement system can be used whilst an antenna is receiving operational signals. The measurement system can be automatically calibrated using a built in noise diode as a noise reference. The calibration uncertainty is close to 2% and the overall measurement accuracy is less than 5% RSS. The measurement sensistivity, which is limited by the statistical nature of the bit error process, has been shown to be 1.2%.

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