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DOCUMENT

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Simultaneous Transmission of GMSK Telemetry and PN Ranging: Measurement Report in Support of the Draft CCSDS Recommendations 401(2.4.22A) and 401(2.4.22B)

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1 INTRODUCTION

The simultaneous transmission of high data rate telemetry and a ranging signal is in the process of being recommended by CCSDS for the 8400-8500 MHz space research service bands [1],[2]. The combined transmission is realized through a CCSDS standard Gaussian minimum shift keying (GMSK) modulator for telemetry and an additional CCSDS standard regenerative pseudo noise (PN) ranging sequence which is phase-modulated on top of the telemetry signal. The receiver first demodulates and estimates the GMSK signal so as to regenerate and remove the GMSK component from the received signal. It subsequently estimates the ranging chips and, through a bank of correlators, the round trip delay of the received ranging signal. The receiver estimates the telemetry symbols from the combined ranging and telemetry signal which degrades its performance when compared to pure telemetry reception. Vice versa, errors in the estimation of telemetry symbols compromise the correct detection of the ranging chips. A careful parameter selection is therefore necessary for the system to work with minimum losses.

The Green Book [3], currently under drafting, will accompany the CCSDS recommendations 401(2.4.22A) [1] and 401(2.4.22B) [2], and provides background information and their main performance characteristics for the applications covered by the recommendations. The performance figures in the Green Book are obtained from simulations. In support of the CCSDS recommendations and as a validation of the simulation results, a measurement campaign has been performed with two modem breadboards in ESA's Ground Station Reference Facility. This document summarizes the results of these measurements.

The measurement campaign focused on the recommended parameter sets for combined telemetry and ranging and its setup is in line with the scenarios provided in the draft Green Book. As such, the measurement results are directly comparable to the results obtained from simulations unless noted otherwise. The measurements cover four areas:

- Spectral performance in terms of bandwidth occupation.
- Telemetry losses in terms of increase in signal to noise ratio (SNR) required to produce a pre-defined symbol error rate (SER).
- Ranging losses in terms of increase in acquisition time required necessary to acquire the ranging sequence with a pre-defined error probability.
- Ranging losses in terms of increase in ranging clock jitter.

1.1 Terminology

The measurements were performed, as explained in section 7, for different permutations of the recommended system parameters for combined GMSK-modulated telemetry and PN ranging. These parameters are:

Telemetry rate R_{TM}, given in symbols per second (sps). Because uncoded transmission is considered, R_{TM} is equivalent to information bits per second.

Ranging chip rate R_{RG}, given in ranging chips per second (cps).

PN ranging modulation index m_{RG}, given in radians. The modulation index is sometimes defined through a parameter $\boldsymbol{h}$. Its relationship to m_{RG} is $m_{RG} = \pi h/\sqrt{2}$.

Time-bandwidth product BT_s, where B is the single-sided 3dB-bandwidth of the Gaussian filter in the GMSK modulator and $T_s = 1/R_s = 1/R_{TM}$ is the symbol period.

Ranging baseband shape (BB shape) during one chip interval. Only a sine shape is considered.

Ranging code (RNG code). This is the Tausworthe code used for the generation of the PN ranging sequence [4]. The options are T2B and T4B.

SER constraint. Performance is compared on the basis of the SNR necessary to achieve a target symbol error rate. Because uncoded transmission is considered, the SER is equivalent to the information bit error rate.

Signal-to-noise ratio E_s/N_0, where E_s is the energy per symbol (in this case per Bit) and N_0 is the spectral noise density.

A detailed explanation of these system parameters is given in the Green Book [3].

1.2 Test Cases

The CCSDS recommendations 401(2.4.22A) [1] and 401(2.4.22B) [2] for the system parameters above are given in Table 1.

Table 1 Recommended system parameter ranges for combined GMSK-modulated telemetry and PN ranging

Parameter	Recommendation
$\frac{R_{RG}}{R_{TM}}$	$\frac{R_{RG}}{R_{TM}} > 1$, A non-integer ratio represents unsynchronized telemetry and ranging signals. Ratios slightly below 1 are also acceptable.
BT_s	$BT_s = 0.25$ for category A missions [1], $BT_s = 0.5$ for category B missions [2]
m_{RG}	$m_{RG} = 0.2 \ldots 0.45$
BB shape	half sine-wave
RNG code	T2B (favoring acquisition time), T4B (favoring jitter)

Based on these recommendations we set up the test cases in Table 2. The first row defines a reference case. The subsequent rows modified only one parameter at a time. In order to match exactly the parameters use for the simulations in the draft Green Book [3], we define a second set of test cases based on a second reference case.

Table 2 Test cases

Case	R_{TM} [Msps]	R_{RG} [Mcps]	$\frac{R_{RG}}{R_{TM}}$	BT_s	m_{RG}	BB shape	RNG code	Remark
1	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	sine	T2B	Reference case 1
2	$1-10^{-3}$	2	$2+\epsilon$	0.25	0.2	sine	T2B	$\frac{R_{RG}}{R_{TM}}$ dependence
3	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.2	sine	T2B	$\frac{R_{RG}}{R_{TM}}$ dependence
4	$1-10^{-3}$	5	$5+\epsilon$	0.25	0.2	sine	T2B	$\frac{R_{RG}}{R_{TM}}$ dependence
5	$1-10^{-3}$	10	$10+\epsilon$	0.25	0.2	sine	T2B	$\frac{R_{RG}}{R_{TM}}$ dependence
6	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.2	sine	T2B	BT_s dependence
7	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.3	sine	T2B	m_{RG} dependence
8	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.45	sine	T2B	m_{RG} dependence
9	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	sine	T4B	RNG code dependence
10	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	sine	T2B	Reference case 2
11	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.222	sine	T2B	$\frac{R_{RG}}{R_{TM}}$ dependence
12	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.222	sine	T2B	BT_s dependence
13	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.444	sine	T2B	m_{RG} dependence
14	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	sine	T4B	RNG code dependence

1.3 References

[1] CCSDS Recommendation 401 (2.4.22A) R-1, CCSDS Recommendation for Radio Frequency and Modulation Systems, April 2014

[2] CCSDS Recommendation 401 (2.4.22B) R-1, CCSDS Recommendation for Radio Frequency and Modulation Systems, April 2014

[3] CCSDS SLS-RFM 14-02, Towards Green Book on Simultaneous Transmission of GMSK Telemetry and PN Ranging, March 2014

[4] CCSDS Pseudo-Noise (PN) Ranging Systems, Recommended Standard, CCSDS 414-B-2, February 2014.

[5] Analysis of GMSK for Simultaneous Transmission of Ranging and Telemetry, CCSDS SLS-RFM_09-08, E. Vassallo and M. Visintin, October 2009.

[6] Analysis of UQPSK and GMSK/PN for Simultaneous Transmission of Ranging and Telemetry: Ranging Correlator Results, CCSDS SLS-RFM 10-03, E. Vassallo and M. Visintin, May 2010.

[7] Synchronization analysis for GMSK/PN Modulation, CCSDS SLS-RFM 11-01, E. Vassallo and M. Visintin, March 2011.

2 SPECTRAL PERFORMANCE

The spectral performance is measured in terms of bandwidth occupation. The 99% power bandwidth (99%-PBW) is defined as the width of a frequency band such that, below the lower and above the upper frequency limits, the mean powers emitted are each equal to 0.5% of the total mean power of a given emission. The 99%-PBW in Table 3 is normalized to R_{TM}.

Table 3 Normalized 99% power bandwidth

Case	R_{TM} [Msps]	R_{RG} [Mcps]	$\frac{R_{RG}}{R_{TM}}$	BT_s	m_{RG}	BB shape	RNG code	99%-PBW (meas.)	99%-PBW (sim. [3])
1	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	sine	T2B	1.025	n/a
2	$1-10^{-3}$	2	$2+\epsilon$	0.25	0.2	sine	T2B	1.848	n/a
3	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.2	sine	T2B	2.855	n/a
4	$1-10^{-3}$	5	$5+\epsilon$	0.25	0.2	sine	T2B	4.836	n/a
5	$1-10^{-3}$	10	$10+\epsilon$	0.25	0.2	sine	T2B	9.635	n/a
6	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.2	sine	T2B	1.152	n/a
7	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.3	sine	T2B	1.236	n/a
8	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.45	sine	T2B	1.569	n/a
9	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	sine	T4B	1.020	n/a
10	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	sine	T2B	1.061	1.062
11	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.222	sine	T2B	2.990	2.953
12	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.222	sine	T2B	1.171	1.183
13	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.444	sine	T2B	1.592	1.559
14	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	sine	T4B	1.078	1.106

Figure 1 to Figure 14 show the normalized power spectrum for each of the test cases above in the same order. The intermediate center frequency is $f_c = 70\text{MHz}$.

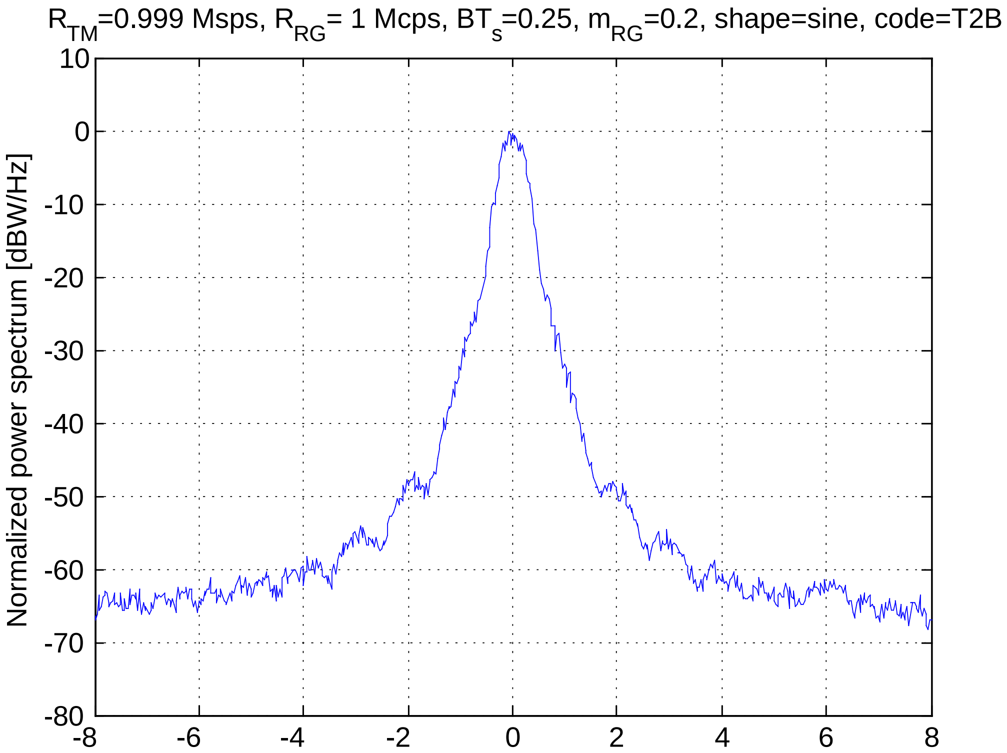

Figure 1 Power spectrum case 1

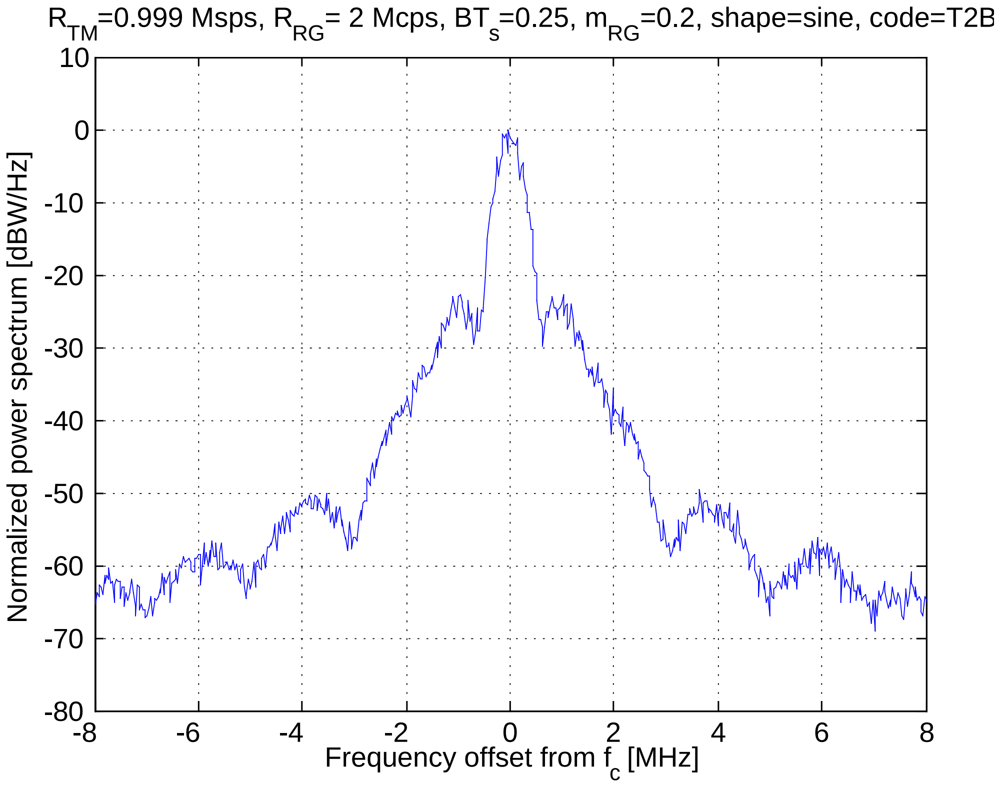

Figure 2 Power spectrum case 2

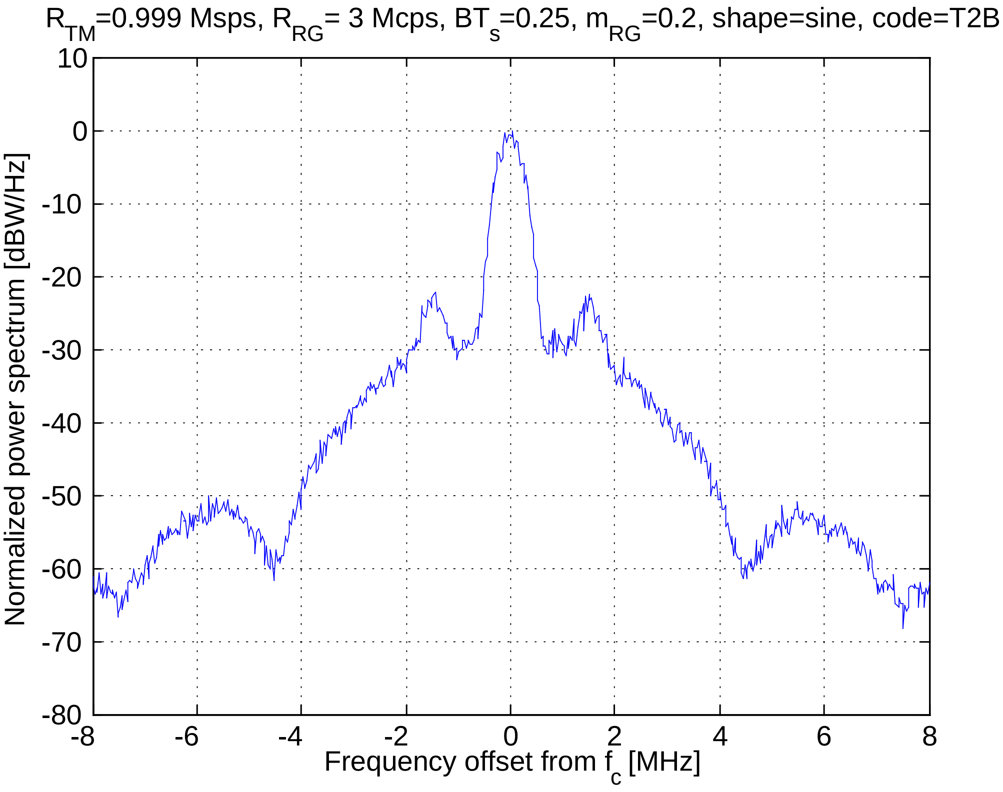

Figure 3 Power spectrum case 3

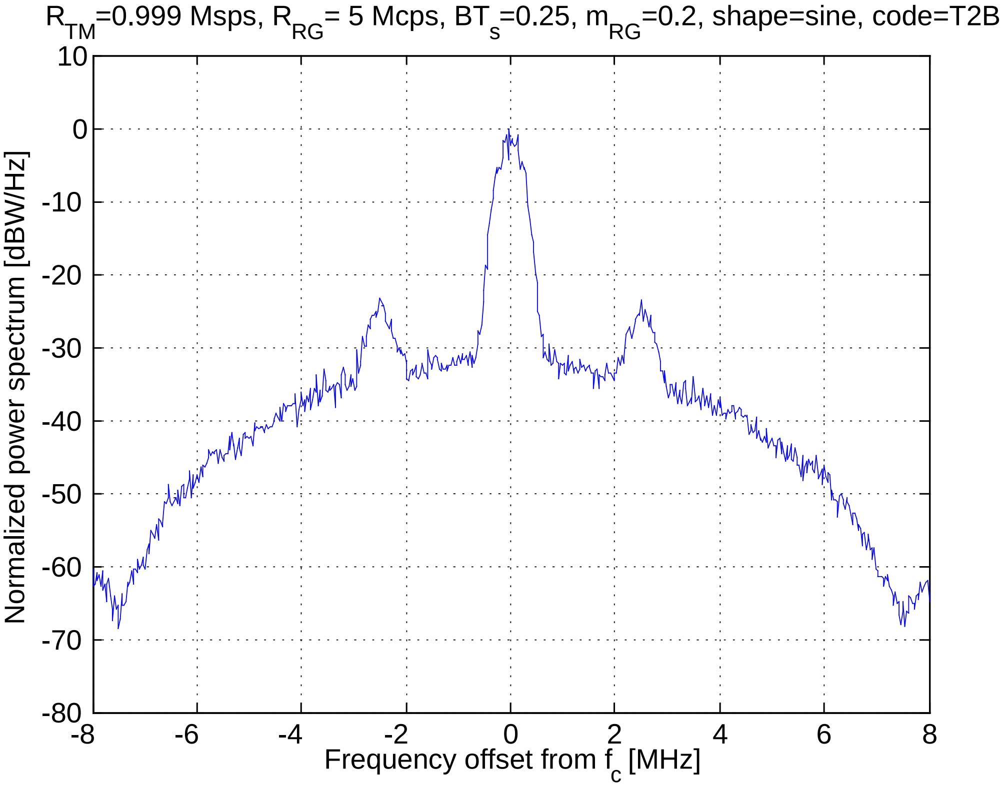

Figure 4 Power spectrum case 4

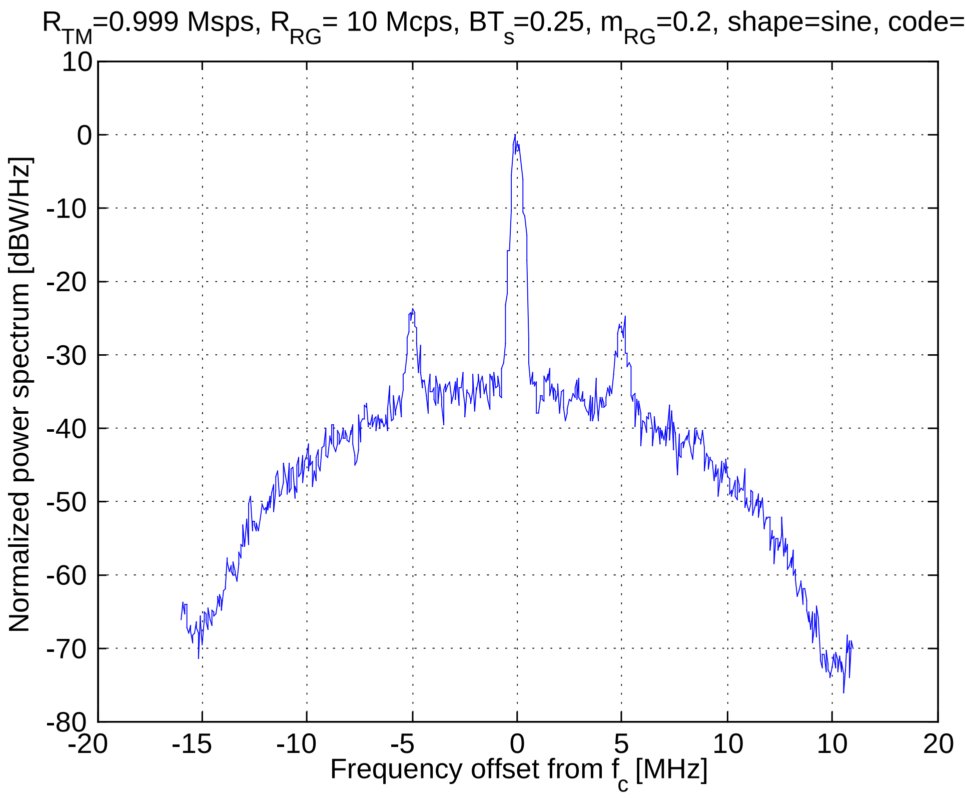

Figure 5 Power spectrum case 5

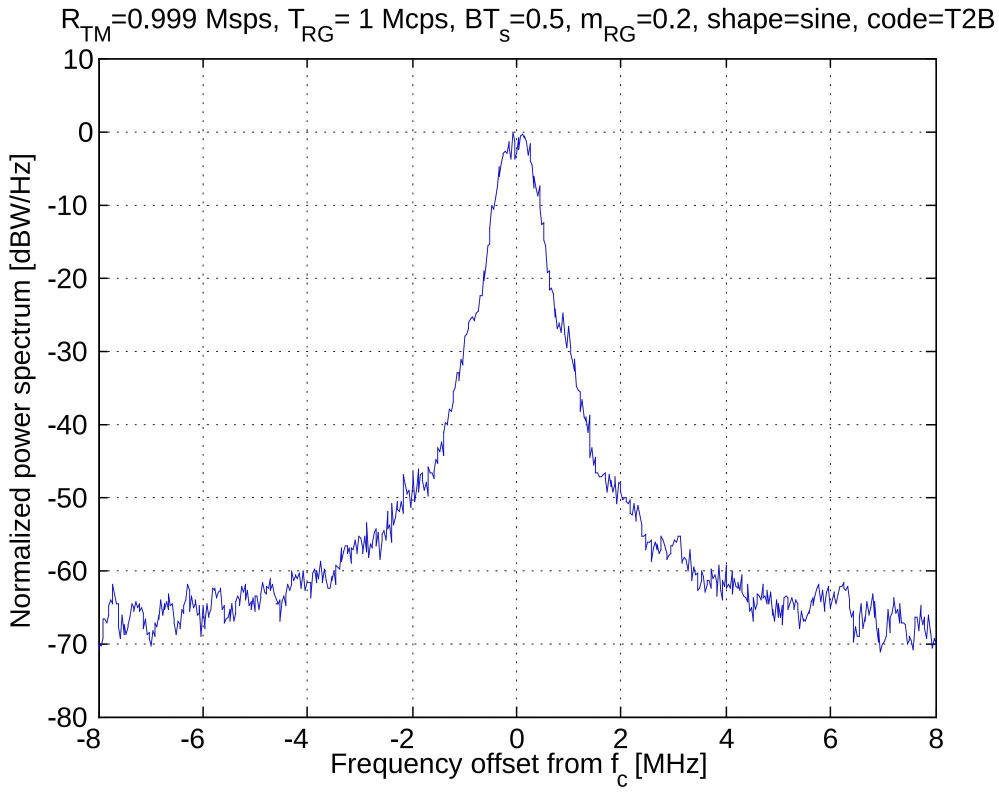

Figure 6 Power spectrum case 6

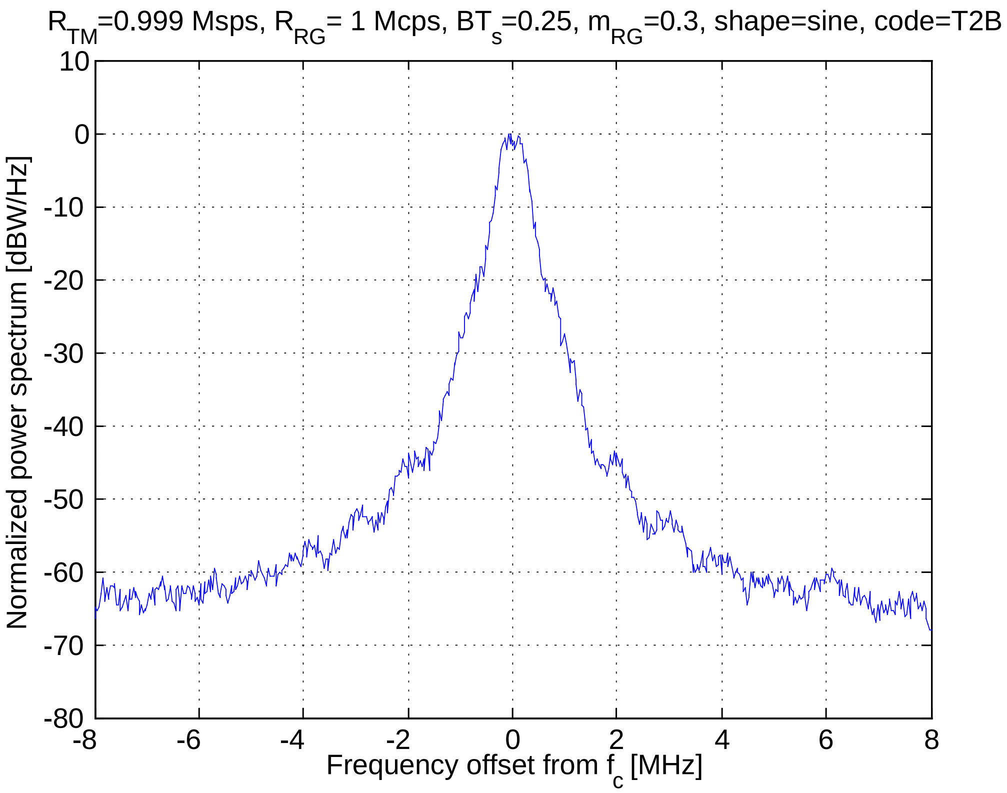

Figure 7 Power spectrum case 7

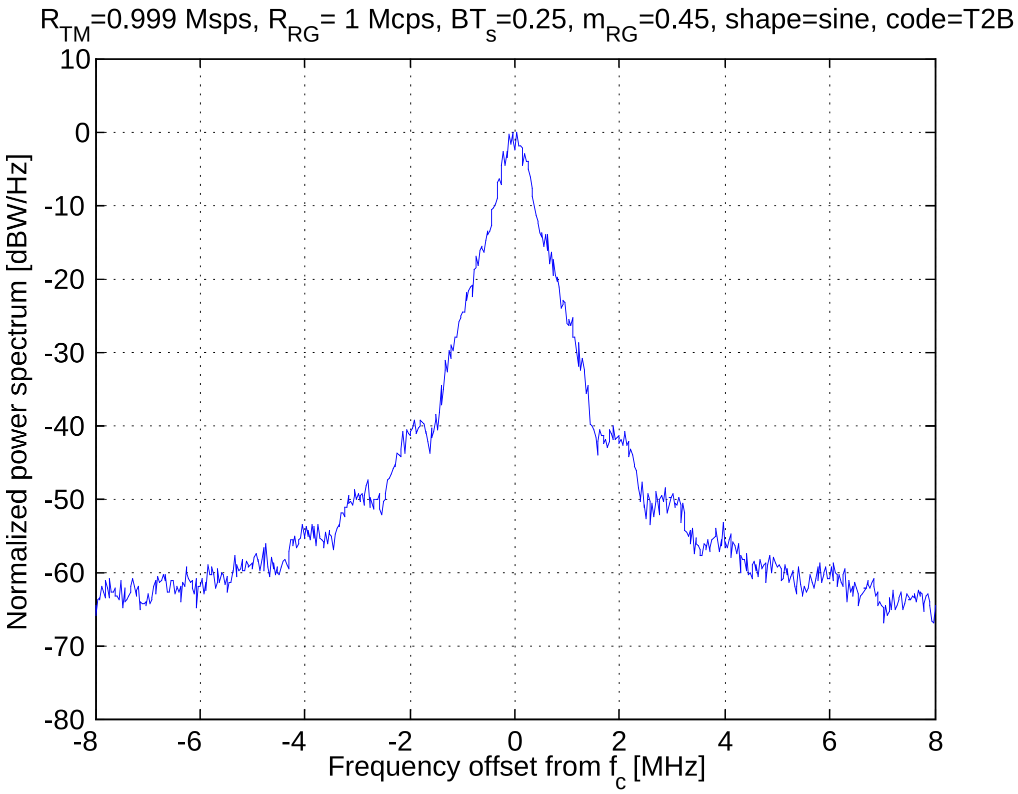

Figure 8 Power spectrum case 8

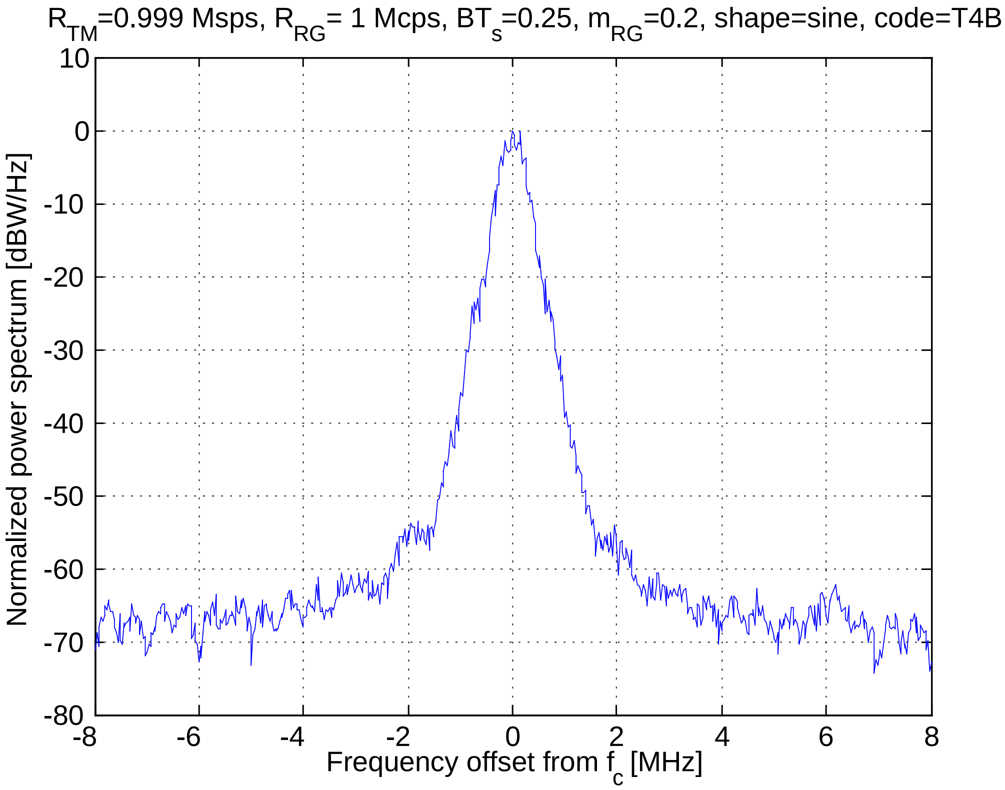

Figure 9 Power spectrum case 9

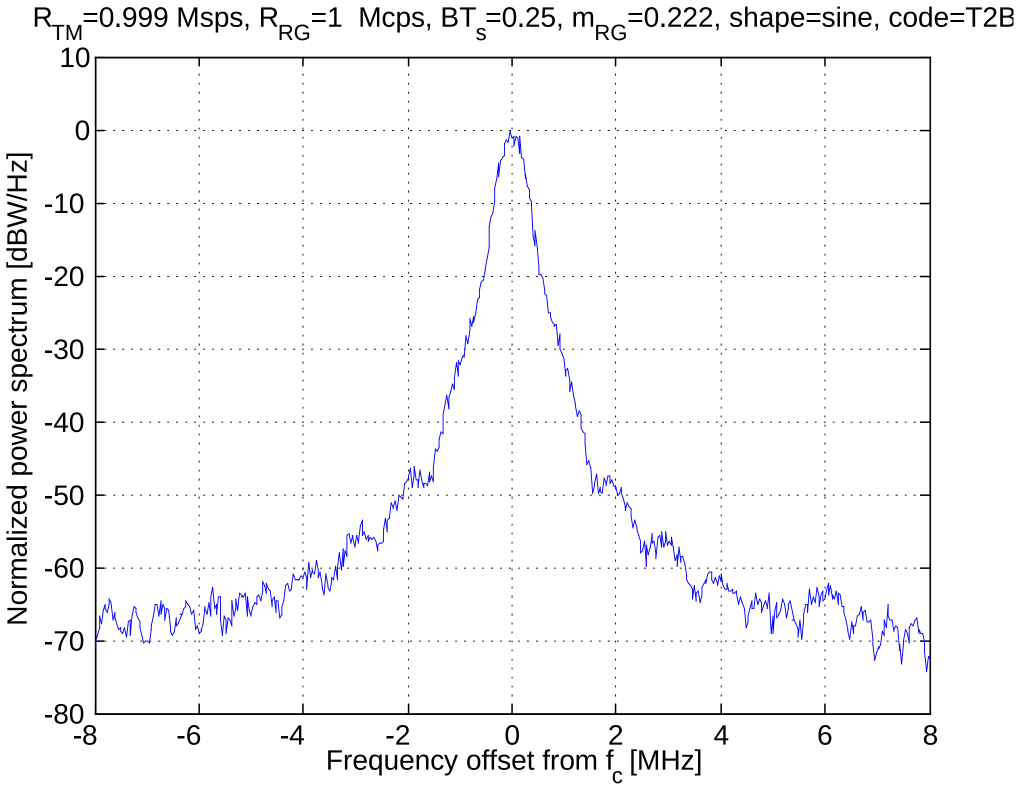

Figure 10 Power spectrum case 10

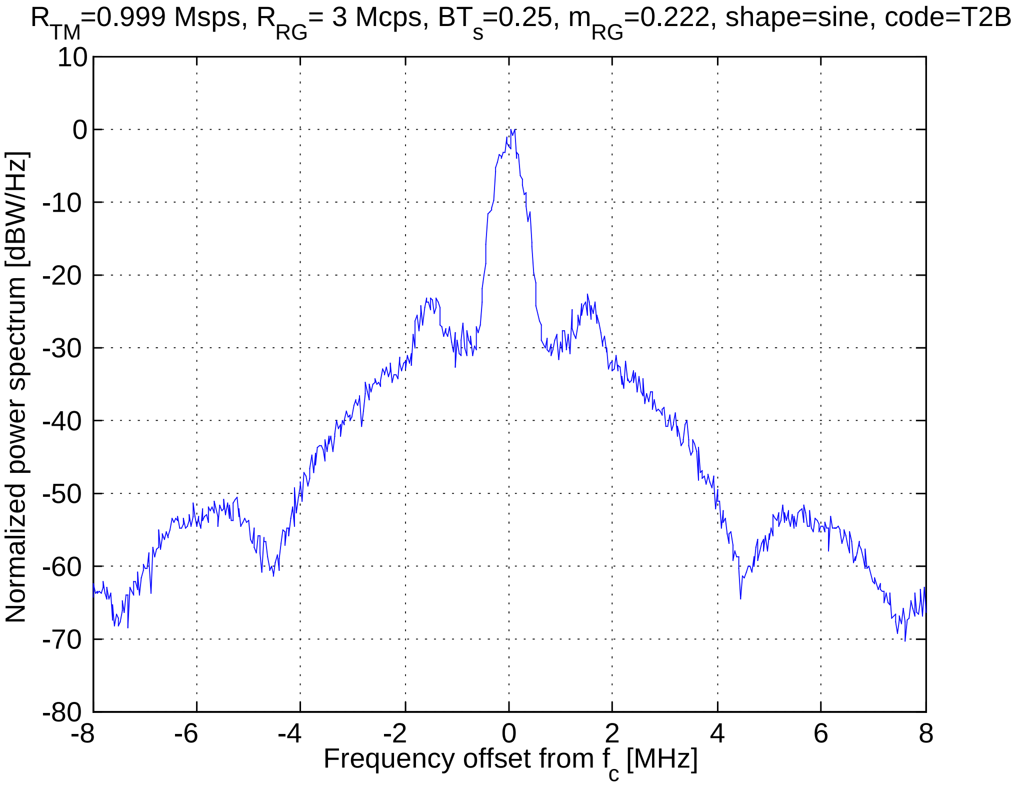

Figure 11 Power spectrum case 11

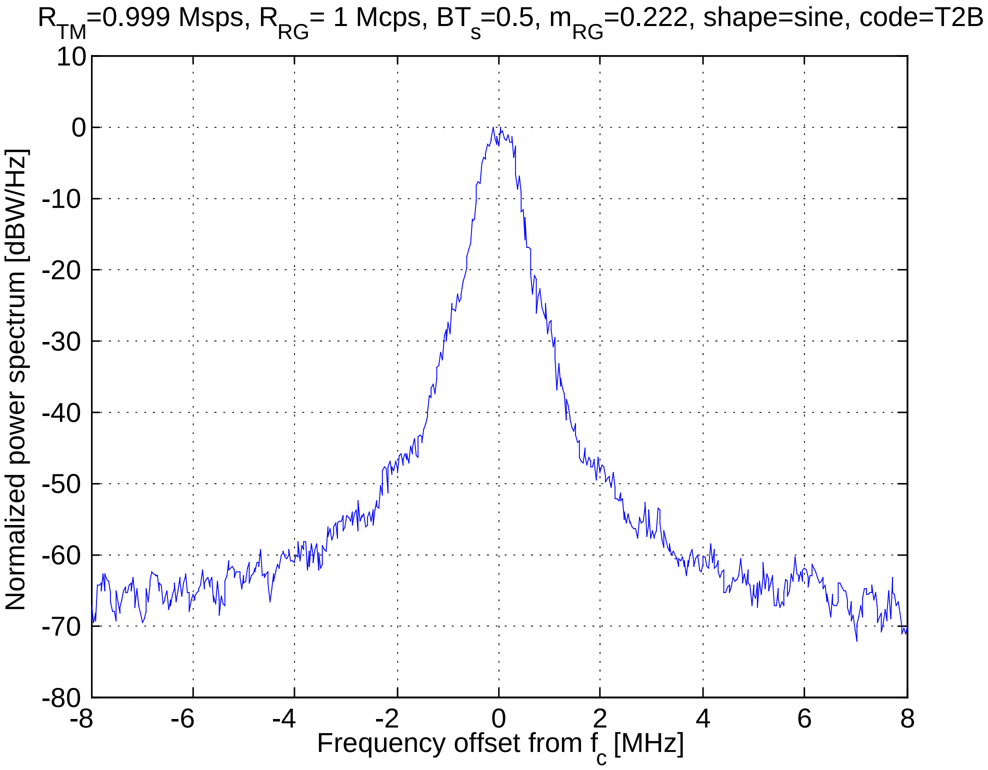

Figure 12 Power spectrum case 12

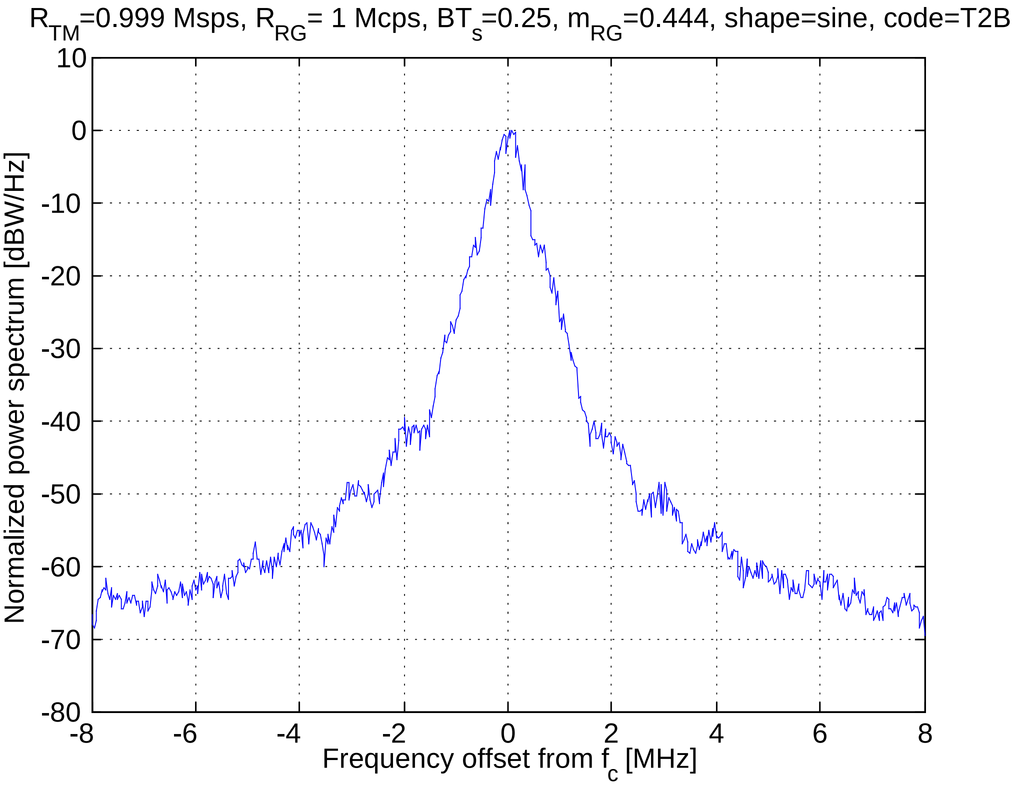

Figure 13 Power spectrum case 13

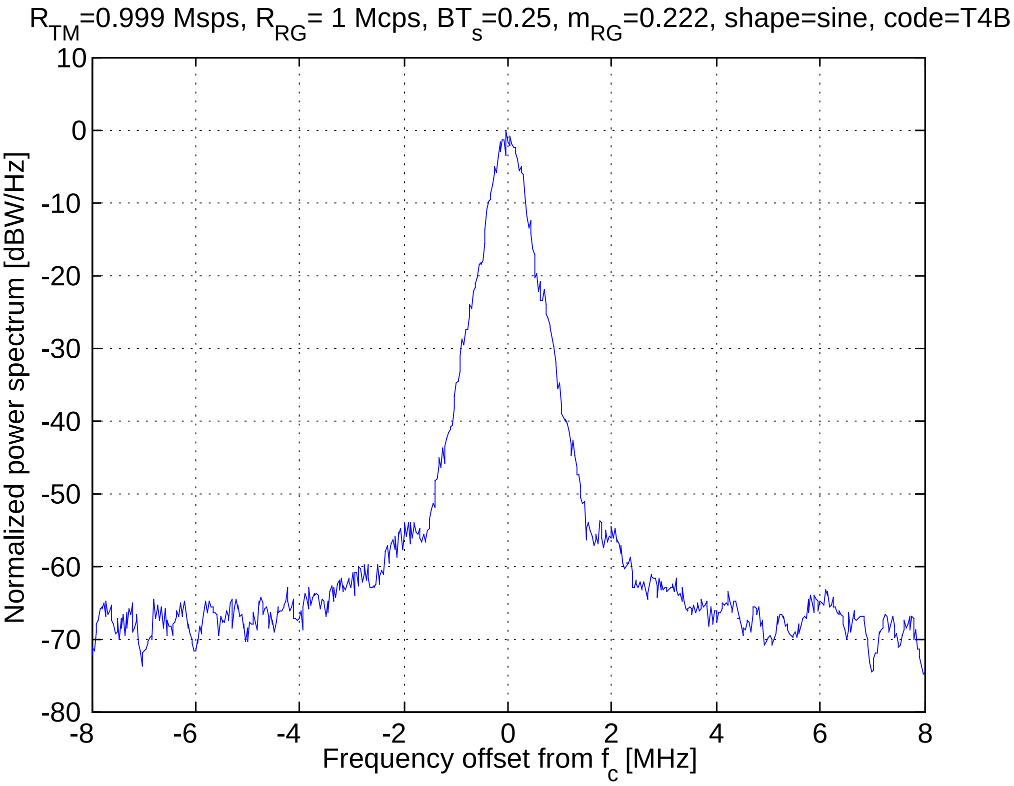

Figure 14 Power spectrum case 14

3 TELEMETRY LOSS

The telemetry loss is defined as the amount by which the SNR must be increased in order to obtain an SER 0f 0.1 when telemetry data is GMSK-modulated and combined with PN ranging. The comparison is made to an SNR of $\frac{E_s}{N_0} = -0.86$dB, necessary to obtain the target SER ($SER = 0.1$) with ideal binary phase shift keying (BPSK) modulation. Therefore the loss shown in the following is thus the total loss, including a) the loss of the GMSK modulation with respect to BPSK, b) the loss due to the fact that a part of the transmitted power is used by ranging, and c) the loss due to the ranging interference. The telemetry clock two-sided loop bandwidth was set to $1 \cdot 10^{-4} R_{TM}$. The ranging signal base band shape is a half sine-wave in all cases. Table 4 shows the measured telemetry losses.

Table 4 Telemetry loss in terms of SNR increase with respect to ideal BPSK modulation (constraint: $SER = 0.1$)

Case	R_{TM} [Msps]	R_{RG} [Mcps]	$\frac{R_{RG}}{R_{TM}}$	BT_s	m_{RG}	RNG code	E_s/N_0 (meas.) [dB]	SNR increase (meas.) [dB]	SNR increase (sim. [3]) [dB]
1	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	T2B	-0.51	0.35	n/a
2	$1-10^{-3}$	2	$2+\epsilon$	0.25	0.2	T2B	-0.55	0.31	n/a
3	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.2	T2B	-0.61	0.25	n/a
4	$1-10^{-3}$	5	$5+\epsilon$	0.25	0.2	T2B	-0.61	0.25	n/a
5	$1-10^{-3}$	10	$10+\epsilon$	0.25	0.2	T2B	-0.61	0.25	n/a
6	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.2	T2B	-0.74	0.12	n/a
7	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.3	T2B	-0.46	0.40	n/a
8	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.45	T2B	-0.07	0.79	n/a
9	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	T4B	-0.57	0.29	n/a
10	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	T2B	-0.58	0.28	0.29
11	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.222	T2B	-0.64	0.22	0.27
12	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.222	T2B	-0.76	0.10	0.13
13	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.444	T2B	-0.15	0.71	0.74
14	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	T4B	-0.63	0.23	0.28

Spot check results for an SER constraint 0f 0.01 is given in Table 5.

Table 5 Telemetry loss in terms of SNR increase with respect to ideal BPSK modulation (*constraint: $SER = 0.01$)

Case	R_{TM} [Msps]	R_{RG} [Mcps]	$\frac{R_{RG}}{R_{TM}}$	BT_s	m_{RG}	RNG code	E_s/N_0 (meas.) [dB]	SNR increase (meas.) [dB]	SNR increase (sim. [3]) [dB]
1*	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	T2B	4.84	0.52	n/a
10*	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	T2B	4.86	0.54	0.51

4 RANGING LOSS – ACQUISITION TIME

The ranging loss in terms of acquisition time is defined as the number of additional ranging chips necessary to acquire the ranging sequence with an error probability of 10^{-3} [3] when telemetry is present. We cannot measure the acquisition time directly and use the following relation instead [5],[6]:

$$10\log\left(N_{chip}\right)=\eta_{dB}-\left(\frac{E_{RG}}{N_0}\right)_{dB}=\eta_{dB}-20\log\left(\left(erf^{-1}(1-2CER\right)\right), \tag{1}$$

where E_{RG}/N_0 is the chip-energy –to-noise ratio, CER is the chip error rate, and η_{dB} is equal to 36.34dB for T4B and 21.17dB for T2B. The formula can be used to estimate the number of ranging chips N_{chip} from the measured CER when telemetry is present, with an error of ± 1dB [6].

In the ideal case there is no interference between telemetry and ranging when both are transmitted simultaneously. In this case, we can derive the CER from (1):

$$CER=\frac{1}{2}erfc\left(\sqrt{\frac{E_{RG}}{N_0}}\right). \tag{2}$$

$\frac{E_{RG}}{N_0}$ can be derived as follows [3]:

$$\frac{E_{RG}}{N_0}=\frac{E_S}{N_0}\frac{\mathrm{R_{TM}}}{R_{RG}}\frac{2J_1^2(m_{RG})}{J_0^2(m_{RG})}, \tag{3}$$

where $\frac{E_S}{N_0}$ is set to the SNR necessary to obtain the target SER of 0.1 with ideal BPSK modulation (-0.86dB). (3) provides a value for CER when there is no interference assumed between telemetry and ranging and at a reference signal-to-noise-ratio. With (3), the ideal acquisition time can be calculated:

$$10\log\left(N_{chip}\right)=\eta_{dB}-\left(\frac{E_s}{N_0}\right)_{dB}-\left(2J_1^2(m_{RG})\right)_{dB}+\left(J_0^2(m_{RG})\right)_{dB}+10\log R_{RG}-10\log R_{TM}, \tag{4}$$

In reality, with interference between telemetry and ranging and imperfect synchronization, the CER and hence the acquisition time will be higher. We measure the CER for each test case when telemetry is present and calculate the acquisition time increase using (1) and (4). The telemetry clock and ranging synchronizer two-sided loop bandwidths were set to $1\cdot 10^{-4}R_{TM}$ and $3\cdot 10^{-5}R_{RG}$, respectively. The ranging signal base band shape is a half sine-wave in all cases. Table 6 shows the results. The column labeled 'CER' shows the measured CER values which the acquisition time was derived from.

Table 6 Ranging loss in terms of acquisition time increase when the telemetry signal is present

Case	R_{TM} [Msps]	R_{RG} [Mcps]	$\frac{R_{RG}}{R_{TM}}$	BT_s	m_{RG}	RNG code	CER (meas.)	Acq. time increase (meas.) [dB]	Acq. time increase (sim. [3]) [dB]
1	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	T2B	0.446	2.61	n/a
2	$1-10^{-3}$	2	$2+\epsilon$	0.25	0.2	T2B	0.460	2.19	n/a
3	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.2	T2B	0.468	2.44	n/a
4	$1-10^{-3}$	5	$5+\epsilon$	0.25	0.2	T2B	0.474	2.10	n/a
5	$1-10^{-3}$	10	$10+\epsilon$	0.25	0.2	T2B	0.482	2.28	n/a
6	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.2	T2B	0.447	2.66	n/a
7	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.3	T2B	0.419	2.60	n/a
8	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.45	T2B	0.378	2.51	n/a
9	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	T4B	0.443	2.10	n/a
10	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	T2B	0.441	2.68	2.63
11	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.222	T2B	0.465	2.41	2.23
12	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.222	T2B	0.441	2.69	2.69
13	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.444	T2B	0.379	2.55	2.58
14	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	T4B	0.437	2.12	2.15

Spot check results for an SER constraint* 0f 0.01 is given in Table 7.

Table 7 Ranging loss in terms of acquisition time increase when the telemetry signal is present

Case	R_{TM} [Msps]	R_{RG} [Mcps]	$\frac{R_{RG}}{R_{TM}}$	BT_s	m_{RG}	RNG code	CER (meas.)	Acq. time increase (meas.) [dB]	Acq. time increase (sim. [3]) [dB]
1*	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	T2B	0.372	0.09	n/a
10*	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	T2B	0.358	0.09	0.10

5 RANGING LOSS – JITTER

The ranging loss in terms of jitter is defined as the increase in ranging clock jitter when telemetry is simultaneously transmitted. As in the previous section, the jitter is compared the ideal jitter performance with no interference between telemetry and ranging so as to calculate the amount of jitter increase. The theoretical ideal variance of the clock jitter normalized to the chip rate, for sine wave shaping, is given in [7]:

$$\sigma_{\epsilon}^{2} = \frac{B_L T_C}{\pi^2 E_{cl,\sin}/N_0}, \tag{5}$$

where B_L is the single-sided loop bandwidth, T_c is the chip period and $E_{cl,sin}$ is the energy per chip of the ranging clock. $E_{cl,sin}/N_0$ can be obtained from the energy of the ranging chip [3]:

$$E_{cl,sin}/N_0 = L_{ck}\frac{E_s}{N_0}\frac{2J_1^2(m_{RG})}{J_0^2(m_{RG})}\frac{R_{TM}}{R_{RG}}, \tag{6}$$

where L_{ck} is equal to 0.881 (0.55dB) for T4B and 0.3936 (4.05dB) for T2B. Again, $\frac{E_s}{N_0}$ is set to the SNR necessary to obtain the target SER of 0.1 with ideal BPSK modulation (-0.86dB). In summary, we get the following expression for the ideal normalized clock jitter variance:

$$\sigma_{\epsilon}^{2} = \frac{B_L T_C}{\pi^2 L_{ck}\frac{E_S}{N_0}\frac{2J_1^2(m_{RG})}{J_0^2(m_{RG})}\frac{R_{TM}}{R_{RG}}}. \tag{7}$$

In reality, the jitter variance is larger than the value predicted by the formula above because due to the interference between telemetry and ranging. The telemetry clock two-sided loop bandwidth was set to $10^{-4}R_{TM}$. In the measurements the single-sided $B_L T_C$ product was set to $1.5 \cdot 10^{-5}$ as opposed to $B_L T_C$=$1 \cdot 10^{-5}$ used in the simulations. The ranging signal base band shape is a half sine-wave in all cases. The ratio (in dB) between the measured and the theoretical jitter variance is given Table 8.

Table 8 Ranging loss in terms of jitter variance increase when the telemetry signal is present

Case	R_{TM} [Msps]	R_{RG} [Mcps]	$\frac{R_{RG}}{R_{TM}}$	BT_s	m_{RG}	RNG code	Jitter standard deviation (meas.) [ns]	Jitter variance increase (meas.) [dB]	Jitter variance increase (sim. [3]) [dB]
1	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	T2B	16.97	0.92	n/a
2	$1-10^{-3}$	2	$2+\epsilon$	0.25	0.2	T2B	11.39	0.47	n/a
3	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.2	T2B	10.27	1.33	n/a
4	$1-10^{-3}$	5	$5+\epsilon$	0.25	0.2	T2B	7.99	1.36	n/a
5	$1-10^{-3}$	10	$10+\epsilon$	0.25	0.2	T2B	5.81	1.61	n/a
6	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.2	T2B	17.44	1.16	n/a
7	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.3	T2B	11.33	0.99	n/a
8	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.45	T2B	7.50	1.05	n/a
9	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.2	T4B	11.54	1.07	n/a
10	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	T2B	15.39	0.99	1.31*
11	$1-10^{-3}$	3	$3+\epsilon$	0.25	0.222	T2B	9.11	1.21	1.06*
12	$1-10^{-3}$	1	$1+\epsilon$	0.5	0.222	T2B	15.77	1.20	1.45*
13	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.444	T2B	7.57	1.01	1.16*
14	$1-10^{-3}$	1	$1+\epsilon$	0.25	0.222	T4B	10.49	1.15	1.26*

*B_LT_C=$1 \cdot 10^{-5}$ was used for the simulations.

Spot check results for an SER constraint* 0f 0.01 is given in Table 9.

Table 9 Ranging loss in terms of jitter variance increase when the telemetry signal is present

Case	R_{TM} [Msps]	R_{RG} [Mcps]	$\frac{R_{RG}}{R_{TM}}$	BT_s	m_{RG}	RNG code	Jitter standard deviation (meas.) [ns]	Jitter variance increase (meas.) [dB]	Jitter variance increase (sim. [3]) [dB]
1*	$1-10^{-2}$	1	$1+\epsilon$	0.25	0.2	T2B	8.85	0.44	n/a
10*	$1-10^{-2}$	1	$1+\epsilon$	0.25	0.222	T2B	7.84	0.31	0.29*

*B_LT_C=$1 \cdot 10^{-5}$ was used for the simulations.

6 CONCLUSION

This document summarizes the results of a measurement campaign in support of the draft CCSDS recommendations 401(2.4.22A) and 401(2.4.22B) for simultaneous transmission of GMSK-modulated high-rate telemetry and PN ranging. In particular, the measured test cases focus on the recommended parameters sets given the accompanying draft Green Book so as to validate the simulation-based results presented in the Green Book with measurements obtained with two modem breadboards. The measurements cover the spectrum occupation by the combined telemetry and ranging signals, telemetry losses due to the presence of the ranging signal, ranging losses due to the presence of a telemetry component.

The measurement results confirm the performance figures obtained from the simulations. The measured spectral occupation in terms of 99%-power bandwidth is in accordance with the simulation results. The telemetry loss in terms of SNR increase, the ranging loss in terms of increase in ranging sequence acquisition time and the ranging loss in terms jitter variance increase reproduce the simulation results with a maximum difference of 0.3dB.

7 ANNEX

The following describes the test equipment and test procedures of the measurement campaign.

7.1 Test Equipment

The test equipment and test setup are given in Table 10 and Figure 15, respectively. Both breadboard modems have independent transmit and receive chains and can be configured as transmitter and receiver.

Table 10 Test equipment

Part	Manufacturer /serial number / calibration date	Remark
Breadboard modem 1	Space Engineering / M1(TX/RX) / n.a.	Configured as transmitter
Breadboard modem 2	Space Engineering / M2(RX) / n.a.	Configured as receiver
Spectrum analyzer	Agilent E4448A / US44020398 / 26-Nov-2013	
Noise source	Noisecom NC6112 / F085 / n.a.	
Variable attenuator	Weinschel Engineering / 6783 / n.a.	Fine noise level adjustment
RF amplifier	HP 461A / 0946A06349 / n.a.	Amplification of the injected noise

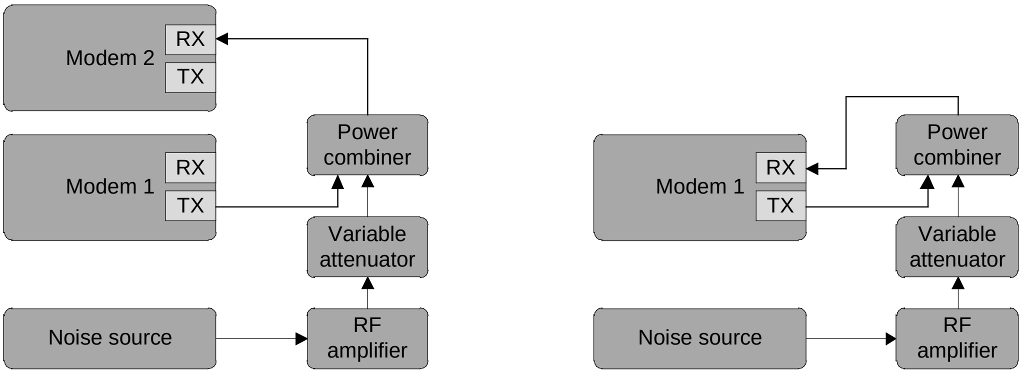

Figure 15 Test setup with both modems (left) and one modem in a loopback setup (right)

7.2 Measurement Procedure – Spectral Performance

Only Modem 1 was used for this test.

1. Configure TX parameters of Modem1 according to the settings in Table 2.
2. Record spectrum of the signal at the TX output and measure 99%-power bandwidth for each test case with the spectrum analyzer.

7.3 Measurement Procedure – Telemetry Losses

The setup in Figure 15 (left) was used for this test.

1. Configure TX parameters of Modem 1 and RX parameters of Modem 2 according to the settings in Table 2.
2. Measure the power P_T of the TX output signal with a spectrum analyzer. The total output power level is assumed to be constant across different test cases.
3. Connect the power combiner output to the RX input and adjust the variable attenuator to obtain the target SER for telemetry reception.
4. Measure the spectral noise density N_0 at the output of the variable attenuator with the spectrum analyzer level. Calculate the SNR required to obtain the target SER: $\frac{E_s}{N_0} = \frac{P_T}{N_0 R_{TM}}$
5. Calculate the difference to the SNR required for ideal BPSK modulation.

7.4 Measurement Procedure – Ranging Losses (Acquisition Time)

The setup in Figure 15 (left) was used for this test.

1. Configure TX parameters of Modem 1 and RX parameters of Modem 2 according to the settings in Table 2.
2. Connect the power combiner output to the RX input and adjust the variable attenuator to obtain the target SER for telemetry reception.
3. Measure the CER at Modem 2 and calculate N_{chip} using (1).
4. Calculate the value for N_{chip} under ideal conditions for each test case using (4). Calculate the ranging loss in terms of the difference $\left(N_{chip}\right)_{meas,dB} - \left(N_{chip}\right)_{ideal,dB}$.

7.5 Measurement Procedure – Ranging Losses (Jitter)

The loopback setup in Figure 15 (right) was used for this test.

1. Configure TX and RX parameters of Modem 1 according to the settings in Table 2.
2. Connect the power combiner output to the RX input and adjust the variable attenuator to obtain the target SER for telemetry reception.
3. Measure the jitter σ_τ at Modem 1.
4. Calculate the normalized jitter variance $\sigma_\varepsilon^2 = \sigma_\tau^2 R_{RG}^2$. Calculate the ideal jitter variance with (7). Calculate the ranging loss in terms of the difference $(\sigma_\varepsilon^2)_{meas,dB} - (\sigma_\varepsilon^2)_{ideal,dB}$