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Modeling ESA's TT&C Systems

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ABSTRACT

After a brief introduction on the need for simulation packages for the analysis and design of satellite communications systems, the software tool developed for the European Space Agency (ESA), its main objectives and the design choices made during the development are presented. A very concise description of the available communications and measurement block follows. The ESA standard Telemetry, Tracking and Command (TT&C) system simulator is then introduced along with a description of the ESA standard modulation and coding schemes. As an example, the simulation of the ranging system which is a non-standard communications block, is described in details. Several examples of TT&C simulations outputs are given and compared with measurement results or theoretical approximations, when available. Finally, future developments like the support of advanced modulation schemes and the dynamic satellite link simulation are presented.

I. Introduction

As telecommunications technology progresses, new design tools are required by the system engineer to evaluate the performance of more and more complex systems and subsystems.

In fact, some equipment is so complex that no theoretical calculations can predict what the performance is going to be. Sometimes only simplified formulas or "rules of thumb" exist to qualitatively compare different hardware implementations. In either case some kind of tools are required to quantify system performance under real operating conditions before any expensive hardware bread-boarding or prototyping is attempted. Digital computer simulation for the analysis and design of communications systems is deemed to be a very powerful tool complementing both theoretical calculations and laboratory tests.

Therefore, the European Space Agency (ESA) has been supporting the development of a sophisticated and reliable simulation package for telecommunications systems which would cover all aspects of satellite communications, from radio frequency modulation to baseband encoding and decoding.

As the next step, the modeling of the ESA standard Telemetry, Tracking and Command (TT&C) ground station and satellite equipment based on the developed CAD package has been undertaken.

The requirement was to be able to evaluate telemetry, telecommand and tracking performance with an accuracy comparable to the measurement accuracy of real tests on flight and ground station hardware.

The main objectives of the TT&C simulator are broadly relating to the computer aided design and analysis functions: the optimization of the communications link of any ESA's mission, the setting-up of the various subsystems parameters, the preliminary assessment of radio frequency compatibility between the satellite and the station equipment, the estimation of the end-to-end system performance under the mission impairment conditions and operation modes, and the possibility of quantifying system degradation due to unexpected events in the mission lifetime.

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II. The Telecommunication System Simulator

For the analysis and design of satellite communications systems, ESA has initiated a research program with the goal of developing a simulation package encompassing up-to-date communications equipment, with a high degree of flexibility in changing parameters and structures yet so user friendly to attract engineers not too keen in learning programming languages.

TOPSIM IV (TOrino Politecnico SIMulator, release IV) [5] is the result of this development. Being written in the FORTRAN-77 language, it can in principle be installed on any digital computer supporting a FORTRAN-77 compiler although the use of its sophisticated graphics interfaces requires that the X Window/Motif software be available.

The simulator is based on the time representation of signals whereby a band limited signal can be uniquely represented by a series of samples taken at the Nyquist rate or higher. This approach has been preferred to the frequency domain representation which is not optimal in dealing with feedback loops and non-linear devices. However, when complicated filters have to be simulated, the time domain approach may result in time-consuming simulation runs; therefore, simulation blocks operating in the frequency domain and integrated in the time domain by FFTs are available.

Linked to the time domain choice is the fact that telecommunications systems normally are characterized by a large ratio between the carrier frequency and the useful signal bandwidth. Therefore, the complex envelope representation of band-pass signals has been adopted to drastically cut down the sampling rate and thus increase the speed of execution. It is well known that a narrowband signal x(t) can be represented as:

$$x(t) = x_p(t) \cos 2\pi f_o t - x_q(t) \sin 2\pi f_o t \tag{1}$$

where $x_p(t)$ and $x_q(t)$ are the complex envelopes of x(t) and f_o is the carrier center frequency. Each signal is therefore represented by a three-position vector where x_p, x_q and f_o are stored. The sampling rate is determined by the bandwidth of the useful signal (x_p, x_q) and not by the carrier frequency.

Since in the time domain representation of signal, the sampling rate must satisfy the Nyquist theorem for the element with the widest bandwidth, the multirate option is also available to further speed up the run time when different rates are used in different parts of the system (spread-spectrum systems for instance.) Special functions like pre-computation, program segmentation and block processing are also available to increase efficiency and user-friendliness.

A very large library of blocks is available (more than 300 blocks modeling communications devices and about 30 blocks performing various measurement functions.) The communications blocks encompass signal and random generators, analog and digital modems, analog channels and non-linear devices, analog and digital filters, carrier and clock recovery circuits, DSP modules, coders, decoders and trellis-coded modems. The measurement library includes qualitative measurements (eye patterns, scattering diagrams), statistical estimates (jitters), bit error rate routines, power and power spectral density evaluation.

User-defined blocks simulating more complex subsystems can be written from scratch on a default template or by using the supplied TOPSIM routines as elementary building blocks, and then included in a personalized library.

Flexibility, one of the goals of the simulator, is achieved in two different ways: first, none of the parameters of the library blocks is fixed to a default number; secondly, the activation of different parts of the simulation (program segmentation) to compare different configurations is supported by means of simple logic variables.

Application programs can be very easily written by drawing the system block diagram on the screen with the graphic input interface (GII) and letting it convert the drawing into TOPSIM code. Similarly, the simulation outputs can be displayed by the X Window based graphic output interface (GOI) either in on-line or off-line mode.

III. The ESA Standard TT&C Simulator

Of the many different application programs written with TOPSIM, SIMSAT has the task of dimensioning all the parameters involved in the link between a TT&C Earth station of the ESA Tracking (ESTRACK) network and an ESA, or CCSDS compatible, Near-Earth or Deep-Space Spacecraft, or Geostationary Satellite.

The program allows simulation of simultaneous transmission of telecommand, telemetry and ranging signals according to the various ESA standards [1]-[4], and models standard ESA Earth station and spacecraft equipment, although different subsystems characteristics can be easily introduced should the need arises.

The most difficult task SIMSAT supports is the selection of telemetry and telecommand subcarrier and ranging tone frequencies, and their modulation indexes minimizing mutual interference and intermodulation due to transponder non-linearity and modulators' spurious signals.

Available simulation outputs are qualitative measurements (eye patterns, scattering diagrams), statistical estimates (timing and phase jitters, ranging and Doppler mean and r.m.s. values), error rates (telemetry and telecommand bit and symbol error rates, ranging erroneous ambiguity resolution probability), power measurements and power spectrum evaluations.

Being SIMSAT based on the ESA funded satellite communications simulator, most of the subsystems used in both the Earth and the space segment are standard library blocks. For those, trimming the various parameters and introducing non-ideal effects (imbalances, skew, non linearity, AM/PM, phase noise, etc.) according to both equipment specifications and measurement results has been the major task in building the simulator.

On the other hand, the blocks simulating the ranging equipment had to be written from scratch. Ranging/Doppler subsystems are in fact not normally contemplated among basic communications equipment.

The standard ESA tracking system, called the Multi Purpose Tracking System (MPTS) has been fully modeled, including its sequence of operations (carrier and tone acquisition and tracking, code ambiguity resolution, range and Doppler measurement.)

Among the blocks written to simulate the MPTS are the ranging code and tone generators, the replica code and tone generators, the frequency-steered digital tone phase locked loop, the IF and digital correlators, the time interval counters and the processing and control module making sure that the sequential steps of the tracking process are correctly performed.

A. The ESA TT&C Systems

The standard ESA uplinking of commands to the spacecraft (telecommand) is specified to use the following modulation scheme: the telecommand data, which is binary Non-Return-to-Zero-Level (NRZ-L) encoded, phase shift-keys (PSK) a sinusoidal subcarrier (8 or 16 kHz); the composite video signal then phase modulates (PM) the sinusoidal uplink carrier together with the ranging video signal.

The ranging signal [2], [7], [8] is a hybrid signal composed of a special code phase modulating the ranging tone. The resulting video signal phase modulates the uplink carrier sharing its power with the telecommand signal.

The uplink signal is therefore given by:

$$S_u(t) = \sqrt{2P_u}\cos[2\pi f_o t + m_{TC} S_{TC}(t) + m_{RG} S_{RG}(t)] \tag{2}$$

where

$$S_{TC}(t) = d_{TC}(t)\ \cos(2\pi f_{TC} t + \emptyset) \tag{3}$$

is the telecommand video signal,

$$S_{RG}(t) = \cos(2\pi\ f_r t + m_r r_n(t)) \tag{4}$$

is the ranging video signal, and

Pu : uplink signal power
fo : uplink carrier frequency
m_{TC} : telecommand uplink modulation index
m_{RG} : ranging uplink modulation index
$d_{TC}(t)$: telecommand baseband data stream
$r_n(t)$: ranging code
f_{TC} : telecommand subcarrier frequency
f_r : ranging tone frequency
m_r : ranging code modulation index
$\varnothing$: telecommand subcarrier initial phase

Telecommand and ranging uplink modulation indexes are selected in order to optimize the TT&C link budget.

For the telemetry signals transmitted from the spacecraft to the Earth station, both NRZ-L and Split-Phase-Level (SP-L) binary encoding, Reed-Solomon, Convolutional or Concatenated (Reed-Solomon plus Convolutional) channel encoding, and sine-wave or square-wave subcarriers may be selected depending on the bit rate and the mission requirements. The resulting video signal finally phase modulates the downlink carrier with the ranging signal which has undergone phase demodulation, filtering and automatic gain control (AGC). Due to the limited filtering performed in the transponder, the ranging signal is normally accompanied by the fed-through telecommand signal. Therefore, telemetry, telecommand, ranging and thermal noise share the downlink power.

The downlink signal is given by [8]:

$$Sd(t) = \sqrt{2Pd}\,\mathrm{Re}\{\exp\{j\ [2\pi\, fc\, t + m_C\, S'_{TC}(t) + m_R\, S'_{RG}(t) + m_{TM}\, S_{TM}(t) + m_e\, n(t)\ ]\}\} \tag{5}$$

where

$$S_{TM}(t) = d_{TM}(t)\ \cos(2\pi\, f_{TM}\, t + \theta) \tag{6}$$

is the telemetry video signal in case of sinusoidal subcarrier, and

$S'_{TC}(t)$ is the filtered and level controlled telecommand video signal,

$S'_{RG}(t)$ is the filtered and level controlled ranging video signal,

$n(t)$ is the thermal noise in the transponder ranging channel, and

Pd : downlink signal power
fc : downlink carrier frequency
f_{TM} : telemetry subcarrier frequency
m_C : telecommand echo modulation index
m_R : ranging effective downlink modulation index
m_e : noise downlink modulation index
m_{TM} : telemetry modulation index
$d_{TM}(t)$: telemetry baseband data stream
θ : telemetry subcarrier initial phase

Calculations of the downlink modulation indexes are reported in [6] whereas analytical expressions for $S'_{RG}(t)$ are given in [8].

B. Modeling the Tracking System

The ranging and Doppler tracking system (MPTS) has been modeled by writing a series of user defined blocks. Only the most important features will be described here. Detailed descriptions of the equipment can be found in [7], [8].

The ranging modulator is made up of a special code generator, a tone generator and a linear modulator where the code synchronously modulates the tone with three operations dependent modulation indexes. The code is a periodic signal actually composed of subcodes in a proper sequence and was design to allow fast ambiguity resolution. The resulting video signal is fed to the uplink modulator for modulation with or without the telecommand signal.

The Doppler unit performs integrated Doppler measurement on the downlink carrier and estimates the expected ranging tone frequency.

The ranging demodulator performs an I-Q correlation between the received IF ranging signal and the replica ranging tone generated on the information from the Doppler unit. After conversion to baseband by multiplication with the recovered carrier, the phase error is sent to the digital tone PLL. This technique (tone frequency steering) has been devised to use very narrow loop bandwidths yet without having too long acquisition times. When the loop is locked, the quadrature correlator IF output is correlated with the locally generated replica code in phase and quadrature. The downconverted output is filtered and fed to the code ambiguity resolver where the ambiguity resolution logic is implemented.

The processing and control module interfaces with the various units, supervises the various stages involved, i.e. the carrier and tone acquisition, the sequencing of codes for ambiguity resolution, the measurement proper, and generates the required statistical outputs (range and Doppler jitter and bias, probability of erroneous ambiguity resolution, etc.)

C. Simulation Examples

Fig. 1 shows the simulated ESA TT&C space and ground segment. Some of the blocks shown are actually macro blocks made up of several elementary blocks like the Ranging System whose internal structure is depicted in fig. 2.

Fig. 3 is a typical result of the system and detailed design phase of a project, the optimization of the satellite transponder back-off. The figure depicts the estimated telemetry BER for the ISO spacecraft as a function of the selected back-off.

Fig. 4 shows the simulated ranging spectrum of a CCSDS compliant mission whereby the ranging tone is fixed at 100 kHz. The tone itself, the sideband created by the code modulation and the odd harmonics of the tone are visible. This kind of plots can be used to select the telemetry subcarrier frequency.

Fig. 5 shows the worst case in-phase and quadrature ranging correlators output for the ISO mission and is used to determine the minimum code integration time necessary to perform the ambiguity resolution with the mission specific probability of error.

Fig. 6 shows the in-phase ranging correlator output during ambiguity resolution for the CLUSTER spacecraft when no noise is present. The actual curve shows a 10% reduction with respect to the design value, due to the limited bandwidth of the flight transponder. This example demonstrates the tool capability to quantify system performance degradation caused by subsystem non compliant with specifications.

Fig. 7 and 8 respectively show the simulated and measured spectra at the output of the transponder. Due to the limited bandwidth of the modulator, spurious lines at the even harmonics of the bit rate are generated. Note the almost perfect match between simulation and measurement.

Comparisons between simulated and measured telemetry bit error rates (BER), for the cases of telemetry only and simultaneous telemetry and ranging, are shown in fig. 9. The theoretical BER value for the telemetry only case is also included. The maximum difference between simulation and measurement is some 0.2 dB, of the same magnitude of the test equipment measurement accuracy.

IV. Future Developments

ESA is currently considering the use of bandwidth and power efficient (suppressed carrier) and spread-spectrum modulation schemes for TT&C support of future missions.
The next generation modems are being introduced in SIMSAT to replace the present standard PSK/PM modulation. Besides, since suppressed carrier signals are deemed more sensitive to Doppler shifts and rates, a dynamic satellite link simulator will be added to TOPSIM. The link simulator is to compute the link geometry parameters (slant range, Doppler shift and rate, elevation angle, etc.) and derive link budget parameters (carrier-to-noise density ratio, Eb/No, etc.) versus time. The generated output file will then feed the present simulation program so that a dynamic simulation is performed.

V. Conclusions

Based on TOPSIM, a digital computer simulation tool tailored to ESA's requirements in the field of space communications, the simulation template for ESA's standard ground and space TT&C equipment has been developed. The very accurate modeling of the various ground and space TT&C subsystems has resulted in very good matching between simulation results and measurements performed on the equipment itself. Thanks to the achieved accuracy, the simulator is very extensively used:

. during conceptual system design (feasibility or Phase A) to trade off various configurations of the same system or different systems performing the same functions;
. during detailed design phase (phase B) to determine mission specific set-ups (modulation indexes, loop bandwidths, correlation times, carrier and subcarrier frequencies, etc.);
. during the implementation phase (phase C/D) to evaluate system performance under the predicted mission impairments for which analytical solutions do not exist;
. after launch to simulate the effects of subsystem degradation's occurred during the mission and validate corrective actions on a model prior to trying it out on the flying spacecraft.

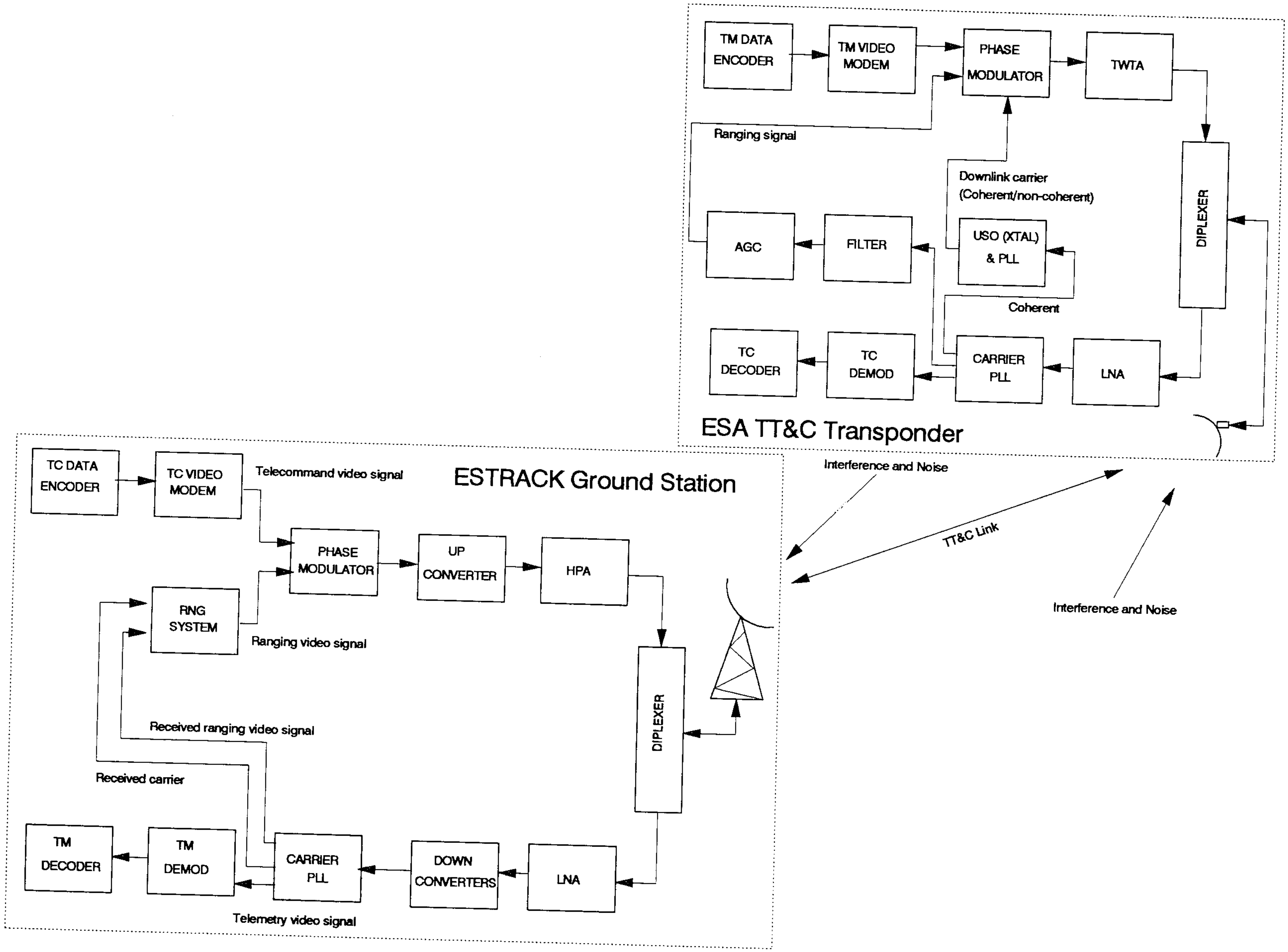
Therefore, although final radio frequency compatibility tests between the space and the ground segment are performed on the actual hardware as prescribed by the ESA standards [1], the complete design of the TT&C link is done by simulation. Potential problems are likely to be discovered by simulations much earlier than the expensive flight hardware is available for testing thereby potentially minimizing schedule risks and program costs.

The performance of the simulator with respect to the actual equipment has encouraged the development of a new template including future ESA modulation schemes and a dynamic satellite link simulator.

VI. References

[1] European Space Agency (November 1989), *RF & Modulation Standard,* PSS-04-105, Issue 1.
[2] European Space Agency (April 1990), *Ranging Standard, Vol. I, Direct Earth-to-Space Link,* PSS-04-104, Issue 1.
[3] European Space Agency (September 1989), *Telemetry Channel Coding Standard,* PSS-04-103, Issue 1.
[4] European Space Agency (March 1979), *S and S/X Band Coherent Transponder Specifications*, PSS-48, Issue 1.
[5] European Space Agency (1986), *TOPSIM IV, Design and Implementation of Software for Simulation and Analysis of Communication Systems,* ESA/ESTEC Contract No. 6981/86/ML/JG.
[6] R. De Gaudenzi and M. Nahvi (1989), T*elemetry degradation due to the ranging signal of the multi purpose tracking system,* CCSDS proceedings, RF and Modulation Subpanel1E, NASA Ames Research Center, CA.
[7] R. De Gaudenzi, E. E. Lijphart and E. Vassallo (1990), *The New ESA's MPTS,* ESA Journal, Vol. 14, No. 1.
[8] R. De Gaudenzi, E. E. Lijphart and E. Vassallo (1992), *A New High Performance Multi-Purpose Satellite Tracking System,* IEEE Transactions on Aerospace and Electronic Systems, Vol. 28, No. 4.

Fig. 1 - ESA TT&C Schematics



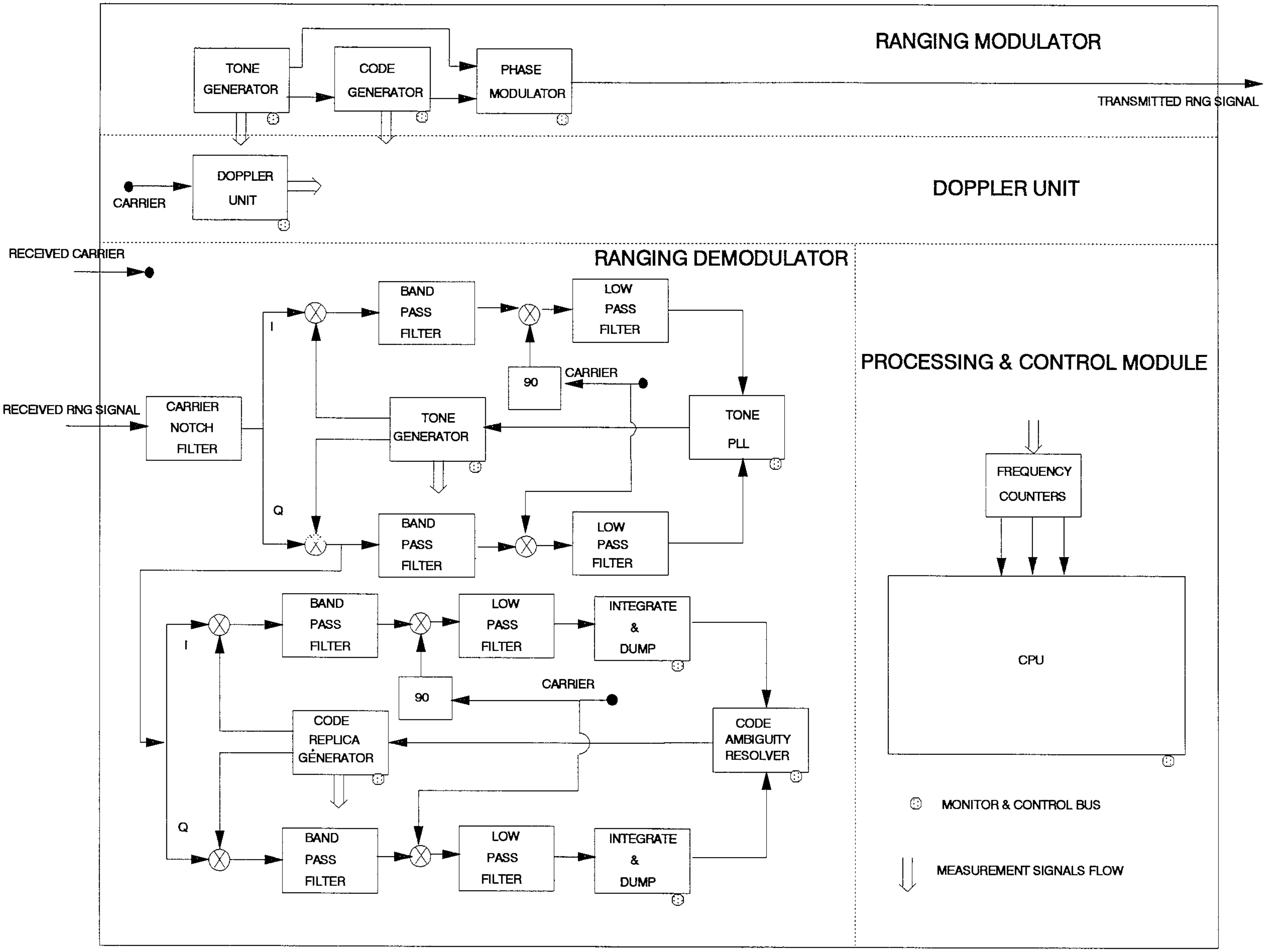


Fig. 2 - Ranging System (MPTS)

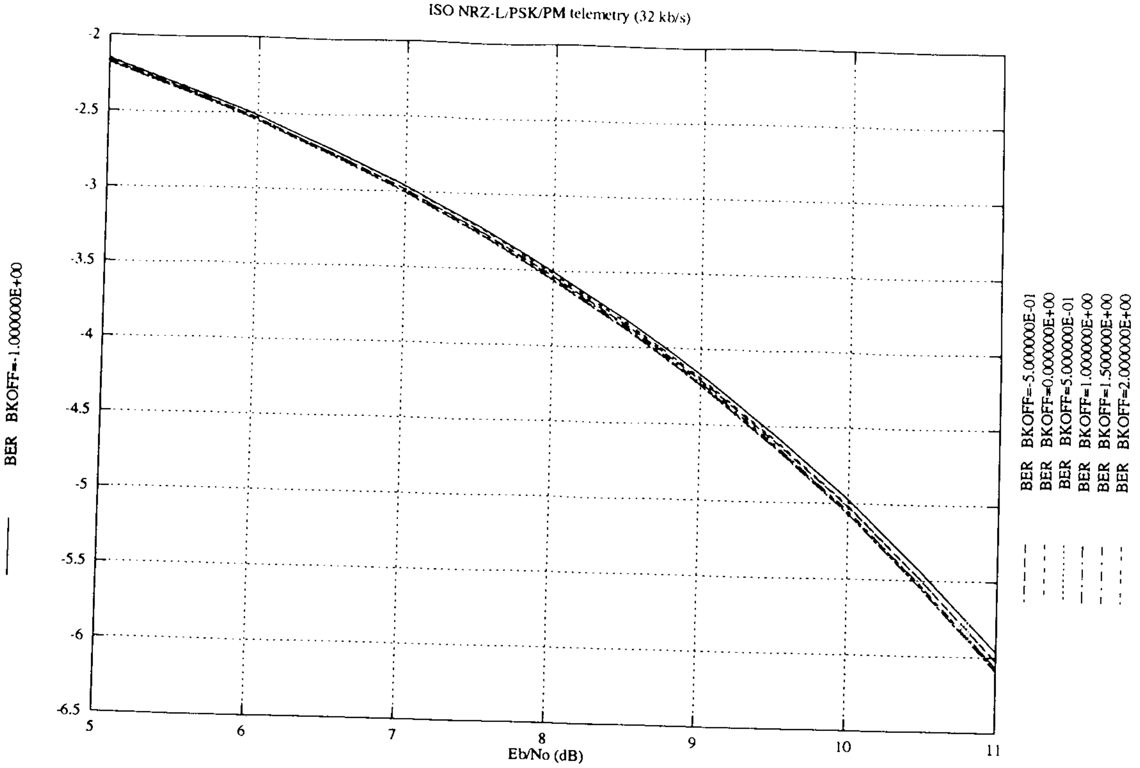


Figure 3. Telemetry BER vs. TWTA back-off

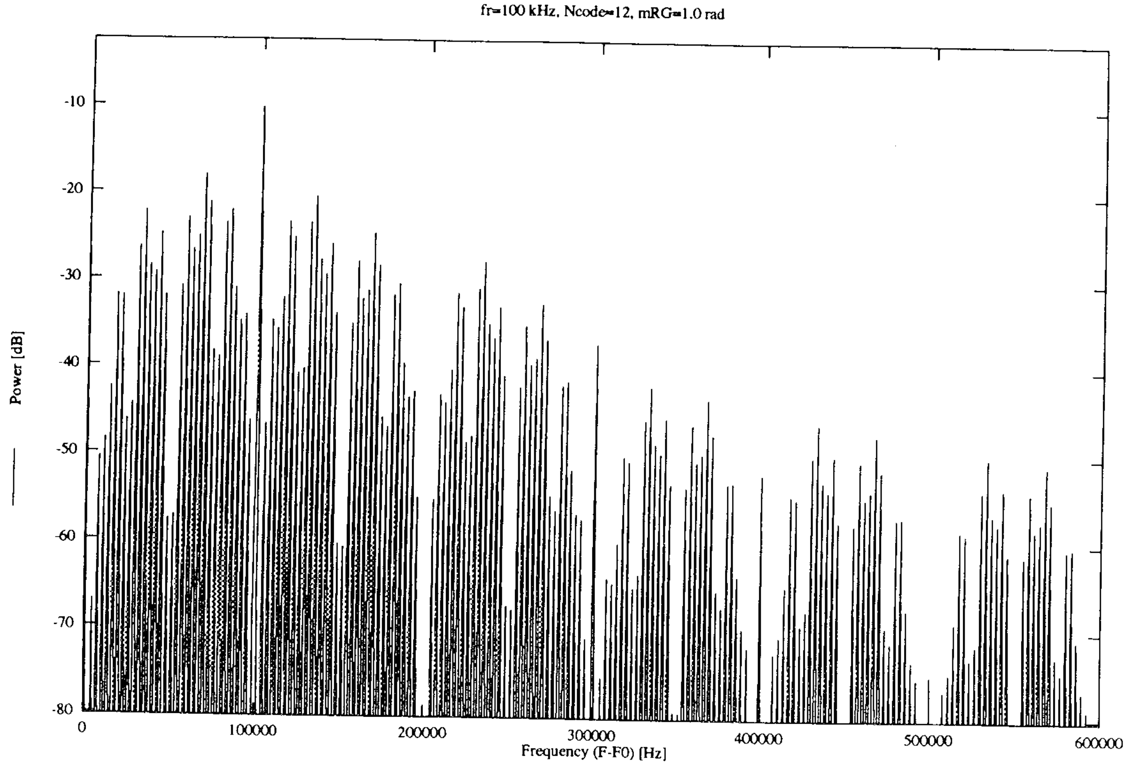


Figure 4. Ranging signal spectrum

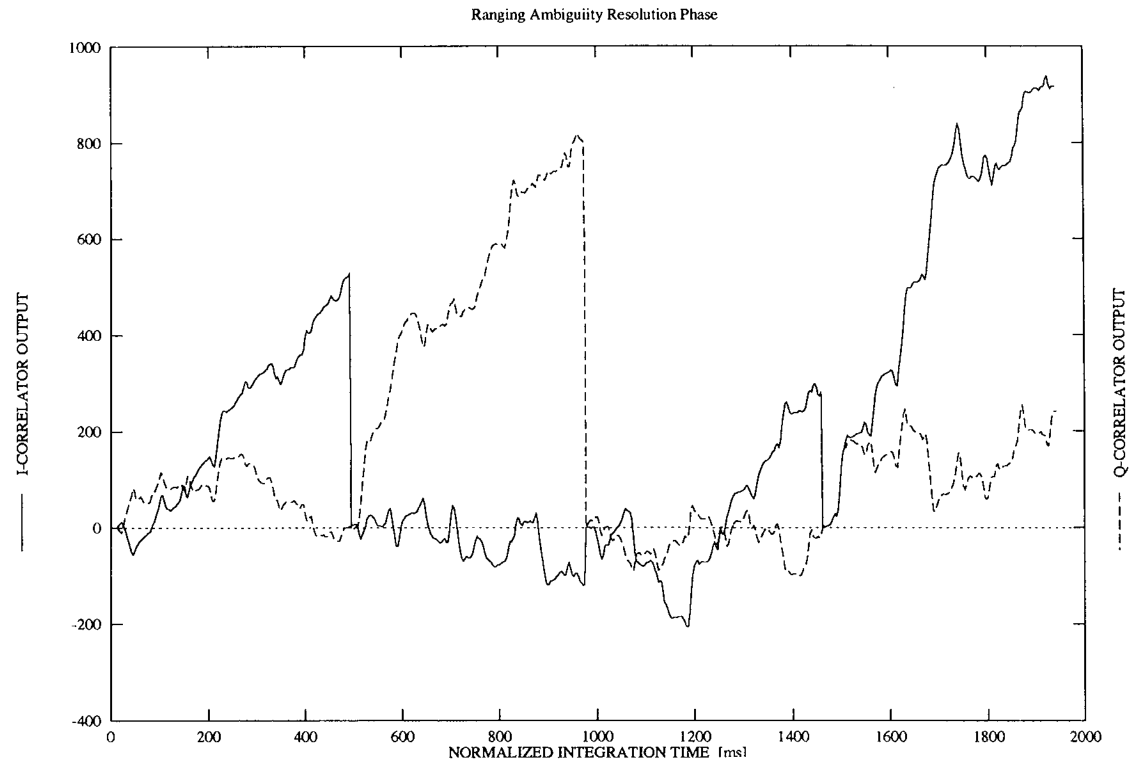


Figure 5. ISO Ranging correlators output

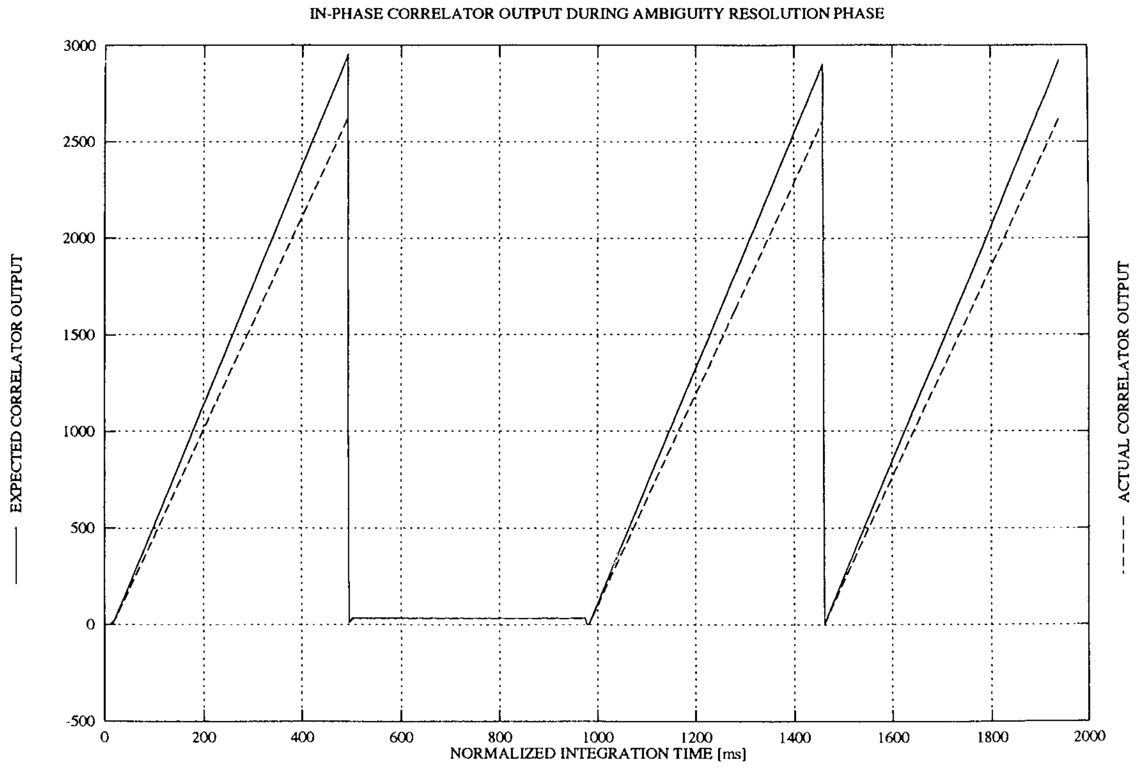


Figure 6. CLUSTER Ranging Correlation

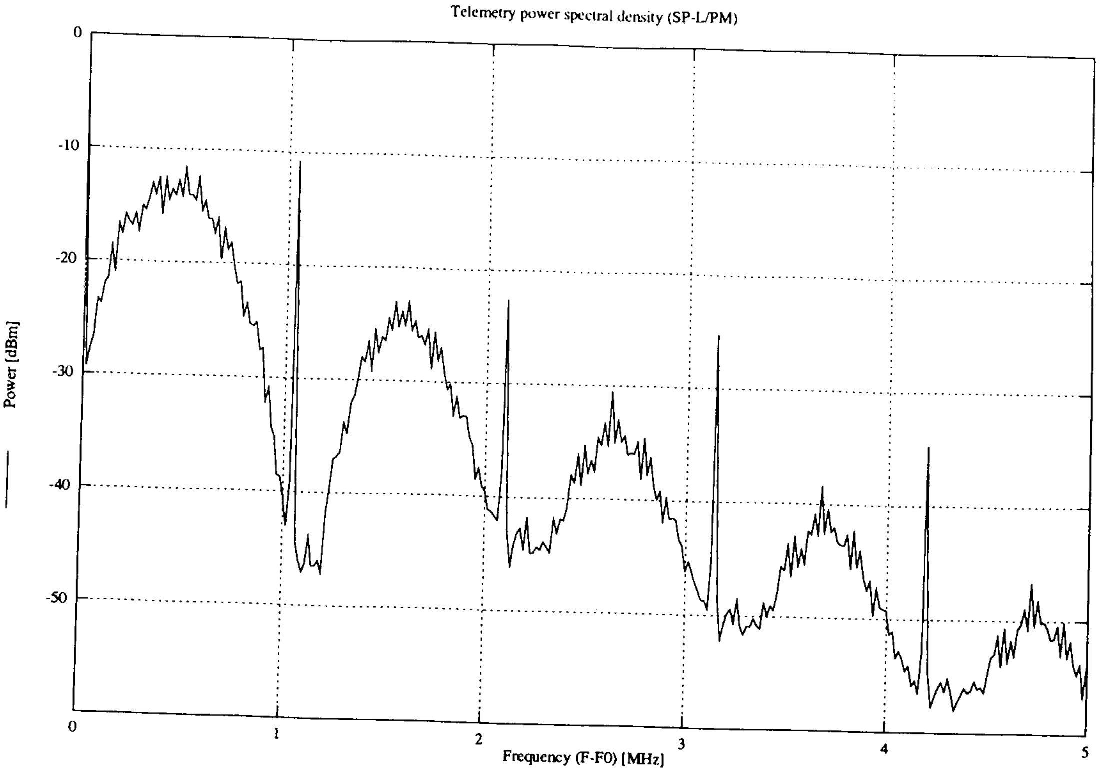


Figure 7. Simulated transponder output

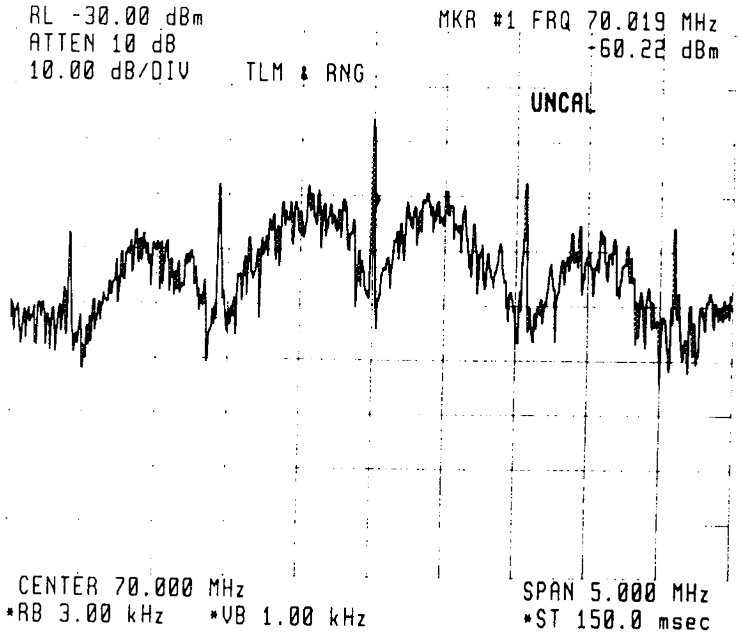


Figure 8. Measured transponder output

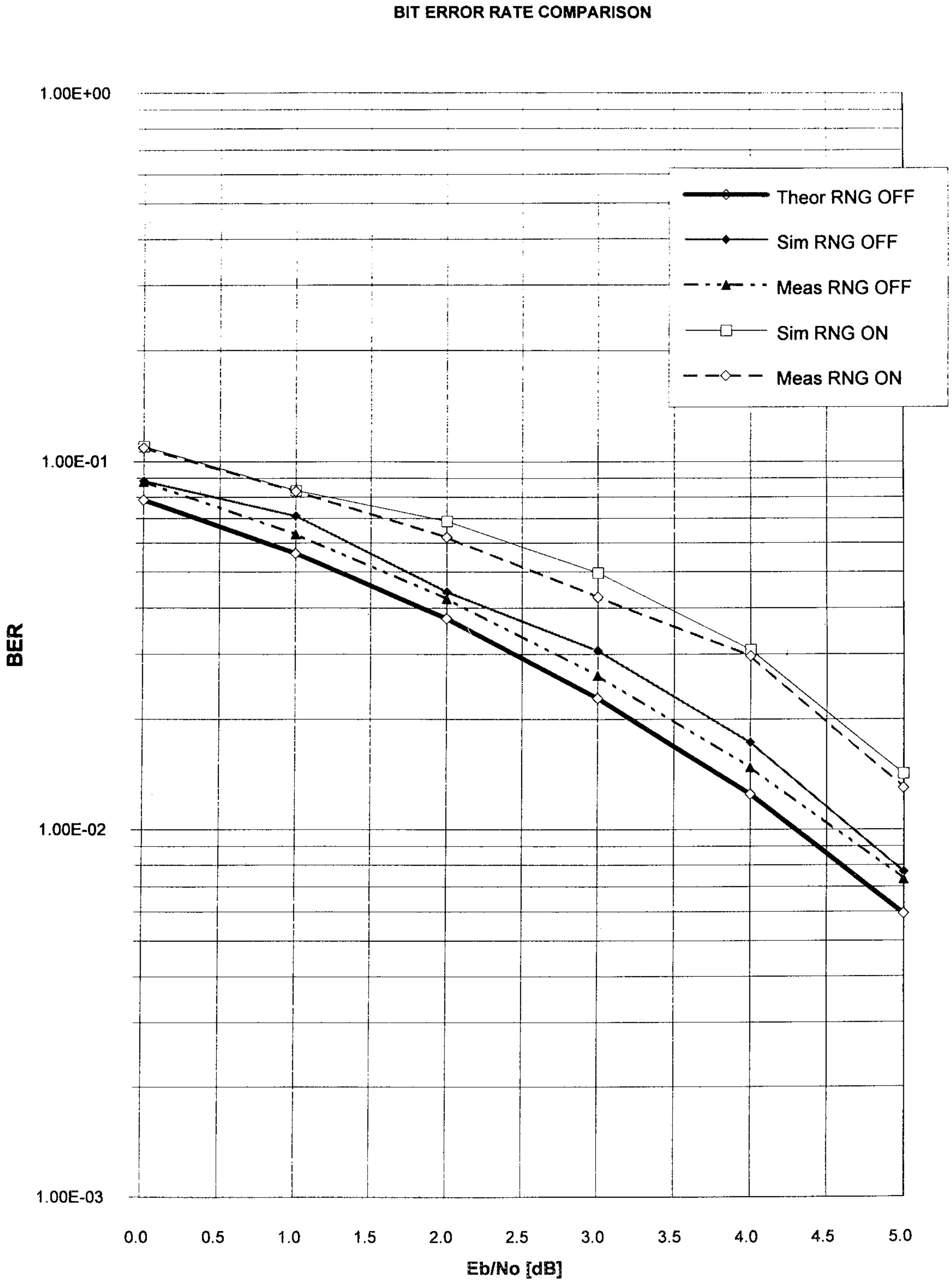


Figure 9. Simulated and measured telemetry BER

Systems Development

5. Simulation

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* *Presented in Poster Session*