Politecnico di Torino

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Master's degree in Communications and Computer Networks Engineering (CCNE)

Development of a Radio-Frequency Compatibility Test (RFCT) to demonstrate the compatibility of the ground to satellite interface for a specific mission

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Abstract

The aim of this thesis is the implementation of a **RFCT (Radio-Frequency Compatibility Test)** used to test the RF compatibility between the **Ground Reference Station (GRS)** and a specified **satellite**, that in this case is represented by a model of the **TCR (Telemetry, Commanding & Ranging)** on-board transponder built ad hoc for the analyzed mission, concerning the **RF parameters** (power level and frequency), **modulation/demodulation schemes** and **coding/decoding functions**.
Moreover also the **TCP/IP** interface used to connect the several ground entities (**ground segment**) used in the mission will be tested.
RFCT is a test activity to demonstrate the correct operability of the satellite's communication systems and of the ground segment before the lift off to support the Launch and Early Orbit Phase (**LEOP**).

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Chapter 1

Introduction

The **RFCT (Radio-Frequency Compatibility Test)** is employed to test the RF (Rafio-frequency) part of the functional links between a satellite and a Ground Station. In the scenario considered in this work the satellite is represented by a **TCR (Telemetry, Commanding & Ranging) suitcase** that is a model of it that reproduces not only the satellite behaviour but also the signals' space propagation created specifically for the considered mission. **Ground Reference Station (GRS)** indeed is actually the common station used to receive satellite's signals. The clear advantage of this approach is that is possible to characterise and test all the communication systems mount on board the satellite before the launch of it. The RFCT is used to verify both up and downlink interfaces for functional and performance characteristics, and it includes verification of telemetry, telecommand and ranging functions, as well as spectral analysis and link budget validation.
In summary tests, to be considered successfully passed, has to cope the link budget, the requirements deliberated by the customers in the **SGICD (Satellite to Ground Interface Control Document)** of the specified mission and the specifications of **CCSDS (Consultative Committee for Space Data System)** and **ECSS (European Cooperation for Space Standardisation)** that are the entities that standardise satellite communications. SGICD is the document that describes completely the TCR interface, it is provided by the costumers and contains all the information about hardware, software, requirements and so on that should be achieved to the good success of the mission.
The mentioned above requirements will be analyzed and described in the chapters of this document that deal with the verification of them.

All the tests are organised, taking as reference the ground station, in 4 sections:

- **Downlink test** that deals with the verification of the operability of the RF link from the satellite to the Earth. This link is used for the transmission of the **Telemetry (TM)** signals;
- **Uplink test** that concerns the validation of the operability of the RF link from the Earth to the satellite. This link is exploited for the transmission of the **Telecommand (TC)** messages;
- **Ranging test** that copes the testing of the transmission/reception of **Ranging (RNG)** signals used to the estimation of the position of the satellite;
- **Network data-flow test** that is the verification of the availability of the TCP/IP connection between the several entities, that will be later described in this thesis, that form the ground segment of the mission.

[1] Telemetry (TM) and Telecomand (TC) represent the basic data flows over a space channel. So, the TM downlink and TC uplink supply a communication route between the satellite and the ground reference station.
On the uplink, satellite receives and decodes all commands and data used for the communication systems. TC is split into:

- **Direct commands** to the satellite for reconfiguration;
- Application-specific commands.

On the downlink instead are transmitted manifold kinds of data generated or acquired from the satellite encapsulated into transfer frames for transmission towards ground. TM data can be split into:

- Satellite **Housekeeping (HK)** data used to know internal functioning of the satellite as power levels, temperature, available memory, etc;
- Orbit data;
- Payload data;
- Telecommand reception status.

Furthermore, Ranging (RNG) signals experience both the uplink and dowlink channel and they are used to determine the **Orbit position** of the satellite.
Finally, the TCP/IP interface tested in the Network data-flow test is crossed by both downlink and uplink messages formatted in the TCP/IP format.

For the test takes into account in this script the **S-Band** frequency are considered. S-Band is one of the most used communication bandwidth in particular it goes from 2 GHz to 4 GHz, it is used for the command part of the satellite communications and it is regulated by ECSS, in particular by its standard **ECSS-E-ST-50-05C**. The part of the standard in which there are pointed out the rules applied for the frequencies used in this test is reported in **Appendix A**.
Moreover, this work deals with the **BER** and **FER** estimation in particular the ones associated with the telemetry messages received from satellite that even if they are not part of RF parameters they are strictly linked to them and play a very important role for the mission achievement. Logically untied, indeed from the RF part but in the same way fundamental for the success of the launch and early orbit phase (LEOP) and more in general of the mission, there is **ground segment** communication.
The ground segment, which structure will be analyzed later in this thesis, plays a fundamental role in a satellite communication inasmuch no telecommand can be send to satellite or ranging measurement can be execute without the central entity of the ground segment authorization.
Moreover, it is the body dedicated to the satellite data processing: it measures the satellite distance through ranging, interprets the receiver telemetry messages and prepares the telecommand to be send.
For all these reasons during the LEOP but also when satellite is in its normal operation is very important to maintain the TCP/IP connection between the several entities that composed the ground segment and therefore to avoid failure of this connectivity also it will be tested in this test campaign.

Chapter 2

Telecommand (TC): data structure description

As said in the introduction, **Telecommand (TC)** represents the basic uplink data flow channel for space communication and TC messages are sent by the Telecommand Unit (TCU) inside the BBU (Base-Band Unit) of the GRS (Ground Reference Station) only if specified by the SCC (Satellite Control Center). Data structure of this entity is standardised in the CCSDS 231.0-B-3 standard. The most important features sanctioned in this standard useful for the scope of this work are reported in this chapter.

2.1 Standard TC data structure and procedures

The following section describes the data structure used to organised data in a Telecommand (TC) message and the procedures to obtain it.

2.1.1 Command Link Transmission Unit (CLTU) format

[2] The **Command Link Transmission Unit (CLTU)** is the data structure which transfers the TC messages as a contiguous series of encoded TC codeblocks. The encoded TC data contained in the CLTU are Input Data generated for specific purpose and encoded following the coding procedures described below in this chapter. Moreover, CLTU ensures synchronization for the codeblock delimiting the beginning of information data and has the standardized structural components shown in the figure below:

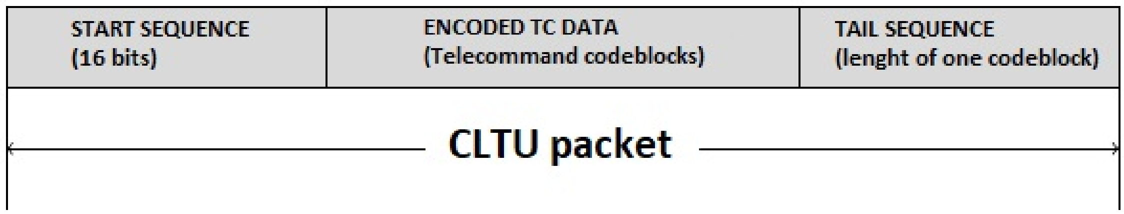

Figure 2.1: CLTU standardized data packet format

Figure underlines that the data format is practically divided in 3 fields:

1. **Start sequence** field delimits the start of the encoded TC data within the CLTU. It consists of a 16-bit synchronization word, $EB90$ in hexadecimal representation or 1110101110010000 in binary representation, used to ensure synchronism;

2. **Encoded TC data** filed consists of a set of TC Codeblocks which have been encoded in accordance with the encoding procedure described in the SGICD document. Encoded TC data field may have been randomized before encoding, or not, as selected for the mission specifications;

3. **Tail sequence** is used to stop the decoding of the CLTU. Standard sanctions that tail sequence shall consist of leading octets having pattern 11000101 (in HEX $C5$), repeated as necessary until the next-to-last octet of the tail sequence field is reached and a last octet sequence with always pattern equals to 01111001 (in HEX 79).

2.1.2 Coding procedures

Codes are employed to establish the reliability and error-controlling of the data channel through which telecommand data bits are transferred. The data are encoded to reduce the effects of noise in the Physical layer channel. For the mission analyzed in this thesis, the BCH(63,56) block code and a randomizing process as recommended by the CCSDS standard are used.

2.1.2.1 BCH code

BCH(63,56) (Bose-Chandhuri-Hocquenghen) code is a systematic[1] binary block code that generates 7 parity check bits per code-block, starting from 56 information bits. The generator polynomial of this code is the following:

$$g(x) = x^7 + x^6 + x^2 + 1$$

and it is generated using the standardize code generator shift register, setted to the "all-ones" state, reported in the following figure

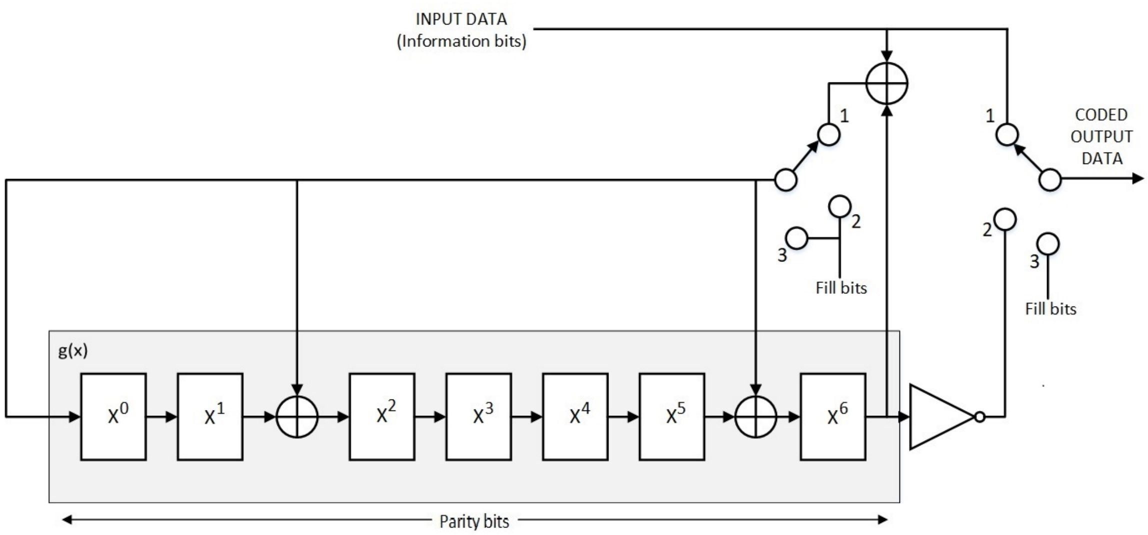

Figure 2.2: BCH(63,56) generator from [2]

As it is possible to see from the graph the systematic of the code is ensure by the use of a ganged switch: that is in position 1 while the 56 info data bits are transmitted, in position 2 when the 7 parity bits are added, and in position 3 for the eventual appending of fill bits. Fill bits are employed when input data do not fit exactly within an integer number of TC Codeblocks, so the last octet(s) and only the last octet(s) of the information field of the last Codeblock within the CLTU can be filled with this kind of bits. The pattern of the fill bits shall consist of a sequence of alternating "ones" and "zeros" starting with a "zero".
At receiver side codeblocks encoded using the BCH(63,56) code is decoded in an error-correcting mode, as specified in the mission requirements. When the error-correcting mode is used, one bit in error will be corrected and two bits in error will be detected.

[1] Input data reproduces without changes in the first bits of coded data

2.1.3 Randomization procedures: Pseudo-Randomizer

Randomization procedure are introduced in order to maintain bit synchronization with the received telecommand signal. As matter of fact it is possible that an incoming signal does not have a minimum bit transition density[2], and so contains long series of "ones" or "zeros" that can break the system synchronization. To avoid these long series randomization is used to mix the bits, for the mission analyzed the typical pseudo-random sequences are considered. Pseudo-random sequences are generated by the standardize BTG (Bit Transition Generator) reported in Figure 2.3 with following generator polynomial

$$h(x) = x^8 + x^6 + x^4 + x^3 + x^2 + x + 1$$

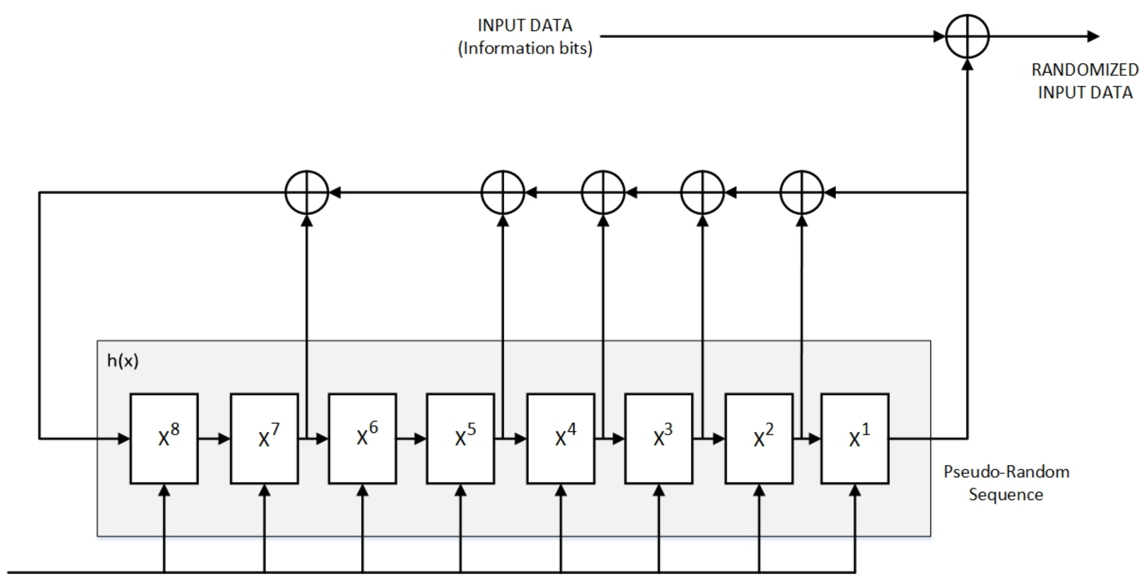

Figure 2.3: BTG generator from [2]

The randomization is applied at the transmitting end, to the Input Data and fill bits presetting the BTG to the "all-ones" state. At the receiving end, the de-randomization, using the same approach of randomization, is applied to the successfully decoded TC data. The BTG remains in the "all-ones" state until the CLTU Start Sequence has been detected.

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[2] The ratio between transitions and the number of unit intervals in a data stream

Chapter 3

Telemetry (TM): data structure description

Opposite to Telecommand there is **Telemetry (TM)** that represents the basic downlink data flow for space communication. All of TM messages are received by the Telemetry Unit (TMU) inside the BBU of the GRS and collected by the SCC. Data structure of this entity is also standardize by CCSDS 131.0-B-3 standard. As before, the most important features sanctioned in this standard useful for the scope of this thesis are reported in this chapter.

3.1 Standard TM data structure and procedures

As been done for telecommand, in the following section is described the data structure used to organized data in Telemetry (TM) messages and the procedures to obtain them.

3.1.1 Channel Access Data Unit (CADU) format

[3] The standard defines a data unit called **Channel Access Data Unit (CADU)** whose content is randomized TM codeblocks. CADU is introduced by an **ASM (Attached Sync Marker)** that for the mission takes into account, where Red-Solomon and convolutional coding are employed, is equal in hexadecimal representation to $1ACFFC1D$ (11010110011111111110000011101 in bynary) and it is used to ensure the capability of the receiver to be synchronized with the data stream coming from satellite.

3.1.2 Coding procedures

Also in this case, Codes are used for the same reason explain in paragraph 2.1.2 of this document. This time **Red-Solomon RS(255,223)**,a **pseudo-noise randomizer** and **Convolutional Code CV(7,1/2)** are employed and the coding/randomization procedures can be summarized with the underneath graph:

Figure 3.1: Telemetry coding/randomization procedures block diagram

3.1.2.1 Reed-Solomon code

The employed RS(255,223) code with interleaving depth $I = 5$ is a systematic no-binary block code able to correct up to 16 symbols wrong received, particularly suited for error burst correction. It is generated according to standard using as generator polynomial:

$$g(x) = x^8 + x^7 + x^2 + x + 1$$

At the received side this code is decoded using a finite-field arithmetic decoder. Considering y the received symbols, c the transmitted codeword and n the transmitted coded symbols, this decoding approach can be expressed as an interpolation problem, in which the codeword is found using a minimum distance method: the decoded codeword c' is the one for which the corresponding error n-tuple $e = y - c$ has minimum Hamming weight.

3.1.2.2 Convolutional code

For the purpose of the analyzed mission convolutional code with rate $r = 1/2$ and constraint-length $k = 7$ is employed. This code is not systematic, well suited for channels with Gaussian noise and has the following connection vector:

$$G1 = 1111001$$

$$G2 = 1011011$$

since symbols inversion is executed on output path where $G1$ is associated with the first symbol output, the resulting convolutional block encoder is:

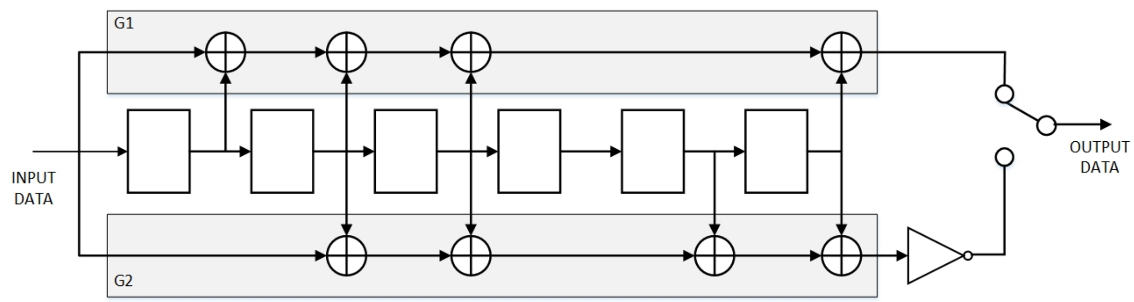


Figure 3.2: Convolutional encoder from [3]

At receiver side it is decoded using a soft implementation of the Viterbi algorithm with 3-bit of quantization. **Soft Viterbi** decoding differs from the classical Viterbi algorithm because it uses a modified path metric to build the trellis which takes into account the a priory probabilities of the input symbols, and produces a soft output indicating the reliability of the decision.
Except for this, it follows the classical Viterbi approach in which after the building of the graph, in which are present all the possible codewords, it tries to find the minimum cost trajectory that represents the most probable transmitted codeword.

3.1.3 Randomization procedures: Pseudo-Randomizer

As happen for telecommand data messages and for the same reason exposed before, also the telemetry ones are subjucted to a randomization procedures. Standard recommends to work with a pseudo-randomizer, setted to the “all-ones” state, to improve several aspects of the telemetry link as receiver acquisition, bit synchronization, convolutional code synchronization and proper frame validation. For the examined mission the classical standardized randomizer is employed with polynomial generator equals to

$$h(x) = x^8 + x^7 + x^5 + x^3 + 1$$

and with the following generator block:

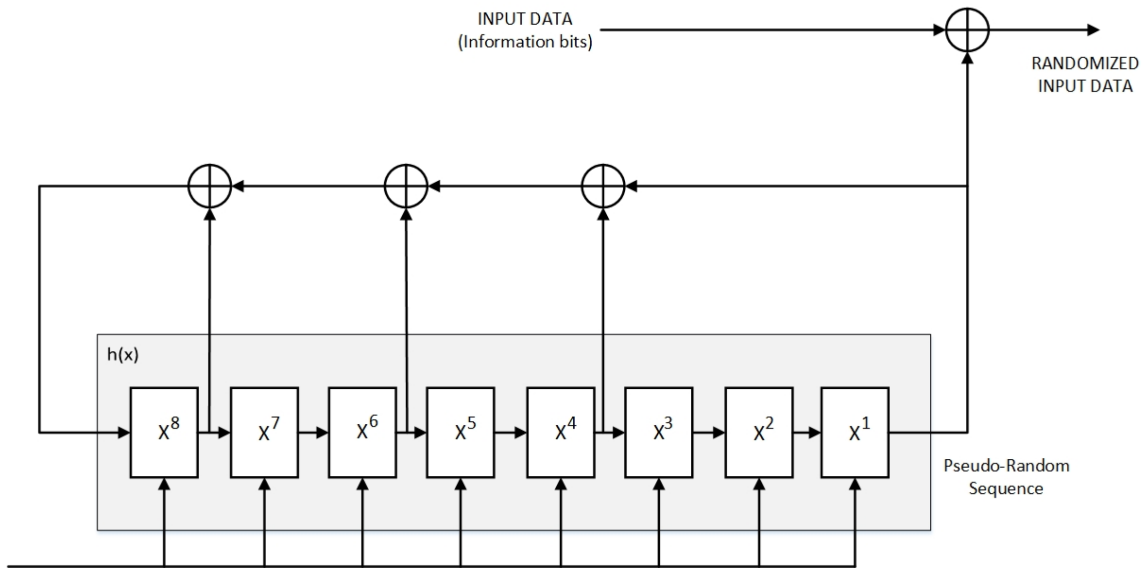


Figure 3.3: BTG generator from [3]

It is important to underline that the pseudo-randomizer does not act on the ASM word since it is attached after the randomization, this because it is already optimally configured for synchronization purposes and to simplify the effort of the de-randomizer at receiver side that after the ASM detection knows that the data immediately following shall be de-randomized.

3.1.4 The advantage of using code

The fundamental advantage of using code is a reduction of the **BER (Bit-Error-Rate)** at same level of Signal-To-Noise ratio with respect to an un-coded transmission. BER is a measure of how many bits are wrong with respect to entire number of bits received. Coding allows to strongly decrease it without the need to increase the transmitted power. This advantage can be seen using the so called **BER curve** in which the BER is represented as function of $\frac{Eb}{N0}$. A more leaning curve underlines as using codes it is possible to reduce a lot the BER maintaining the same $\frac{Eb}{N0}$, this fact is fundamental for channel where the noise can be considered a primary problem. Also the standard underlines the advantage of employing codes with the BER curves reported in figure.

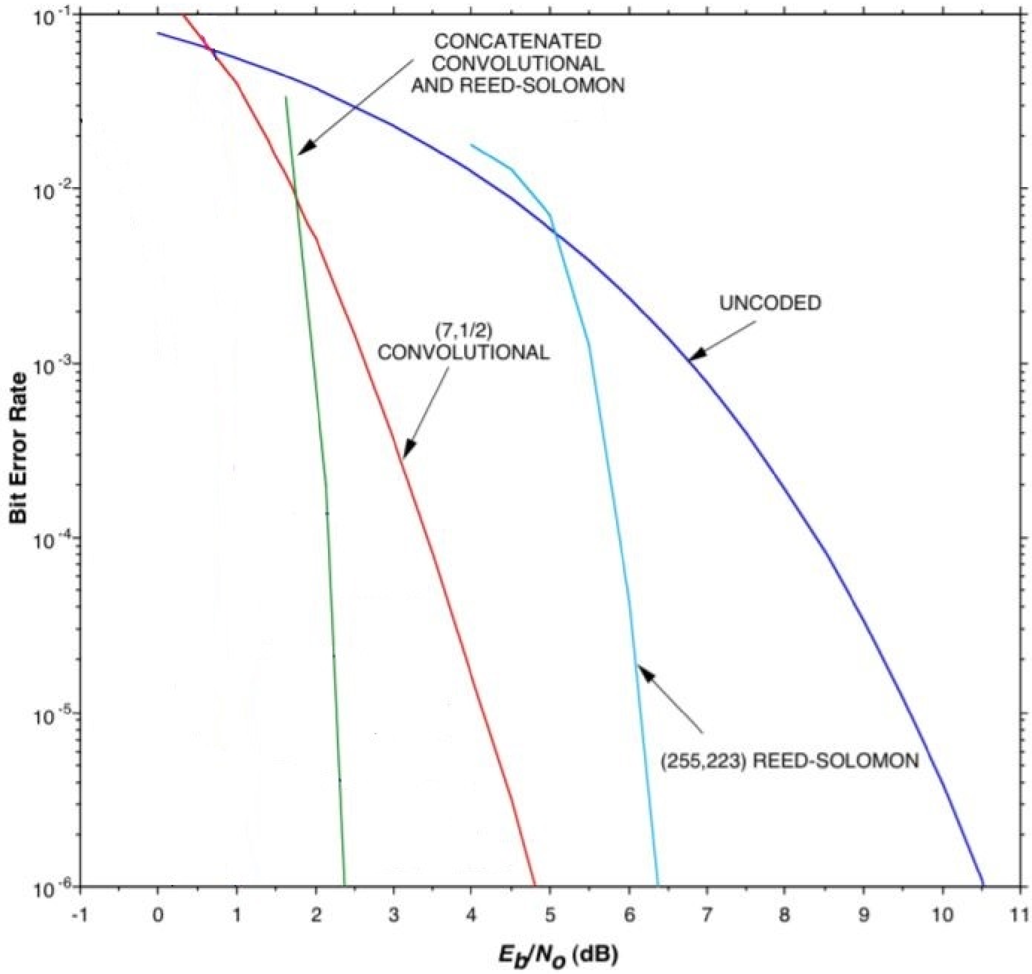


Figure 3.4: Performance comparison of selected Convolutional, Reed-Solomon and Concatenated code from [3]

As it possible to see the solution apply in the considered mission (concatenated convolutional and Reed-Solomon coding) ensure better performances with respect solutions in which only one of the two considered codes is employed or when no code is used.

Chapter 4

Ranging (RNG) procedures description

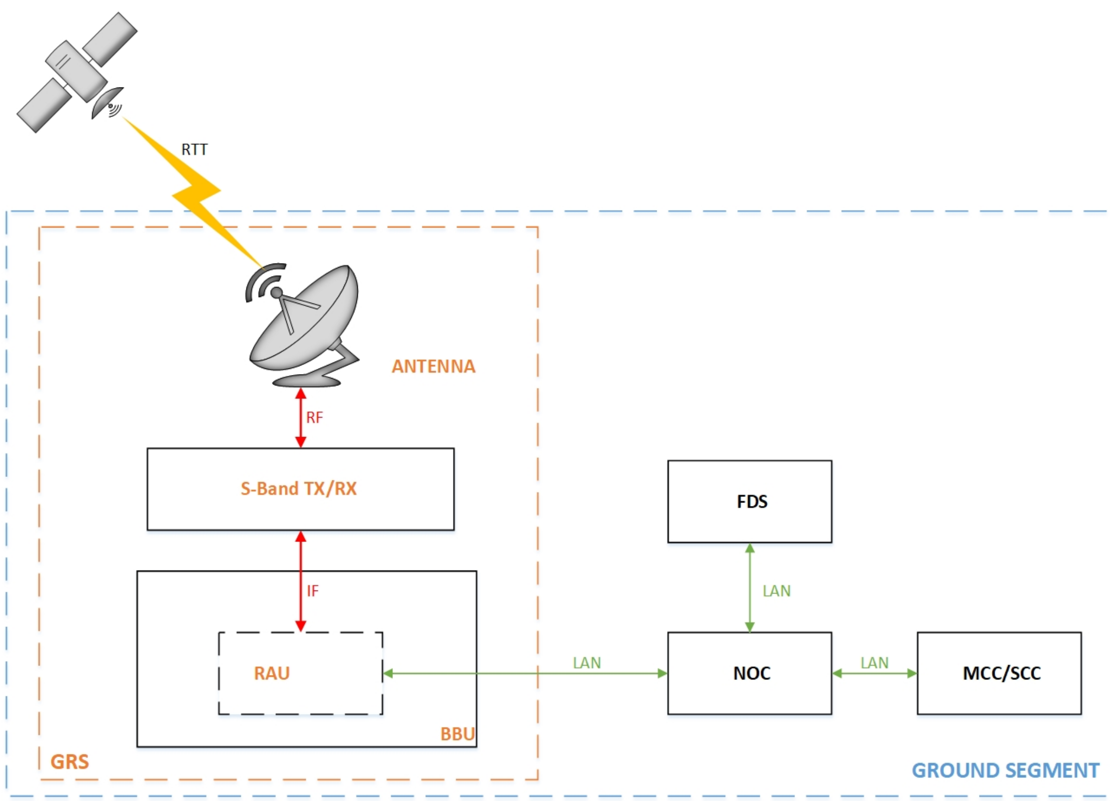


Figure 4.1: RNG signal transmission/reception

[4] **Ranging** is used to determine and track the orbital position of satellites.
It is based on the transmission and reception using S-Band of two tones with specific frequencies that for the mission taken in consideration are equal to ± 114.681 kHz with respect to the central one. These tones are sent by the GRS using PM modulation to the satellite, only if the SCC (Satellite Control Center) through the NOC (Network Operation Center) and then with **FDS (Fly Dynamic System)** sends to it a ranging request. Then the tones are received by the satellite that acting as a transparent entity simply sends back them to the GRS that using the **RAU (Ranging Unit)**, contained inside the BBU, measures the **Round Trip Time (RTT)** of the tones transmission/reception and so, using the speed of propagation (v), it is able to compute the distance (d) of the satellite exploiting the well know following formula:

$$d = \frac{RTT * v}{2}$$

To avoid measurement errors are taken several measurements and as true value is considered an average of them, this procedures is done automatically by the BBU but the operator can choose the number of measurements on which the average will be done. For the case takes into account 100 values are considered, this number ensure a good reliable computation without an excessive computational cost and time.

4.1 RAU: Ranging request management

RAU (Ranging Unit) is the entity inside the BBU responsible for the ranging measurements. RAU receives from the SCC throgh the NOC, that are two coordinate entities of the mission, a **ranging request** on the RNG (Ranging) port, accepts the request if it is correct or refuse it, in case of acceptances a positive primary acknowledgment message is returned on port RNG, in case of failure a negative ack is conveyed to the same port.
After that, the tones are prepared to be sent and the transmission/reception measurement phase can start.
In case of success the computed measurements are sent through the MEAS (measurement) port to the NOC that drives it to the FDS, that is the system piloted by

the SCC, used for ranging purpose. Instead, in case of failure a negative secondary acknowledgment is returned to port RNG.
At this point, if the request is a continuous mode request, other tones are sent to ranging measurements until the stop ranging command is received.
If instead it is not a continuous mode request, RAU returns a positive secondary acknowledgement message to RNG port and the procedure ends.
To better understand how the ground segment of a mission during the LEOP is organized reference is made on Figure 7.3 where all the entities involved in the ground segment are drawn and described.

Chapter 5

Test bench configuration

The test bench employed in the analyzed test campaign is composed basically by 3 facilities:

1. **Telemetry, Commanding & Ranging (TCR) suitcase**
2. **Ground Reference Station (GRS)**
3. **Measurement instruments**

5.1 Telemetry, Commanding & Ranging (TCR) suitcase description

The TCR suitcase is a representative model of the satellite TCR S-Band transponder, it includes a human machine interface (HMI), based on a remote notebook and connected via a standard LAN interface, providing the mean to configure, monitor and control the apparatus. The figure below shows the block diagram of the suitcase:

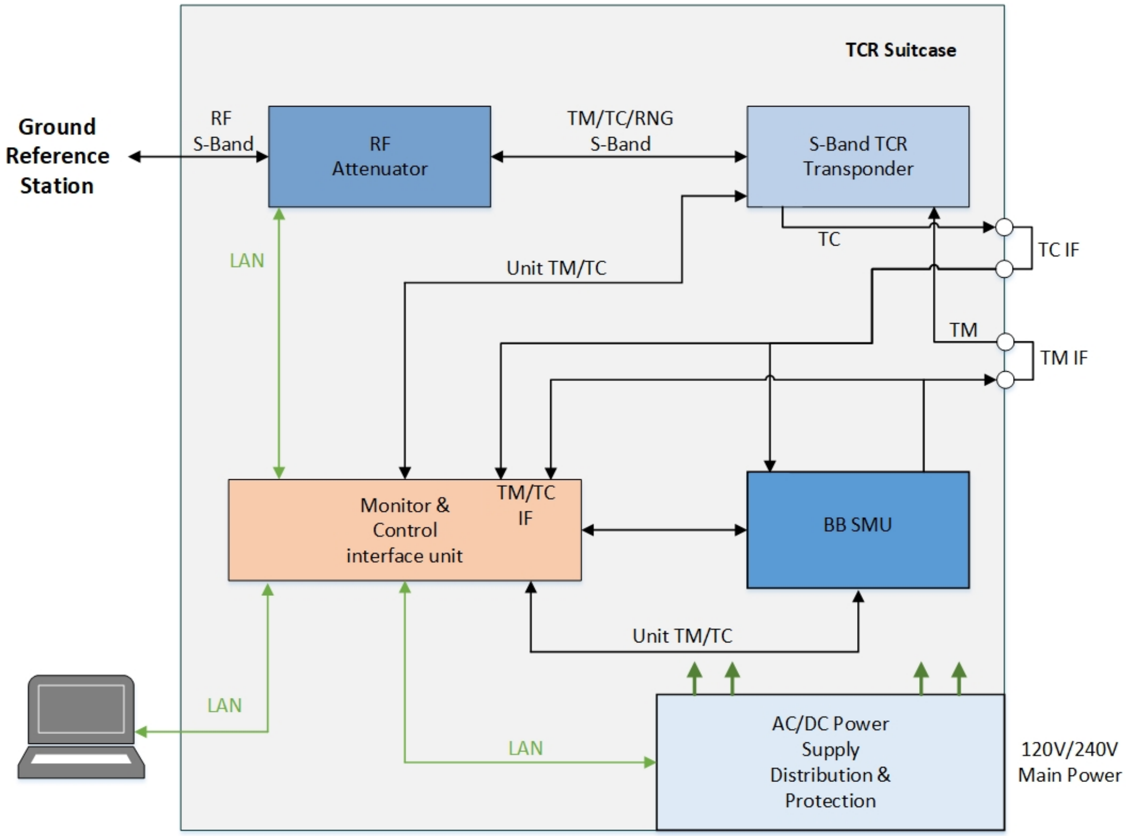


Figure 5.1: TCR suitcase block diagram granted by Telespazio s.p.a.

As shown from the image, it is divided into two parts: a **Intermediate-Frequency part** in which the data are processing and a **Radio-Frequency part** where the transmitted signals are up-converted to be transmitted and the received signals are down-converted to be processed. Moreover, it is possible to see that the TCR suitcase is composed by several interfaces, two of them are external interfaces that link it to the ground station and to the remote PC, while the other are internal interfaces that connect all the components of it. In particular the interface between the TCR suitcase and the Ground Reference Station are two: one in input of the TCR that represents the telecommand/uplink from Earth to satellite and one in output from the TCR that constitutes the telemetry/downlink from satellite to ground segment. TCR suitcase is essentially composed by 6 components, that are reported with their functions in the following list:

1. **RF attenuation block** simulates all the attenuations experienced by the

signals during the space propagation and it is composed by a fixed attenuator of 30 dB and a programmable attenuator with a range of 0-90 dB;

2. **Base-Band (BB) SMU (Satellite Management Unit)** works at base band frequency processing the telemetry (TM) signals to be transmitted preparing it to the frequency up-conversion and handling the received telecommand (TC) signals;

3. **S-Band TCR transponder** moves the telemetry signals from the BB SMU to the frequencies of the S-Band (up-conversion) and send them to the ground station using two different links (if it is not a simulated satellites should be employed two different antennas) with distinct polarization (RHCP and LHCP). Moreover, it applies the down-conversion to the signal received from the Earth and passes them to the BB SMU;

4. **Monitoring and Control Interface Unit** uses to monitor and control the whole system trough the remote HMI (Human-Machine-Interface);

5. **AC/DC Power Supply Distribution/Protection** provides the power to make the system working;

6. **TCR Suitcase ground connection** must be connected before the application of mains power to the TCR Suitcase System for security issue. Both TCR Suitcase and Ground Reference Station equipment must be connected to the test area grounding connection point.

Moreover, the hardware presents inside the TCR suitcase introduces in the output signal power a further attenuation of 5.82 dB. Therefore, the total fixed attenuation that must be taken into account for power measurements introduced by the TCR suitcase is 35.82 dB.

5.2 Ground Reference Station (GRS) description

Ground Reference Station (GRS) represents the Earth equipment used to capture and process the signal sent by satellites (in this case by the TCR suitcase) and to route messages towards satellites. Its main functionalities are:

- Reception, demodulation, time-tag and processing of the telemetry data coming from the TCR suitcase;

- Modulation and transmission of telecommands received by the SCC/MCC to the TCR suitcase;
- Execution of ranging measurements;
- Data messages exchange with the Network Operation Center (NOC) and then with Satellite Control Center (SCC).

The GRS block diagram is reported in the figure below:

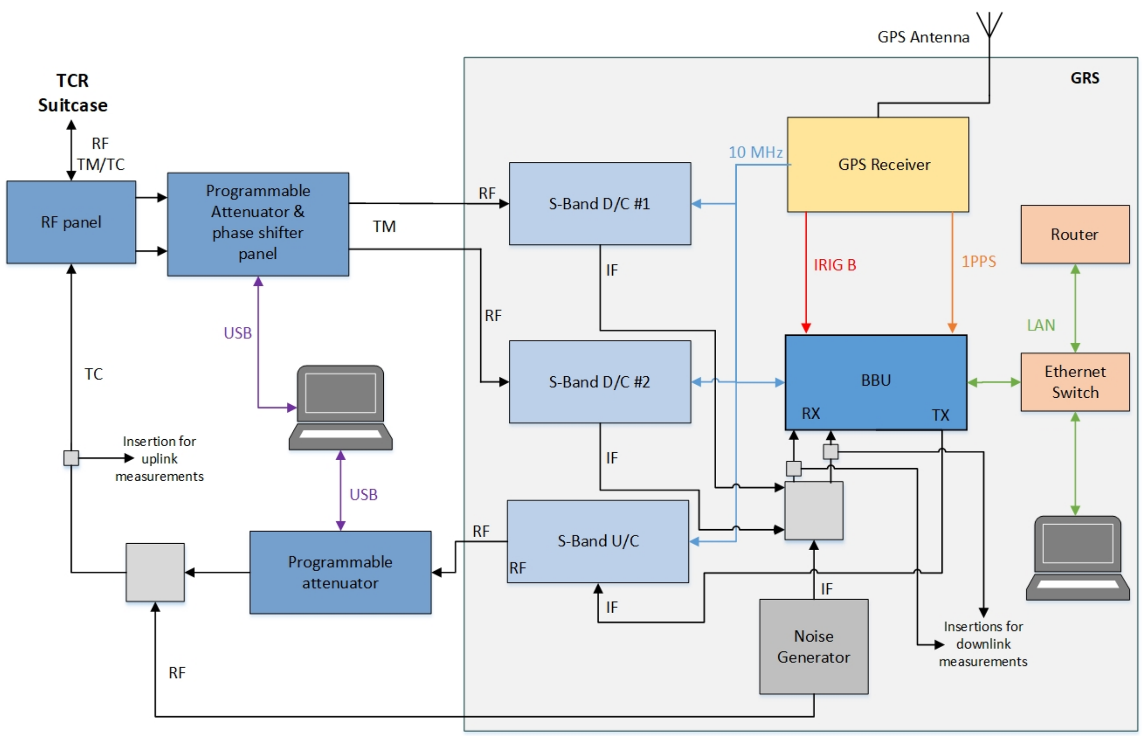


Figure 5.2: GRS block diagram published under Telespazio s.p.a. permission

In the following sub-chapters all the components present in the block diagram will be analysed.

5.2.1 Base-Band Unit (BBU)

It is the unit responsible for the processing of a signal in a telecommunication system before the frequency up-conversion and after the down-conversion. It is linked by a physical interface to the the Radio-Frequency part of the system that is the unit that up-converts or down-converts the signals to S-band frequency, preparing them to be transmitted or processed. Moreover, it is connected to a GPS receiver,used as reference of time and frequency, to the output of an adder that introduces noise in the simulated scenario and to the interface that shows the results to operator.
It implements a lot of tools with different features as reported in its user manual, the most important for the work considered are:

- **Coding** and **Decoding unit** able to code and decode Reed-Solomon code, BCH code, Convolutional code and to de-randomize the bits used to protect the information during the transmission against noise and to maintain synchronism;
- **IF modulator** and **demodulator** able to handle PCM/NRZ-L, BPSK and PM used for the modulation/demodulation of TC,TM and RNG messages;
- **PLL**, in particular the second order Digital PLL, able to retrieve, in very accurate way due to the two feedbacks employed, the phase shift of the signal and thus ensure a good synchronism and so a fine reception of telemetry and ranging signals. Moreover, this employed PLL has a bandwidth that can be change from 100 Hz to 3 KHz;
- **TCP/IP unit** that is the interface between the BBU and the LAN and it transmits/receives the information collected from the satellite or to be send to it in a typical TCP/IP network connected to the NOC and to the SCC/MCC;
- **TMU (Telemetry Unit)**, one for RHCP and one for LHCP, employed to process the telemetry messages received from satellite and to be transmitted to NOC;
- **TCU (Telecommand Unit)** involved in the processing of telecommand messages received from the NOC and destined to satellite;
- **RAU (Ranging Unit)** used to transmit/receive ranging messages to compute the RTT (Round Trip Time) and send them to the NOC (that sends it to the FDS) to estimate the orbital distance between the satellite and the GRS.

FDS, NOC, MCC, SCC and all the entities involved in the ground segment will be discussed later in this thesis.

5.2.2 Up-Converter (S-Band U/C) and Down-Converter (S-Band D/C)

As the names said these blocks are used to increase or decrease the signal frequency, in particular the up-converter is used in transmission and increases the frequency of the signal from the BBU from 70 MHz to 2075.0979 MHz, that is the frequency indicates in the mission specification for uplink communications.
While the down-converter is used in reception and it is able to decrease the signal received by the antenna from a frequency of 2253.5 MHz, that is the frequency indicates in the mission specification as downlink frequency, to a frequency of 70 MHz, makes the signal usable by the BBU.
In this scenario the down-converters are two since at receiver side the two circular polarizations sent by each of two antennas present on board the satellite are obviously received and processed separately.
Up and down converter are linked to the Radio-Frequency part of the system, responsible of the physical reception of the signal, to the GPS receiver and to the BBU.

5.2.3 GPS receiver

In general, GPS receivers are either "positional" receivers that are designed to provide very accurate positional information, or "timing" receivers that are designed to provide very accurate timing information.
In this scenario a "timing" receiver is employed since, it is used to know in a very accurate way frequency and time, to be fashionable as references.
GPS "timing" receivers are able to provide accurate timing outputs since they work in a **stationary mode of operation**, that is it is wired in a stationary environment, where the latitude and longitude can be calculated and locked-in, alleviating the GPS receiver's need to continuously calculate its current position.
GPS receiver, as said before, are connected to BBU and up/down-converters that used its information as reference of time and frequency.
This instrument ensures a precision in time and frequency estimation of the order of nanosecond and for this reason it has been chose for this test execution.
However, even with a slightly less precise reference, GRS is able to work in correct way, so it is possible to change this tool with for example a PTP (Precision Time Protocol) generator with a less precise accuracy but easier to implement and carry.

5.2.3.1 IRIG-B, 1PPS and 10 MHz

The references of time and frequency provided by the GPS receiver are:

- **IRIG-B** (Inter-Range Instrumentation Group time codes), that is a standard format for transferring timing information. In particular this B version has the following characteristics: bit-rate of 100 Hz, bit-time of 10 ms, frame time 1000 ms and frame rate of 1 Hz.

- **1PPS** (1 Pulse Per Second) as the name says is an electrical signal that stressed in a very accurate way the begging of a second.

- **10 MHz** is a pulse centered at 10 MHz used to compute accurately the frequency.

5.2.4 Noise generator

It is the module able to simulate the noise due to the space propagation, it has a frequency range from 10 MHz to 2,5 GHz, an output flatness of $\pm 1,5$ dB, so it is able to add noise both at Radio-Frequency than at the Intermediate-Frequency.
In this test the noise measures at the Malindi ground station and the one measure at South-Point station are considered since they represent the worst case scenario respectively for downlink and uplink between the stations employed for the mission analyzed.
Therefore, the measured noise density of -118 dB/Hz in Malindi or -115 dB/Hz in South-point is introduced, at IF for the downlink or at S-Band frequency in uplink, with a coupler in the reception or transmission chain.

5.2.5 Radio-Frequency (RF) panel

It is the interface panel between the TCR suitcase and the Ground Reference Station.
The figure below shows its block diagram:

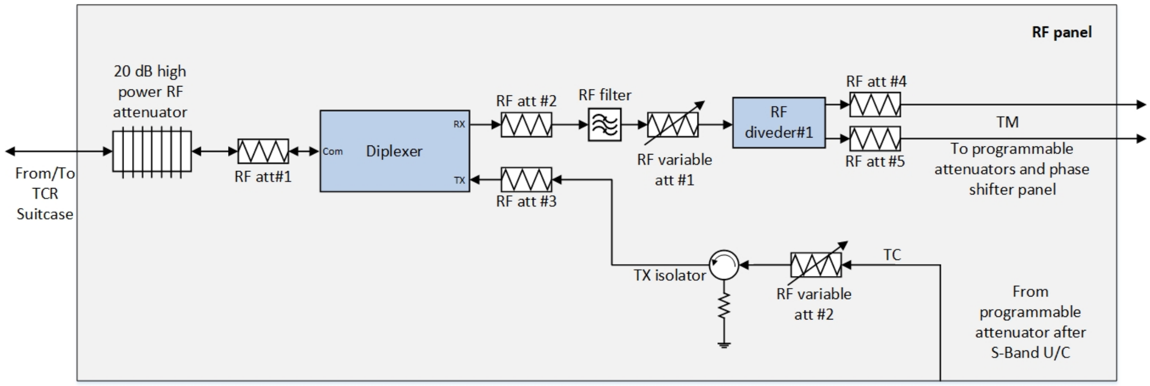


Figure 5.3: RF panel block diagram granted by Telespazio s.p.a.

It is composed macroscopically by 3 paths:

1. **Common path**: crossed both by received and transmitted signals, it is characterized by a 20 dB power attenuator and by a S-Band diplexer able to handle both received and transmitted signals;

2. **Receive (RX) path**: traversed only by the received signals, it is composed by a filter with a range of 2200-2300 MHz that cleans up the signal, two variable attenuators of 0-20 dB use to make fashionable the signal for the RF divider that separates the two polarizations received by the satellite to avoid signal self-interference;

3. **Transmit (TX) path**: passed through only by the transmitted signal, it follows practically the same idea of the received path except for the fact that it has only one polarization so the RF divider is not necessary and in this path a TX isolator is introduced in order to avoid back-propagated signal interference.

5.2.6 Programmable attenuators and phase shifter panel

The block diagram of this panel is reported below:

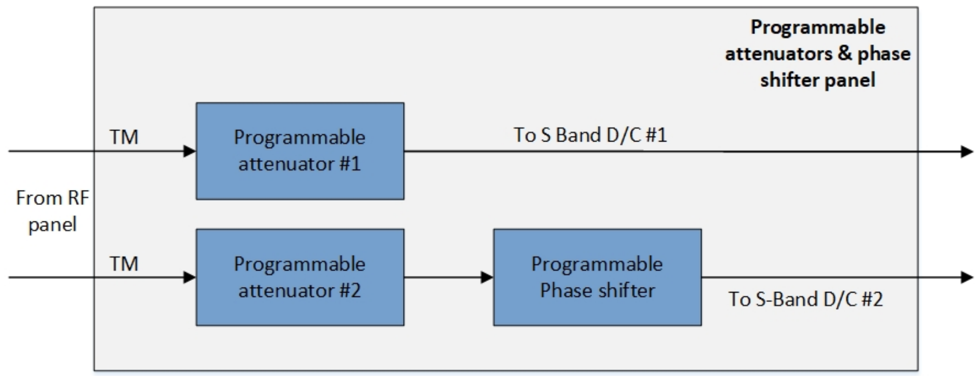


Figure 5.4: Programmable attenuators and phase shifter panel block diagram granted by Telespazio s.p.a.

The module is composed by two programmable attenuators piloted by a computer in which it is possible to introduce very smooth attenuation profiles that simulate very well the attenuation due to the satellite rotation around its axis during its first positioning, moreover is present a phase shifter able to simulate the doppler effect due to the orbiting of the satellite around the Earth.
Thus, because of the presence of these components merged with the attenuators in the TCR suitcase it is possible to simulate the whole scenario between a certain satellite and its ground reference station and so it is viable to simulate and check before the satellite launching the correct operation of it not only in a steady state scenario but also in all the operations needed during the so called **LEOP (Launch and Early Orbit Phase)** that is one of the most critical phases of a mission in which the satellite separates from the launch vehicle and starts to orbit around the Earth.

5.2.7 Radio-Frequency (RF) physical interface description

Table below describes the used physical interface between the GRS and the TCR suitcase:

APPLICABILITY	**TCR SUITCASE**	**GROUND REFERENCE STATION**
DIRECTION	Bi-directional	Bi-directional
CONNECTOR LOCATION and REFERENCE	• Cabinet • RF input/output S-Band pannel	• RF pannel
CONNECTOR TYPE	N-type (F) coax 50 Ω on TCR Suitcase pannel	N-type (F) coax 50 Ω on RF pannel
INTERCONNECTION HARNESS	RF coax cable (5 m) with male connector	RF coax cable (6 m)
LEVEL	The RF attenuator is composed of a 30 dB fixed attenuator and a 0-90 dB programmable attenuator • Input level: The RF interface input level should be <-20dBm • Output level: The RF interface output level should be < 7 dBm	There are several fixed/variable attenuators. • Input level: Depends on Test Case • Output level: Depends on Test Case
IMPEDANCE	50 Ω, VSWR < 1.25	50 Ω

Table 5.1: Radio-Frequency physical interface description

The reported features are the ones defined in the SGICD document for the interface between the satellite and the Ground Stations and they are also fully applicable for the TCR Suitcase, with the exception of the specific physical connections between it and the Ground Station.
The requirements of the transmission across the space link described in the SGICD indeed are reported in the two tables below, the first one is referred to RF Uplink from GRS to TCR Suitcase, while the second one deals with RF Downlink from TCR Suitcase to GRS.
The reported parameters will be use in the following chapters as the input parameters of the tests.

Parameter	**Value**
Uplink Carrier Frequency	2075.0979 MHz
Carrier Frequency Stability	$\pm 5*10^{-9}$, under all conditions
S/C Rx circuits losses	4,98 dB nominal; 7.98 dB worst.
Modulation type	PCM/NRZ-L/PSK/PM
TC Modulation index RNG Modulation index	1.0±5% rad.pk 0.6±5% rad.pk
PSK sub carrier (freq/type)	8 KHz/Sine
Bit Rate	2000 bit/s
TC carrier sweep	Sweep rate 32 kHz/s Sweep range ±60 kHz
Coding/Randomization procedures	BCH(63,56) Randomizer

Table 5.2: RF Uplink parameters from GRS to TCR Suitcase

Parameter	**Value**
Downlink Carrier Frequency	2253.5 MHz
Carrier Frequency Stability	$\pm 2*10^{-5}$, under all conditions
S/C Tx circuits losses	4.98 dB nominal; 7.98 dB worst.
Modulation type	PCM/NRZ-L/PSK/PM
TM Modulation index RNG Modulation index	1.15±6% rad.pk 0.5±5% rad.pk
PSK sub carrier (freq/type)	65.536 KHz/Sine
Bit Rate	16384 bit/s
Transfer frame length	8920 bits
Coding/Randomization procedures	RS(255,223) + CV(7,1/2) Randomizer

Table 5.3: RF Downlink parameters from TCR Suitcase to GRS

5.2.8 Router/Ethernet switch

A router and an Ethernet switch are employed to link the BBU with the LAN that connects the MCC/SCC (Mission Control Center/Satellite Control Center) and the NOC (Network Operation Center), the functionalities and the correct behaviour of these two elements will be test in the "End to End Network data-flow test" next in this thesis, to better understand the importance of these apparatuses just thinking that without an explicit command from the MCC/SCC neither telecommands, telemetry or ranging messages are transmitted/received by the GRS.
How the LAN is organised is shown in the figure includes in the chapter dedicated to the above mentioned test.

5.3 Measurement instruments description

The RFCT (Radio-frequency compatibility test) execution requires the availability of the whole described test bench and also of a set of measurement instruments and accessories as cables, attenuators, connectors and adapters that must be taken into account in the power estimation since they can introduce some attenuation terms.
The measurement instruments are basically 3:

- **Spectrum analyzer** used to visualized the spectrum of the received or transmitted signals;
- **Power meter** obviously employed to measure the signals power level;
- **Frequency counter** that allows to know the value of signals frequency.

These instruments are connected with the GRS and with the TCR transponder and by the means of a human readable interface display the results.
Moreover, several outcomes are obtained exploiting the interface of the Monitoring and Control software of the BBU and of the TCR suitcase.

Chapter 6

Antennas description

Even if in this compatibility test the antennas are the only not tested components of mission's ground segment, since the spacecraft is not yet in Earth's orbit, it is however important analysing the antennas used by satellite and ground station to better understand the subsequent real implementation of the work and to interpret in a finer way the reason of the realization of the GRS in the previously exposed way. As said in the introduction, the command part of the considered mission is accomplished exploiting the S-Band, so the antennas taken into account are the ones suitable for these frequencies chosen by the customer in the SGICD to face the mission's requirements.

6.1 TCR on board: S-Band antenna

[5] The antennas for the telemetry and telecommand transmission/reception of a satellite have as basic needs the underneath requirements:

- Provide coverage all around the satellite (full sphere);
- Be extremely reliable;
- Have minimum losses.

A single antenna is unable to provide full sphere coverage so for this mission two antennas of the same type, in the opposite polarisation and position are used. Moreover, this solution is applied to solve the fact that low-gain wide-pattern antennas are affected by the presence of the satellite body and appendages, which produce spurious scattering altering their radiation patterns.

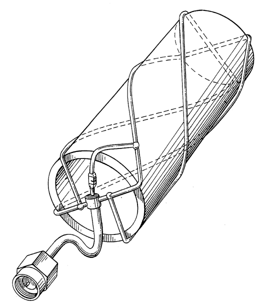
Particularly, for the mission analyzed in this thesis two **Quadrifilar S-Band Helix** antennas, fed with separate beam forming networks for the two frequencies (one in transmission, one in reception), are used on board the satellite. This kind of antenna ensures:

- **Hemispherical coverage** for each antenna (and so together a **full sphere coverage**);
- **Right Hand Circular Polarization (RHCP)** for one antenna and **Left Hand Circular Polarization (LHCP)** for the other one;
- **Bandwidth 2200-2290 MHz** for **telemetry**;
- **Bandwidth 2025-2110 MHz** for **telecommand**;
- **Gain > -3.3 dBi**[3] in free space for each antenna.

6.1.1 Quadrifilar S-Band helix antenna

[6] A Quadrifilar helix antenna for satellite communications comprises four conductive wires arranged to define two separate helically twisted loops. The two separate loops are connected to each other in a way that ensures that the antenna matches the chosen impedance, electric phasing, coupling and power distribution. In the considered case, this kind of antenna is employed in the axial or end-fire mode in which the diameter and height of the helix are comparable to the wavelength. The antenna behaves as a directional antenna radiating circularly polarized wave from the end of the helix, along the antenna's axis.
Figures below show a graphical description of the antenna, a real antenna and a schematic view of the typical radiation pattern and the way in which the radiation is spreaded out using this kind of feelers.

[3] dBi indicates how much the gain of the antenna is bigger or lower with respect to an ideal isotropic antenna



(a) Graphical description taken from [6]

(b) Real antenna from [7]

Figure 6.1: Graphical and real representation of a Quadrifilar Helix antenna

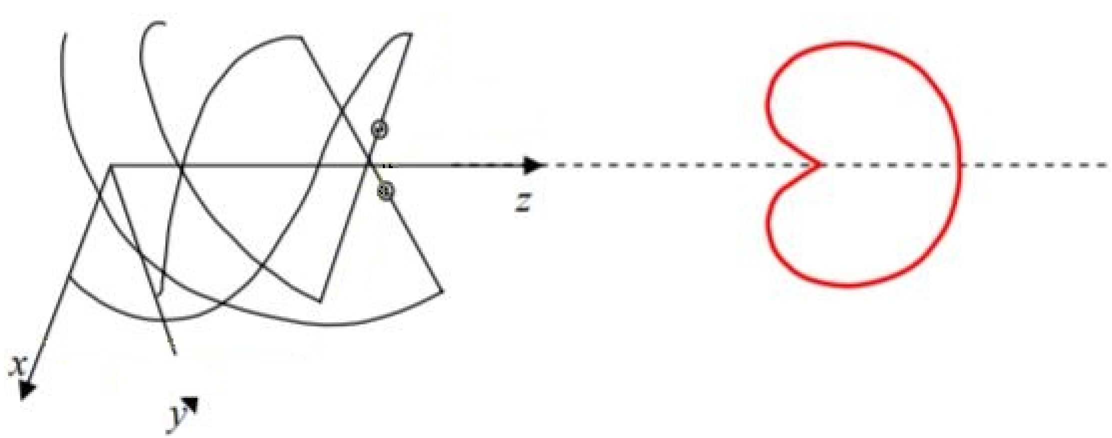


Figure 6.2: Quadrifilar Helix antenna radiation taken from [5]

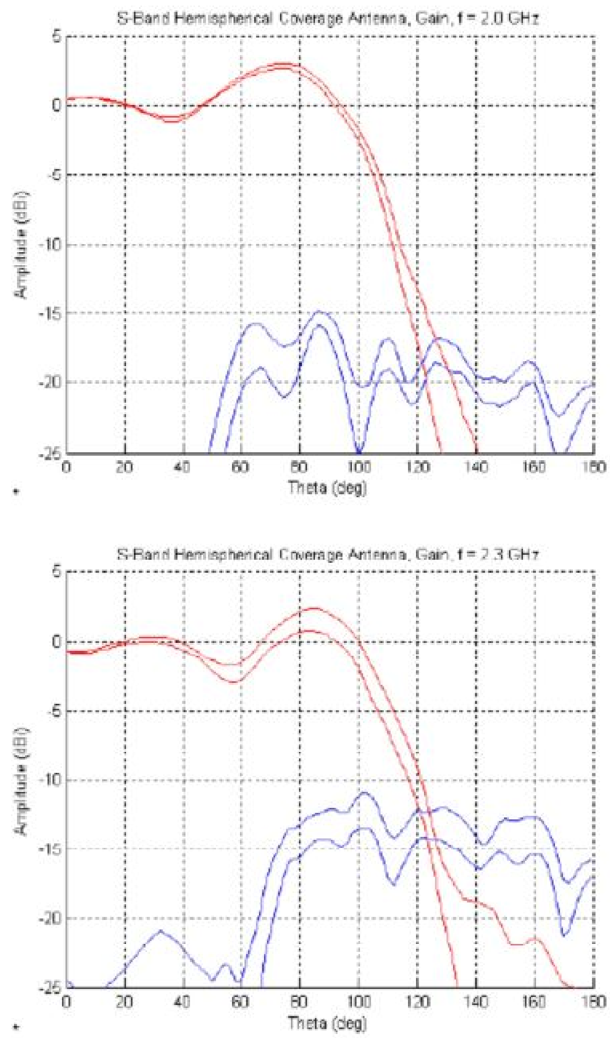


Figure 6.3: Quadrifilar Helix antenna typical radiation pattern in uplink (up) and downlink (down) conceded by Telespazio s.p.a.

Figure 6.2 and figure 6.3 underline well as this kind of antenna ensure a hemispherical coverage and the fact that the employment of two of them guarantees a full coverage of the space around the satellite and a quite good directivity. Figure 6.1, indeed, focuses the attention on the dimensions and the geometry of the structure: the dimensions are compact to be light and suitable to be mounted on board, geometry is quite complex but fundamental to cover the above mentioned requirements.

6.2 GRS: S-Band antenna

Antennas on ground are used to control the satellite, received its telemetry and to track its position in space. They are usually quite large, to compensate for the very low gain of antennas on board the satellite and for the losses introduced by the space propagation. Differently from the on-board side, the ground antenna is not specified in the SGICD, so it is possible to use any kind of antenna compatible with the mission specifications and able to face the S-Band. In the mission analyzed in this thesis a **Prime focus S-Band** antenna with a diameter of 10 meter will be employed. An image of the antenna is reported below under the permission of Telespazio s.p.a.

Figure 6.4: S-band prime focus antenna provided by Telespazio s.p.a.

6.2.1 Prime focus S-Band antenna

Prime-focus antenna is a parabolic reflecting antenna achieved by sectioning a paraboloid with a plane perpendicular to its axis, the fire of this kind of antenna is in axis with the antenna itself and therefore it is located in the center of it.
In particular, the employed prime focus antenna has the characteristics reported, under the Telespazio s.p.a. permission, in the list below:

- Antenna type: Prime-focus;
- Antenna diameter: 10 m;
- Transmitter frequency band: 2025-2120 MHz;
- Receiver frequency band: 2200-2300 MHz;
- Receiver gain: 45.2 dBi;
- Transmitter Gain: 44.5 dBi;
- Max EIRP[4]: 69 dBW;
- Transmitter Polarization: LHCP or RHCP (not at the same time);
- Receiver Polarization: LHCP and RHCP (simultaneously).

Moreover, this kind of antenna is equipped with a mechanism of **auto-tracking** able to follow automatically the satellite during its passage in visibility based on the searching and staying locked to the maximum peak of receiver power.
The block diagram of the antenna, also granted by Telespazio s.p.a, is shown, described and commented underneath

[4]EIRP (Equivalent Isotropic Radiated Power) is the effective density radio power irradiated by an antenna

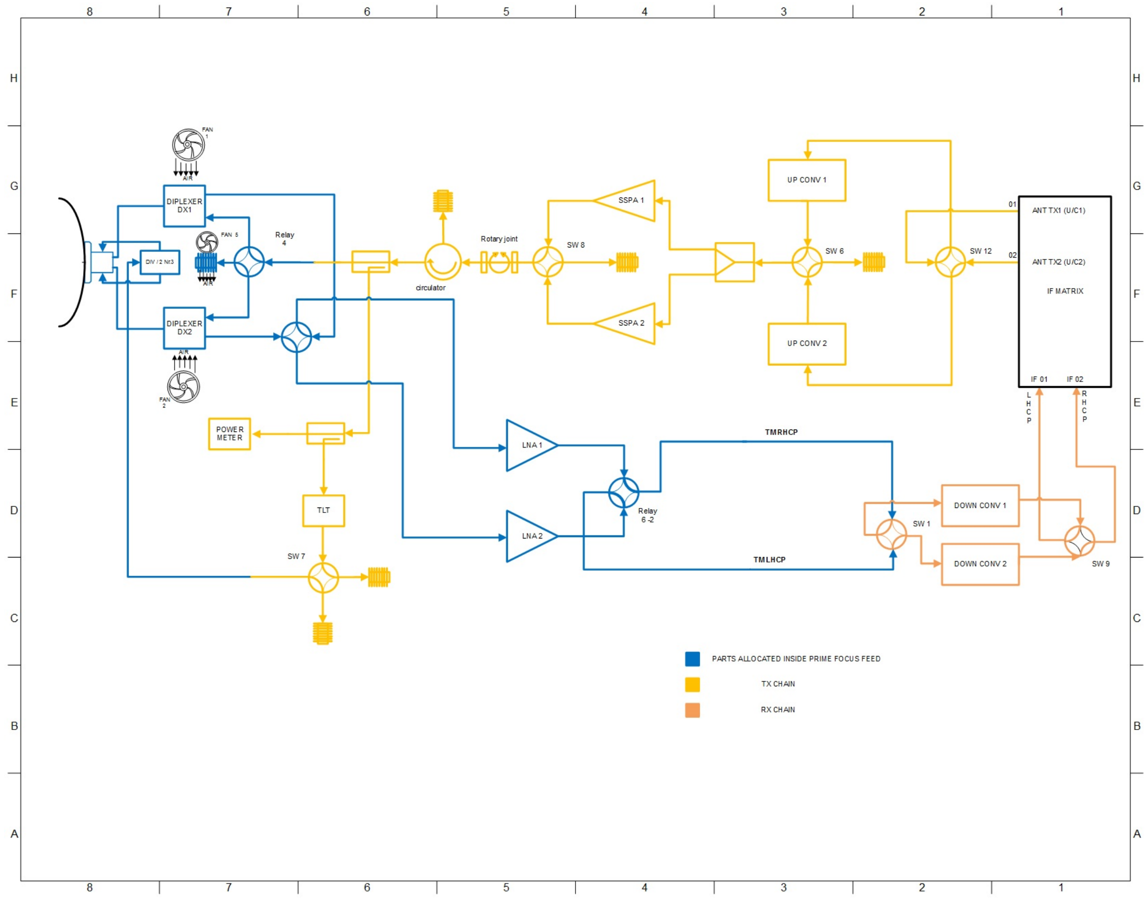


Figure 6.5: S-band prime focus antenna block diagram granted by Telespazio s.p.a.

As the block diagram underlines the antenna is practically composed by 3 blocks observable by the different colors used to represent them.
The **blue block** is the part of the antenna allocated inside the **prime focus feed**, the most important modules of this part are:

- The two **diplexer** (DX1 and DX2) that used to separate received and transmitted signals;
- The two **LNA (Low Noise Amplifier)** with a gain of 45 dB and a very low noise figure (< 0.5 dB) employed to amplify the received signals without introducing more noise;
- The three **cooling devices** that cool down the diplexers to avoid the overheating of the antenna.

The **yellow block** indeed is the **transmission chain**, it is exploited for signals transmission and it is implemented by the following components:

- **TLT (Test Loop Translator)** that is the entity used to fill up the delay (ranging calibration) introduced by the ground station in the ranging measure. It simply acts as a frequency converter that takes the transmitter signals and after frequency conversion injects it on the receiver chain;

- **Circulator** used to avoid return power from the prime focus of the antenna;

- **Rotary joint** employed to maintain the connection between the wave guide and the antenna during the rotation of it;

- Two **SSPA (Solid State Power Amplifier)** (SSPA 1 and SSPA 2) with a gain of 70 dB and a noise figure of 8 dB have the task to amplify the transmitted signals;

- Two **Up-Converters** (UP CONV 1 and UP CONV 2) used to brig the transmitted signal from 70 MHz to S-Band frequency, they are two to ensure the redundancy.

On the contrary, the orange part represents the **receiver chain**, it is utilized for signals reception and is simply composed by:

- Two **Down-Converters** (DOWN CONV 1 and DOWN CONV 2) with the target of decreasing the frequency of the received signals to 70 MHz, in this case they are two because both RHCP and LHCP are sustained.

Moreover, there is an **IF matrix** that is the tool able to route the signals from the antenna to the several BBUs and vice-versa in the stations employed for the mission. Finally the **radiation pattern** and the **return loss** of the considered antenna, measured by Telespazio s.p.a and under its permission, are shown below:

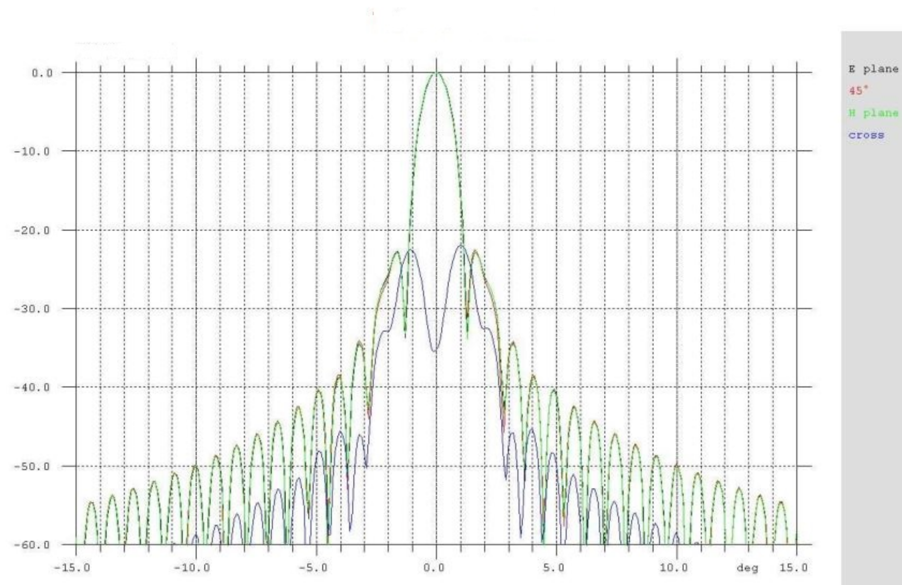


Figure 6.6: S-Band prime focus antenna radiation pattern granted by Telespazio s.p.a

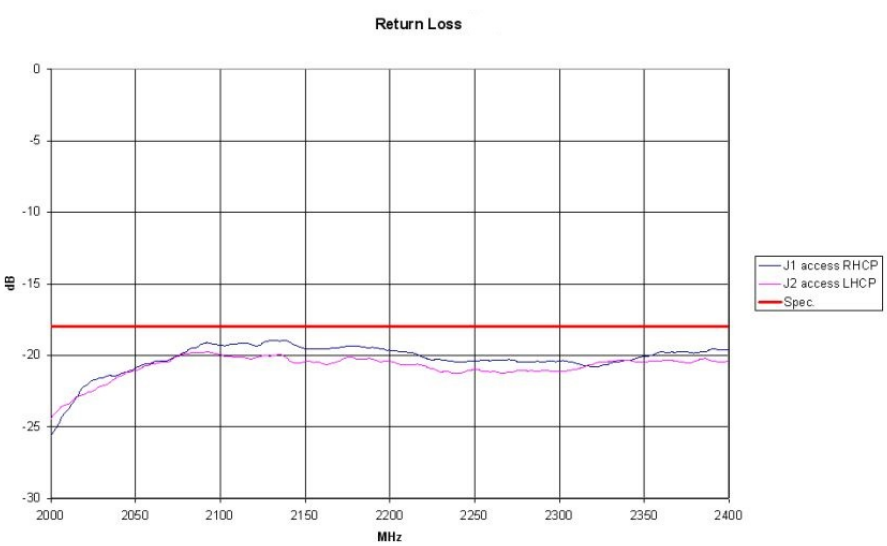


Figure 6.7: S-Band prime focus antenna return loss published under Telespazio s.p.a. permission

As the first image emphasizes the antenna has a very high directivity for the frequencies employed in the mission since the main lobe of the radiation pattern is more that 21 dB higher with respect to the side lobes.
Also the return loss, that is a measure of the loss of power in the reflected signal, is very good since it maintains a value under the specified one for all the considered frequencies.

Chapter 7

Tests description

This chapter is dedicated to the tests description and for each test block, except for the test bench calibration where no requirements should be complied, will be reported a table where are pointed out the input parameters of test, the requirements, outlined by the SGICD, CCSDS and ECSS, to be verified and the expected results, achieved with an analytical analysis of the problem.
Moreover, will be presented the method implemented in the test execution used to get the outcomes and the employed measurement instruments.
The results obtained by the tests execution will be reported later and it will be checked if they are compliant with the requirements and expected results exposed in this chapter.

7.1 Test bench calibration

The beginning of the proper test is anticipated by a fundamental test bench calibration and a parameters verification, that is divided in four test's sequences:

7.1.1 Satellite output power

Aim of this sequence is to evaluate the total power of the downlink signal at the S-Band transponder output port and in particular its peak. This power is computed sending a PM signal from the TCR suitcase, using a power meter and taking into account all the attenuation terms introduce by the instruments. Table below points out the input parameters and the expected result of this test:

INPUT PARAMETERS
• TCR suitcase maximum output power P_{tx}= 37.4082 dBm • TCR suitcase maximum power at output port $P_{out} = P_{tx} - D/L_{path}$= 1.58 dBm (Computed for the best D/L_{path} = 35.83 only fixed attenuation of the TCR) • Power at the measure point $P = P_{tx} - S/C_{loss} - D/L_{path}$ where S/C_{loss} is the insertion loss of interconnection and D/L_{path} is the insertion loss due to the path. • Using the reverse equation it is possible to know the actual transmitted power: P$_{tx} = P + S/C_{loss} + D/L_{path}$
EXPECTED RESULTS
Maximum expected power (P_{out}) variation is ± 0.5 dB.

Table 7.1: Sequence 7.1.1 inputs and expected results

7.1.2 Satellite output frequency

As well as for power also the frequency is evaluated by the means of PM modulated signal. In particular this test's sequence evaluates the downlink carrier frequency short-term stability using a spectrum analyzer and a frequency counter. The underneath chart summarises input and expected outcomes of this sequence:

INPUT PARAMETERS
• D/L carrier frequency = 2253.5 MHz
EXPECTED RESULTS
The expected value of the D/L frequency is 2253.500 MHz and the frequency stability of the carrier should be $\pm 2 * 10^{-5}$ under all conditions and for the lifetime of the satellite

Table 7.2: Sequence 7.1.2 inputs and expected results

7.1.3 Satellite output signal analysis

Purpose of this test is to measure and validate the downlink signal features in order to verify that they are compliant with SGICD, that is the document supplied by the costumers in which it describes the characteristics requested by its application, and the above mentioned ECSS-E-ST-50-05C standard. As before a spectrum analyzer is used and a table reports in explicit way the inputs and the expected results of this test section:

INPUT PARAMETERS
• D/L carrier frequency = 2253.5 MHz • Modulation type = PCM[NRZ-L]/PSK/PM (subcarrier=65.536 kHz) • Symbol Rate = 16.384 ksps • TM modulation index = 1.15 rad [±6%]
EXPECTED RESULTS
It shall be verified that there are not unexpected discrepancies in the downlink signal and that the spectra does not contain unwanted spurious. The spurious emissions shall not exceed -60 dBc[5]

Table 7.3: Sequence 7.1.3 inputs and expected results

7.1.4 Ground reference station (GRS) output signal analysis

Objective of this block is to verify that the output signal from the GRS is compliant with the SGICD and with the ECSS-E-ST-50-05C standard but also that it is conformed with the signals expected at the TCR suitcase, so, in order to avoid problem of compatibility that can bring to TCR suitcase break-down, this test is executed disconnecting the TCR suitcase and the GRS and closing the connection with a matched load at 50 Ω.

[5]dBc indicates that this quantity is computed as the ratio in dB between the signal power and the carrier power

To execute this test the GRS is configured to transmit a modulated signal. Actually this test should prove also the case in which is employed an un-modulated signal (clean carrier) since in the next paragraphs it is used to verify the threshold, when only the carrier reception will be taken into account. However, since the modulated signal represents a more critical case it is enough to validate the expected results of this scenario to be sure that are also complied those of the other one. Un-modulated signal means that the signal is modulated only with a PM modulation at radio frequency while the modulated one is also modulated at intermediate frequency using a BPSK modulation. Input parameters and expected results are better pointed out in the under table:

INPUT PARAMETERS
• U/L frequency = 2075.0979 MHz • Modulation type =PCM[NRZ-L]/PSK/PM (subcarrier=8 kHz) • Symbol Rate = 2.000 ksps • TC modulation index = 1 rad
EXPECTED RESULTS
• U/L frequency = 2075.0979 MHz $\pm 5 * 10^{-9}$ • Modulation type =PCM[NRZ-L]/PSK/PM (subcarrier=8 kHz) • Symbol Rate = 2.000 ksps • TC modulation index = 1 rad [±5%]

Table 7.4: Sequence 7.1.4 inputs and expected results

7.2 S-Band downlink test block

This test block is used to validate the compatibility between the signal generated by the TCR Suitcase and received by the Ground Reference Station (GRS) equipment in particular by the BBU.
The assessment will be performed using an external noise source to simulate the system noise density at the receiver input. This test block is further divided into 6 sub-blocks, reported in the following sub-chapters. S-Band downlink test block is considered successfully accomplished if all of the computed thresholds are under the ones estimated by the link budget analysis and if all the expected results exposed in the following sub-chapters are respected.

7.2.1 Telemetry receiver threshold

Purpose of this first sub-block is to evaluate the $\frac{C}{N0}$ lock-in/lock-out threshold for the down-link carrier acquisition by the TM receiver, that is the minimum signal-to-noise ratio needed to retrieve the telemetry signals without considering the correct reception of data but taking into account only the carrier acceptance.
This procedure, as its dual for uplink described after in 7.3.1, should employ an un-modulated signal but it is not possible to set this feature in the TCR suitcase and so a modulated one is used. Since all of these measures are executed considering the worst case scenario the ranging channel and telecommand reception are active for all of them. It is executed adopting the following method: the TCR Suitcase transmitter sends the RF signal modulated by the telemetry data. Before injecting it into the IF Receiver of the GRS input port, an externally generated noise is added. The initial downlink signal level at the BBU input is set for the worst case scenario after the starting of the Telemetry transmission it is decreased by means of the computer interface of the Programmable Attenuator with steps of 1 dB until carrier lock loss occurs. It is detectable by the status indicator on the BBU front panel, and by the spectrum displayed by the spectrum analyzer interface, this value of C represents the minimum signal level to retrieve the carrier, subtracting from it in dB (dividing if linear unit is considered) the noise level the threshold is obtained.
The threshold should confirm the analytic value computed by the link budget analysis (taking into account path loss, hardware attenuation, antenna gains and so on).

Table below summarized the input parameters, the requirements to be verified and the expected outcomes for this first sub-block:

INPUT PARAMETERS
• D/L Carrier frequency = 2253.5 MHz • Modulation type = PCM[NRZ-L]/PSK/PM (subcarrier = 65.536 kHz) • Symbol rate = 16.384 ksps • TM modulation index = 1.15 rad [±6%] • Noise density level = -118 dB/Hz[6]
REQUIREMENTS
• GRS should be able to receive the HK TM and RNG signals in the band 2200-2290 MHz. • The GRS shall be compatible with these D/L carrier frequencies, used in the mission: - 2253.5 MHz - 2243.5 MHz (back-up frequency)[7] • GRS TM downlink physical layer should comply the standard reported in Appendix A.
EXPECTED RESULTS
The expected receiver threshold should be according to the link budget analysis for a PLL bandwidth of 100 Hz, equals to 41.19 dB/Hz for worst case scenario

Table 7.5: Test 7.2.1 input, requirements and expected results

[6] Actually for RHCP noise density level is -118.79 dB/Hz while for LHCP is equal to -117.96, however for simplicity it is possible to assume for both of them -118 dB/Hz without loss of generality

[7] Back-up frequency indicates the frequency employed in any case the use of the principal frequency value is not possible for reasons of interference, faults and so on

7.2.2 Telemetry frame lock threshold

INPUT PARAMETERS
• D/L Carrier frequncy = 2253.5 MHz • Modulation type = PCM[NRZ-L]/PSK/PM (subcarrier = 65.536 kHz) • Symbol rate = 16.384 ksps • TM modulation index = 1.15 rad [±6%] • Noise density level = -118 dB/Hz[6]
REQUIREMENTS
• GRS should provide the capability for simultaneous HK, TM, TC and RNG during all mission phases (verification done only for the worst case) • GRS shall be able to receive a PCM (NRZ-L)/PSK/PM HK TM downlink modulation scheme with a subcarrier of 65.536 KHz, a Carrier Modulation index of 1.15 radians peak (±6%) and a symbol rate equal to 16384 bps. • The GSN Ground Stations' TM decoder shall apply the Viterbi soft algorithm the received TM Transfer Frames, as they are subject to Convolution code CV(7,1/2). • After deconvolution, the GRS TM decoder shall perform a TM Frame Synchronisation based on the ASM marker 1ACFFC1D. • Then it should be able to de-randomize the TM Frames, as they are subject to pseudo-randomization. • Finally, GRS shall decode the Reed-Solomon applied to the TM Frames, which are subject to Reed-Solomon (255,223) encoding with an interleaving depth I=5. • GRS TM downlink physical layer should comply the standard reported in Appendix A
EXPECTED RESULTS
GRS should be able to face all the specified requirements and form the link budget the expected lock threshold should be equal to 46.55 dB/Hz

Table 7.6: Test 7.2.2 input, requirements and expected results

Purpose of this test's sub-block is to verify the threshold for the correct execution of the "search/check/lock" procedure of the Frame Synchroniser (F/S) for data reception under noise conditions and with the ranging channel and telecommand reception

active that corresponds to the worst case scenario. It is executed using this method: The TCR suitcase transmitter sends the RF signal modulated by the TM data. Before injecting it into the IF GRS receiver input port, an externally generated noise is added. By changing the $\frac{C}{N0}$ value, it is possible to reach the unlock condition of the F/S that can be detected by the status indicators of the monitoring and control interface. At this point it is possible to compute the threshold as the difference in dB between the signal level and the noise level and it should confirm the result obtained by the link budget (taking into account path loss, coding, modulations, interference, hardware attenuation and so on).
As before the parameters of the test are reported in a table at the begin of sub-chapter.

7.2.3 Coupling of ground station telemetry with TC uplink

During the phase in which the satellite experience a rotation, for example when it is enjected from the launch vehicle, the apparent polarisation of the satellite's downlink signals seen from the Ground Station may change up to twice every 15 minutes since satellites have TCR antennas with opposite polarisation and position (RHCP and LHCP) and only one of the two is in visibility. So when this happens, it is fundamental to ensure the coupling of the Ground Station telemetry with the telecommand uplink, to be able to switch the uplink polarisation according to the received one. In this test's sub-block two programmable attenuators, with the attenuation profiles reported in the graph below, simulates the satellite's downlink signal variations.

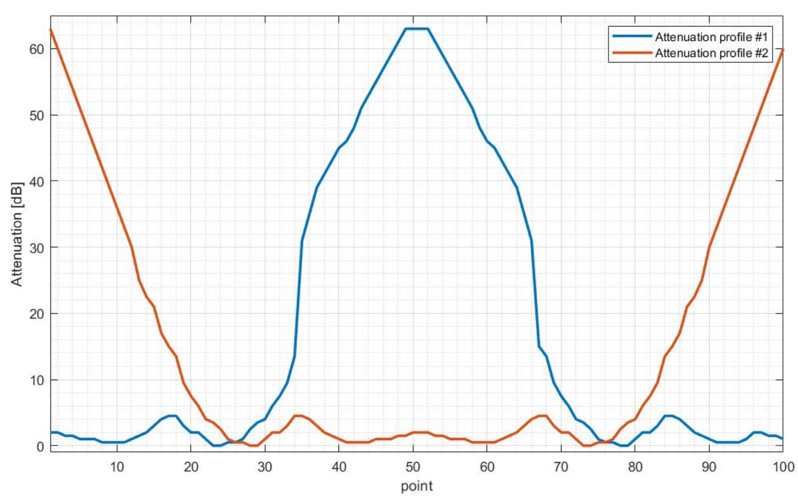


Figure 7.1: Attenuation profiles

As the figure shows the two attenuation profiles are opposites, that is, when an antenna is not attenuated the other one is attenuated to the maximum.
This behaviour simulates very well what happens during a satellite rotation where it is possible to have an antenna completely in view and the other one completely obscured, vice-versa or both of them partially in view. The received signal is then monitoring using the monitoring and control interface of the BBU. Table below reports the input parameters, the requirements and the expected results of this test

INPUT PARAMETERS
• D/L frequency = 2253.5 MHz • Modulation type = PCM[NRZ-L]/PSK/PM (subcarrier = 65.536 kHz) • Symbol rate = 16.384 ksps • TM modulation index = 1.15 rad • Noise level = -118 dB/Hz
REQUIREMENTS
The GRS shall ensure that the TC RF uplink signal be coupled with the TM RF downlink signal so that the uplink polarisation be switched according to the downlink polarisation.
EXPECTED RESULTS
The NOC operator shall be able to monitor the downlink signal level variation and coordinate the GRS in configuring the best uplink polarisation

Table 7.7: Test 7.3.1 input, requirements and expected results

7.2.4 Dynamic downlink doppler simulation

Purpose of this test sub-block is to verify that the receiver is able to work properly with the doppler rate expected at the perigee acquisition that represents the worst case scenario since the satellite has maximum speed and so there is the maximum doppler effect. This test is executed injecting a RF signal that simulate the doppler computed as exposed in the next sub-chapter (Dynamic Doppler profile and Dynamic

Doppler rate show in Figure 7.2) and then monitoring the behaviour of the receiver using the monitoring and control interface of the BBU.

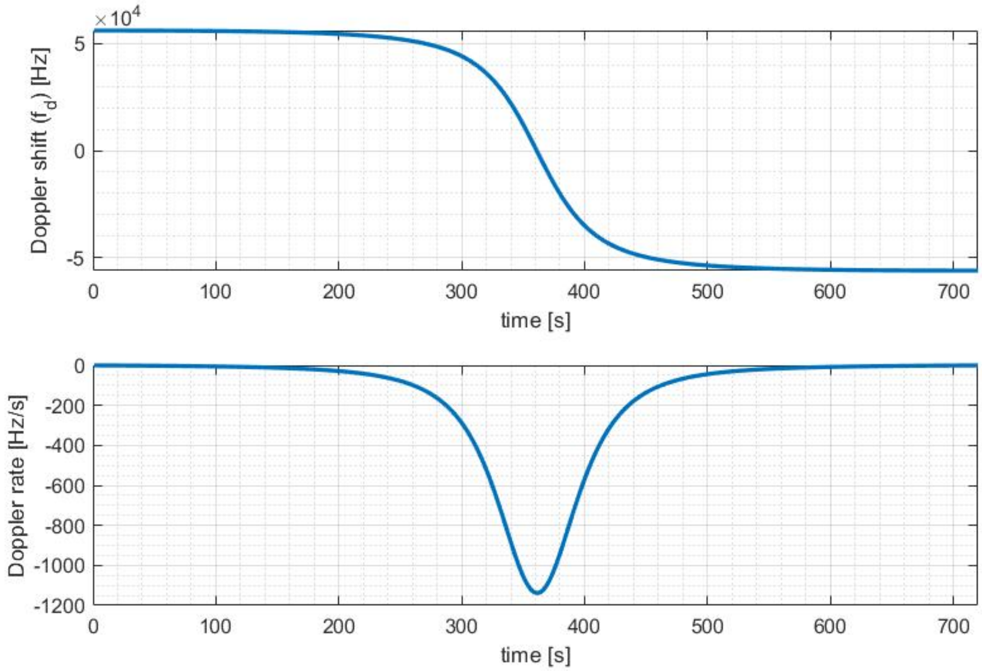


Figure 7.2: Doppler parameters

In this case the inputs are the same before and the requirements are only that the GRS should be able to face frequency excursion of ±50kHz and a maximum doppler rate of almost 1100 Hz/s as underlined by the figure, so they are not reported in a table. Obviously, the expected result is that the GRS is able to retrieve the signal also when doppler is present.

7.2.4.1 Doppler shift and doppler rate computation

In this sub-chapter is exposed how the doppler shift and the doppler rate are computed before to use them in the signal generator that simulates the doppler effect. The theory behind this result is illustrated afterwords while the computation is done using the MATLAB® code reported in **Appendix B**.
First of all, the next figure better clarify the geometry of the problem.

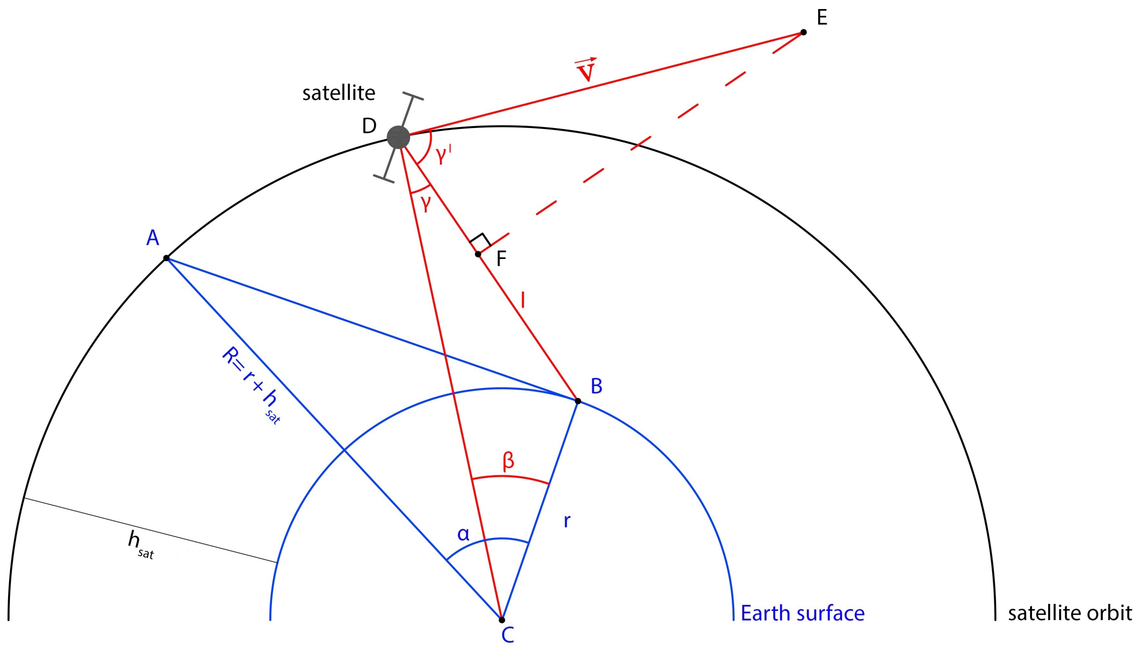


Figure 7.3: Geometry of the doppler computation problem

The fundamental quantity used to compute the doppler shift is the radial component of satellites speed v_r, computed using the following formula:

$$v_r = v * cos(\gamma')$$

Giving for known the radius (r) and the mass (M_{Earth}) of the Earth, the radius of the satellite (h_{sat}, set to 250 km, that is the minimum perigee distance of the analyzed satellite) and the gravitational constant (G), v that is the speed of satellite is calculated as:

$$v = \sqrt{\frac{G * M_{Earth}}{h_{sat}}}$$

while for γ' computation two trigonometry laws must be taken into account: the first one is the **law of sines** that applied to the triangle DBC leads to

$$\gamma' = 90^\circ - asin[(r/l) * sin(\beta)]$$

and the second one the **Carnot theorem** applied alway to the triangle DBC allows the calculation of l as

$$l = \sqrt{r^2 + R^2 - (2 * r * R * cos(\beta))}$$

l is the range of satellite and represents the distance between the satellite and the ground station.
β indeed is computed as the ratio between the angle of the entire passage

$$\alpha = 2 * acos(r/R)$$

(where $R = r + h_{sat}$) and the time duration of the passage itself set in this case to 12 min (duration of perigee passage for the considered satellite).
At this point computed the radial component of the satellite speed v_r, it is possible to estimate the **doppler shift** (f_d) as:

$$f_d = f_0 * \frac{v_r}{c}$$

with $c \simeq 3{*}10^8$ m/s the speed of light and $f_0 = 2253.5$ MHz the downlink frequency.

Finally the **doppler rate** is evaluated as the difference between the present value of the doppler shifth and the previous and it provides a measure of changing of frequency during the passage. As expected it is higher when the speed of satellite with respect to the Earth and so the doppler shift is more elevated.

7.2.5 Telemetry message BER estimation

This sub-test is a qualitative estimation of the **BER** (Bit Errror Rate) of the telemetry messages received at ground segment in several case conditions. It is based on the bit-to-bit comparison of the messages at the output of the base-band unit (BBU) at the receiver side and the telemetry message simulated by the BBU itself in which a network of adder, mixer and attenuators introduces noise, disturbances and attenuations typical of the space channel. For this preliminary test session of the mission of course the sending telemetry message is know at priory.
BER calculation is done using the python code, developed with Jupyter notebook for this thesis, in **Appendix C**. Since the comparison is done bit-to-bit but the telemetry messages are composed by hexadecimal words a preliminary conversion is executed by the code that moreover removes the header and postamble introduced by the BBU for the next TCP/IP transmission in order to estimate the BER only on bits that really represent information bits.
Furthermore, in this procedure to get telemetry messages it is employed the **`replay` mode** of the BBU, that as sayd before is the capability of the BBU to resend a file stored in its memory, instead of the TCR suitcase because the telemetry messages

sent by the latter are not know until they are received and so it is not possible to compute the BER.
The expected results of this test are the ones known from theory that is: the BER gets worse as the $\frac{C}{N0}$ decreases and it should be better for coding transmissions with respect to un-coded ones.

7.2.6 Telemetry message FER estimation

A more accurate analysis with respect to the previous one is possible to the **FER** estimation. FER stands for Frame Error Rate and represents an important parameter for network performance evaluation. It is computed as the ratio between the number of frames containing errors divided by the total number of transmitted frames. It is a more restrictive qualitative parameter with respect to BER since an entire frame is considered false even if only one bit is wrong. This analysis is possible since the BBU implement two counters that after the decoding technique operations are able to count the number of corrected frames (marked as `Good frame`) and the number of erroneous frames (stressed as `Bad frame`).
Obviusly, this estimation does not take into account the possible undetected errors, described later in this documents, that can appear during the transmission. However since this kind of errors appear with a quite low probability, this approximation does not introduce a so big discrepancy between the obtained results and the real ones.
FER estimation is conducted using the TCR suitcase and the BBU, test is done for several $\frac{C}{N0}$ starting from the lower one and using the following method: set the $\frac{C}{N0}$ the transmission is made start and it is stopped until the `Bad frame` counter notify a value of 100 erroneous frames, at this point the FER is computed and the procedure is repeated for another higher $\frac{C}{N0}$.
$\frac{C}{N0}$ is modified using the programmable attenuators and it is checked using a spectrum analyzer.
Procedure ends when the transmission takes a very high time to be affected by 100 frame errors and can be affirmed that for that $\frac{C}{N0}$ the FER is for sure smaller with respect to the last computed one. The obtained results are then compared with the requirement reported in the SGICD that sanctioned a FER of 10^{-6} for a $\frac{C}{N0} \simeq 41.33$ dB/Hz and with the ones known from theory that is that increasing the $\frac{C}{N0}$ the FER should be better.
Both for telemetry message BER and FER estimation the input parameters are the common ones used for telemetry signal transmission, reported in the tables of the previous sub-chapters.

7.3 S-Band uplink test block

This test block is the opposite of the previous one and it is executed to validate the compatibility with respect to the signal generated by the Ground Reference Station and received by the TCR Suitcase. S-Band uplink test block is considered successfully passed if the two thresholds computed in the following have a lower value with respect to the ones computed using the link budget analysis.

7.3.1 Uplink acquisition threshold

INPUT PARAMETERS
• U/L frequency = 2075.0979 MHz • Modulation type = PCM[NRZ-L]/PSK/PM (subcarrier = 8 kHz) • Symbol rate = 2.000 ksps • TC modulation index = 1 rad • Noise density level = -115 dB/Hz
REQUIREMENTS
• GRS shall transmit the TC's at an S-band TC rate equal to 2000 bps at CLTU level (Communication Link Transmission Unit). • GRS shall transmit an acquisition sequence with a length of at least 128 bits. • The GSN Ground Stations shall be compatible with this uplink carrier frequency used by the satellite of the missions: 2075.0979 MHz • GRS TC uplink physical layer shall comply with the standard in Appendix A
EXPECTED RESULTS
The expected Uplink acquisition threshold should be, according to the link budget analysis, equal to 54.29 dB/Hz for the worst case scenario

Table 7.8: Test 7.3.1 input, requirements and expected results

Purpose of this test case is to evaluate the lock capability of the on board receiver when the un-modulated uplink carrier (clean carrier) reception is ruined decreasing

the $\frac{C}{N0}$ starting from the worst case scenario. The threshold is found using the common approach: decrease the Signal-to-Noise ratio until the on board receiver is not able to lock its PLL with the signal transmitted by the GRS and applying the common computation (threshold in dB = minimum signal level in dB − noise level in dB). Also in this case the measured value should be conformed with the one obtained with the link-budget analysis (that takes into account path loss, hardware attenuators, coding, modulations and so on).
As usual, table above contains all the information used to this test implementation.

7.3.2 Telecommand rejection threshold

INPUT PARAMETERS
• U/L frequency = 2075.0979 MHz • Modulation type = PCM[NRZ-L]/PSK/PM (subcarrier = 8 kHz) • Symbol rate = 2.000 ksps • TC modulation index = 1 rad • Noise density level = -115 dB/Hz
REQUIREMENTS
• GRS shall transmit the TC's at an S-band TC rate equal to 2000 bps at CLTU level (Communication Link Transmission Unit). • GRS shall transmit an acquisition sequence with a length of at least 128 bits. • GRS TC uplink physical layer shall comply with the standard in Appendix A.
EXPECTED RESULTS
The expected TC rejection threshold should be according to the link budget analysis equals to 59.53 dB/Hz in worst case scenario

Table 7.9: Test 7.3.2 input, requirements and expected results

This test case is executed to determine the Telecommand Rejection Threshold when an uplink modulated signal (i.e. with data) is sent in the worst case scenario (ranging and telemetry channels active). The Telecommand Rejection Threshold is defined as the lowest $\frac{C}{N0}$ at the transponder RF input leading to erroneous telecommands data reception. To find this threshold the common approach is used, employing the spectrum analyzer and applying the usual computations.
Table at the incipit of this sub-chapter summarises all of the above.

7.4 S-Band ranging test block

This test block refers to the tests act to validate the Ranging (RNG) procedures performances. S-Band ranging test is considered verified if the calculated thresholds are lower with respect to the link budget's ones and if the expeceted results exposed in the next sub-chapters are proved.

7.4.1 Ranging signal verification

The purpose of this test case is to verify the RNG uplink and downlink carrier characteristics for a transmission at nominal $\frac{C}{N0}$. This test is carried on maintaining the transponder in non-coherent mode, this means that the two employed PLLs the on-board and the ground one have two different references[8], and exploiting 2 different scenarios:

1. **Ranging mode not available on satellite**: the RNG tones are ignored by the satellite and so the GRS is not able to complete the ranging procedure, a telecommand should be sent to satellite to make this mode available.

2. **Ranging mode available on satellite**: the PM modulated tones (RNG tones) are received and transmitted back by the satellite to the GRS that can compute the Round Trip Time (RTT) and so the orbit position of it.

The expected results are that at nominal $\frac{C}{N0}$ the carrier characteristics, evaluated through the modulation index and ranging tones frequencies, should not be so different with respect to the nominal ones. In case of ranging mode not available indeed the expected results are that no ranging signals come back from the satellite. A more

[8]As in reality the on board PLL and the ground PLL use two different time and frequency references

accurate description of the requirements, inputs and expected results in case of ranging mode available is provided in the table underneath:

INPUT PARAMETERS
• U/L frequency = 2075.0979 MHz • RNG tone frequency = 114.681 kHz • U/L RG Modulation Index = 0.6 rad • TC modulation index = 1 rad • D/L RG modulation Index = 0.5 rad
REQUIREMENTS
• GRS shall be compatible with ranging performances • GRS RNG physical layer shall comply with the standard in Appendix A
EXPECTED RESULTS
RNG transmission should not modify the U/L RG Modulation Index of ±5% and the D/L RG Modulation Index of ±5%

Table 7.10: Test 7.4.1 input, requirements and expected results

7.4.2 Ranging threshold

Purpose of this test block is to measure the thresholds of the ambiguity resolution process with respect to $\frac{C}{N0}$ of the Uplink and Downlink signals. Now, the thresholds to be computed and verified are actually two since ranging signal experiences both uplink and downlink channel. These thresholds are evaluated using an approach not so different from the previous ones since alway the $\frac{C}{N0}$ is decreased but this time the threshold is considered reached when the RAU inside the BBU notifies a ranging measurement accuracy below the 97% (`Quality Factor` smaller than 0.97).
As usual, the obtained results are compared with the ones computed with the link budget analysis in the worst scenario. In this case since the inputs are the same of 7.4.1, the requirement is simply to find the threshold that should be compatible with

link budget analysis, there is no need to report them in a table.

7.5 End to end network data-flow test

This last test will verify the capability of the ground segment to correctly manage the telemetry, telecommand and ranging data flows between the MCC/SCC (Mission Control center/Satellite Control center) through the NOC (Network Operation Center), the GRS and the satellite (TCR suitcase).
MCC is the most important entity that coordinates the entire TC,TM and RNG procedures, it is linked to the NOC that has the aim to make feasible the information from the MCC to the GRS, that has the responsibility to send it to the satellites, and viceversa. The protocols employ in this connection are the SCOS 2000, developed by ESA, for the link between the MCC and NOC, while the association between the NOC and the BBU is managed through a protocol property of the BBU builder and so it cannot be mentioned in this thesis.
Therefore the NOC acts as a sort of protocol translator that is able to make possible the communication between GRS and MCC.
However, the messages passing between MCC, NOC and GRS are managed with a LAN that uses the TCP/IP connection so it is possible to analysed the correctness of the data-flow exchanging by means of a network analyzer software (`Wireshark`).
Furthermore, it is important to underline that for a correct command passing the considered GRSs should use all the same model of BBU to avoid compatibility issues.
A figure, in the next page, summarizes and visualizes the ground segment described in this paragraph adding also the no tested FDS (Fly Dynamic System) that is the entity that piloted by the MCC receives and processes the ranging measurements.
Test is considered passed with positive results if the above mentioned capability are accomplished in correct way and it is logically divided in 3 sub-tests:

1. **Telecommand data flow test** employed to validate the telecommand flow.
2. **Telemetry data flow test** used to prove the telemetry message exchanging.
3. **Ranging data flow test** that dimostrates the capabilities of the ranging flow.

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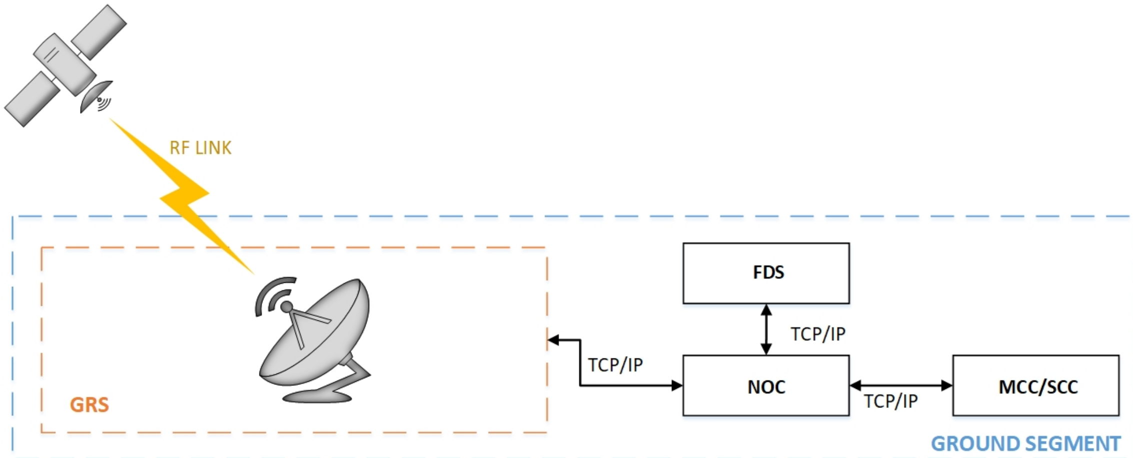

Figure 7.4: Ground segment organizzation

Chapter 8

Link budget analysis

Link budget analysis is the plan of actions executed in an **analytic way** in a project to determine the practicability of any specific system. It is also an optimal tool to start to understand all the variables which has to be taken into account to realize a determined target respecting given costs and requirements before the realization of the system itself.

Link budget analysis is for the case takes into consideration a collection of all of the gains and losses from the transmitter, through the medium (free space) to the receiver in a satellite communication. It accounts for the attenuations and the amplifications of the transmitted signal due to propagation, as well as the antennas and instruments gains/losses, modulations, interferences, coding techniques but also randomly varying channel gains such as doppler are taken into account by adding some margin.

The purpose of this link budget analysis is to know in an analytic way the $\frac{C}{N0}$ necessary for the receiver to achieve the mission specified requirements and the several thresholds that have to be verified before the beginning of the RFCT. Knowing these quantities preliminary to the test execution is fundamental to set in an accurate way the employed signal powers and verify if the features reported in the SGICD are feasible for the available hardware.

In this chapter will be reported the analytic method employed to compute the several thresholds mentioned in Chapter 7. The theory behind the results and the obtained outcomes will be commented in this chapter while the computations to obtain them are reported in **Appendix D** and developed for this thesis using **MATLAB®**.

This analysis is designed for the worst case scenario since it is the most conservative case that ensures the correct operability of all the others. So the worst stations for the uplink and downlink involved in the mission are the only considered in this analysis. For the uplink the worst case scenario is represented by the station of South-Point in Hawaii, while concerning the downlink the worst case scenario is constituted by the Malindi station in Kenya. Moreover, being the most critical situation taken into account the ranging channel is always considered active.

8.1 Spectrum of PM signals and Bessel function

Since the considered signals are **PM (phase modulation)** modulated, the modulating signal $m(t)$ goes to change the phase $\phi(t)$ of the modulated one and the resulting signal is:

$$u(t) = A * cos(2\pi f_c t + \phi(t))$$

where $\phi(t) = k_p * m(t)$ and k_p is a proportional coefficient called **phase deviation constant** and it is a characteristic of the modulator.

At this point, it is possible to define the **modulation index** β as:

$$\beta = \Delta\phi_{max}$$

where $\Delta\phi_{max}$ is the **maximum phase deviation** and it is equal to $k_p * max|m(t)|$.

The modulation index is a fundamental parameter of phase modulation and performs a key role in the definition of the spectral characteristics of the signal.
As matter of fact, it is possible to know the spectral characteristics of the PM signal re-writing the above signal $u(t)$, using the modulation index and the **Bessel functions**, reaching:

$$u(t) = \sum_{k=-\infty}^{+\infty} A_c J_n(\beta) cos[2\pi(f_c + k f_m)t]$$

In which $J_n(\beta)$ are the Bessel functions of fist kind and has, changing n, the trends reported in the figure underneath, obtained using MATLAB®.

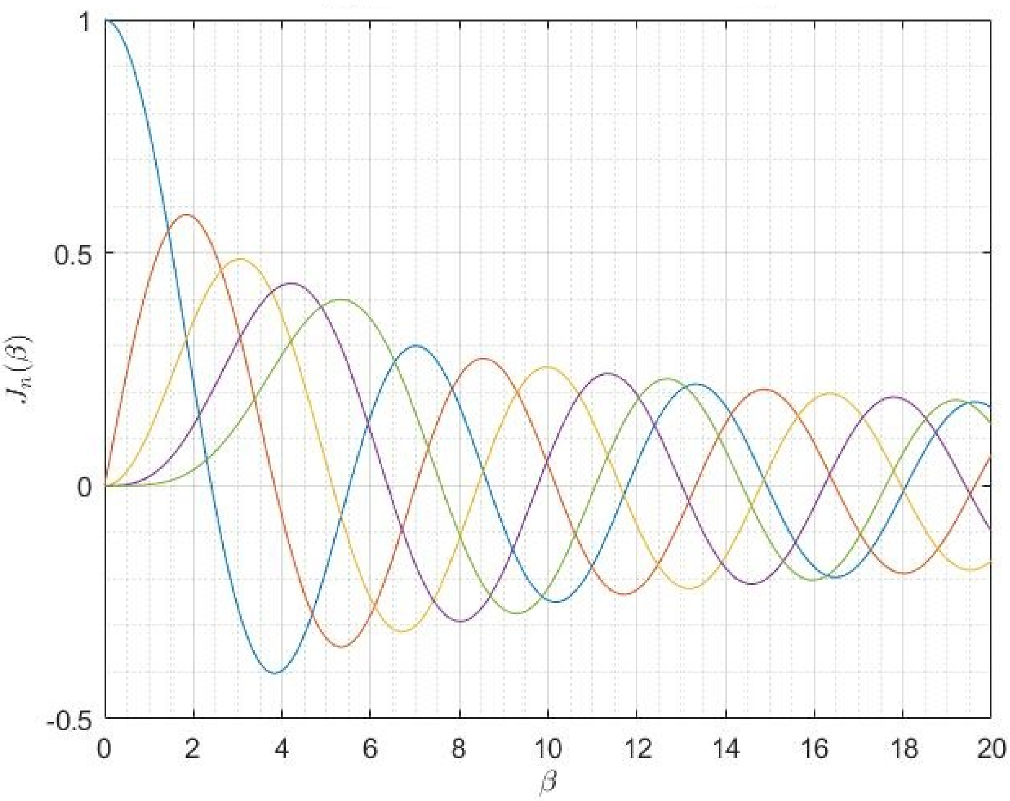

Figure 8.1: Bessel function of first kind

Knowing the formula of the signal and the trend of the Bessel functions is clear that its spectrum is composed by infinity lines. Therefore, this non-linearity of the PM modulation leads to a infinity spectrum that is not usable in reality since it has an infinity band occupation. However an approximation makes this kind of modulation workable: only the Bessel function of order $n < \beta + 1$ are considered different from zero and so it is possible to write the band of the signal as:

$$B = 2(\beta + 1)f_m$$

It is worth to know that this band approximation contains the 98% of the signal and so it is a very good and feasible band definition.

8.2 Expected thresholds

Understood the theory behind the spectrum of PM modulation, it is possible to use it to estimate, using MATLAB®, for the case in analysis the expected thresholds (TH). They are computed as:

$$TH = \frac{C}{N0} - Margin$$

where the $\frac{C}{N0}$ is the station measured signal-to-noise ratio in the worst case scenario and the $Margin$ is computed as the real expected $\frac{Eb}{N0}$ or $\frac{C}{N0}$ minus the $\frac{Eb}{N0}$ or $\frac{C}{N0}$ required by the customer and reported in the SGICD of the mission.
$Margin$ is a limit that represents how much the $\frac{C}{N0}$ can degrade ensuring always that the analyzed requirement is respected. Exceeded this quantity, the system is under threshold and it could be no more able to work properly.
To compute $\frac{C}{N0}$ indeed are involved all the losses experienced by the signals, estimated using the above mentioned theory using the Bessel functions, the modulation index and considering the worst case scenario. Worst case scenario that is reached in two different configurations of modulation index depending on if only the carrier is considered or if also the sub-carriers are taken into account:

- **Worst case scenario** considering only the **carrier** is represented by the possible maximum value of the modulation index inasmuch a greater modulation index means that the power is more spread from the central carrier frequency and so from the point of view of the receiver is more difficult to lock itself to the signal peak.

- **Worst case scenario** when also the data and so the **sub-carrier** is considered, is represented indeed by the minimum possible value of the modulation index, because a lower value of this parameter means that the power is very concentrated around the central frequency and so the remaining power in the sub-carrier frequency are not so much, this translates in a harder data decoding at the receiver side.

Figure below obtained simulating in MATLAB® three spectra of the same PM signal with different modulation index set to 1.15 $\pm 6\%$ rad explains graphically what mention before:

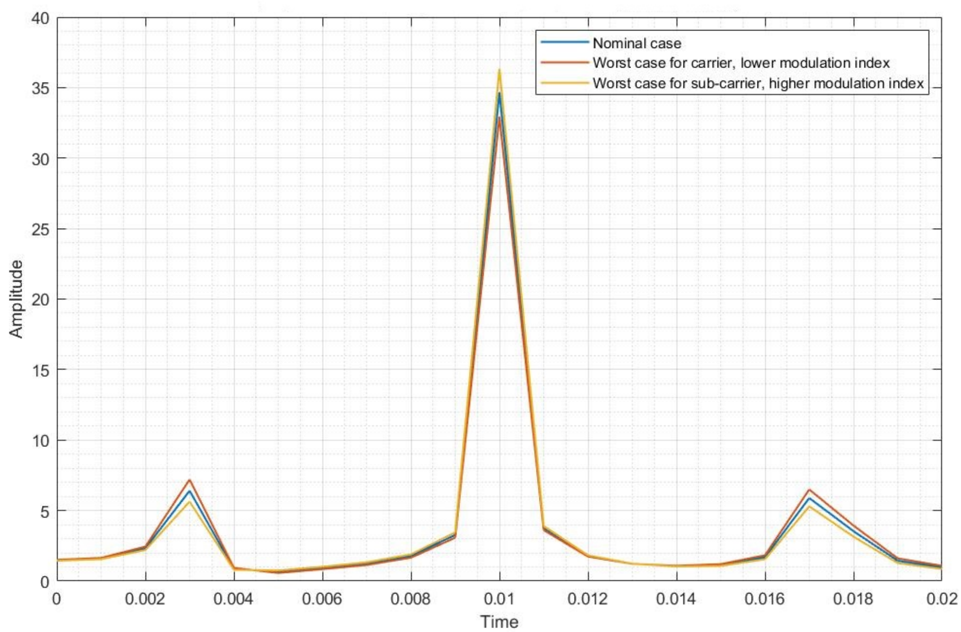

Figure 8.2: Spectra of PM signal varying modulation index

Finally, when also the data reception is considered to estimate the $\frac{Eb}{N0}$ are adding to the before described losses also the employed bit-rate for data transmission.
In the following sub-chapters all the thresholds used in the test will be computed and briefly described for the worst case scenario.

8.2.1 Telemetry receiver threshold

In order to compute the margin of this threshold the highest possible modulation index and the Bessel functions of first kind of zero order, that represents the part of the spectrum due to the carrier, are employed since it is not necessary consider also the other ones because the examined case concerns only the carrier recovery, so the useful power is only the one associated with the part of central frequency remained after the signal transmission. The losses accounting in this threshold calculation are the ones due to carrier modulation, due to the cohabitation in the same channel of telemetry, ranging signal and the partially reflected telecommand (echo of TC)[9], due to instruments and obviously the losses due to noise. The computation done using

[9]Due to phenomena of reflection, refraction and scattering during the space propagation

MATLAB® is reported in **Appendix D** and leads to an expected threshold, to be verified with the text execution, equals to:

$$TH_{rec} = 41.19 \text{ dB/Hz}$$

8.2.2 Telemetry frame lock threshold

In this case since not only the carrier but also the data are involved in the analysis the entire spectrum of the signal[10] has to be considered so the lowest possible modulation index and the Bessel functions of first kind and first order are taken into account for the margin computation. The expected threshold, calculated with the MATLAB® code in **Appendix D** is:

$$TH_{loc} = 46.55 \text{ dB/Hz}$$

Also in this case the losses takes into consideration are the ones reported in the previous paragraph but this time since data are involved also the bit rate is taken into account. Obviously, also this result will be verified during the test implementation.

8.2.3 Uplink acquisition threshold

Still in this case since the attention is only on the carrier the Bessel functions of first kind and zero order and the highest possible modulation index are used to compute the margin and so the threshold. Using always the above mentioned MATLAB® code, the uplink acquisition threshold of the receiver on board the satellite is

$$TH_{up} = 54.29 \text{ dB/Hz}$$

This quantity also will be verified during the test.

[10] Actually, using the approximation described before, the spectrum considered is only the part that contains the 98% of the power

8.2.4 Telecommand rejection threshold

For the same reasons exposed in the 8.2.2 section also in this case the Bessel functions of first kind and first order, the lowest possible modulation index and the employed bit rate are considered. The MATLAB® code sanctions a value of this threshold equivalent to:

$$TH_{rej} = 59.53 \text{ dB/Hz}$$

to be verify in chapter 9.

8.2.5 Ranging Thresholds

Finally, the ranging thresholds are evaluated using the losses already accounted for the downlink and uplink channels and considering the ranging (RNG) modulation index, reaching the following results:

Downlink ranging threshold $TH_{RNG-down} = 40.93$ dB/Hz

Uplink ranging threshold $TH_{RNG-up} = 52.61$ dB/Hz

also these two last thresholds will be verified during the test execution.

Chapter 9

Test execution and results

This chapter is dedicated to the description of the test execution and to the comment of obtained test results. All The measurements presented in this chapter are carried out with a **power meter**, a **frequency counter** and a **spectrum analyzer**, these instruments are calibrated and their parameters have been optimally set before the starting of the experiments.
The power meter, its power sensor, and the cable to connect them have been calibrated using the function `calibration` of the power meter itself. While the spectrum analyzer has been set with a frequency, bandwith, amplitude and video resolution suitable for the visualization of the analyzed signals.

9.1 Test bench calibration

The first part of the test execution is represented by the test bench calibration. It is performed using the above described test bench and it is useful to understand the parameters involved in the future tests and to verify if the specification provided by the TCR suitcase and other apparatus constructors are correct. This preliminary test bench calibration is carried out without introduce noise into the signals since it is only a validation of the parameters of the instruments.

9.1.1 Satellite output power

As described in 7.1.1 the first step of this test bench calibration is to measure the maximum **output power** from the satellite that, in this case being represented by the TCR suitcase, it is the output power from it. To accomplish this step a power meter, the TCR suitcase, a channel cable and a power sensor are employed. The method practised to have the result is the one described in table 7.1. Therefore, the power sensor is connected with the output port of TCR suitcase and with the power meter by the means of the channel cable. As result of calibration the cable and the power sensor do not introduce any attenuation, so the measure reported in the underneath figure is the actual output power of the TCR suitcase:

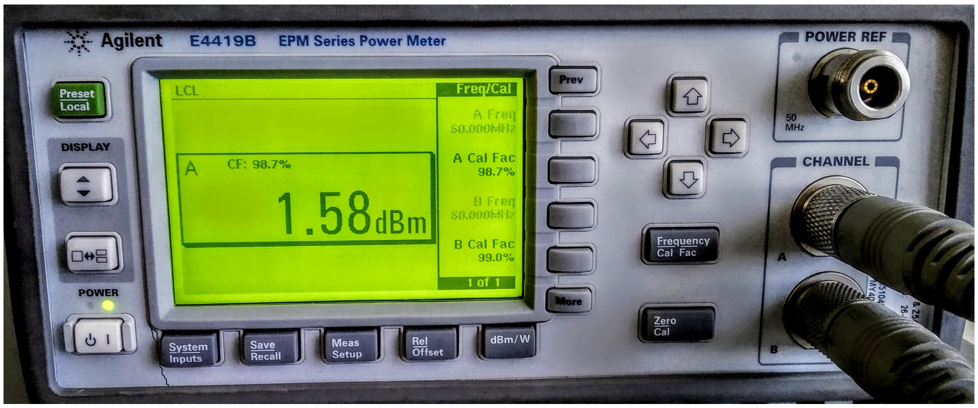

Figure 9.1: Output power of siganl from TCR suitcase from power meter interface

As can been seen, the measured power (P) is 1.58 dBm. Suddenly, using the reverse formula reported in table 7.1:

$$P_{tx} = P + S/C_{loss} + D/L_{path}$$

an estimation of the output power is done. Knowing that the TCR suitcase introduce a fixed attenuation of 35.82 dB (D/L_{path}), setting, using its remote HMI, the variable attenuation to 0, and being the cable attenuation equals to 0 dB (S/C_{loss}) for the reason above, it is possible to conclude that the TCR suitcase output power (P_{tx}) is 37.4082 dBm as written in the SGICD and that the maximum power at the output port (P_{out}) is the one show by the power meter 1.58 dBm, precisely equal to the nominal value declared in its data sheet, reported in chapter 7 and plentiful inside the expected tollerance of ±5%.

9.1.2 Satellite output frequency

This part of the test bench calibration refers to the **output frequency** of PM modulated signal sent by the TCR suitcase. To execute this measurement a spectrum analyzer is employed and it is repeated under several attenuation condition in order to verify the stability of the **central frequency** to its nominal value of 2253.50000 MHz. The central frequency is found out using a peak marker that is a marker able to find the maximum of the signal and therefore its central frequency. After all these measurements it has been observed that the central frequency (boxed in red) of the signal is practically aligned with the one reported in the SGICD. To confirm what mention before is reported in the figure below the output of the spectrum analyzer with the peak marker for an attenuation of 40 dB and as can been seen its basically lined with the requirements.

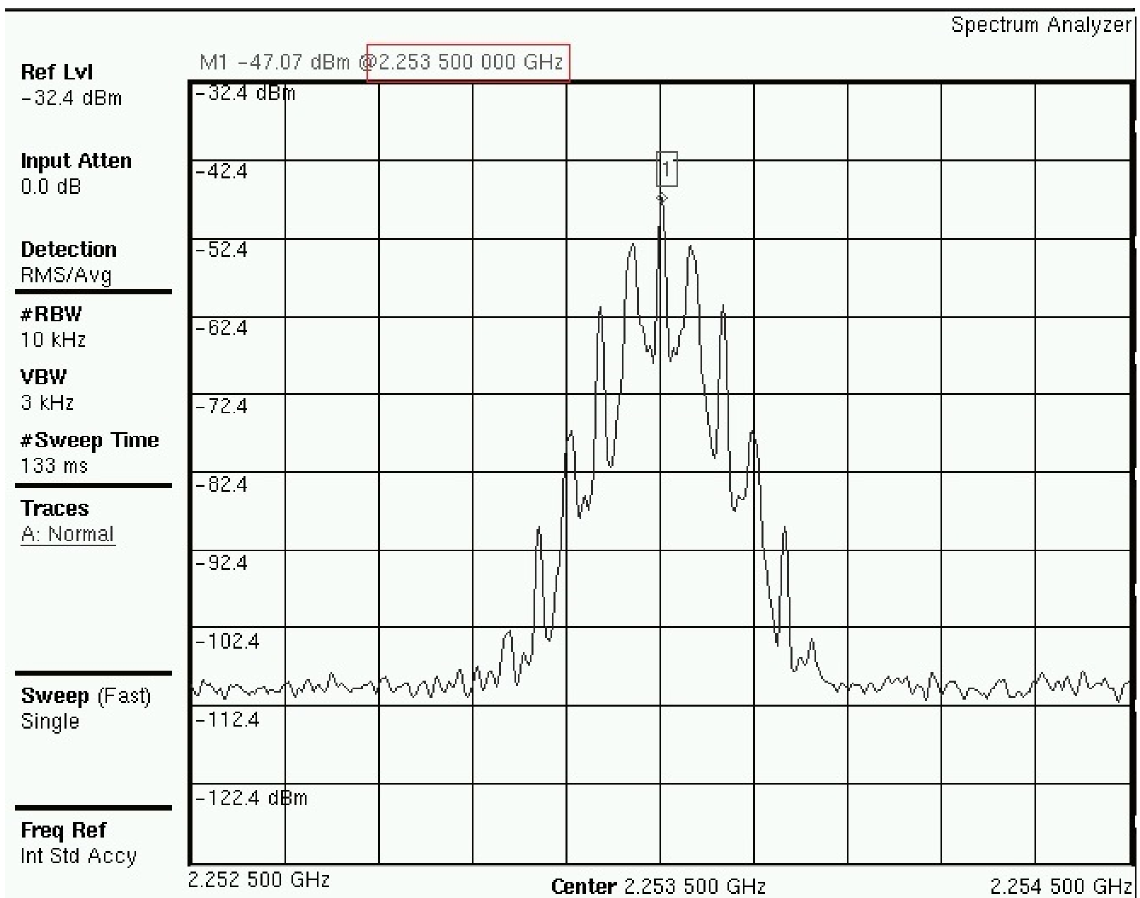

Figure 9.2: Central frequency of signal from TCR suitcase from spectrum analyzer interface

9.1.3 Satellite output signal analysis

Knowing the central frequency and the output power of the signal from the TCR suitcase, this section is instead dedicated to an analysis of the structure of the signal. First of all, the check is done on the modulation employed, according to the SGICD it should be a PM modulation with a **subcarrier** (fm) of 65.536 kHz this is confirmed by the output of the spectrum analyzer reported below that show the well know spectrum of PM modulation and a subcarrier of 65.534 kHz that can be considered correct even if not completely aligned with the requirements.

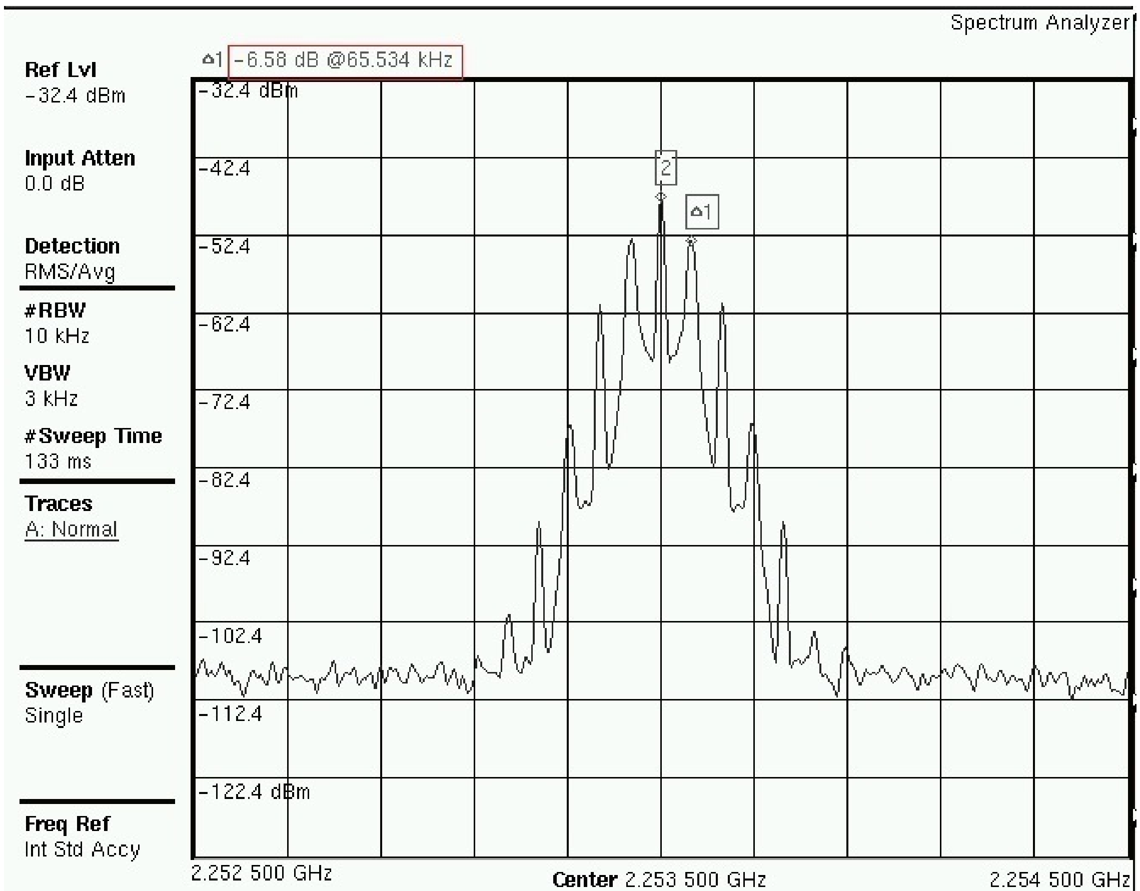

Figure 9.3: Subcarrier frequency of signal from TCR suitcase from spectrum analyzer interface

Moreover, from the image can be verified also another parameters, indeed knowing the difference in dB between the signal power at the central frequency and at subcarrier frequency, equals in this case to 6.58 dB, and using the Bessel function computed using the table, it is possible to retrieve the **modulation index**, that this time is equal almost to 1.1 rad. This value is also achievable using the definition of bandwith (B_w) expose in the chapter 8:

$$B_w = 2(\beta + 1) f_m$$

as matter of fact, measuring the bandwith of the signal that contains the 98% of the power using the spectrum analyzer as reported in figure:

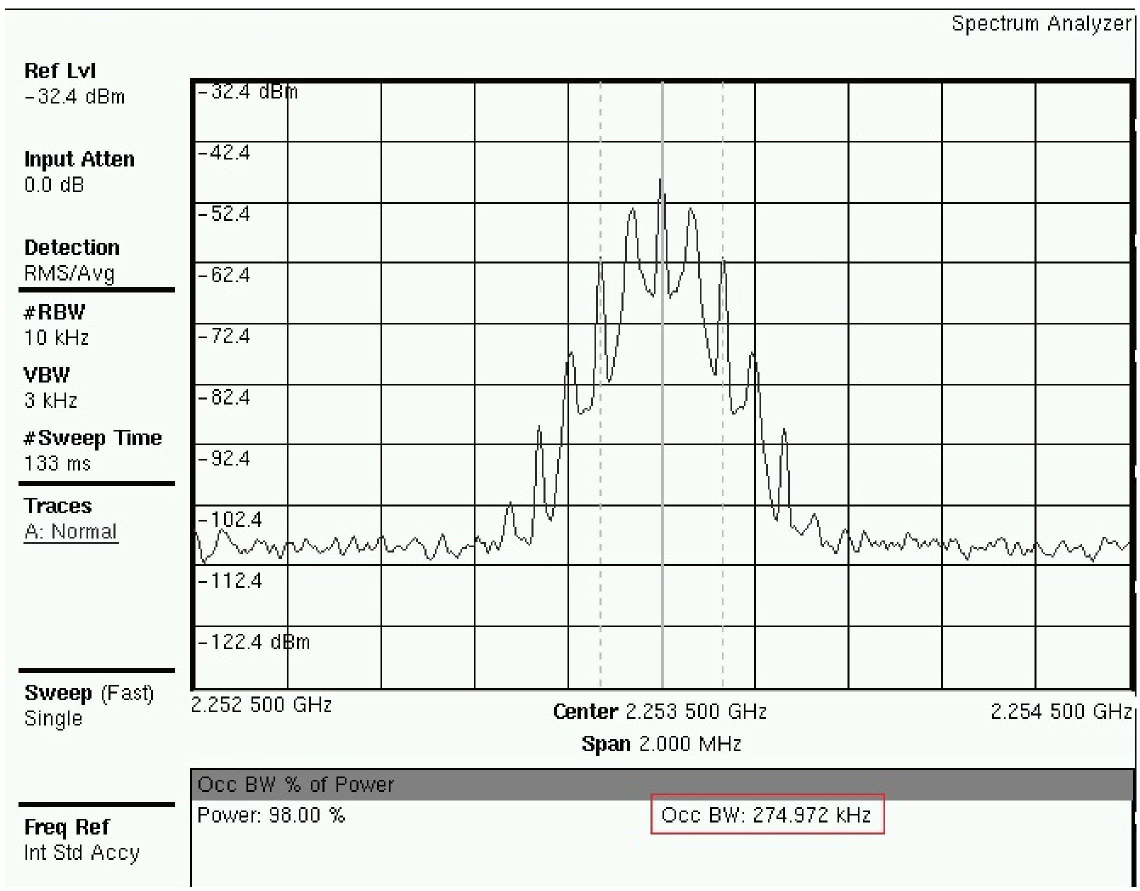

Figure 9.4: Bandwidth of signal from TCR suitcase from spectrum analyzer interface

it reaches a value of 274.972 kHz and then using the inverse formula of the previous one to get the modulation index (β):

$$\beta = \frac{B_w}{2 * fm} - 1$$

it is found a value (1.1005 rad) almost equals to the previous one. This value departs from the nominal one (1.15 rad) of about the 4% and therefore it is acceptable from the point of view of requirements that sanction a tolerance of ±6%.
Finally the last requirement of this test step is verified, always by using of spectrum analyzer that underlines in its interface reported in the underneath figure, how the **spurious emissions** present in the signal do not overcome the required value of -60 dBc.

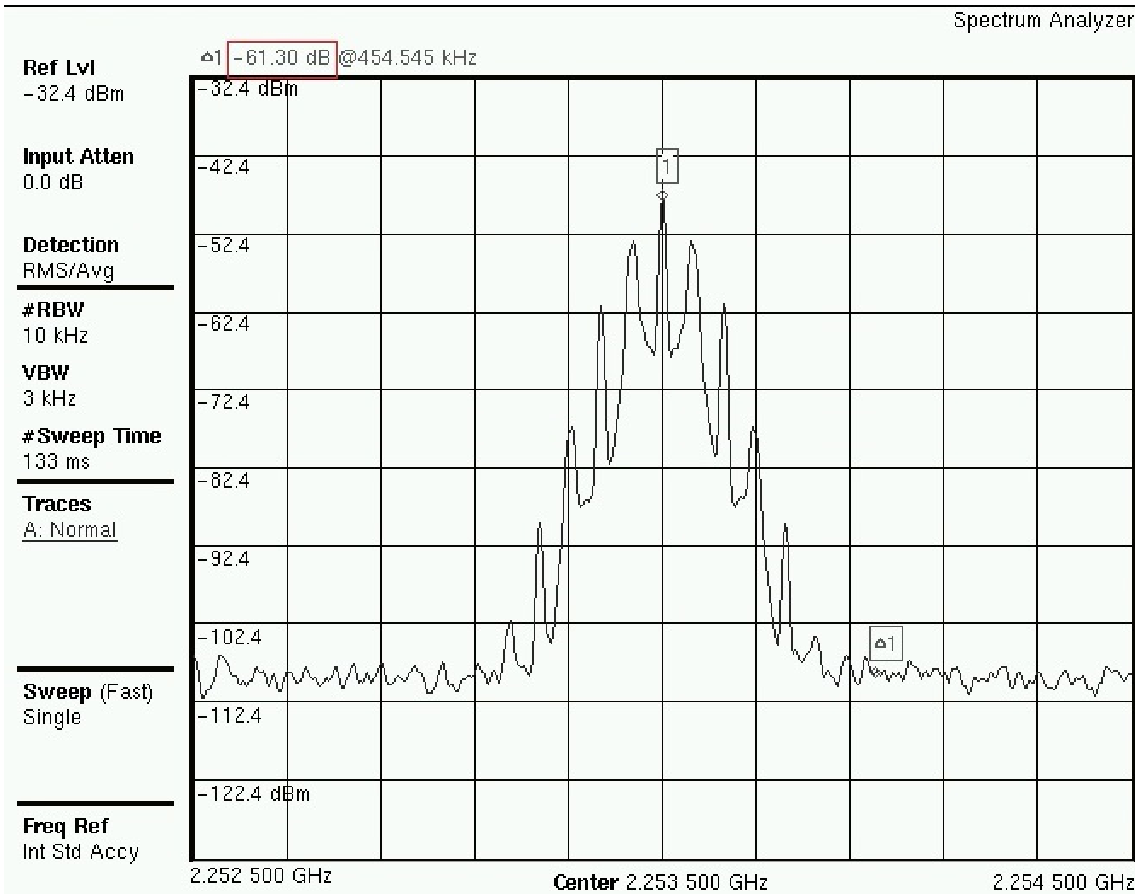

Figure 9.5: Spurious emissions of signal from TCR suitcase from spectrum analyzer interface

9.1.4 Ground reference station (GRS) output signal analysis

This last calibration sub-test is dedicated to the validation of the signal from the GRS to the satellite and of every expected result exposed in table 7.4. As described in paragraph 7.1.4 and for the reason exposed in it, only a modulated signal is employed for this test. The measurements are taken using a spectrum analyzer and a frequency counter, since this time the spectrum analyzer does not have enough resolution to see the accuracy requested by the requirement, linked to the GRS by the means of a RF cable. The only possible checks done on the un-modulated one is the verification that it is PM modulated with a **central frequency** of 2075.097900000 MHz and this requirement is valid for sure if also the modulated signal present a central frequency with the same value and a shape corresponding to a PM modulation, so only the test for the modulated signal verification are executed and reported below.

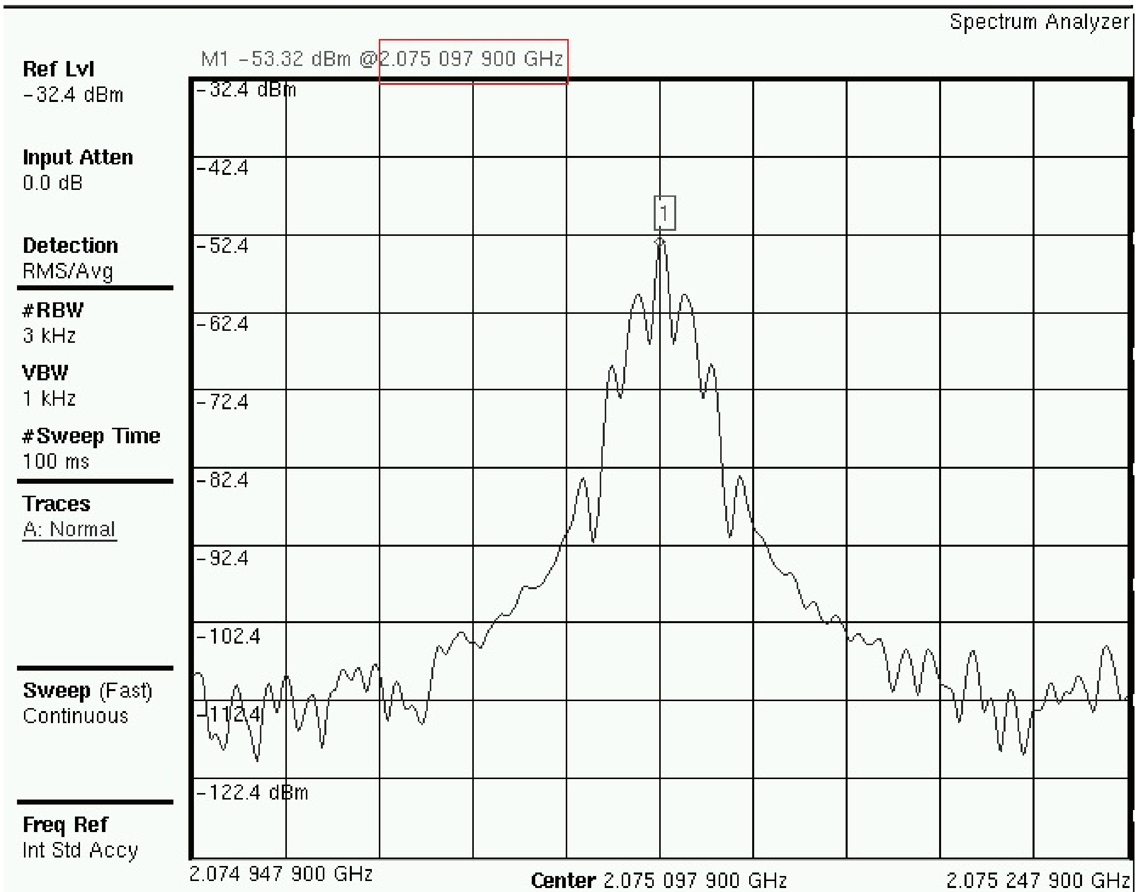

Figure 9.6: Central frequency of signal from GRS from spectrum analyzer interface

As figure shows spectrum has the classical shape of a PM modulation and the central frequency is practically aligned with the nominal value, confirmed also by the measures of the frequency meter that shows, for several attenuations, always a value of 2075.097900000 MHz that confirms how the requested accuracy is widely respected. The second check is indeed the validation of the **subcarrier** frequency (f_m) that it should be according to the SGICD equals to 8 kHz. Figure underneath reports its value, as done before also a first check on the modulation index is get from this image.

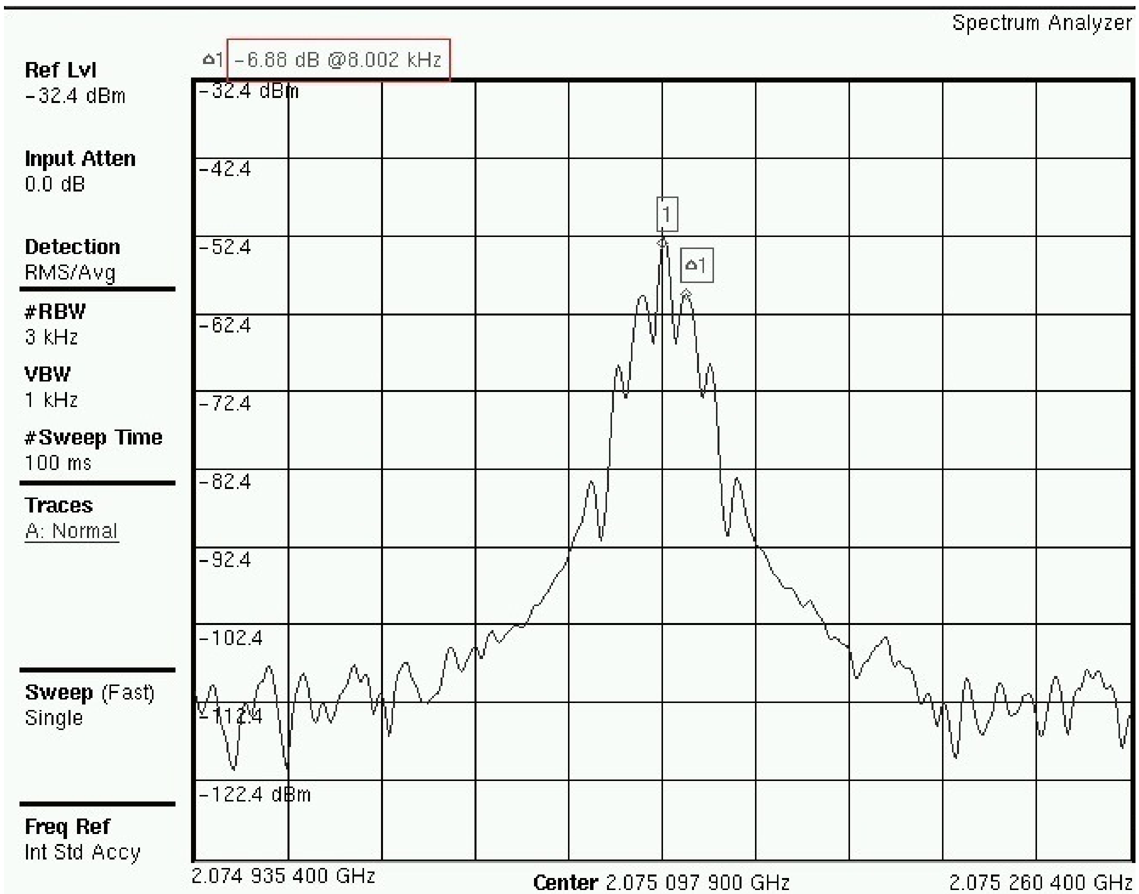

Figure 9.7: Subcarrier frequency of signal from GRS from spectrum analyzer interface

The graph underlines as the subcarrier frequency is equal to 8.002 kHz, this value even if is not exactly the nominal one is considered acceptable. Moreover it stressed with a red box the difference in dB between the peak and the first side-lobe showing a value of 6.88 dB, as before using the Bessel table a modulation index (β) of almost 1 rad is computed. Furthermore, the analysis of the bandwidth (B_w) that contains the 98% of the signal power, that as a value of 31.851 kHz pointed out in the next figure,

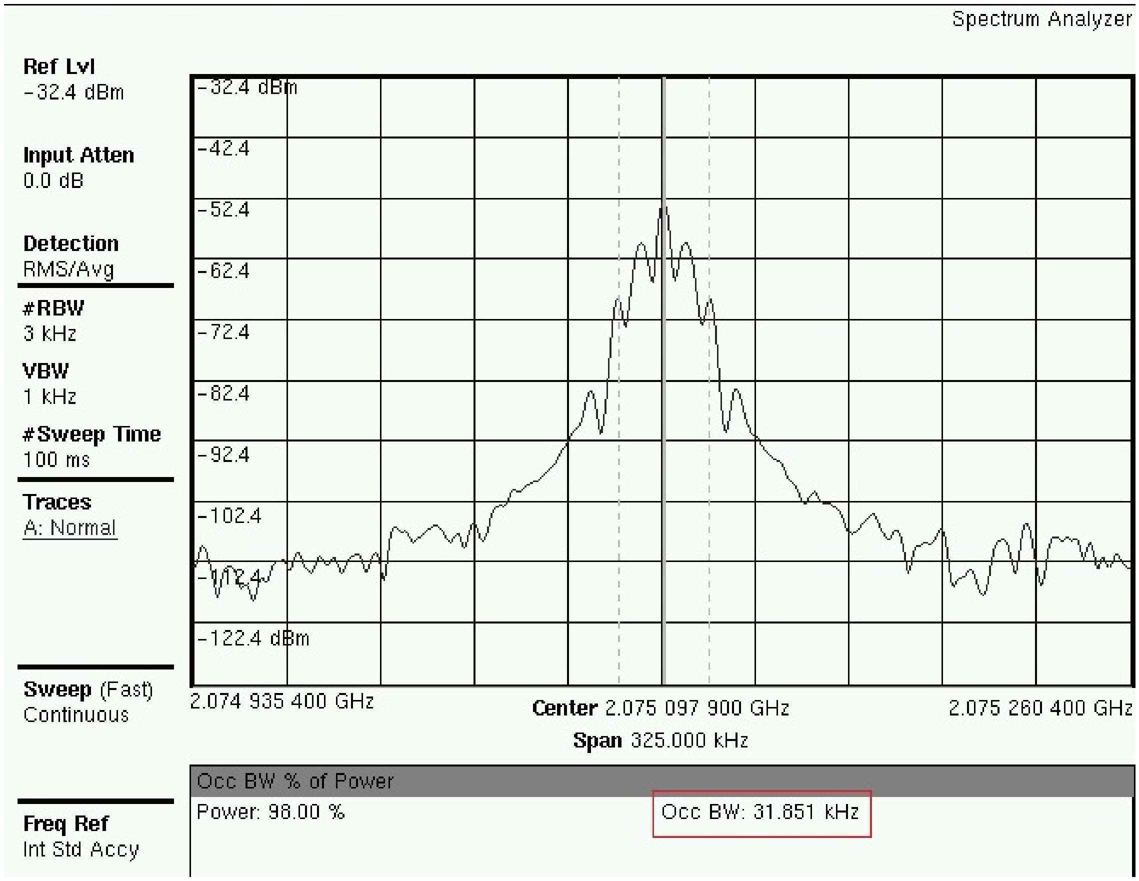

Figure 9.8: Bandwidth of signal from GRS from spectrum analyzer interface

executed using the same formula of the previous paragraph:

$$\beta = \frac{B_w}{2 * fm} - 1$$

leads to a value of β of 0.99 rad that is essentially the same obtained with the table. This value is admissible since it is not so far from the nominal value (1 rad) and it is widely inside the expected tolerance of $\pm 5\%$.
This last test states the end of the test bench configuration. It can be considered successfully completed and so the real test can start. Since the modulation index, the central frequency, the subcarrier and the power have already test in this sub-chapter they will not be re-tested in the continuation of this thesis.

9.2 S-Band downlink test block

This test block is the largest test block of the entire RFCT, it is divided in 6 sub-blocks executed using a spectrum analyzer and the control and management interface of the BBU inside the GRS and the one of the TCR suitcase.
Concerning the downlink spectra analyzed in this section to find the thresholds, it is possible to visualized them at IF frequency (70 MHz) since the GRS allows to retrieve them at the end of the down-conversion procedures. This is not possible for the uplink spectra since the TCR suitcase does not implement this possibility. Moreover, thanks to the fact that it is feasible retrieve the information bits the BER and the FER can be estimated, which is not possible for the messages destined to the TCR suitcase. Obviously, the following tests are executed introducing noise inside the signals since they are a validation of the correctness of a real communication between satellite and ground segment. Signals are obtained setting the S-Band transponder, through its monitoring and control interface, to transmit telemetry messages as the ones describe in chapter 3. This configuration will be maintained for all the tests in which the sending of telemetry messages is involved and it is shown in the underneath figure, that underlines also as the worst case is taken into account since both ranging and telecommand channels are active during the telemetry transmission and the coherent mode is not considered. Thresholds computation and comments are done considering only one polarization since both of the them experience the same attenuation and pattern and therefore they have the same performances. For this reason one of the two receivers is not considered and its attenuation is put to maximum value.

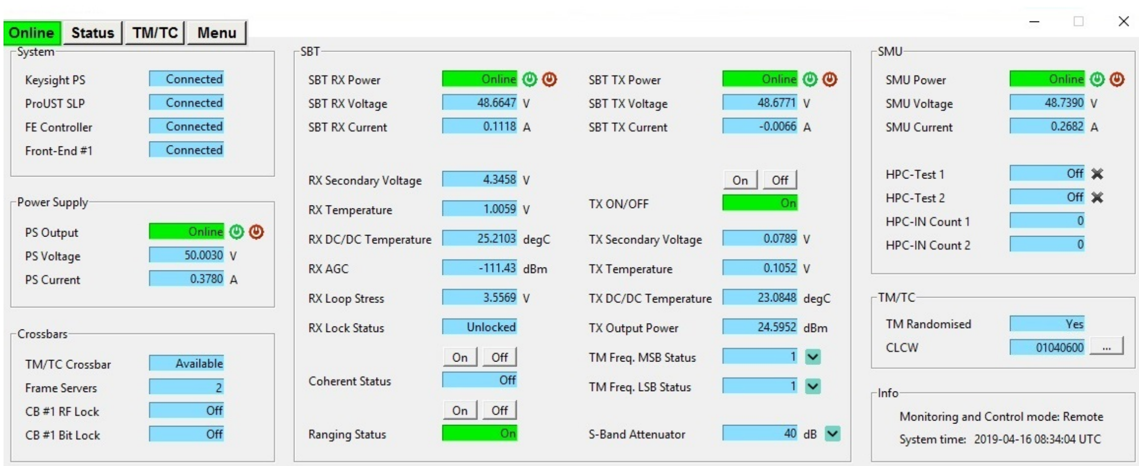

Figure 9.9: TCR suitcase configuration and parameters

9.2.1 Telemetry receiver threshold

To obtain the **Telemetry receiver threshold** the test bench and the method describe in 7.2.1 are employed. This method is based on reducing the $\frac{C}{N0}$ acting on C with a programmable attenuator until the receiver and the transmitter are un-locked. At receiver side, since this threshold is refereed only to the carrier reception, it is monitored the lock/un-lock status of the PLL receiver through the BBU monitoring and control interface and it is checking the spectrum shown by the spectrum analyzer. Obviously, since this time the spectrum is acquire after the down-conversion it is monitoring at IF frequency. The thresholds, not only this one but all those considered in this thesis, are computed as the ratio, difference in dB, between the peak signal level show from the spectrum analyzer and the noise level injected by the noise generator (-118 dB/Hz downlink case).
To be precise the peak value of signal can be acquired or from the spectrum analyzer or from the `IF level` field of the monitoring and control interface of the BBU. These two values are not the same, even if they are not so different, and to compute all the thresholds considered in this work one of the two must be chosen. The choice fall, when it is possible, on the one displays by the spectrum analyzer because it is an instrument built to measure power with very high precision and so it for sure shows the most accurate value.
At the beging of the test the PLL of the receiver inside the BBU is locked (highlighted in green) with the received signal and the spectrum analyzer displays the maximum peak of the signal as shown from figures below:

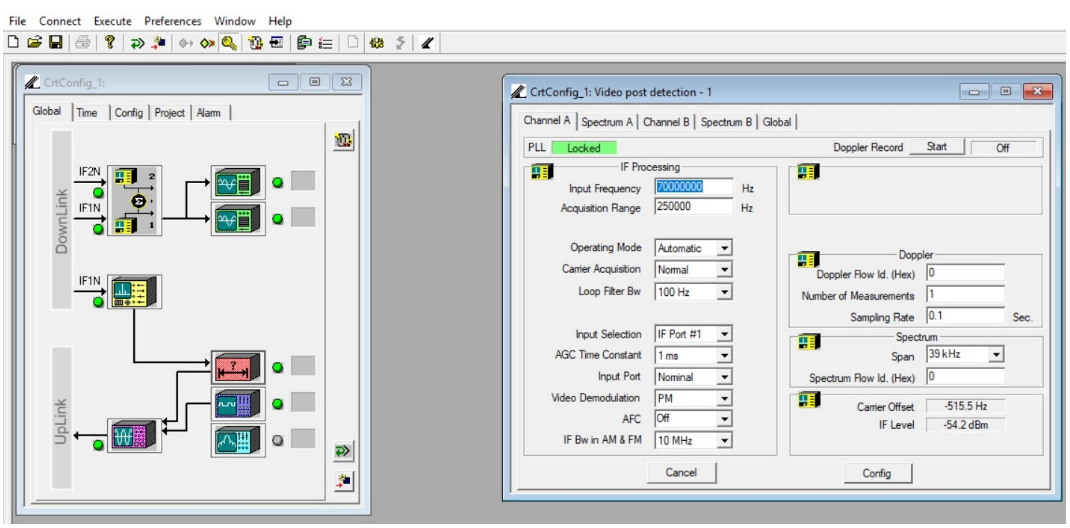

Figure 9.10: BBU PLL receiver locked

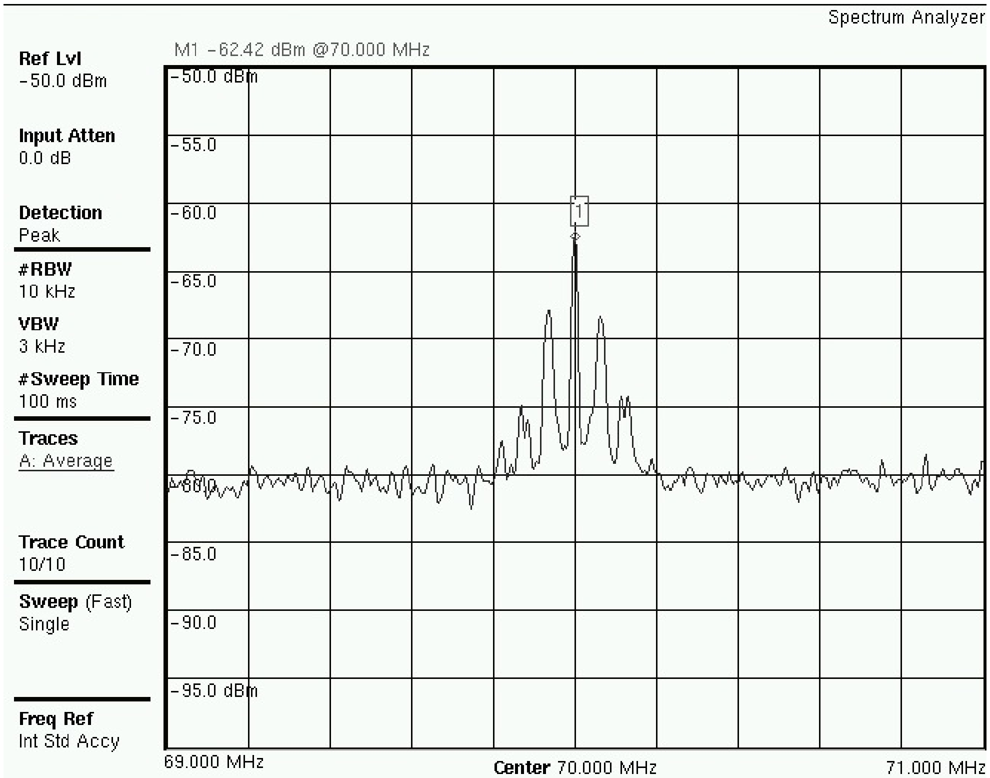

Figure 9.11: Spectrum analyzer interface at the begin of 9.2.1 test

Moreover, figure 9.10 underlines the configuration of the BBU arranged as specified in the SGICD for what concern the GRS input frequency and the bandwidth used by the PLL. Figure 9.11 instead shows the spectrum at the receiver side and stress very well the fact that the ranging channel is active since two more peaks (RNG tones) outside the main lobe of the spectrum of the PM telemetry signal are present, these tones are centered at a frequency of $\pm$ 114.681 kHz with respect to the main frequency and they will be better visualized, changing the span of the spectrum analyzer, and inspected later in this thesis when ranging signal and ranging thresholds will be considered.
At the end of the test conversely the BBU monitoring and control interface shows that the PLL is unlocked (highlighted in red) and this is confirmed by the spectrum analyzer that underlines in accurate way the fact that the level of signal is practically the same of noise and so is no more possible to retrieve its peak:

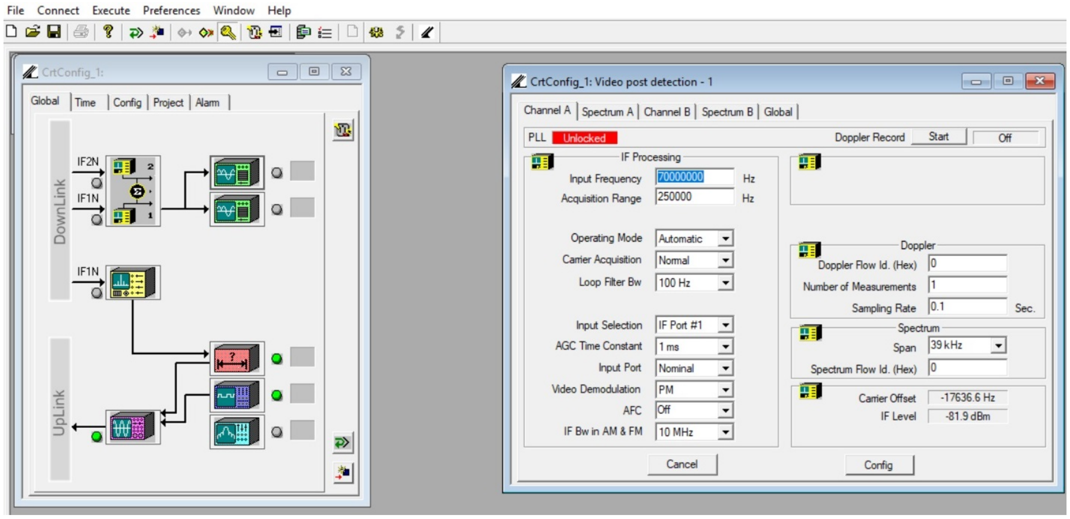

Figure 9.12: BBU PLL receiver un-locked

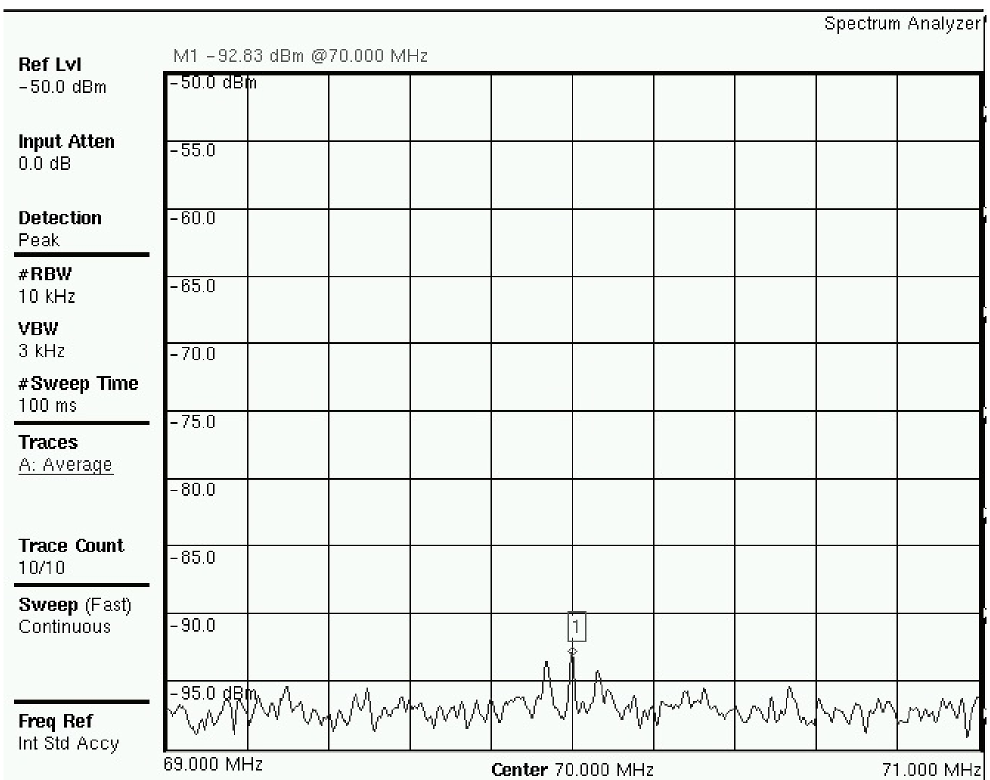

Figure 9.13: Spectrum analyzer interface at the end of 9.2.1 test

The several attempts and computations done in order to obtain the threshold are tabulated below only for the main frequency of 2253.5 MHz since the results acquired for the back-up frequency are practically the same.

Spectrum analyzer reading [dB] (C)	Attenuation [dB]	Noise Level [dB/Hz] ($N0$)	$C/N0$ at input of the receiver [dB/Hz] ($C/N0\|_{dB/Hz} = C\|_{dB} - N0\|_{dB/Hz}$)	PLL status
-62.2	0	-118	55.8	LOCK
-72.1	10	-118	45.9	LOCK
-79.3	20	-118	38.7	LOCK
-85.3	25	-118	32.7	LOCK
-89.9	30	-118	28.1	LOCK
-90.7	31	-118	27.3	LOCK
-91.8	32	-118	26.2	LOCK
-92.8	33	-118	25.2	UN-LOCK

Table 9.1: Attempted Telemetry receiver threshold measurements

The found threshold is **26.2 dB/Hz**, it is a value far below from the one expected by the link budget (41.19 dB/Hz). Therefore, it is an acceptable value and underlines as the receiver has a very good sensibility, indeed even if in the link budget analysis is considered the worst case scenario in which the receiver can work for this mission it has demonstrated that it is able to manage also more critical cases.

9.2.2 Telemetry frame lock threshold

Telemetry frame lock threshold is different from the previous one since now also the data reception is taken into account thus this time the correct demodulation and decoding of data are monitoring too always using the monitoring and control interface of the BBU at the receiver side. Inasmuch, from the point of view of the spectrum, it is the same signal of the previous test case, since the TCR suitcase does not allow to transmitt clean carrier, it is not report with images. Moreover, the expected threshold at time is higher with respect to the previous one because to retrieve data and not only the carrier is necessary a higher $\frac{C}{N0}$. The test bench and the method to find this threshold are described in table 7.6, the requirements present in this table are considered satisfied if the BBU monitoring and control interface does not show errors during the demodulation/decoding of the signal. The two following images display the BBU's data receiver at the beginning and at the end of the test.

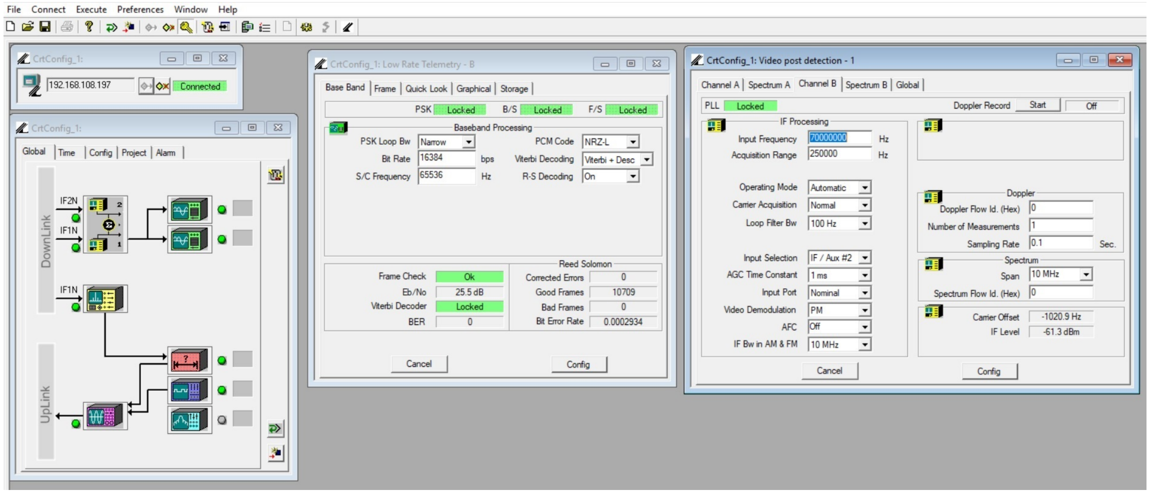

Figure 9.14: BBU frame receiver locked

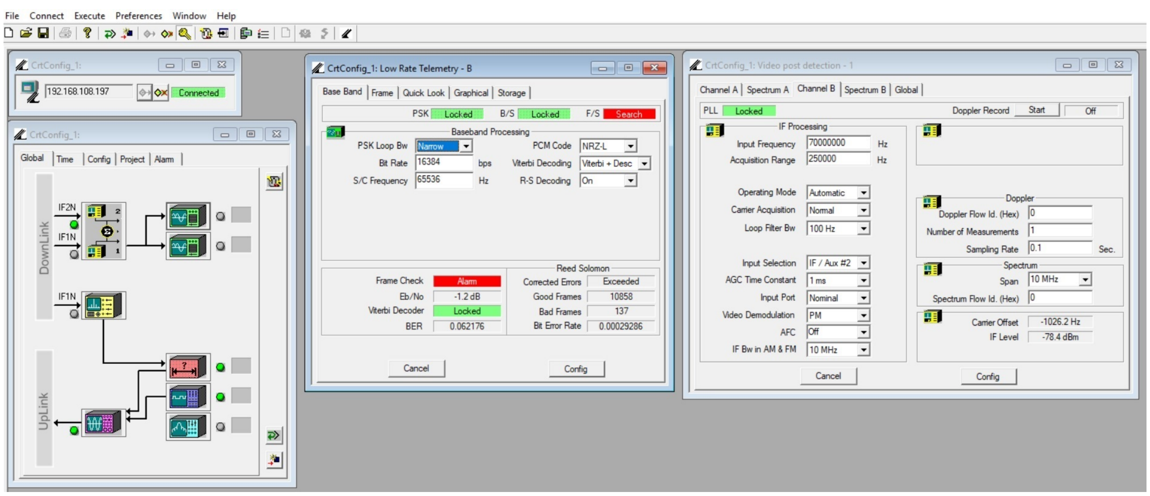

Figure 9.15: BBU frame receiver un-locked

As it is possible to see at the starting point of the test all the parameters are set as disposed by requirements and the receiver is able to get all the data in correct way while at the closing point, when the threshold is reached, it is no more able to decode the several coding techniques (Reed-Solomon, Convolutional and Scrambling) apply on data, to demodulate (PCM[NRZ-L]/BPSK/PM) them and to maintain the synchronism ensured retrieving the ASM sync word and so it is no longer able to correctly recover data. This fact is underlines by the `Bad frame` counter that is incremented any time a not usable frame from the point of view of the ground segment is found. Below, as before, are reported the several attempts and computations executed to find the threshold, also this time only the results obtained for the main frequency are reported since the other ones are basically the same.

Spectrum analyzer reading [dB] (C)	Attenuation [dB]	Noise Level [dB/Hz] ($N0$)	$C/N0$ at input of the receiver [dB/Hz] ($C/N0\|_{dB/Hz} = C\|_{dB} - N0\|_{dB/Hz}$)	Receiver status
-62.2	0	-118	55.8	LOCK
-66.2	5	-118	51.8	LOCK
-72.2	10	-118	45.9	LOCK
-75.4	15	-118	42.6	LOCK
-76.3	16	-118	41.4	LOCK
-77.5	17	-118	40.5	LOCK
-78.6	18	-118	39.4	**UN-LOCK**

Table 9.2: Attempted Telemetry frame lock threshold measurements

The measured threshold of **40.5 dB/Hz** is under the one computed by the link budget (46.55 dB/Hz) thus it is acceptable and furthermore confirm the goodness of the receiver. Moreover, as expected, it is higher with respect to the telemetry receiver threshold as confirmed by figure 9.15 that emphasizes how reached the Telemetry frame lock threshold the frame reception is lost but the carrier and the PLL are still locked.

9.2.3 Coupling of ground station telemetry with TC uplink

This test block does not involved the computation of a threshold but it is used to validate the fact that the NOC ad more in general the entire ground segment is able to appreciate the antenna and so the linked polarization that is in visibility from the satellite. This is very important to maintain the same polarization of the uplink and downlink, to ensure the correct reception of the telecommand, in particular during phase in which satellite experiences rotation and so the polarization in visibility change in quite rapid way. To obtain this verification the method and the attenuation profiles discussed in 7.2.3 are loaded in the programmable attenuators in order to have progressively an antenna no attenuated (in visibility) and the other one completely attenuated (not in visibility). This time, the spectra of the two transmissions are monitoring using the monitoring and control interface of the BBU and should be possible to see the spectrum changes as the attenuation varies. The two attenuation profiles has been obtained simply loading a .txt file where there are reported the several values of attenuation during time in the programmable attenuators, which software reading this file is able to build the profiles. The time duration of the attenuation profiles is set to 15 minutes for the reason exposed in 7.2.3. Also this test case is performed considering the worst case scenario and therefore the ranging and telecommand channel active. Figures below shows the spectra of the signals and the corresponding attenuation by the means of the monitoring and control interface of the BBU and of the programmable attenuators at the beginning of the test.

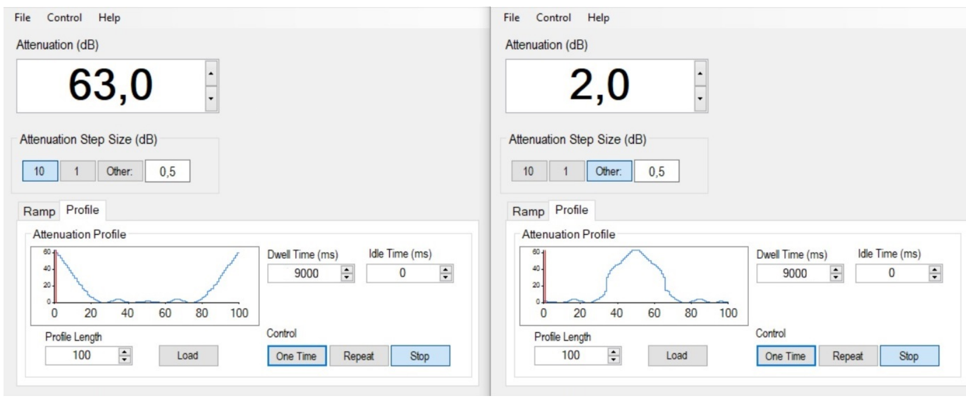

Figure 9.16: Attenuation profiles at the beginning of 9.2.3 test

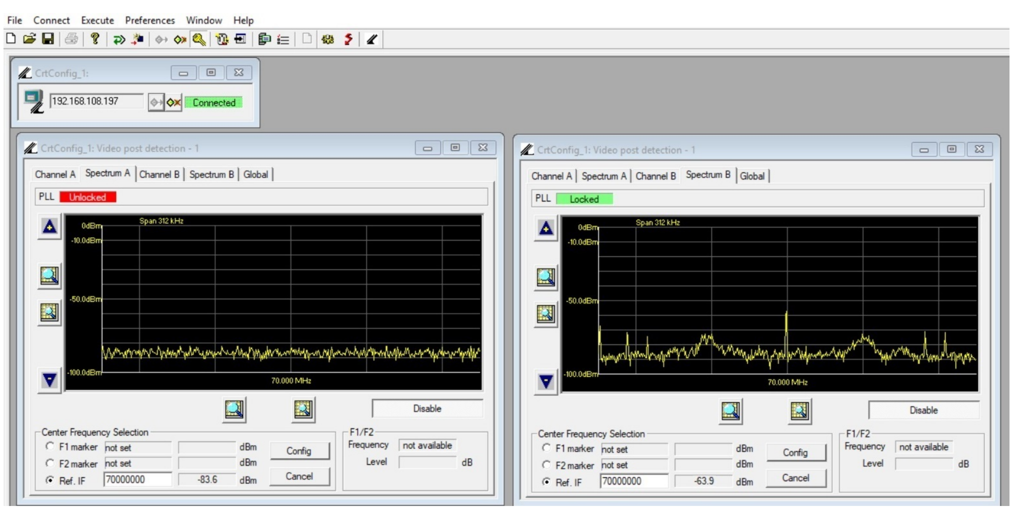

Figure 9.17: Spectra at the beginning of 9.2.3 test

As can be seen, at the test starting point one polarization is completely attenuated and so the spectrum is not visible since its power is at noise level while the other one it is not attenuated and so its spectrum is shown by the monitoring and control interface of the BBU. It is worth notice that even if one of the two polarizations is not get and the receiver PLL is un-locked both the two frame receivers are able to obtain data without any lost frame. This is possible since the two frame receiver and the two PLL work in `combining` mode and so when one PLL is un-locked its frame receiver automatically switch to the other one without data lost. This thing is verified by the image report below that show as even if one PLL is un-locked the two frame receivers are perfectly locked and there are not bad frames.

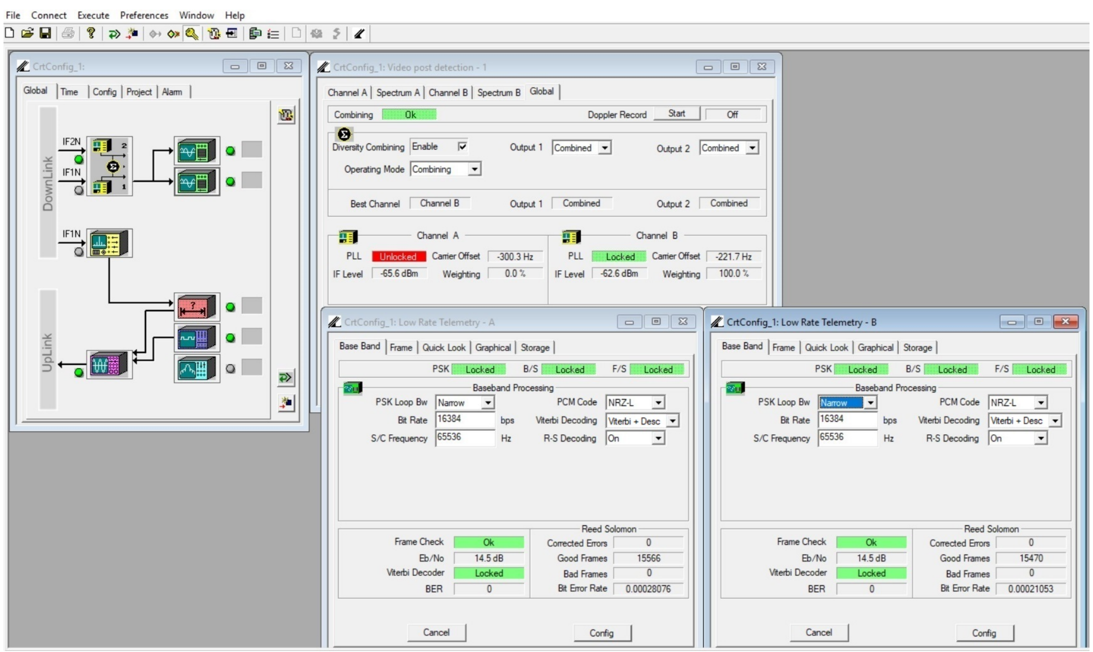

Figure 9.18: Frame receivers with one PLL un-locked

Continuing monitoring the received polarization, it is reached a point in which the attenuations are such that both of the two polarizations are in visibility thus both the spectra are visible and both the PLL are locked. This point is displayed in figures underneath.

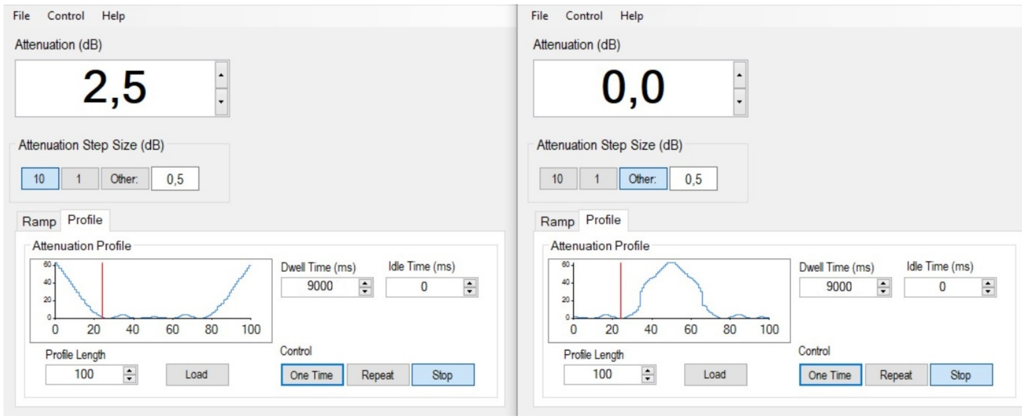

Figure 9.19: Attenuation profiles with both polarization in visibility

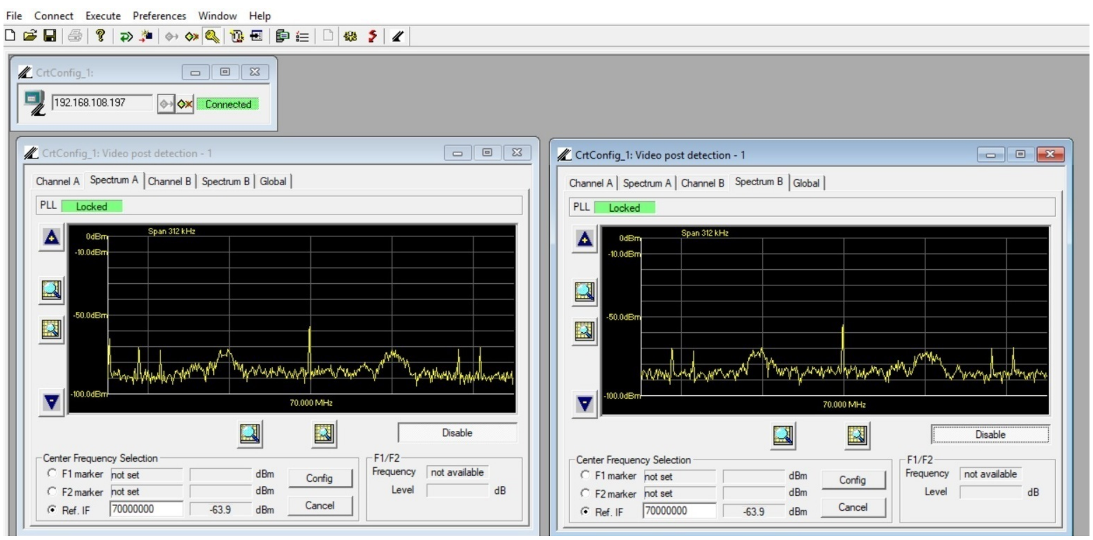

Figure 9.20: Spectra whit both polarization in visibility

Then, it is achieved the period in which the polarization observable at the starting point is no more evident but the other one begins to be appreciable. This period corresponds to almost the middle point of the attenuation profiles and it is remarked in the next figures.

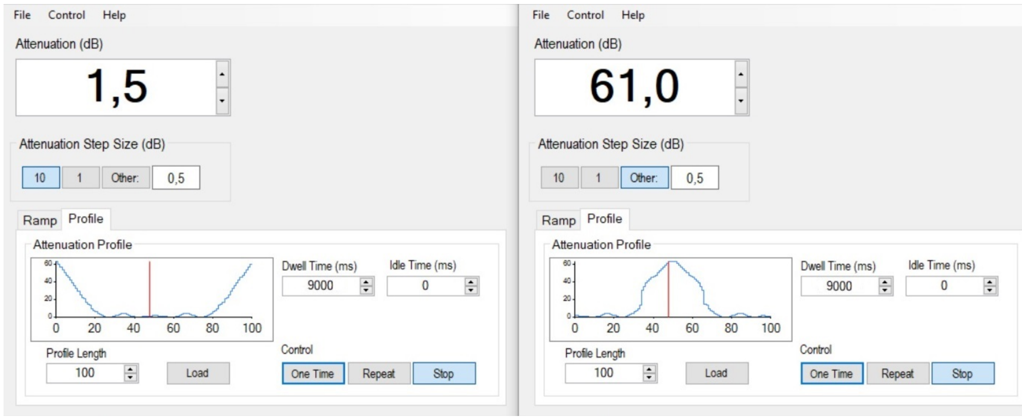

Figure 9.21: Attenuation profiles at the middle 9.2.3 test

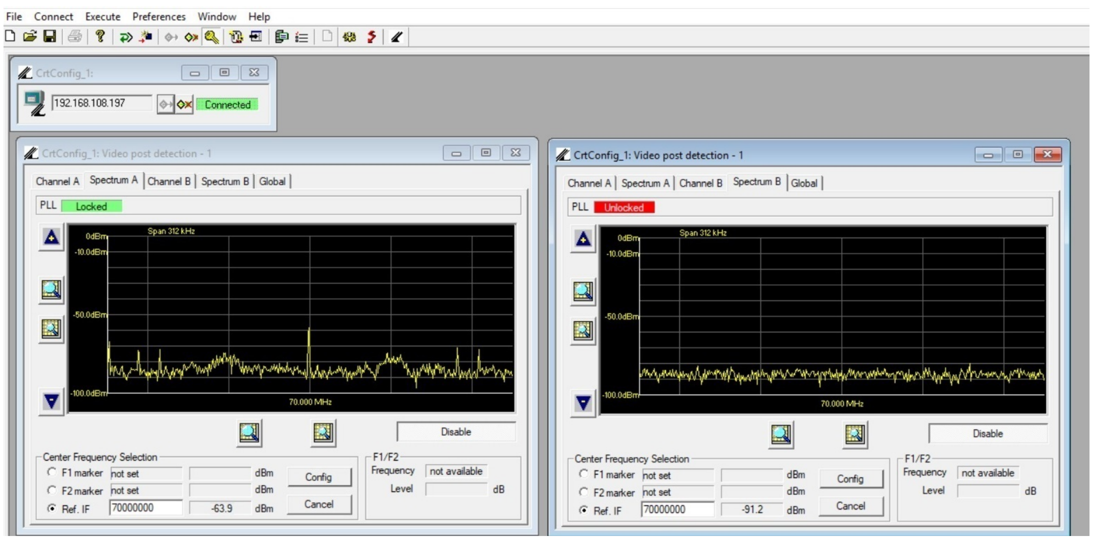

Figure 9.22: Spectra at the middle of 9.2.3 test

Finally, the end point of the test is reached and the spectra obtained in this case are equal to those at the beginning and therefore they are not reported. The test can be considered successfully passed since it has been possible to spot all the polarization changes at the receiver side and so the uplink polarization can be easily adapted and because setting the `combining` mode no frame loss occurs even if only one polarization is in visibility.

9.2.4 Dynamic downlink doppler simulation

This forth test case instead is dedicated to the simulation of the doppler experiences by a signal during an orbital passage in the worst case scenario represented by the perigee where the satellite reachs its higher speed. Ensure a good reception of the data under this condition is fundamental during the LEOP in which any data should not be lost. The doppler signal is injected in the reception chain using a mixer and the phase shifter and it is generated by a signal generator piloted by the two profiles show in sub-chapter 7.2.4. These two profiles have been obtained starting from a two .txt files computed as exposed in sub-chapter 7.2.4.1 and using MATLAB® code in **Appendix B** that simulates the signal frequency variation due to doppler with respect to the central frequency for a test duration of 12 min.
During the test are monitored the PLL lock status and the frame reception in order to validate the capability of the receiver to retrieve data in a correct way also in this critical scenario.
The receiver inside the BBU at the beginning of the test case has the following configuration:

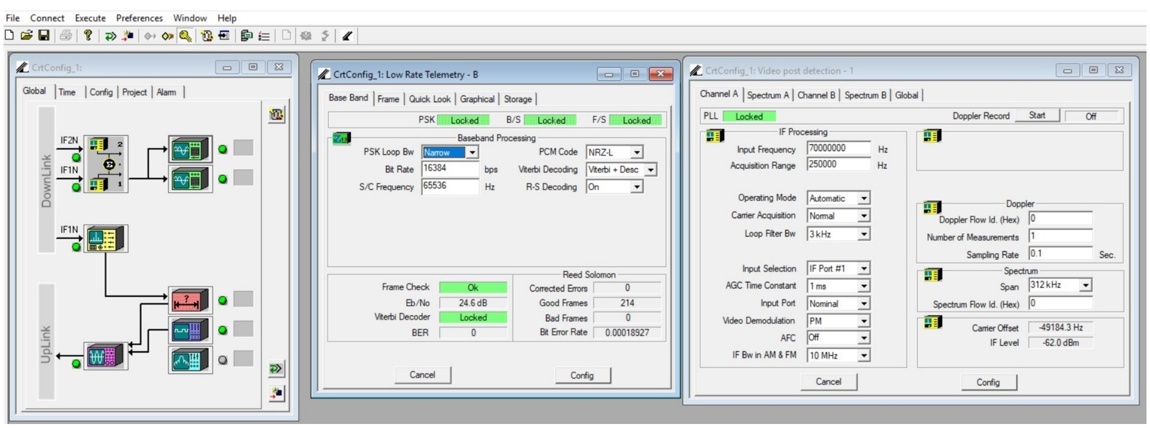

Figure 9.23: BBU receiver at 9.2.4 test starting point

After several minutes when the radiation component of the satellite's speed reachs its maximum the PLL un-locks and the `Bad frame` counter starts to notify losses as the figure below shows:

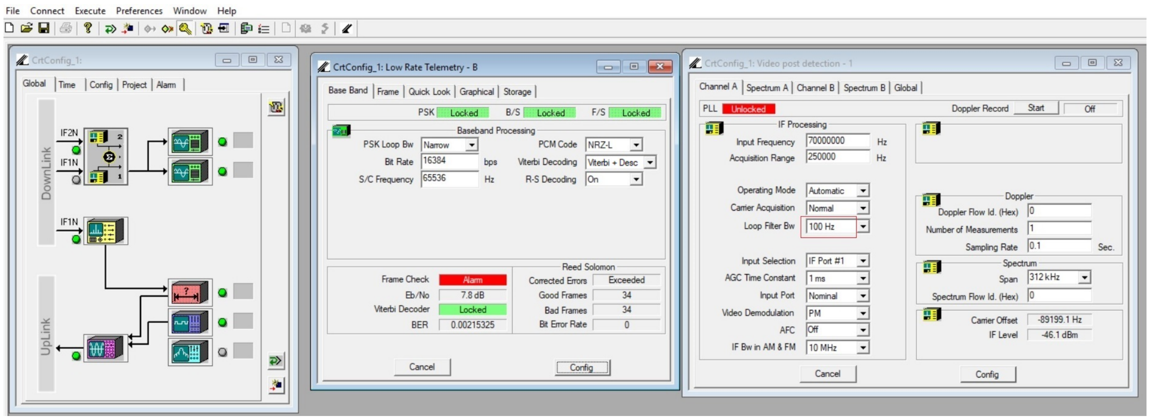

Figure 9.24: BBU receiver with PLL bandwith of 100 Hz and maximum doppler

This happens because the PLL is not "faster" enough to cope the phase variation of the signal due to doppler. Therefore to try to solve this problem the PLL bandwidth is increase first until the last but one permitted value of 1 kHz but also this value is not sufficient and finally to the maximum allowed value of **3 kHz** and with this quantity the PLL and the frame receiver remain locked for the entire test duration and thus the data are correctly recovered.

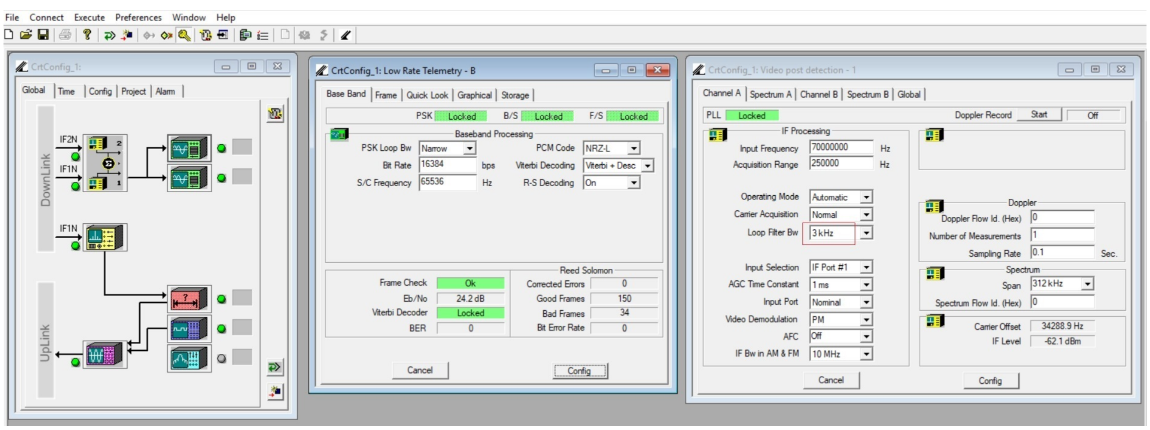

Figure 9.25: BBU receiver re-locking with PLL bandwith of 3 kHz

This result is fundamental since makes know that to retrieve data during a LEOP perigee the receiver PLL bandwith must be set to 3 kHz.
However, there is a trade-off between the "reactivity" of the PLL and the presence of noise and jitter in the receiver signal, indeed higher the bandwidth, higher the

reactivity but higher also the noise and jitter, lower the bandwidth, lower the reactivity but lower noise and jitter, therefore is advisable use smaller bandwidths during normal conditions of use.
In the case under analysis the reason why it is possible to tolerate more noise is due to the fact that, being the satellite during the LEOP perigee closer with respect to its final orbit, the $\frac{C}{N0}$ is elevated and compensates the presence of distrurbs.

9.2.5 Telemetry message BER estimation

The aim of this test, as expose in 7.2.5, is to estimate the **BER** at receiver side in order to understand as coding techniques and different $\frac{C}{N0}$ influence this parameter. The method used to execute this computation is the one exposed in the above mentioned sub-chapter and the software employed is reported in **Appendix C**.
For the execution of this test is employed the BBU and the receiver chain but not the TCR suitcase for the reason expose in 7.2.5. Moreover two files are taken into account to reach the scope of this section:

- **Input file** built with a software provided by the BBU producer able to assemble a file that contains a stream of several telemetry frames as the ones described in chapter 3 or simply several frames without any coding technique. Loading this file in the BBU and using its `replay` mode, this stream of frames modulated and coded according to the SGICD specification is sent from the BBU transmitter trough the receiver chain that simulates the space channel to the BBU receiver;

- **Output file** is computed by the BBU receiver starting from the corrupted by the simulated space channel stream of frames contained in the input file applying on it the several decoding and error correction techniques described in the SGICD and commented in chapter 3.

Input file must be composed by a conspicuous number of frames in order to obtain a reliable BER measurement. For the analyzed case, in which only a qualitative estimation of the BER is executed, the file is made-up by 303 frames to avoid computational cost and time issues.
BER obviously is computed comparing the input and the output files as describe in 7.2.5. Before the starting of the real BER computation the software in **Appendix C** used for this scope also check if the two files contains the same number of bits and if some header/postamble introduced by the BBU are present on them.
So to obtain the BER the following procedure is carried out during the test: first of all, the output file retrieved by the BBU and the input file are read by the software,

then the space and new line character present on them are removed to avoid error due to misalignment, next the above mentioned checks are executed and when they are positive the binary conversion can be place. At this point the two files contains only binary symbols and the bit-to-bit comparison can be done to compute the number of different bits. Finally, the BER is computed as the ratio between the number of different bits and the whole number of bits.
This procedure has been executed for 3 particular cases discriminated by the received $\frac{C}{N0}$, changed with the use of the programmable attenuators and verified using the monitoring and control interface of the BBU, in order to see how this parameter influences the correct data reception.
These 3 particular cases are the following:

- **Under threshold case** where it is taken a value of $\frac{C}{N0}$ equals to 39.5 dB/Hz that is under the one computed in section 9.2.2 that represents the real Telemetry frame lock threshold;
- **Threshold case** in which is considered the $\frac{C}{N0}$ computed in 9.2.2 with a value of 40.5 dB/Hz;
- **Nominal case** that stands for the case where no attenuations except those of the space channel are introduce in the signal level. The $\frac{C}{N0}$ is equal to 61.4 dB/Hz.

Firstly, the procedure is executed for the input file containing the telemetry frames without any coding technique starting from the lower $\frac{C}{N0}$ represented by the under threshold case. In this case the BER computation is not possible since the output file has a size smaller with respect to the input one because several frames are discarded by the receiver that having a not enough high $\frac{C}{N0}$ sometimes lost his lock capability. Then the $\frac{C}{N0}$ is improved until the threshold case is reached. This time no frames are lost and therefore a BER computation is possible, obtaining a result of $0.96 * 10^{-2}$. However since the frames are only 303 for time and computational issues this result should be not completely true. Increasing further the $\frac{C}{N0}$ the nominal case is reached and a BER equals to 0 for the considered 303 frames is estimated, also this result is not completely reliable however have 0 wrong bits over 278736 simulated can be considered a good result that confirms as using a higher signal level ensures better performances.
Secondly, the test is repeated using the input file containing the telemetry frames with the several above mentioned coding and randomization techniques. With this

file no wrong bit are found for the last 2 cases while the lost of some frames does not permit the computation of BER in the under threshold scenario. These frames are lost because the Reed-Solomon receiver detecting frames with a number of errors higher than its error correction capability ($T = 16$), due to the bad synchronism of the GRS receiver (this behaviour will be better clarify in the next sub-chapter), discarding them.
A BER equals to 0, considering the 303 frames, can be explain in 3 ways:

1. $\frac{C}{N0}$ is enough high to have no errors as happens in the nominal case of the previous test;
2. coding techniques are able to detect and correct all the errors;
3. coding receiver never experiences the so called "undetected error".

[8] "Undetected error" indicates the possibility that a codeword contains a number of errors greater than the error correction capability (T) of the code however it is closer with other codewords inside the distance of T symbols. So the receiver is fooled and it does not detected error and cosiders the codeword correctly recovered. This possibility is particularly rare and takes a probability equals to $\frac{1}{T!}$, where

$$T = \frac{n - k}{2}$$

is the error correction capability of the code, n is the whole number of bits in a codeword and k is the number of information bits inside a codeword.
In our cases this probability reach a value of $4.77 * 10^{-14}$ considering only the Reed-Solomon code and an even lower one considering also the convolutional encoding. Therefore, to appreciate this phenomena and so a BER different from zero should be transmitted a huge number of frames that goes behind the computational cost, the time and the scope of this test that simply wants to demonstrate that:

- reducing the $\frac{C}{N0}$ the BER increases since for the receiver is harder to retrieve data in correct way when the noise power begins to be compatible with signal level;

- the presence of coding and scrambling techniques, as describe in 3.1.2.4, relieves this problem ensuring a lower value of BER and better performances.

Therefore even if only 303 frames are considered and operating with a $\frac{C}{N0}$ big enough to avoid the receiver un-locking these outcomes can be considered acceptable since they are complied with the theoretical expected results exposed in 7.2.5.

9.2.6 Telemetry message FER estimation

Joint with the previous one there is this last S-Band downlink sub-test that has the aim to estimate the telemetry message **FER**, the method to retrieve this parameter is exposed in 7.2.6 and the expected results are a value of FER compatible with the one requested by the customer in SGICD and a behaviour agrees with theory.
First of all, the FER estimation is done for a value of $\frac{C}{N0}$ of 39.51 dB/Hz that is under the receiver lock threshold therefore the 100 wrong frames are reached in a quite small time and the computed FER value is 0.1. This so high value is due, as said before, to the fact that the receiver is under threshold and the signal level is almost at the same magnitude of noise then even if several coding techniques able to correct errors are employed the wrong bits, due to bad receiver synchronism, exceeded their error correction capability and several frames result corrupted and marked by the receiver as `Bad frame`.
Second, a value of $\frac{C}{N0}$ of 40.51 dB/Hz, that is similar to receiver threshold computed in 9.2.2 and to the one indicated in the SGICD, is set and the test is repeated, letting the transmission runs for several days, and no wrong frame are notify by the BBU receiver even if more than one million frames are transmitted.
Therefore it is possible to conclude that with very high probability the FER sanctioned in the SGICD (10^{-6}) is respected and the coding techniques, since the receiver synchronism is maintained for the entire transmission, are able to retrieve information in correct way[11] as expected from theory.
Reaching this point, no other tests are executed since they will required a not supportable expenditure of time and computational cost and because practically the expected results are already reached by the previous outcome.

[11]It is worth to remember that undetected errors are not notify by the BBU receiver however they are very rare (probability of the order of 10^{-14}) and therefore these results, even with this approximation, do not loose their generality

Knowing the outcomes of this test, jointly with the ones of the BER estimation test, it is possible to assert that the receiver has a behaviour that can be defined "on/off", inasmuch or practically all the frames are marked as `Good frame` or the most are indicated as `Bad frame`. The cause of this kind of performance must be sought in the synchronism of the receiver because coding techniques do not have a behaviour like this since only 0.5 dB of worsening of $\frac{C}{N0}$ does not lead to this dramatically decrease of quality in a simple coding transmission but simply lowers slightly the results.
Therefore, this behaviour is due to the lost of synchronism of the receiver that retrieves information, when it is possible, in disorder and the decoder, that probably, as result of the goodness of several coding techniques embedeed on it, is able to manage also more critical $\frac{C}{N0}$ with respect to the one of the threshold, is not able to correctly reorganized the data and so to recover frames rightly.
This kind of actions can be considered reasonable since the receiver until is locked provides the maximum of performances while when it is under threshold even of few tenths of dB produces very bad performances but notifying it so that it possible to take measures to improve the $\frac{C}{N0}$ and restore the correct synchronism and functioning of the receiver itself.

Moreover, these last S-Band downlik test sub-block results and what said before underline in a very clear way as, despite the fact that the two analyzed $\frac{C}{N0}$ are apparently near, the behaviours of the receiver are dramatically different, this emphasizes significantly how much is important that the signal-to-noise ratio does not come down the computed receiver thresholds because even a very small decreasing can produce a very high FER and so an important performances degradation.

9.3 S-Band uplink test block

Opposite to the S-Band downlink test block there is the S-Band uplink test block that as the name sayd is used to validate the signal from the GRS to the TCR suitcase. The main differences with respect to the previous ones threshold calculations are that in this case to compute the value of threshold for which the PLL un-lock without considering data transmission, it is possible to use a clean carrier and so a only PM modulated signal and the fact that for uplink transmission only one polarization is used and so only one channel. This thing is possible because the BBU allows to chose if transmit data or not that is to apply sub-carrier modulation or not. As happen for the downlink case the threshold in which also the data transmission is considered is higher with respect to the one in which data are not transmitted.

9.3.1 Uplink acquisition threshold

To compute the **Uplink acquisition threshold** the method and the test bench configuration described in 7.3.1 are employed. This method is the common one and it is based on the decreasing of the $\frac{C}{N0}$ until the TCR suitcase receiver unlock and its monitoring and control interface notifies it. This time the $\frac{C}{N0}$ is the one reffering to the clean carrier without data transmission and it is reduced not using the programmable attenuator but directly changing the output carrier level C of the BBU transmitter. The clean carrier is modulated following the requirements exposed in table 7.8 and as shown by the monitoring and control interface of the BBU reported in the next figure.

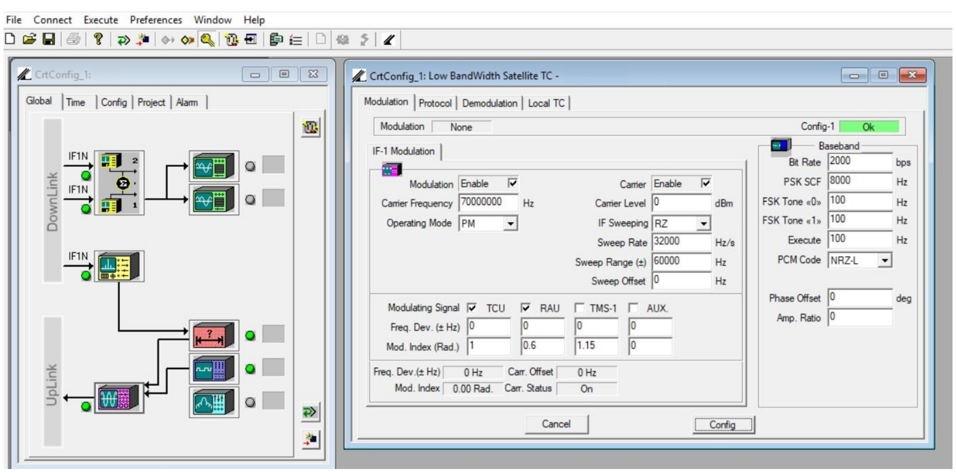

Figure 9.26: BBU configuration for test 9.3.1

Threshold as usual is computed following the same approach before as the ratio, difference in dB, between the peak signal displayed by the spectrum analyzer and the noise level injected by the noise generator (-115 dB/Hz uplink case) in this case at RF frequency.
Figures below, captured at the starting point of the test, underline respectively the spectrum interface in which it is possible to see that only the carrier without data modulation is transmitted by the BBU transponder and the monitoring and control interface of the TCR suitcase where is boxed in red that the on board carrier receiver is locked.

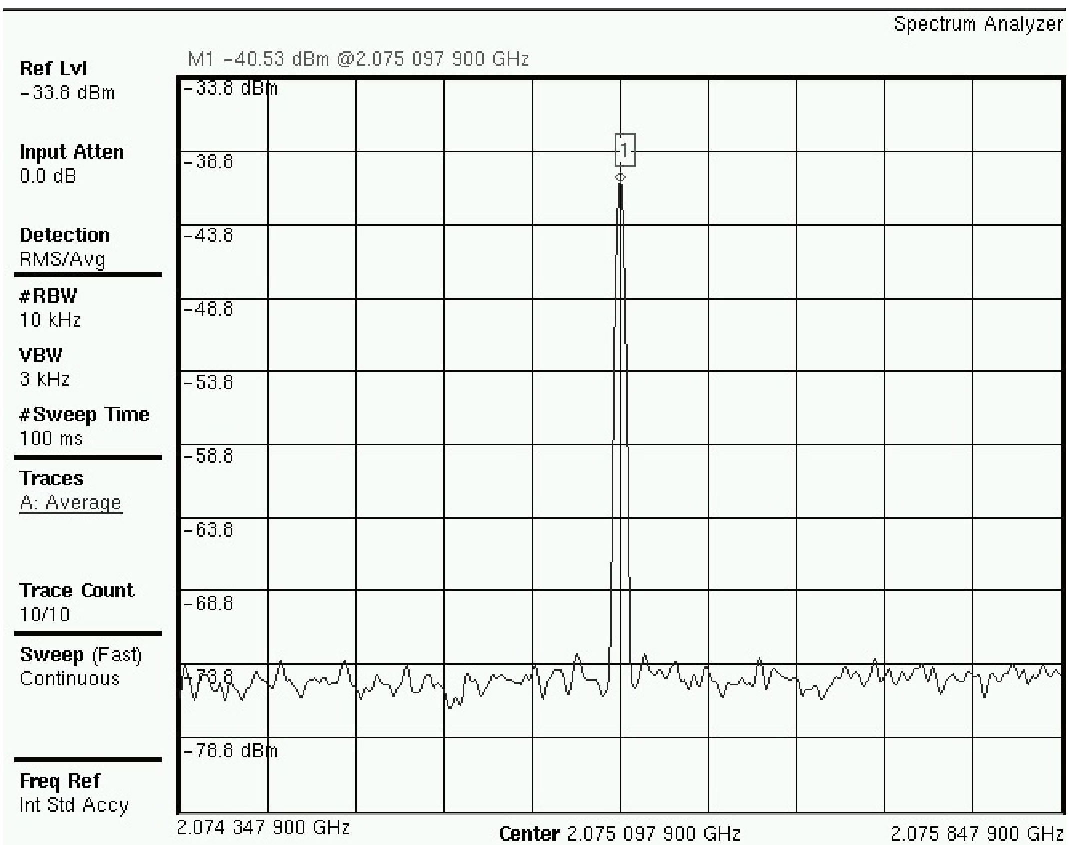

Figure 9.27: Spectrum analyzer interface at the begin of 9.3.1 test

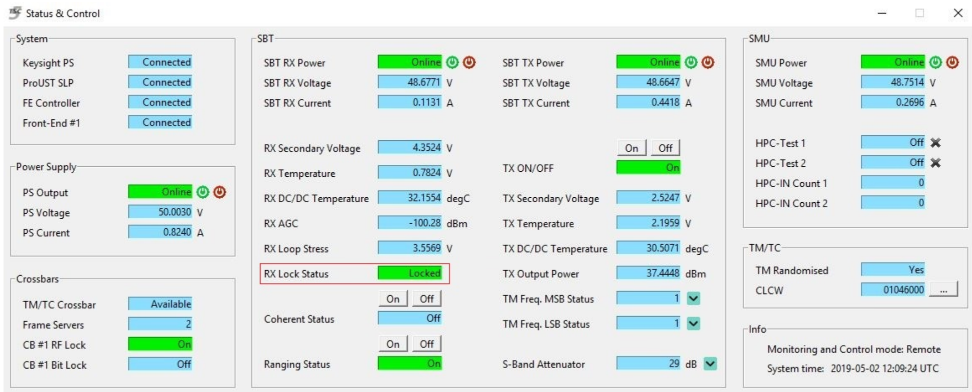

Figure 9.28: TCR suitcase carrier receiver locked

Indeed, at the end of the test, when the value of the threshold is reached and as figure 9.30 shows, the monitoring and control interface of the TCR suitcase notifies the un-lock of the carrier receiver and the signal peak shown by the spectrum, reported in figure 9.29, corresponds practically to the noise level.

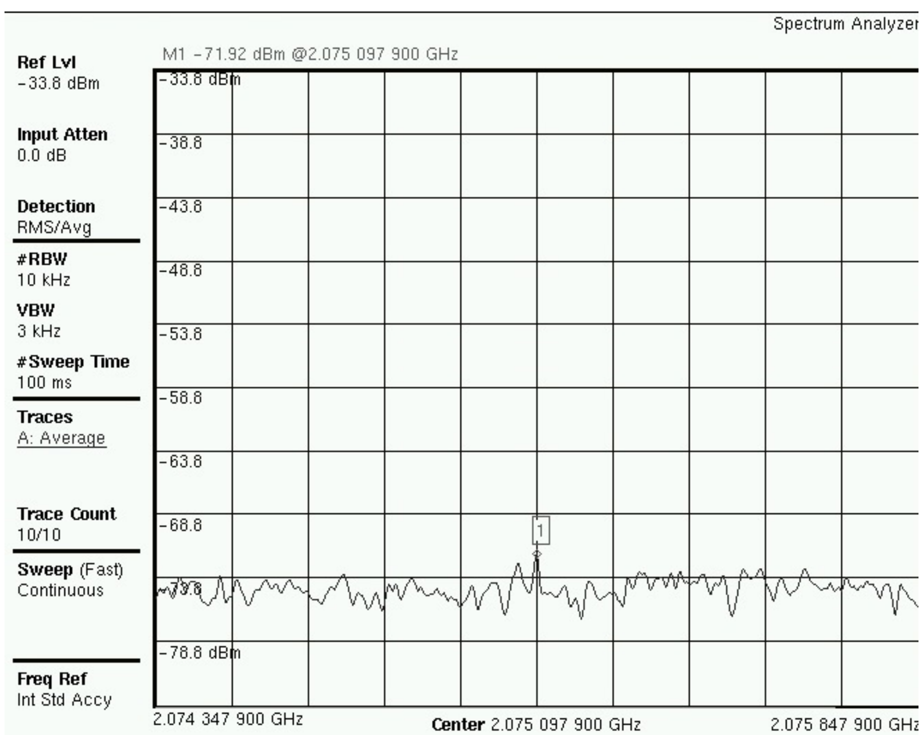

Figure 9.29: Spectrum analyzer interface at the end of 9.3.1 test

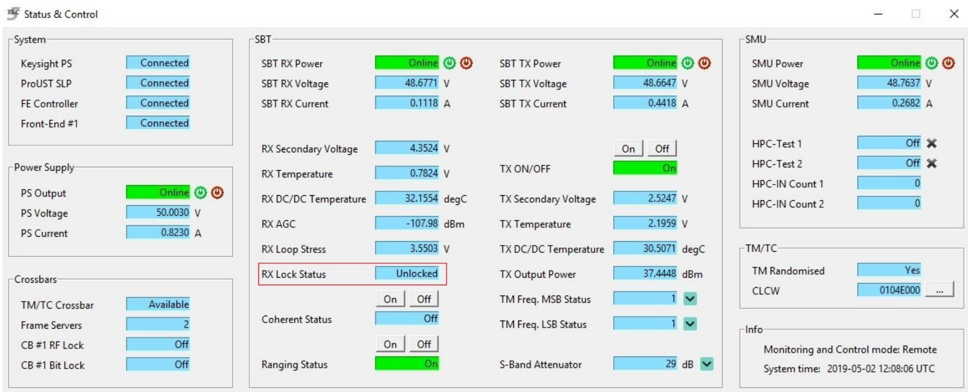

Figure 9.30: TCR suitcase carrier receiver un-locked

The several attempts and computations to retrieve the value of the threshold are reported, as done for the downlink case, in the table below, as discuss before this time the $\frac{C}{N0}$ is modified using the monitoring and control interface of the BBU and not using the programmable attenuator thus instead of the item "Attenuation" there is the "Carrier level" element.

Spectrum analyzer reading [dB] (C)	Carrier level [dB]	Noise Level [dB/Hz] $(N0)$	$C/N0$ at input of the receiver [dB/Hz] $(C/N0\|_{dB/Hz} = C\|_{dB} - N0\|_{dB/Hz})$	PLL status
-40.9	0	-115	74.1	LOCK
-50.8	-10	-115	64.2	LOCK
-60.9	-20	-115	54.1	LOCK
-65.9	-25	-115	49.1	LOCK
-68.7	-28	-115	46.3	LOCK
-69.8	-29	-115	45.1	LOCK
-70.9	-30	-115	44.1	LOCK
-71.9	-31	-115	43.1	UN-LOCK

Table 9.3: Attempted Uplink acquisition threshold measurements

The found threshold is **44.1 dB/Hz**. This value is quite below from the one computed with the link bufget analysis of 54.29 dB/Hz. Therefore, it is an acceptable value and underlines as also the receiver on board the satellite and not only the one of the GRS has a very good sensibility and it is built to manage also more critical cases with respect to the worst case scenario of the considered mission.

9.3.2 Telecommand rejection threshold

Telecommand rejection threshold differs from the previous one since it takes into account also the correct data reception of the on board transponder. The right data reception is checked using the monitoring and control interface of the TCR suitcase, in particular the `Bit lock` field that if the receiver is correctly locked notifies it with the word `On` or if it is not locked show the word `Off`.
As mentioned before this threshold deals with the data reception therefore the BBU is set to transmitt a series of 100 telecommand messages having the structure exposed in chapter 2. At the beginning of the test the spectrum of signal is the one show in the following figure.

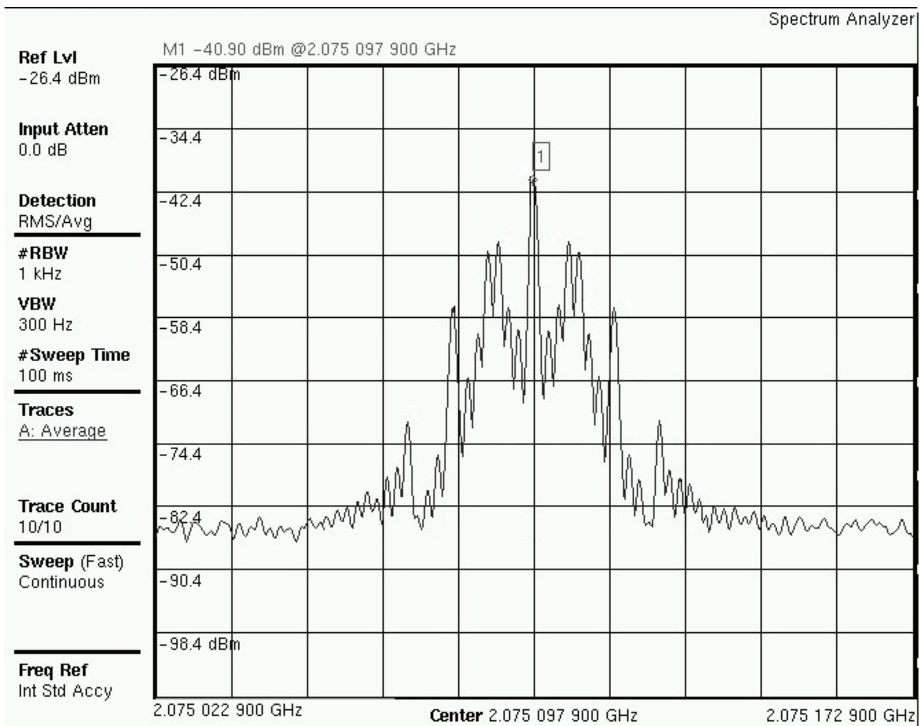

Figure 9.31: Spectrum analyzer interface at the begin of 9.3.2 test

As it possible to see it is slightly different with respect to the one in wich only the carrier is transmitted since now the sub-carrier modulation is apply however the peak of the signal remain almost at the same level.
Always at the test starting point the monitoring and control interface of the TCR suitcase notifies that its data receiver is locked as it is stressed in the underneath figure.

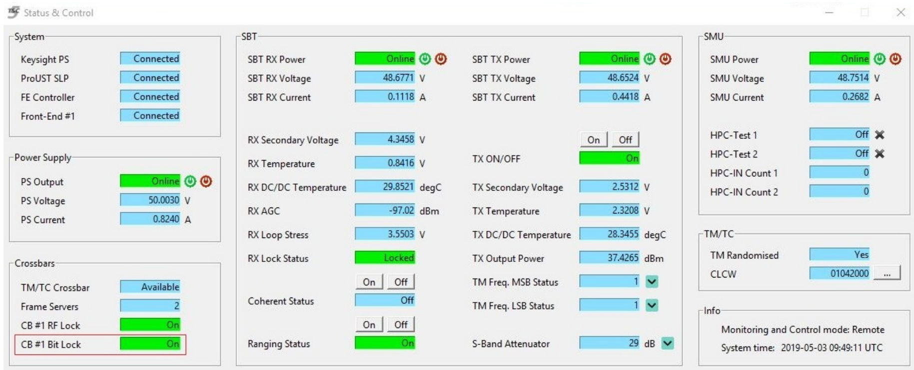

Figure 9.32: TCR suitcase data receiver locked

Descreasing the carrier level the threshold is finally reached and the monitoring and control interface notifies it switching the `Bit lock` field to `Off` and the spectrum analyzer displays as the subcarrier power is almost at noise level and therefore is no more possible to retrieve them and maintain the locking.

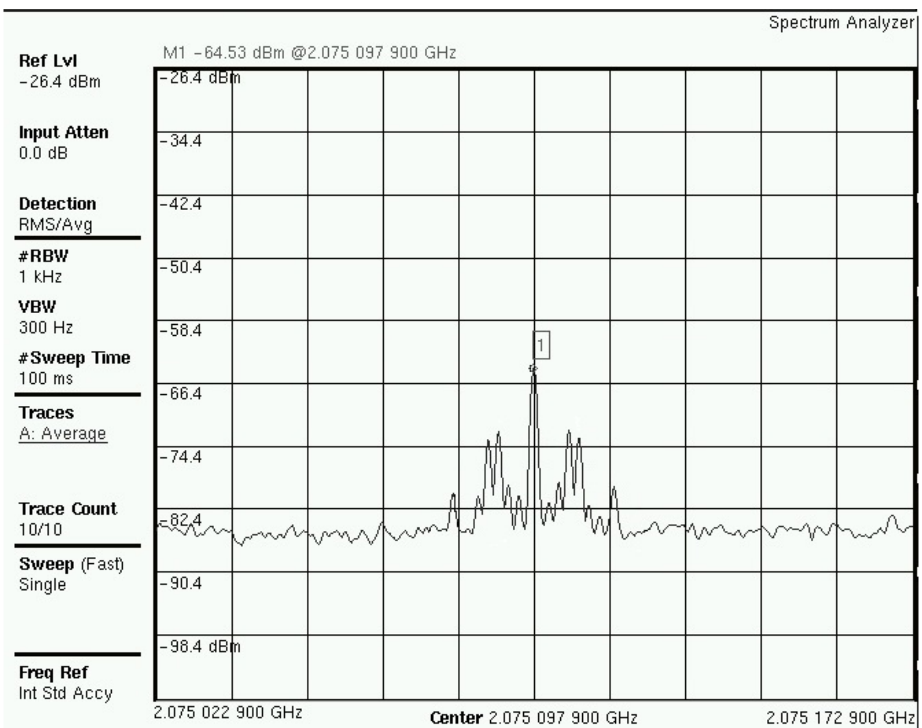

Figure 9.33: Spectrum analyzer interface at the end of 9.3.2 test

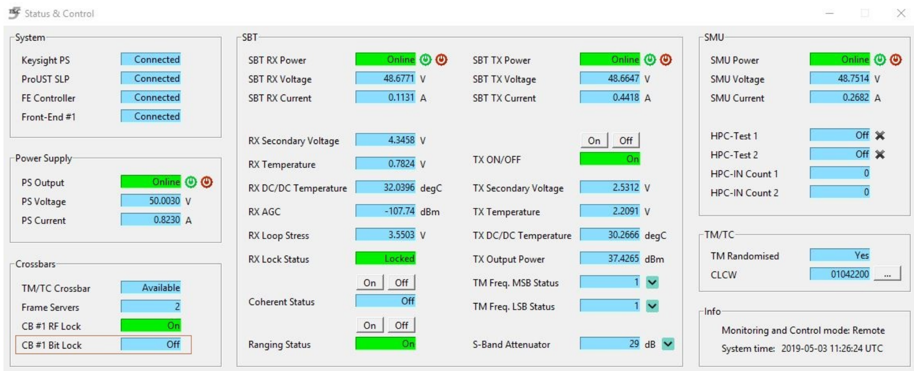

Figure 9.34: TCR suitcase data receiver un-locked

As before the several attempts and computations executed to retrieve the threshold are tabulated below.

Spectrum analyzer reading [dB] (C)	Carrier level [dB]	Noise Level [dB/Hz] ($N0$)	$C/N0$ at input of the receiver [dB/Hz] ($C/N0\|_{dB/Hz} = C\|_{dB} - N0\|_{dB/Hz}$)	Receiver status
-40.9	0	-115	74.1	LOCK
-50.8	-10	-115	64.2	LOCK
-57.4	-15	-115	57.6	LOCK
-60.5	-18	-115	54.5	LOCK
-61.4	-19	-115	53.6	LOCK
-62.6	-20	-115	52.4	LOCK
-63.5	-21	-115	51.5	LOCK
-64.5	-22	-115	50.5	UN-LOCK

Table 9.4: Attempted Telecommand rejection threshold measurements

Unsurprisingly, as happen for the downlink case, when also the data reception is taken into account, the receiver needs a more higher $\frac{C}{N0}$ to work in correct way thus the threshold that deals with the data recovering has a greater value. The computed value of threshold is **51.5 dB/Hz**, it is under the one estimated by the link budget of 59.53 dB/Hz and therefore it can be considered acceptable.
This result furthermore confirms, as said in the previous threshold result comment, how the receiver is able to manage more critical situations with respect to the worst case scenario of the considered mission and how the builder of TCR suitcase, even if was aware of the mission worst case scenario, has made the on board receiver with a certain margin on its locking capability.

9.4 S-Band ranging test block

This test block completes the RF part of this entire work since the last part of this thesis is dedicated to the end-to-end test that employ the TCP/IP connection. Ranging is used to compute the distance between the satellite and the Earth and it is a fundamental procedure to drive satellite during the LEOP. Ranging signals use both uplink and downlink channel and they are sent by the GRS that waits that the TCR transponder send back the same signal to compute the Round Trip Time (RTT) measurement and so the orbit distance. Distance measurements are computed and averaged automatically by the RAU several times to avoid errors.

9.4.1 Ranging signal verification

This first S-Band ranging test sub-block logically belongs to the test bench calibration however for practical reason it is executed at this point of the work and it is considered in it also the noise since as seen in previous tests the presence of it does not modify the signal characteristics. It is described in section 7.4.1, where also the expected results are exposed and it is divided in two cases, that will be analyzed separately in the following.

Ranging mode not available on satellite Using this mode no ranging measurements are possible since the TCR transponder are not able to send back the signal and the RAU inside the BBU notifies it showing `Open Loop` in the measurement status, as figure below underlines.

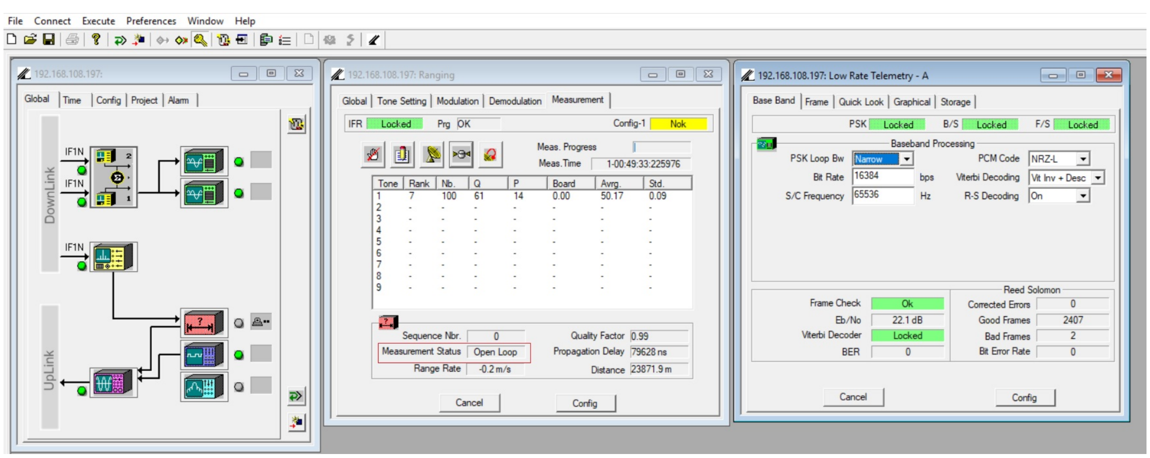

Figure 9.35: RAU not able to execute ranging measurements

Obviously, with this mode beside the distance measurements also no signal spectra from the satellite are available therefore the other mode must be set to execute the ranging signal verification and the ranging thresholds estimation.
In a real case to activate the available mode on board the satellite a telecommand has to be send to face this purpose, in the analyzed case indeed it is enough to switch on it on the monitoring and control interface of the TCR suitcase.

Ranging mode available on satellite With this mode it is possible to visualize the spectrum of the ranging tones both in downlink than in uplink case in order to verify the ranging tone frequencies and the modulation indexes. The first image shows the uplink signal with the clean carrier and the ranging tone while the second one the downlink signal also with data since the TCR suitcase does not allow to transmitt only the clean carrier.

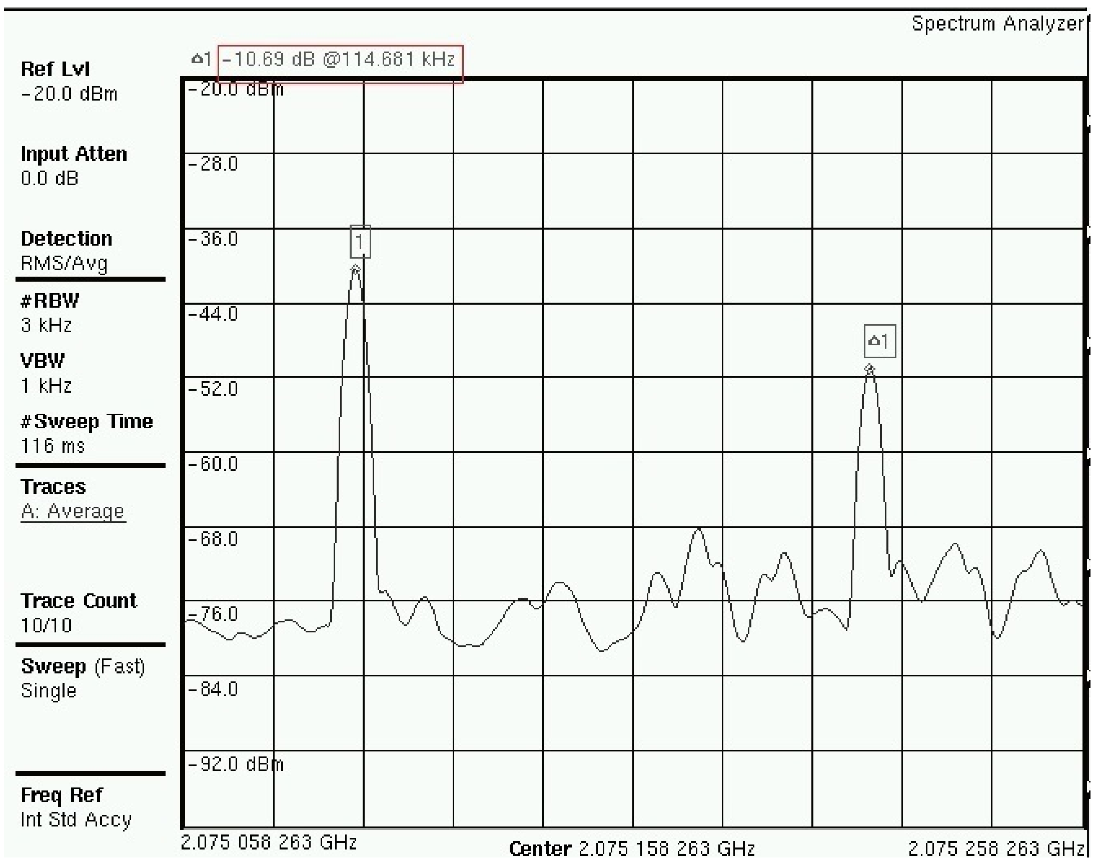

Figure 9.36: Spectrum of the uplink signal with ranging tone

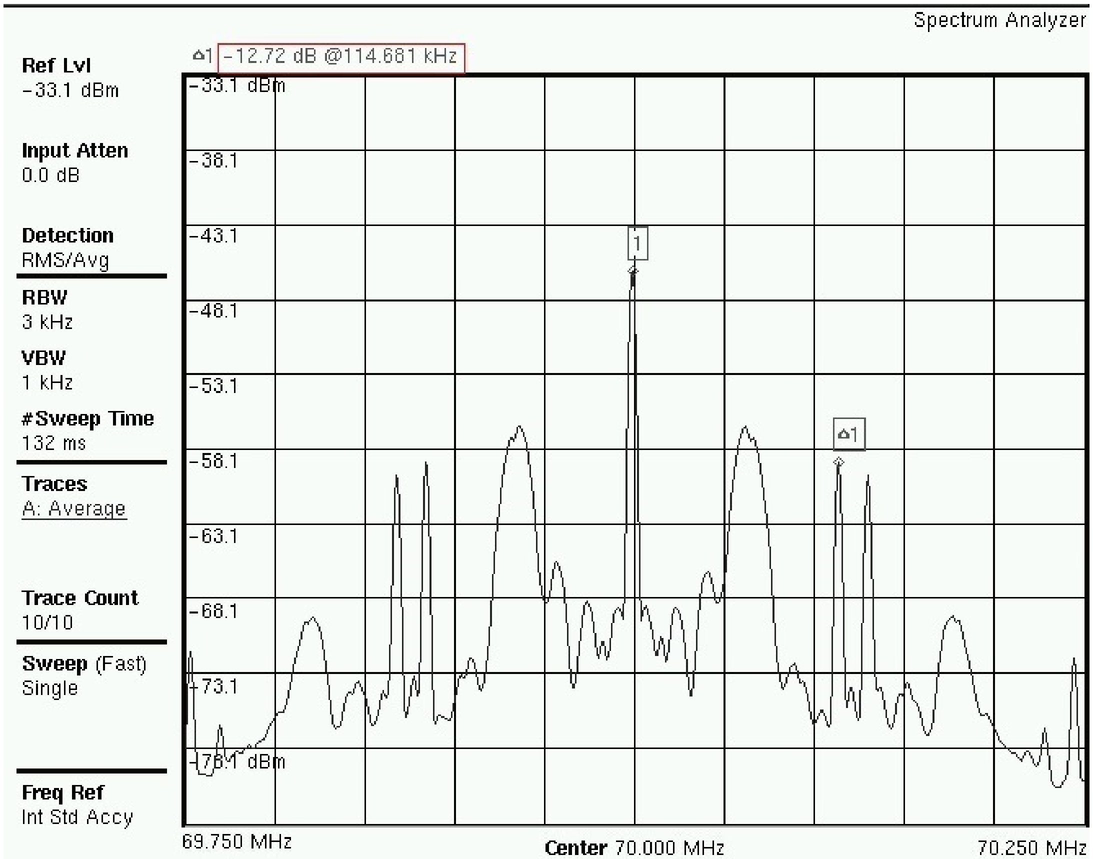

Figure 9.37: Spectrum of the downlink signal with ranging tone

In both figures the ranging tone frequency is boxed in red and it is practically aligned with the one requested in the SGICD and reported in table 7.10. Moreover, it is underlined the difference in dB between the peak of the signal and the ranging tone that is 10.69 dB for the uplink and 12.72 dB for the downlink.
Knowing this two values and using the same approach exploited in the sub-chapter about the test bench calibration, it is possible by the means of the Bessel table compute the modulation indexes that reach for the uplink a value of almost 0.63 rad and for the downlik it is near to 0.48 rad, resulting both of them inside the tolerance sanctioned in the SGICD respectively of the $0.6 \pm 5\%$ rad and $0.5 \pm 5\%$ rad.

9.4.2 Ranging thresholds

Ranging (RNG) thresholds are different from the previous ones since to evaluate them are monitored the accuracy of the distance measurement and not the locking of the receiver. This accuracy is show by the RAU inside the BBU through its monitoring and control interface and it decreases as the $\frac{C}{N0}$ lowering. As exposed in 7.4.2 the thresholds to be evaluated are two since ranging signals utilize both downlink and uplink channel. To get the results reported in this sub-chapter several ranging measurements are executed by the RAU exploiting the transmission of ranging signals as describe in chapter 4 and waiting the answer of the TCR suitcase, with the ranging mode set to `On`, that acting as an transparent entity simply sends back the signals to be processed. First of all, the ranging threshold of the uplink case is evaluated using the approach described in 7.4.2. Spectra of signal both in downlink and uplink case are not reported since at the starting point of the test they are completely equal to the ones shown in the previous sub-chapter and at the ending point of the test they are practically at level of noise and it is no more visible the ranging tone used to get the measurements.

Uplink ranging threshold

At the beginning of this uplink ranging threshold test the RAU appears as the image below shows.

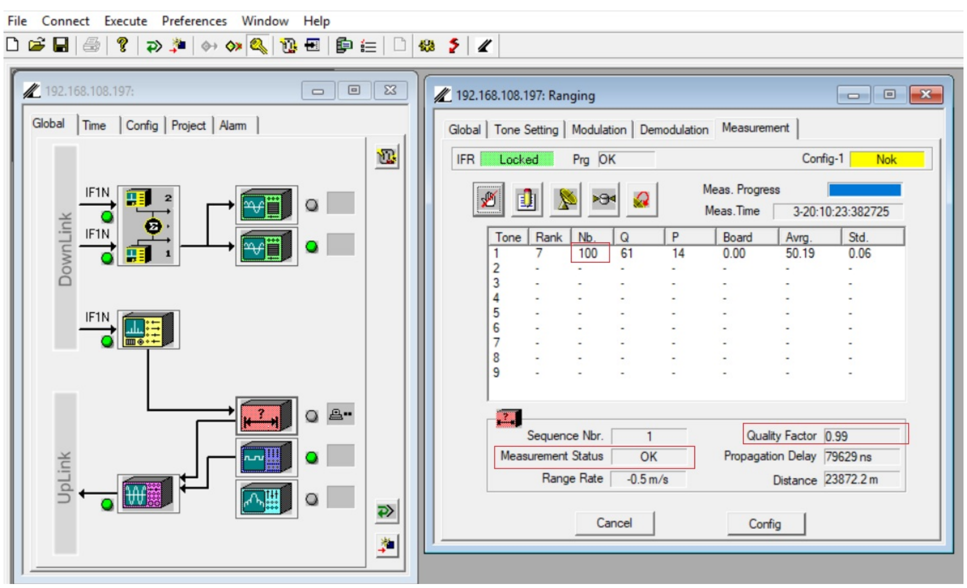

Figure 9.38: RAU at the beginning of Uplink RNG threshold test

In the figure are boxed in red several important information, firstly, the number of measurements average to obtain the distance estimation (`Nb` set, as sayd before, to 100), secondly the `Measurement Status` that is `OK` and no more `Open Loop` since this time the ranging mode is activated at the TCR suitcase and finally the `Quality factor` that is the quantity that allow to know when the threshold is reached, indeed if this quantity goes down 0.97 the threshold is considered gained.
Since the uplink channel is under test the noise density of the worst uplink case scenario is considered (115 dB/Hz) and the $\frac{C}{N0}$ is decreased using the programmable attenuator contained in the uplink path until the RAU notify a `Quality factor` of 0.95 as the figure underneath highlightes.

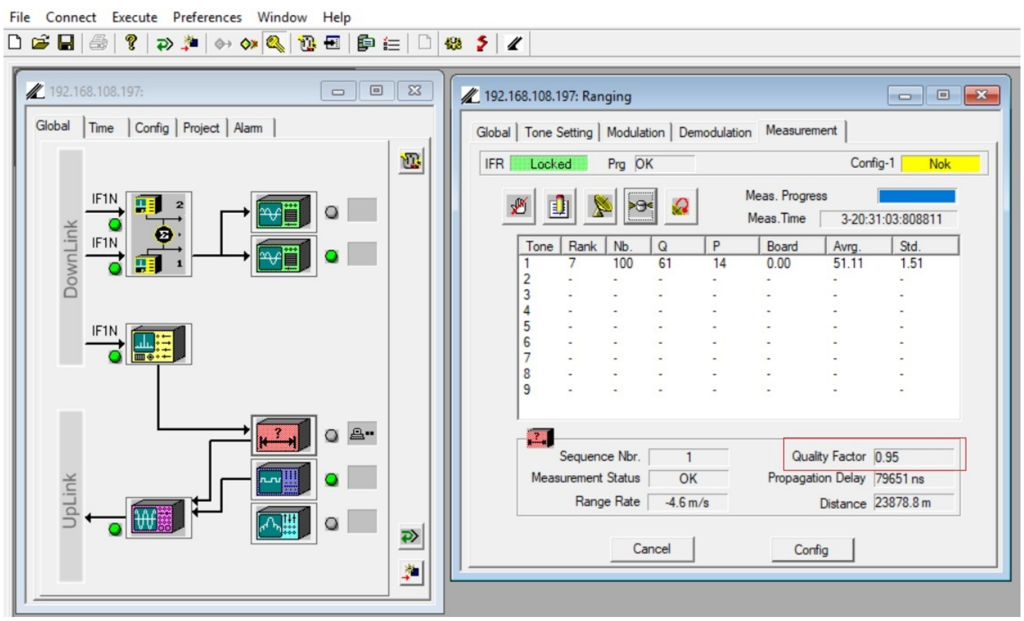

Figure 9.39: RAU at the end of Uplink RNG threshold test

Moreover, figure 9.39 underlines as the standard deviation increases as the $\frac{C}{N0}$ decreases, indeed in the second figure is higher with respect to the first one. Standard deviation provides a measure of the dispersion of the computed values and therefore is another parameter that helps to better understand how ruining the signal-to-noise ratio the ranging measure accuracy degrades.
Also in this case, the several attempts and computations executed to get the result are tabulated and reported below.

Spectrum analyzer reading [dB] (C)	Attenuation [dB]	Noise Level [dB/Hz] ($N0$)	$C/N0$ at input of the receiver [dB/Hz] ($C/N0\|_{dB/Hz} = C\|_{dB} - N0\|_{dB/Hz}$)	Quality factor
-40.9	0	-115	74.1	0.99
-50.8	-10	-115	64.2	0.99
-55.9	-15	-115	59.1	0.98
-61.0	-20	-115	54.0	0.98
-61.9	-21	-115	53.1	0.98
-62.8	-22	-115	52.2	0.98
-63.9	-23	-115	51.1	0.97
-64.8	-24	-115	50.2	**0.95**

Table 9.5: Attempted Uplink ranging threshold measurements

The computed threshold for uplink case is **51.1 dB/Hz**, it is under the one computed by the link budget analysis equals to 52.61 dB/Hz and therefore it is an acceptable result.

Downlink ranging threshold

Kwnowing the threshold in the uplink case the one for the downlink is now taken into account. The main difference between this two quantities is that the first one is computed acting on the uplink channel and therefore is the receiver inside the TCR transponder that is not able to send back in correct way the ranging signal because of the small $\frac{C}{N0}$ while the second one is estimated acting on the downlink channel and therefore is the RAU that receives a signal too much ruined to compute a reliable measurement.
As said before, this time the downlink channel is considered therefore the added noise density is 118 dB/Hz measured for the worst downlink case scenario and the attenuation is introduce in the downlink path by the means of the programmable attenuator. Moreover, since measurements are always executed by the RAU inside the BBU of the GRS, the monitoring and control interface of it at beginning and the end of this test shows exactly the same quantities before and for this reason they are not reported here. Obviously, the fundamental thing that changes is the threshold in which the `Quality factor` gets a value lower than 0.97.
Table below shows the several attempts and computations done to reach the result.

Spectrum analyzer reading [dB] (C)	Attenuation [dB]	Noise Level [dB/Hz] ($N0$)	$C/N0$ at input of the receiver [dB/Hz] ($C/N0\|_{dB/Hz} = C\|_{dB} - N0\|_{dB/Hz}$)	Quality factor
-47.5	0	-118	70.5	0.99
-57.6	-10	-118	60.4	0.99
-72.5	-25	-118	45.5	0.98
-73.6	-26	-118	44.4	0.98
-74.6	-27	-118	43.4	0.98
-75.5	-28	-118	42.5	0.97
-76.4	-29	-118	41.6	0.97
-77.5	-30	-118	40.5	0.97
-78.4	-31	-118	39.5	**0.95**

Table 9.6: Attempted Downlink ranging threshold measurements

The estimated threshold for downlink scenario is **40.5 dB/Hz**, it is under the one computed with the link budget (40.9 dB/Hz) and so it can be considered an acceptable value.
These two last computed thresholds are the thresholds more near to the theoretical values expected by the link budget, this is probably due to the drawbacks that is possible to have during a ranging estimation and also to the not precise accuracy calculation executed by the RAU inside the BBU at the receiver side.

As happened also for the other thresholds, the $\frac{C}{N0}$ admissible at the input of the Earth receiver to obtain some results can be smaller with respect to the one at the input of the on-board receiver. For example to retrieve telemetry data it is tolerated a smaller $\frac{C}{N0}$ by the ground receiver with respect the one accepted by the satellite receiver to recover telecommand messages data. This means that the GRS receiver has a higher sensibility and a more important capacity to discriminate signals with respect to the satellite one. This discrepancy can be justified through the fact that for uplink signal it is possible to change the signal level C in a quite simple way without any power issue and so it is possible to smooth it to the needs of the on-board receiver. Indeed the signal level from satellite to Earth is almost fix and it cannot suffer large variations to avoid an exceed power consuption, therefore it is no possible to increase simply the signal power to better receive the information but since the signal has to be retrieve the ground receiver must compensate this issue. Furthermore, this gap can be explained by the fact that the ground receiver can be considered a "general purpose" receiver that must face several signals of several missions with respect to the on-board one that is built for only one specified mission and to work with only few ground reference stations.

9.5 End to end network data-flow test

This last test conlcudes this thesis, it is described in 7.5 and has the scope to validate the TCP/IP connection inside the network formed by the BBU (Base-band unit) inside the GRS (Ground Reference Station), the NOC (Network Operation Center) and MCC/SCC (Mission Control Center/Satellite Control Center).
To accomplish this test the network analyzer **Wireshark** is employed in order to sniff the packets between the above mentioned structures during data transmission, this sniffer is run on the terminal of the NOC since it is the entity involved in every data flow, able to make readable the data from the BBU to MCC/SCC and viceversa and therefore it has the capability to see every packets exchanged in the network.
Moreover, NOC has two different IP addresses: one for BBU connection and one for MCC/SCC communication. To better understand the Wireshark captures reported next in this sub-chapter in the following table are indicated the IP addresses of each ground segment unit.

Entity	**IP adress**
BBU (Base-Band Unit)	`192.168.108.197`
NOC (Network Operation Center) for BBU	`192.168.185.175`
NOC (Network Operation Center) for MCC/SCC	`192.168.182.175`
MCC/SCC (Mission Control Center/Satellite Control Center)	`192.168.182.221`

Table 9.7: IP addresses of ground segment entities

As exposed in 7.5 the ground segment follow a hierarchy that will be verified in this chapter and this test is logically divided in 3 sub-tests one for each possible data flow. The following paragraphs describe and comment the results obtained for this 3 cases.

9.5.1 Telecommand data flow test

Telecommand data flow test is used to prove the telecommand data flow from MCC/SCC towards the NOC and then to the BBU. To execute this test the BBU is configured to send telecommands and the TCR suitcase to receive them in order to see the telecommand leaved from the MCC/SCC reaching the TCR suitcase. Test starts with the MCC/SCC, that is the entity that generates and controls the telecommand messages, that produces one telecommand and sends it to NOC that in case of successfully reception answer with an `ACK` as the two Wireshark captures underneath underline very well:

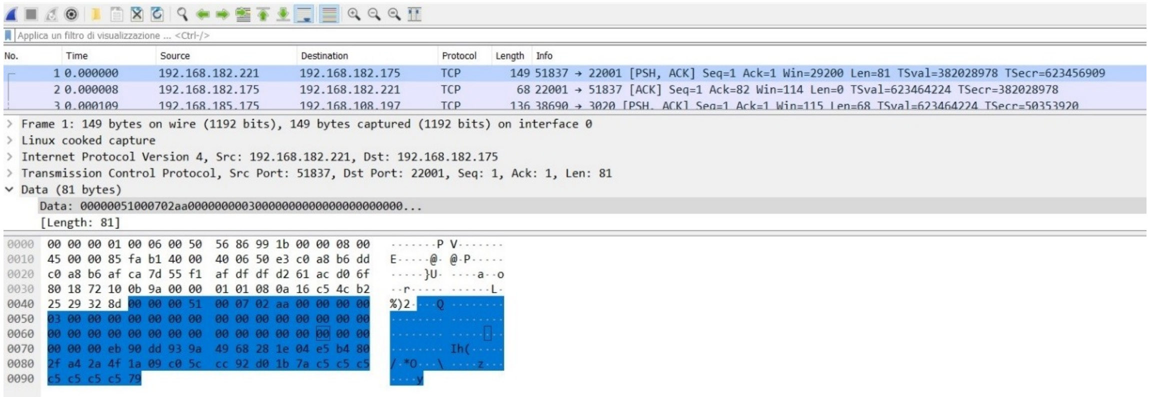

Figure 9.40: Telecommand message from MCC/SCC to NOC

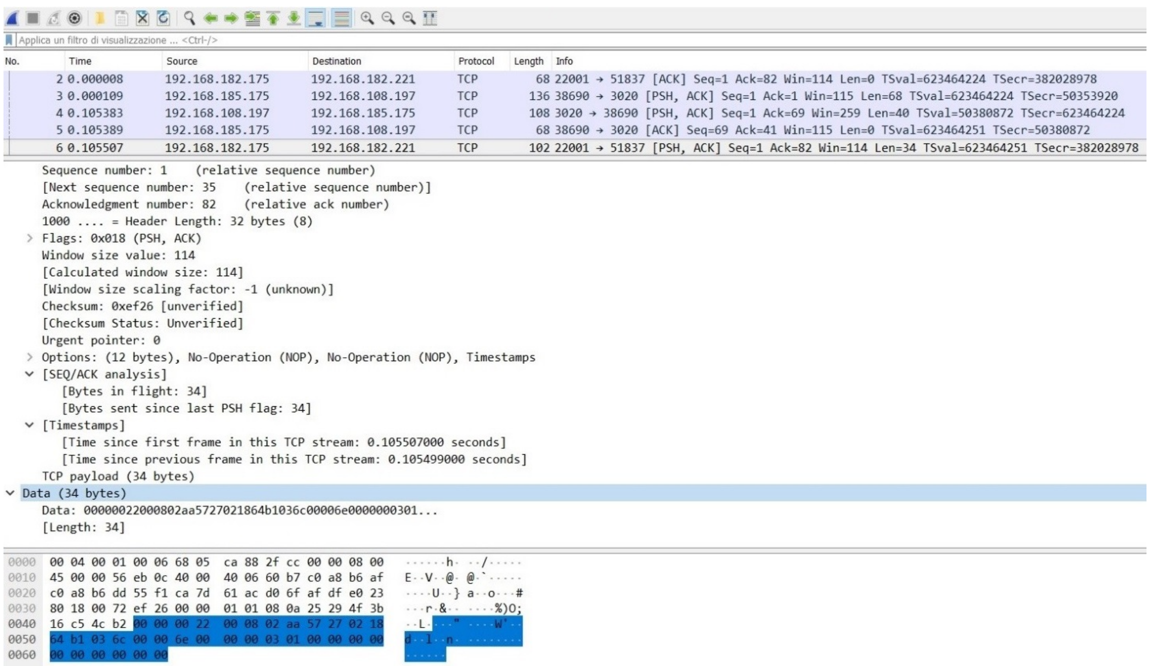

Figure 9.41: ACK from NOC to MCC/SCC

Validated this first part of the data flow also the second one that is the telecommand transmission from NOC to BBU is tested. As the following images shown the NOC, proccessed the message, sends it to BBU that answers towards an ACK. The fact that this connection has been successful and the test is overcame is moreover confirm by the Monitoring and control interface of the TCR suitcase that show the correct reception at RF frequency of the telecommand message leaved by the MCC/SCC.

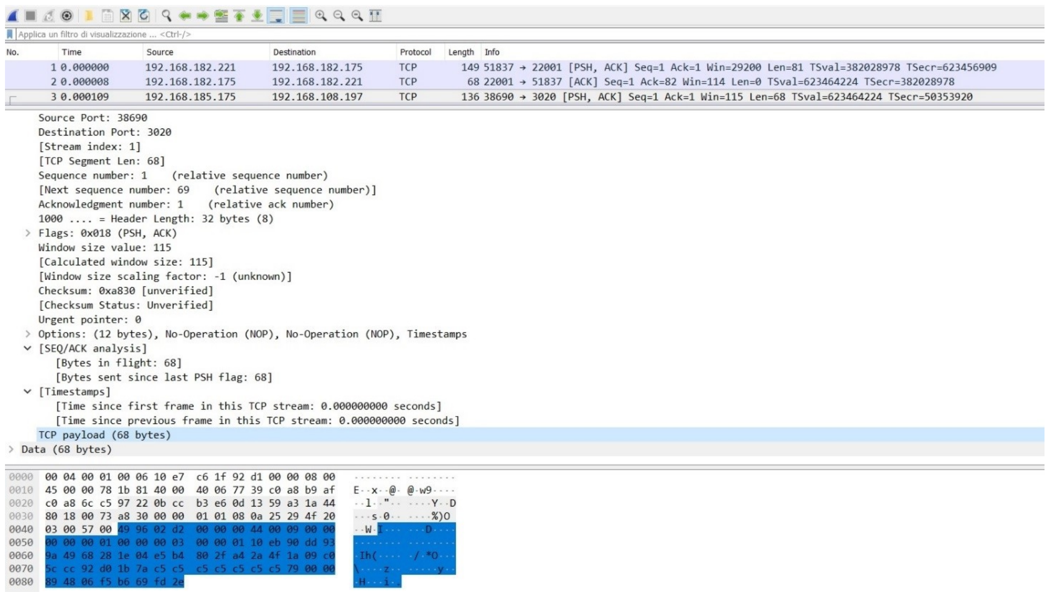

Figure 9.42: Telecommand message from NOC to BBU

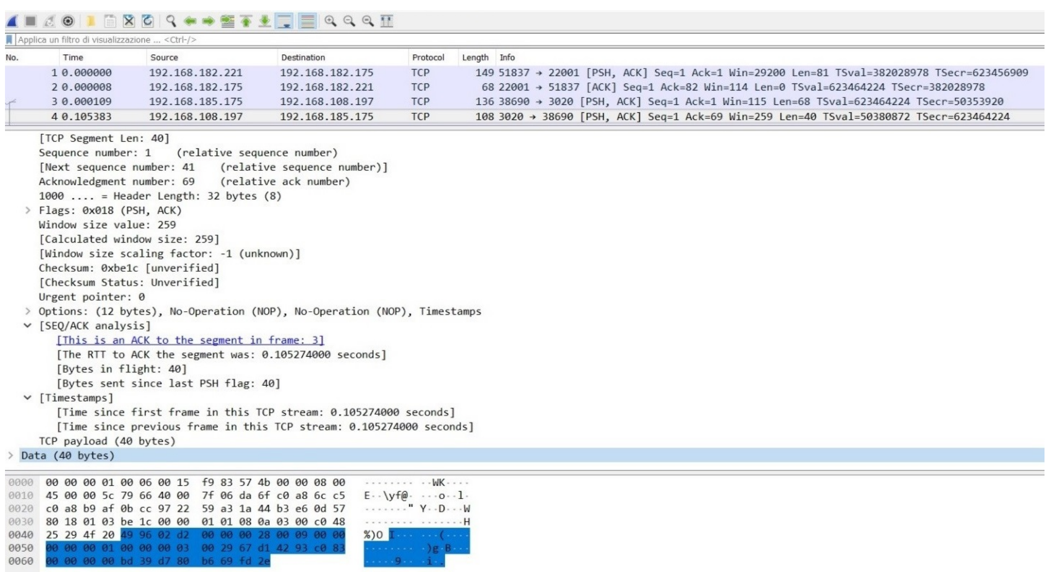

Figure 9.43: ACK from BBU to NOC

9.5.2 Telemetry data flow test

Opposite to Telecommand data flow test there is **Telemetry data flow test** used to validate the Telemetry messages exchange between BBU, NOC and MCC/SCC. This test is executed during a telemetry transmission in RF between the TCR transponder and the BBU.
BBU received these telemetry messages from the TCR suitcase, prepares them to be transmitted in the above mentioned TCP/IP network and in case of correct "Telemetry request" from the MCC/SCC through NOC as the one shows in the figure 9.44 sends them to it as it illustrated in figure 9.45.
Of course the rules of a TCP/IP connection are always valid and both the entities in case of successfully association answer with an ACK even if this time, differently from sub-chapter before, they are not reported in the next paragraphs.

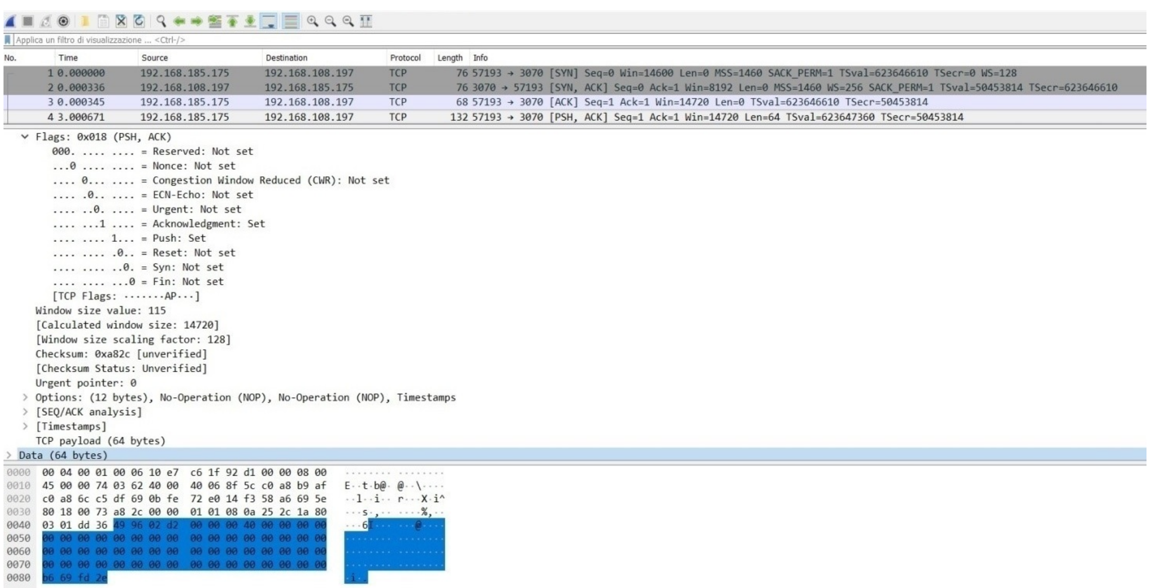

Figure 9.44: "Telemetry request" from NOC to BBU

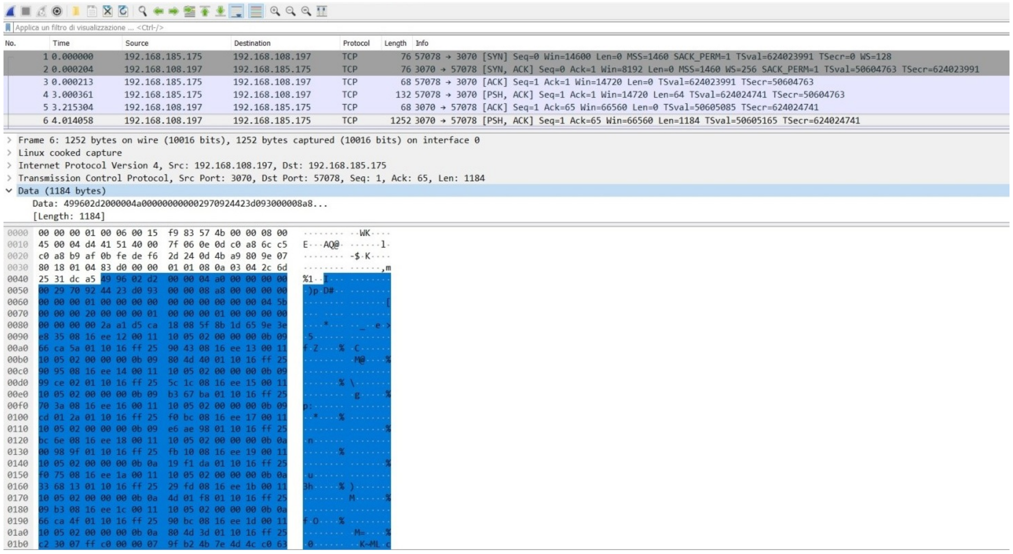

Figure 9.45: Telemetry message from BBU to NOC

NOC received the telemetry, processes and sends it towards MCC/SCC (Figure 9.46) that answers with an ACK (not reported) since the message exchanged has been successful this sub-test can be considered verified.

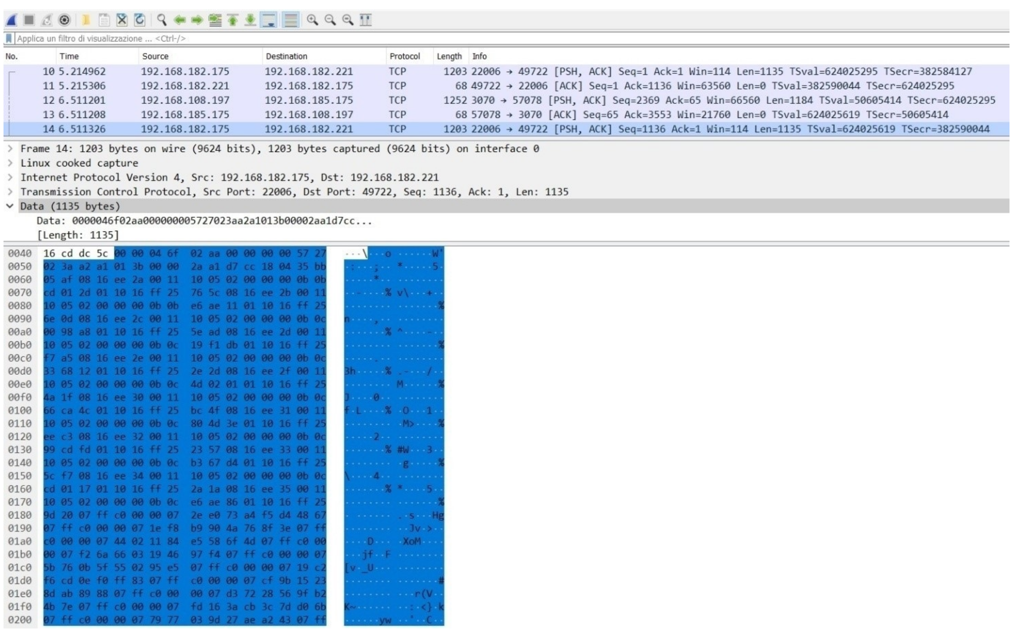

Figure 9.46: Telemetry message from NOC to MCC/SC

9.5.3 Ranging data flow test

Finally, also the ranging data flow is tested. This test is executed following the procedure describe in 4.1, that is the MCC/SCC through the NOC send a Ranging measurement request to the RAU inside the BBU towards its **RNG port** (`3034`), that in case of success answer with a positive acknowledgement. This first part of procedure is illustrated by the following Wireshark captures.

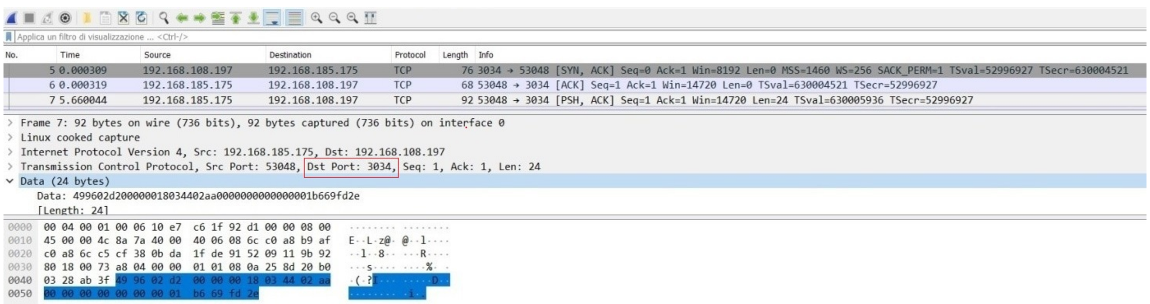

Figure 9.47: "Ranging measurement request" from NOC to BBU

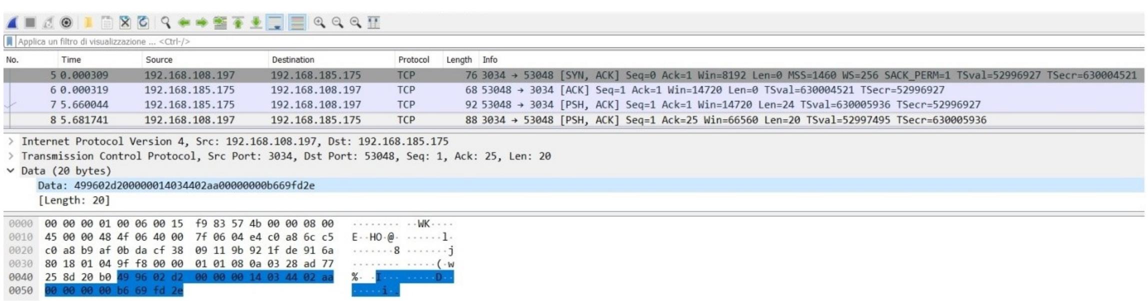

Figure 9.48: Positive `ACK` from BBU to NOC

The fact that this connection took place correctly is furthermore confirm by BBU interface that shows the starting of ranging measurement has stressed out in figure below.

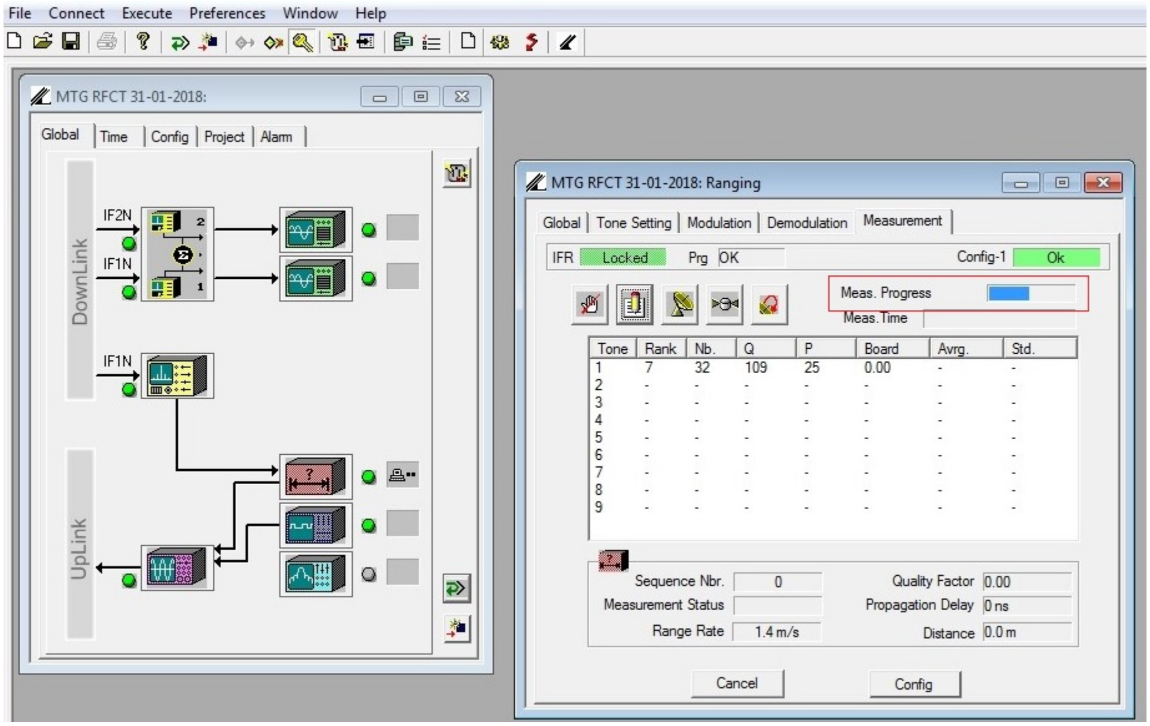

Figure 9.49: BBU start ranging measurement

At the end of ranging estimation the RAU sends two different messages to the NOC: the first one is the notification of the end of the measure, since the ranging request is not a continuous mode, on 3034 (RNG) port to close the connection, as reported below

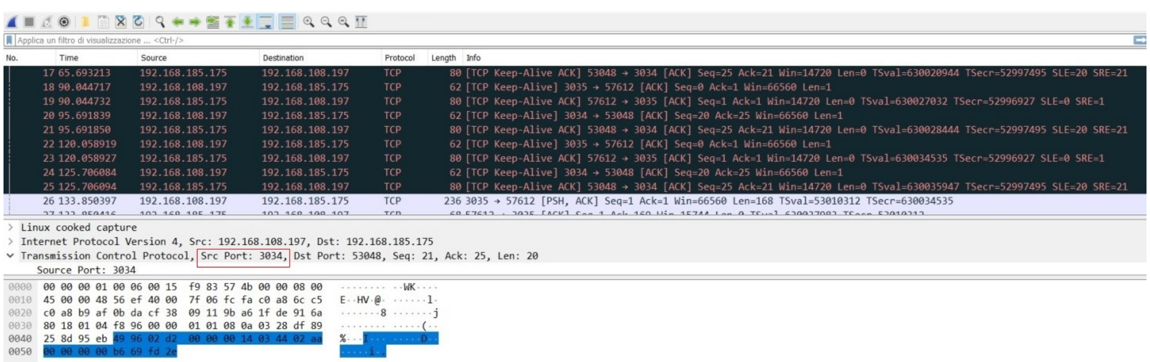

Figure 9.50: Positive end of measure ACK from BBU to NOC

while, the second one is the actually measurement send exploiting the **MEAS port** (`3035`) as underlined in the following figure.

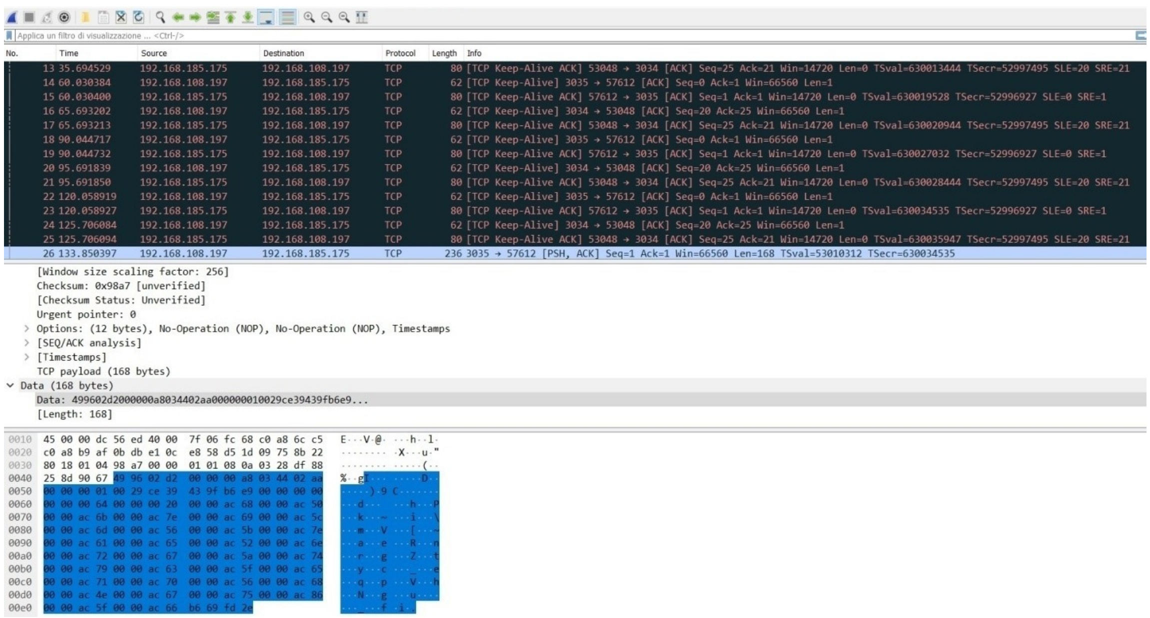

Figure 9.51: Ranging measurement from BBU to NOC

At this point NOC receives the two messages, answers with two no reported `ACK`s and this last test can be considered successfully accomplished since practically the last connection between the NOC and MCC/SCC is the same before and therefore already tested and verified in the previous end-to-end network sub-tests.

The presence of several `Keep-Alive` messages in the last 2 captures it is simply explained by the fact that the TCP connections are opened before the starting of the ranging measurement procedure and no data are sent on it until the end of the process that employs more time to be accomplished with respect to the duration of the timer associated with the `Keep-Alive` procedure.

Chapter 10

Conclusions

In conclusion, it is possible to affirm that the several tests that compose the **RFCT (Radio-Frequency Compatibility Test)** analyzed in this thesis are a fundamental procedure to carry on before the starting of the launching and putting into orbit of satellites to avoid unsolvable issues.
Inasmuch, it not only ensures the verification of the several requirements requested by customers in SGICD but also the validation that the communication between satellite and ground can take place in compliance with current regulations (ECSS and CCSDS standards), with the results obtained by the link budget analysis and without any problems.
Moreover, this work can be considered particularly reliable and completed since every test in it is performed in the worst possible scenario taking into account not only the problems due to the presence of noise of the two worst stations employed in the mission but also issues due to space propagation like doppler, up to the problems due to the possible satellite rotation.
The completeness of this RFCT is also ensured by the fact that every possible data flows between satellite and ground has been tested, validating: **Telemetry**, **Telecommand**, **Ranging procedures** and also the hardware and software employed to the correct operability of them.
Furthermore, it is done a brief analysis on the two quality parameters of **BER** and **FER** to have an idea of the behaviour of the receiver concerning the data reception in critical conditions, that is when it is very near to its lock threshold, and to verify the fact that coding and scrambling techniques are fundamental to ensure transmissions with better performances compared with un-coded ones.
In addiction, the **TCP/IP** end-to-end network, composed by the several ground entities that composed the ground segment, is tested because as it explains in this

thesis also these entities are fundamental for the success of the mission and of the LEOP and their incorrect functioning cannot be tolerated.
Finally, this thesis sanctions towards all the described test campaign that there are no compatibility problems between the satellite and ground station S-Band interfaces also with operations conducted under the worst case conditions defined by the link budget and that the fully operability of the ground segment can be considered respected.

Therefore the test campaign can be considered successfully passed and the several obtained results can be employed during the **LEOP (Launching and Early Orbit Phase)** to put the satellite into orbit but also during the normal operation of it to maintain its trajectory, to retrieve its data and to send it commands.

Regarding future works and possible extensions of this thesis could be implemented in an RFTC two additional problems, the first one is represented by interference, however this issue is often not considered as in the analyzed elaborate since it is very hard to have it on a satellite communication, for several reasons: the powers and the frequencies employed by the ground station antennas are not compatible with any other instruments, employed antennas are particularly directive and so not so exposed to interferences, moreover ground reference station are placed in very controlled environments and finally satellites are built and managed to avoid interference between each other during their orbital operations.
However, it is not possible to exclude a priory that this problem can arise in future in particular due to the fact that some malicious can begin to have interest to ruin satellite communications or due to the self-interferences that are in some ways also more critical to control.
The second issue that could extend the RFCT instead is how both the on-board and ground receiver react to the phenomena of multi-path, in particular the one due to the combination of the signals received by the different antennas of the satellite which no implement different polarizarions.
Therefore to further complete this work a possible implementation of the above exposed problems could be carried out, merged with "stress-tests" act to validate the receivers operability when the connection is densely used.

Appendix A

Standard ECSS-E-ST-50-05

From the range of frequency between **2025-2120 MHz** the ECSS-E-ST-50-05C standard establishes that:

1. the EIRP transmitted from the Earth station shall be selected to allow for a margin of 3 dB on the link budget, in order to minimise interference to the Earth-space links of other spacecraft or to the space-space links from data relay satellites to user satellites, which are particularly susceptible to RF;

2. the use of an EIRP value higher than the one specified in 1. shall be analysed and justified;

3. Earth station transmitters shall provide the functionality for adjustable RF output power in steps of 3 dB or less;

4. operators shall not activate the Earth-space links during periods when no tracking and telecommand operations are performed in order to alleviate the frequency sharing situation.

From the range of frequency between **2200-2300 MHz** indeed the standard establishes that:

1. the maximum bandwidth for satellite shall not exceed 6 MHz;

2. operators cannot use the space-to-Earth links during periods when the ground station is not in visibility of satellite;

3. The devices on satellite used to switch-off emissions shall have a reliability which is commensurate with the mission lifetime.

These last 2 rules are introduce to alleviate the frequency sharing situation and interference issues since the considered band is densely occupied.

Moreover, it is not possible to transmit from the Earth to Satellite using an antenna with a tilt angle with respect to the ground surface (elevation) lower than 5° to avoid human healty issues.

Appendix B

MATLAB® Code for Doppler computation

```
clear all
close all
clc

%% Doppler shift and doppler rate computation
%for the geometry description of the problem referring to figure 7.3
%for theory explanation referring to sub-chapter 7.2.4.1

%mass of the Earth
M_earth = 5.98*10^24;

%gravitational constant
G = 6.673*10^-11;

%speed of light
c = 3*10^8;

%radius of the Earth
r = 6380*10^3;

%distance satellite-Earth
h_sat = 250*10^3;

%downlink frequency
f0 = 2253.5*10^6;

%passage duration set to 12 min (720 sec)
pass_time = 720;
```

```
%distance between satellite and center of the Earth
R = r + h_sat;

%satellite speed
v = sqrt((G*M_earth)/R);

%vector of time that simulates the duration of the passage
t = 0:1:pass_time;

%angle alpha: angle of half passage
alpha = acos(r/(r+h_sat));

%rad conversion
alpha_deg = rad2deg(alpha);

%angle beta: angle traveled by satellite in 1s
beta = 2*alpha_deg/pass_time;

%rad conversion
beta_rad = deg2rad(beta);

%angle traveled in the entire passage
beta_pass = beta_rad*t;

%angle step by step
beta_diff = alpha - beta_pass;

%range:distance satellite station
l = sqrt(r^2 + R^2 -(2*r*R*cos(beta_diff)));

%angle gamma
gamma = asin((r./l).*sin(beta_diff));

%angle gamma'
gamma_prime = deg2rad(90) - gamma;


%radial component of satellite speed
v_r = v*cos(gamma_prime);

%doppler shift computation
fd = f0*(v_r/c);
```

```
%doppler rate computation
for i=2:1:pass_time

 d_rate(i) = (fd(i)-fd(i-1));

end

%file writing: the obtained results are written in
%two files to be loaded in the signal generator.

%doppler shift file
doppler_shift = fopen('doppler_shift.txt' , 'wt');
fprintf(doppler_shift ,'%6.2g\n' , fd);
fclose(doppler_shift);

%doppler rate file
doppler_rate = fopen('doppler_rate.txt' , 'wt');
fprintf(doppler_rate ,'%6.2g\n' , d_rate);
fclose(doppler_rate);


%doppler shift plotting
subplot(2,1,1)
plot(fd, 'LineWidth', 2);
ylabel("Doppler shift (f_d) [Hz]")
xlabel("time [s]")
xlim([0,720])
grid on
grid MINOR

%doppler rate plotting
subplot(2,1,2)
plot(d_rate, 'LineWidth', 2);
ylabel("Doppler rate [Hz/s]")
xlabel("time [s]")
xlim([0,720])
grid on
grid MINOR
```

Appendix C

Python Code for BER estimation

```
##BER Estimation
#for theory explenation reffering to sub−chapter 7.2.5
#import libraries
#import math library to use math symbols
#in hexdecimal to binary conversation
import sys
import math

#in order to change the file, change the name in the window
#that the script opens when it is executed and press Enter.
#NB: the extension has to be .txt and
#files should be of the same length to have reliable comparison
print("Insert name of first file with extension and press Enter:")
file1=input()

print("Insert name of second file with extension and press Enter:")
file2=input()
print("\n")

#opening and reading the 2 files
f1=open(file1, "r")
f2=open(file2, "r")

content=f1.read()
content2=f2.read()

#check if the read function acts as exepected visualizing
#the heads (first 50 elements) of the files
print("Head of first telemetry file:")
print(content[0:50])
```

```
print("\n")
print("Head of second telemetry file:")
print(content2[0:50])

#content of files processed to remove space and new line characters
f1=content.replace(" ","")
f1=f1.replace("\n","")

f2=content2.replace(" ","")
f2=f2.replace("\n","")

#removing header intrduces by the BBU in the telemetry messages
#to compute the BER only for information bits.

#script ask to user if BBU header is present or not, press y + Enter
#if it present or n + Enter if it is not.

#METHOD: use find() to find the synch word and from it remove all
#hexdecimal symbols of header, then find and remove the postamble
print("If file contains BBU header press y otherwise n, then press
    Enter")
print("\n")
decision=input()

#in case of BBU header
if decision == "y":

    header1=0   #counter of headers of the first file
    header2=0   #counter of headers of the second file
    index=0     #index uses for the search in the first file
    index2=0    #index uses for the search in the second file


    #removing of header of telemetry message beging from the synch
    #word added by BBU to transmit then the packet to ultimate user
    print("BBU header/postamble removing...\n")
    while index != -1:
        index=f1.find("499602d200000444000000000")
        f1=f1.replace(f1[index:index+128],"")
        if index != -1:

        #counter to count the header in file1, any time a header word
        #is found it is incremented
            header1=header1+1
        else:
            print("...first file BBU header removing completed\n")
```

```
    while index2 != -1:
        index2=f2.find("499602d20000044400000000")
        f2=f2.replace(f2[index2:index2+128],"")
        if index2 != -1:

         #counter to count the header in file2 , any time a header word
         #is found it is incremented
            header2=header2+1

        else:
            print("...second file BBU header removing completed\n")

    #removing of postamble of the telemetry message added by BBU for
    #the same reason before
    f1=f1.replace("b669fd2e","")
    f2=f2.replace("b669fd2e","")

#printing of number of headers removed
print("Number of headers remove in first file:",header1)
print("Number of headers remove in second file:",header2)

#in case of not validit entry the program stops and invites the user
#to restart the section
if decision != "y" and (decision != "n"):
    print("\n NOT VALIDIT ENTRY!!!!!! Restart the section!\n")
    sys.exit()

#in case the file does not contain BBU header it is ready for
#binary conversation without header removing

#check if the data processing is correct printing
#the heads of the two strings
print("\nHeads of the two file after the header removing:")
print(f1[0:50])
print("\n")
print(f2[0:50])

#hexadecimal to binary conversation
#counters initialization
i=0
j=0
r=0
count=0
```

```
#lists of results initialization
bin_f1=["0" for j in range(0,len(f1))];
bin_f2=["0" for r in range(0,len(f2))];

#conversation from hexadecimal value to binary value file 1
while i < len(f1):
    bin_f1[count]=str(bin(int(f1[i],16))[2:])

    #adding 0 padding to have symbols of equal length=4
    if len(bin_f1[count]) < 4:
        while len(bin_f1[count]) < 4:
            bin_f1[count]="0"+bin_f1[count]
    count=count+1
    i=i+1

#counters reset to convert the content of file 2
i=0
j=0
count=0

#conversation from hexadecimal value to binary value file 2
while i < len(f2):
    bin_f2[count]=str(bin(int(f2[i],16))[2:])

    #adding 0 padding to have symbols of equal length=4
    if len(bin_f2[count]) < 4:
        while len(bin_f2[count]) < 4:
            bin_f2[count]="0"+bin_f2[count]
    count=count+1
    i=i+1

#check if the binary conversion is performed
#printing the heads of the lists of results
print("heads of the two lists after binary conversation:")
print(bin_f1[0:10])
print(bin_f2[0:10])
print("\n")

#list to string conversion to compare later the data
bin_f1=''.join(bin_f1)
bin_f2=''.join(bin_f2)

#printing of the heads of the strings to verify
#if the conversation is successful
print("heads of the two files after binary conversation:")
```

```
print(bin_f1[0:50])
print(bin_f2[0:50])
print("\n")

#check if the two strings have the same length to have a reliable
   comparison
print("length of first string:", len(bin_f1))
print("length of second string:", len(bin_f2))

#check and count the number of different bits
#METHOD: using a while cycle read the two files
#and compare bit to bit the contents, any time a
#difference is found the counter "different" is increased

different=0
i=0

while i < len(bin_f2):

    if bin_f1[i] != bin_f2[i]:
        different=different+1
    i=i+1

print("Number of different bits:", different)

#BER computation and printing
#METHOD:number of different bits found
#divided by the whole number of bits
BER=different/len(bin_f1)

print("BER:",BER)
```

Appendix D

MATLAB® Code for Link budget

```
clear all
close all
clc
%%Link Budget Computations
%for theory explanation referring to chapter 8
%% DOWNLINK
CN0 = 52.706; %measure C/N0 from Malindi station

%C/N0 required for telemetry acquisition from SGICD
CN0_req = 17; %used to acquire only the carrier

%C/N0 required for ranging acquisition from SGICD
CN0_req_RNG = 19; %used to acquire only the RNG tone

%Eb/N0 threshold from SGICD
EbN0 = 2.8; %used to acquire signal considering also date demodulation

%% TELEMETRY RECEIVER THRESHOLD

%in this part of the code are computed the losses present in the
%telemetry link (that is the same used for ranging reception)
%from satellite to GRS, using the Bessel function and the modulation
%index reported for the specific link and modulation.
%losses of carrier modulation: the modulation introduces some losses
%in the carrier
carrier_mod_index = 1.219; %computed as the nominal one 1.15 rad + 6%
                            %worst case scenario

TM_carrier_mod_loss = -10*log10(besselj(0,carrier_mod_index)^2);
```

```
%C/N0 for worst case scenario
CN0_worst = CN0 - TM_carrier_mod_loss;

%losses due to ranging: the presence of the ranging in the same channel
%of telemetry introduces some losses
RNG_tone_mod_index=0.280;

TM_due_to_RNG_loss = -10*log10(besselj(0,RNG_tone_mod_index)^2);

%losses due to TC echo modulation: part of the power received in the
%uplink channel is accidentally send back generating lossses
back_TC_mod_index=0.419;

TM_due_to_TC_echo_loss = -10*log10(besselj(0,back_TC_mod_index)^2);

%losses due to noise modulation: noise in the path introduces losses
noise_mod_index=0.105;

TM_due_to_noise_loss = -10*log10(exp(-(noise_mod_index)^2));

%Ground station losses due to PLL (bandwith = 100 Hz)
PLL = 10*log10(100);

%total losses
total_loss = TM_carrier_mod_loss + TM_due_to_RNG_loss + ...
    TM_due_to_TC_echo_loss + TM_due_to_noise_loss + PLL;

%downlink C/N0 considering the losses
CN0_loss= CN0 - total_loss;

%Margin: computed es the actual C/N0 considering losses
%and the C/N0 requested
margin_th_rx = CN0_loss - CN0_req;

%expected TELEMETRY RECEIVER THRESHOLD: computed as the C/N0 meausered
%and the margin
TH_rec = CN0 - margi_th_rx;

%% TELEMETRY FRAME LOCK THRESHOLD

%This term is different since now also the
%data acquisition is involved, so we must consider the entire spectrum
%of the signal, this is possible using also the Bessel function of
%first order and the bit rate
%losses of sub-carrier modulation: the modulation introduces some
```

```
%losses in the sub-carrier
sub_car_mod_index = 1.081; %computed as the nominal one 1.15 rad - 6%
                           %worst case scenario

TM_sub_car_mod_loss = -10*log10(2*besselj(1,sub_car_mod_index)^2);

%loss due to ground station demodulator
Gs_tech = 1;

%total loss computed using the results obtained before
total_loss = TM_sub_car_mod_loss + TM_due_to_RNG_loss + ...
    TM_due_to_TC_echo_loss + TM_due_to_noise_loss + Gs_tech;

%bit rate from SGICD
bit_rate = 7100;

%losses due to bit rate
bit_rate_dB = 10*log10(bit_rate);

%downlink Eb/N0 considering the losses and the employed bit-rate
EbN0_lock = CN0 - total_loss - bit_rate_dB;

%Margin: this time the Eb/N0 is employed since the attention is not
%only on the carrier acquisition but also on data reception
margin_lock = EbN0_lock - EbN0;

%expected TELEMETRY FRAME LOCK THRESHOLD
TH_lock = CN0 - margin_lock;

%RANGING THRESHOLD, downlink case

%since ranging use the same downlink channel of telemetry, it
%experiences the same losses so the same quantities computed
%before are used to estimate this threshold
%ranging C/N0 considering the losses
CN0_RNG = SN0 - total_loss - RNG_mod_loss;

%Margin
margin_RNG = CN0_RNG - SN0_req_RNG;

%expected RANGING THRESHOLD for downlink
TH_RNG_down = SN0 - margin_RNG;

%% UPLINK

CN0 = 67.568; %measure C/N0 from South-Point station
```

```
%C/N0 required for telecommand acquisition from SGICD
CN0_req = 19; %used to aquire only the carrier

%BER and the correspondig Eb/N0 required for correct
%telecommand decoding from SGICD
TC_BER_req = 10^-5;

EbN0_req_for_BER = 9.6;

%% UPLINK ACQUISITION THRESHOLD

%in this part of the code are computed the losses present in the
%telecommand link (that is the same used for ranging transmission)
%from GRS to satellite, using the Bessel functions and the modulation
%indexes reported for the specific link and modulation.
%losses of carrier modulation: the modulation introduces some losses
%in the carrier, moreover, the presence of RNG signals also introduces
%some losses
carrier_mod_index = 1.05; %computed as the nominal one 1.00 rad + 5%
                          %worst case scenario

up_tone_mod_index = 0.63; %computed as the nominal one 0.6 rad + 5%
                          %worst case scenario

TC_carrier_mod_loss = -10*log10(besselj(0,carrier_mod_index)^2*...
    besselj(0,up_tone_mod_index)^2);

%satellite carrier acquisition technical loss
sat = 2;

%satellite losses due to PLL
PLL = 960;

PLL_dB = 10*log10(PLL);

%total losses
tot_loss = TC_carrier_mod_loss + sat + PLL_dB;

%uplink C/N0 considering the losses
CN0_worst = CN0 - tot_loss;

%Margin: computed es the actual C/N0 considering losses
%and the C/N0 requested
margin_th_ac = CN0_worst - CN0_req;
```

```
%expected UPLINK ACQUISITION THRESHOLD: computed as the C/N0 meausered
%and the margin
TH_up = CN0 - margin_th_ac;

%% TELECOMMAND REJECTION THRESHOLD

%bit rate from SGICD and losses due to bit rate
TC_bit_rate = 2000;
TC_bit_rate_dB = 10*log10(TC_bit_rate);

%this term is different since now also the
%data acquisition is involved, so we must consider the entire spectrum
%of the signal, this is possible using also the Bessel function of
%first order and the bit rate.
%losses of sub-carrier modulation: the modulation introduces some
%losses in the sub-carrier
sub_carrier_mod_index = 0.95; %computed as the nominal
                              %one 1.00 rad - 5% worst case scenario

TC_mod_loss = -10*log10(2*besselj(1,sub_carrier_mod_index)^2*...
    besselj(1,up_tone_mod_index)^2);

%uplink Eb/N0 considering the losses and employed bit-rate
EbN0 = CN0 - TC_mod_loss - sat - TC_bit_rate_dB;

%Margin
margin_th_rej = EbN0 - EbN0_req_for_BER ;

%expeceted TELECOMMAND REJECTION THRESHOLD
TH_rej = CN0 - margin_th_rej;

%RANGING THRESHOLD, uplink case

%since ranging use the same uplink channel of telecommand, it
%experiences the same losses so the same quantities computed
%before are used to estimate this threshold
%ranging C/N0 considering the losses
CN0_RNG = SN0 - RNG_mod_loss - TC_mod_loss - sat;

%Margin
margin_RNG = CN0_RNG - SN0_req_RNG;

%expected RANGING THRESHOLD for uplink
TH_RNG_up = SN0 - margin_RNG;
```

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