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**Master Thesis**

# System Design for a Compact Antenna and RCS Test Range

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# Assignment of Tasks

The Institute of High Frequency Technology plans to refurbish its antenna measurement facility and to replace the traditional far field range by a modern Compact Range. In the course of this thesis, some fundamental system design issues regarding such an installation will be investigated and their impact on the requirements of the main sub-systems such as

- Anechoic chamber
- Reflector and feed antennas
- Radio frequency instrumentation
- Mechanical antenna positioners
- Control and data postprocessing software

shall be quantified.
These findings shall be summarized in a Requirements Specification which will eventually be used to evaluate proposals from potential suppliers of Compact Ranges.

# Summary

## System Design for a Compact Antenna and RCS Test Range

The purpose of this master thesis was to determine the fundamental design features of the subsystems that conform a Compact Antenna and RCS Test Range.
The major part of this work focused on evaluation and investigation regarding the RF Instrumentation subsystem possibilities of the future measurement range.
Since one of the parameters that have more impact on the performance of the future range is the Measurement Dynamic Range, e.g. in order to deal with sidelobesupression generated in this kind of ranges, the goal of the project focused on conceiving a procedure to obtain a reliable Dynamic Range estimation once the antenna range instrumentation characteristics are known. In addition, comparisons of different RF instrumentation layout options are presented, including not only performance in terms of Dynamic Range; but also in terms of optimal settings for each component configuring the RF Instrumentation subsystem. This circumstance led not only to results regarding performance confrontation between different instrumentation geometries and components, but also to the development of a software tool able to calculate and evaluate the previous characteristics mentioned.
This document will describe the procedure to evaluate compact range RF system performance in terms of Dynamic Range. Afterwards, the results obtained through analysis of concrete layouts options will be presented and an introduction to the developed software calculation tool will be exposed.

# Kurzfassung

## System Design für eine kompakte Antennen und RCS Messkammer

Der Zweck dieser Masterarbeit war, die grundlegenden Entwurfseigenschaften der Subsysteme festzustellen, die eine kompakte Antennen und RCS Messkammer anpassen. Insbesonders führt die Arbeit zur Auswertung und Analyse der Eigenschaften und Möglichkeiten des RF-Instrumentenausrüstungssubsystems der zukünftigen Antennenmessanlage.
Eines der Parameter, dessen Auswirkung auf die Leistung der zukünftigen Anlage am einflussreichsten ist, ist die Systemmessdynamik, z.B., zwecks Nebenzipfelunterdrückung, dessen Erzeugung durch dieser Art von Kammern nicht ausgeschlossen bleibt. Deshalb war ein Brennpunkt die Ermittelung eines zuverlässigen Verfahrens das fähig ist, sobald die Instrumentation Eigenschaften festehen, die Systemmessdynamik zu bestimmen. Zusätzlich wird ein Vergleich der verschiedenen Auslagemöglichkeiten der RF -Instrumentenausrüstung dargestellt. Dieser Vergleich umfasst nicht nur Systemleistung vom Sichpunkt Messdynamik aus, sonder kann durch diesen Vergleich auch die optimalen Einstellungen für jedes Bestandteil des Systems bestimmt werden. Dieses führt nicht nur, zu Resultate betreffend Leistungskonfrontation zwischen verschiedenen Instrumentenausrüstungsgeometrien und dessen Bestandteilen, sondern auch, zur Entwicklung eines Software-Tools, das fähig ist, die erwähnten Eigenschaften zu berechnen und auszuwerten.
Dieses Dokument beschreibt nicht nur das Verfahren um, im Rahmen einer kompakten Antennenmessanlage, die RF -Systemsleistung, in Dynamikwerten ausgedrückt, auszuwerten, sonder auch die Resultate darzustellen die durch Analyse der konkreten Auslageplanmöglichkeiten erreicht wurden. Zusätzlich, folgt eine Einführung zu dem entwickelten Software-Berechnungswerkzeug.

# Contents

# 1. Introduction

The Institute of High Frequency Technology (IHF) works, among other topics, on research of new antenna systems and its development. This the research also covers the study of innovative methods regarding measurement techniques for this antenna systems. Nowadays, communication technology shows a tendency towards interdisciplinary procedures, e.g. classical antenna technology together with wireless and/or mobile communication encryption procedures. This fact turns out into rising requirements to be reached by the antenna measurement technique. As a consequence of this background scenario, the range is demanded to characterize small to middle antennas, and/or antenna systems. This demand should be done within the interesting frequency range in such systems going, from 0.8 GHz to 60 GHz. Measurements of the radar cross section (RCS) of objects are also demanded. Thus, in order to cope with the current demands and to obtain a greater profit of the anechoic chamber found at the institute, the future range is conceived as a Compact Range (CR) working in combination with a Spherical Near Field Range (SNF). See appendix A for more information.

In a first stage, the operation of a CR is straightforward; advantages of plane wave propagation can be found plus the advantages related of having the option to place the range indoors. However, its ultimate design, construction, and installation should be carefully considered. Obtaining maximum measurement capacity is one of the fundamental challenges of laying out this type of ranges. That is why the definitive decision concerning the design and layout of the range should be studied accurately. This concept will be introduced in chapter 2.

Chapter 3 consists of a description of how CR's are able to perform any testing that can be accomplished by a traditional far-field range, with the significant difference that it is done avoiding distance restriction attached to maximally permissible phase difference or far-field condition. Detailed description of CR working fundamentals and ways a CR can be implemented will be also listed in this chapter.

To fulfill the antenna measurement requirements, an accurate analysis of the antenna measurement system is done. These results lead to the definition and description of a procedure able to determine the critical parameters. These parameters are the measurement Dynamic Range ($DR$), measurement speed and measurement accuracy. But also interface requirements between components configuring the system[1] should be reviewed. The extended development of this procedure and a concrete example are found in chapter 4.

As the calculation of these parameters is tied to multiple variables, a software tool

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[1] In this case, the study refers to a CR RF instrumentation subsystem, even if this analysis can be extended to other type of antenna test ranges.

has been created intended to ease the selection and characteristic statement of a concrete system layout option. An approach to this MATLAB® based tool is provided in chapter 5.

The software developed plus the conclusions reached in chapter 4 led to trial concrete system configuration alternatives. These alternatives are based on different geometries regarding the position of components. Specific settings for each component working within different configurations have been also strictly studied. In chapter 6, the results are expressed in terms of performance comparison between different options.

The developed work represents a study of CR performance in terms of RF measurement instrumentation. Obtaining a general procedure added to the software aid, applied to concrete system options analysis, permitted stating what is to expect in case these alternatives are laid out within the future range. Finally, it is significant to mention that, considering the way this method is conceived it will be able to be adapted to possible future new layout proposals and requirements.

# 2. Motivation-Compact Range measurement performance

The choice to pick a concrete measurement range and measurement technique, in this case the CR, is a consequence of considering this technique able to meet performance requirements. Nevertheless, implementing a concrete method into a concrete range, in this case the IHF's anechoic chamber, is directly related to electrical limitations which, at the same time, can affect the expected performance. In other words, despite the benefits related to a CR, it has to be proved that working within its future site, it will reach expected performance. That means working out the settings and conditions that will allow optimal overcoming of inherent limitations of this kind of ranges [1].
The recognition and quantification of measurement requisites is necessary. The fact that the possibility to perform RCS measurements is demanded, sets tight requirements regarding measurement resolution which, at the same time, turn into requirement of Dynamic Range ($DR$) values around 80 dB [2] [3] [4].
Another key factor regarding $DR$ requirements is related to the CR technology itself. It is essential to remind that CR is based, in the case of the IHF, on a reflector and a feed in the reflector's parabola focus. Even if that means higher cross-polar levels due to loss of symmetry within the structure, sidelobe suppression level increases considerably as better control of sidelobe level is possible to be achieved [5]. It can be assumed that, sidelobe suppression levels of 50 dB will be present in the system [6] [7] [8].
Therefore, considering the intrinsic loss budget[1] found in the system in extreme cases (Figure 2.1), at least 50 dB measurement $DR$ should be guaranteed.

Measurement $DR$ depends on the power level received and minimum detectable power level, in other words, the sensitivity level. The value taken for this level is the noise floor of the system, directly related to the bandwidth of the receiver. As the sensitivity level is defined as the noise floor, this level should be as low as possible to ensure maximum $DR$. However, as it will be seen in chapter 4, noise floor reduction through bandwidth narrowing is an option at the expense of measurement time/speed. Here, one of the trade offs that will appear when evaluating measurement performance of the system shows up [9]. In chapter 4 the $DR$ concept will be exposed meticulously. Also the concrete and detailed requirements for the future range can be found in appendix A.
On the other hand, in practice, $DR$ enhancement is tied to the available power at the reception side. This level is firmly tied to the spatial distribution of the components [10].

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[1] Cable losses are only considered up to 50 GHz. From this frequency on waveguide solutions will be implemented. See subsection 4.1.3 for more information.

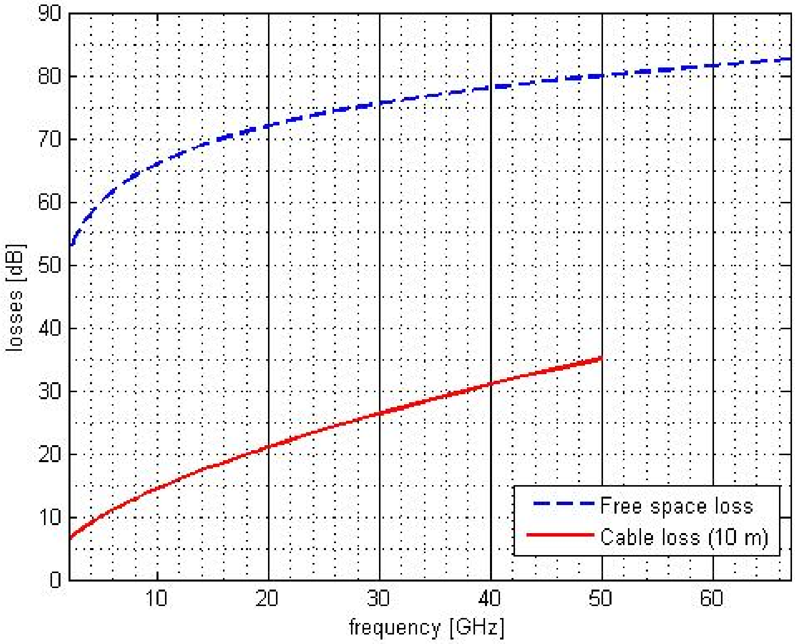


Figure 2.1.: Example of average RF System inherent losses due to facility characteristics. Taken from appendix A.

An example can be seen for two different geometries and component combination in Figure 2.2.
Same geometries but different components can mean as well several differences in terms of measurement performance. In Figure 2.3 received power level comparison is pictured for two different providers both proposing remote frequency downconversion. Even with same components with different settings the same situation can be found. For example, noise floor or noise power reaching the receiver is given by the expression that follows [9]:

$$N = kTB \tag{2.1}$$

$k$ is Boltzmann's constant, $1.38 \times 10^{-23}$ J/K
$T$ is the equivalent noise temperature, K
$B$ is the bandwidth of the receiver, Hz

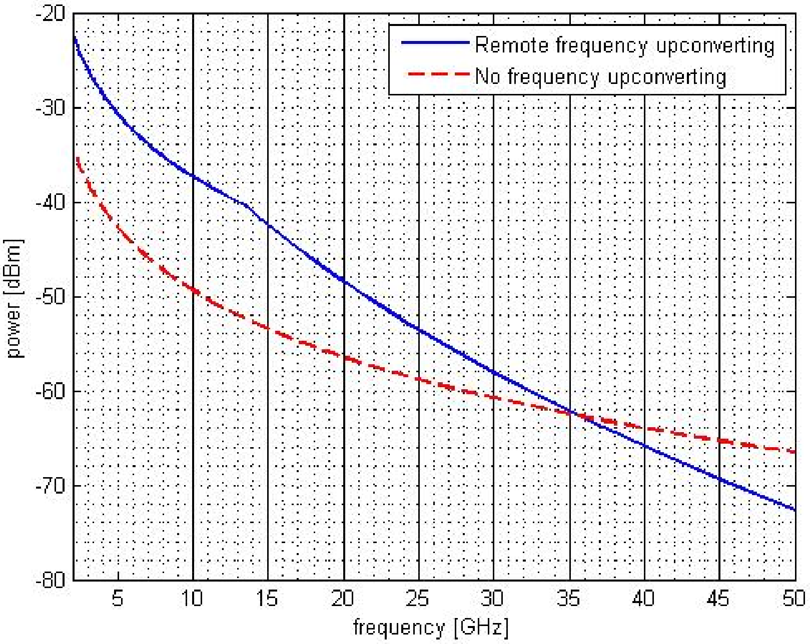


Figure 2.2.: Comparison between different system geometries. Taken from chapter 6.

If the bandwidth of the receiver is narrowed by a factor of 10, e.g. from 10 kHz to 1 kHz, noise power can be reduced by 10 dB, but in detriment of measurement speed by a factor that will be around the same magnitude [11] [4].
This proves the need to obtain a reliable $DR$ estimation and simultaneously analyze, weigh up and evaluate the way measurement instrumentation is going to be implemented into the range.

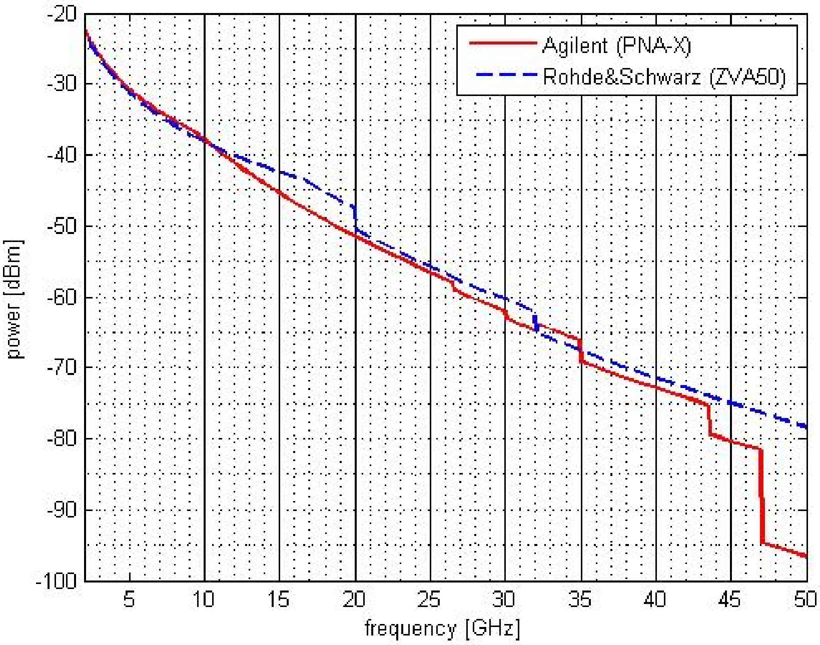


Figure 2.3.: Comparison between different providers, both considering working with remote frequency converting options. Taken from chapter 6.

# 3. Compact Range working fundamentals

As it has been introduced in previous chapters, the future range at the IHF is going to be a Compact Range (CR). Antenna measurement, in other words, Antenna Under Test (AUT) characterization, requires the device to be illuminated by a uniform plane wave, also known as far-field conditions. That means, being subjected to the far-field distance/frequency restriction applying to the range length. In order to avoid that bond and simultaneously cover the desired frequency range within the anechoic chamber, the CR generates the far-field conditions by collimating the spherical wave front coming from the feed antenna into a plane wave incident on the AUT. This transformation is achieved with illuminating lenses or reflectors. Under physical optics approach and within the reflector's proximity, it is possible to consider that the reflected rays are parallel and in phase.

Roughly, following the general pattern for antenna measurement ranges [9], the subsystems configuring a CR can be divided into anechoic chamber, reflector, feed antennas, Radio Frequency (RF) instrumentation and mechanical antenna positioners. Finally there is a last subsystem, the control and data processing software.

Even if the focus of this work is centered on RF instrumentation, a brief analysis has been drawn up on each of this subsystems since in a minor or greater manner they influence overall system performance.

## 3.1. Compact Range-Definition

The purpose behind developing a CR is to generate far-field conditions within a specific zone of interest. Far-field conditions are an indispensable requirement for antenna characterization when no further mathematical processing is applied to the measured data. In cases like this it would concern to a Spherical Near Field Range [9].

The electromagnetic waves forming the radiation field of an antenna can be characterized by its Poynting vector $\vec{\wp} = \vec{E} \times \vec{H}$. The exact expression for the electric ($\vec{E}$) and the magnetic ($\vec{H}$) field can be obtained by developing Maxwell's Equations in terms of wave equations [5]. In this case, they would have a real and an imaginary term, in other words, spherical wave properties which mean dependencies of the type $1/R^2$ and $1/R$, for both phase and amplitude, and where $R$ is the relative distance to the radiation origin.

A criterion used to establish the far field distance restriction consists in setting the maximum permissible phase error to consider uniform wave propagation. When this bound is replaced into the expression of the radiation pattern, or Fourier transformation of the aperture distribution, the resulting expression gives the tie in terms of distance that follows [5]:

$$r > \frac{2D^2}{\lambda} \tag{3.1}$$

$D$ is the largest aperture dimension of the AUT
$\lambda$ is the measuring wavelength

Due to the reflector or lens of a CR, this restriction can be avoided as seen in Figure 3.1. However, this conditions apply only locally, that is to say, close to the aperture of the reflector and along a restricted portion of space. Due to this circumstance, the planar electromagnetic front available for AUT illumination is limited to the mentioned restricted space volume, which is called Quiet Zone (QZ) as Figure 3.1 shows. It could be explained through reflector´s principle of operation which is inherited from optics. Even if a CR could implemented with reflectors or lenses, this work will focus on reflector CR, as the future facility at the IHF is conceived as a single reflector CR. This issue will be discussed in the next section.

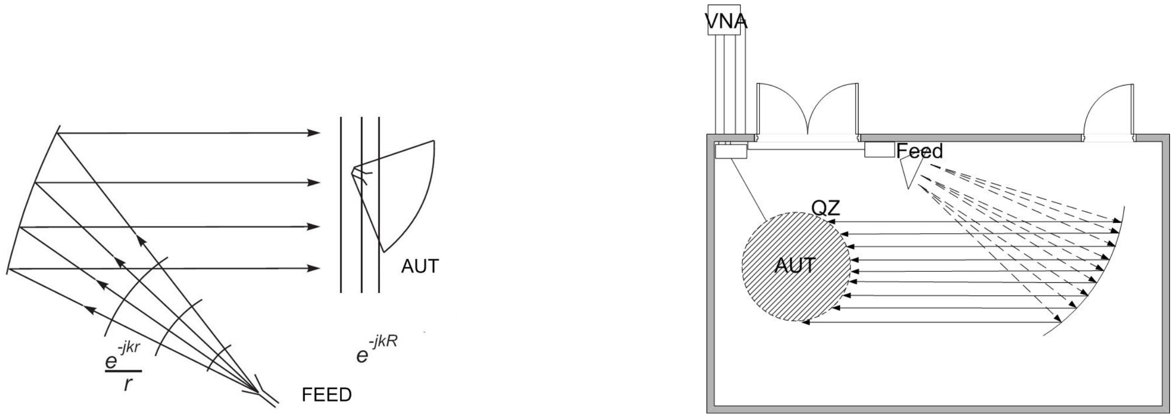


Figure 3.1.: Compact Range schematic.

It is established by means of a geometric optics approach that any wave with its source placed in the reflector's focus will be reflected in a parallel way as a consequence of Snell's law. In addition, if the curvature of the reflector is locally considered negligible, it can be approximated that the traveled path for each ray is the same length when reaching reflector's aperture [5]. The approach at hand is sufficiently good if the curvature radius is greater than $\lambda$. This condition, plus additional facts appearing in the next section, will show how significant the relations anechoic chamber-reflector size and reflector-feed position are. The circumstance that the dimensions of the reflector are not infinite plus the imperfections/limitations of the rest of the components, evince that the QZ will reveal imperfections found in form of both amplitude taper and ripple, plus, phase ripple across its volume [12].
The concrete settings and measurement quality parameters applying for the future IHF CR can be found in Appendix A.

## 3.2. Compact Range main subsystems

**Anechoic chamber and absorber layout**

The reflector system's size imposes the frequency range and the QZ volume, but at the same time, the chamber's size. But if it is the other way round, as the case of the future IHF's range, chamber dimensions are given (Appendix A). This fact involves that the future reflector system must cover the demanded frequency range with the required performance within these dimensions. Moreover, if RCS measurements are demanded from the range, it is fundamental to isolate the targets from the scattering coming from the chamber and the positioning equipment. By doing so, measurement distortion is avoided.

Therefore QZ quality is one of the most important parameters of the CR. Apart from the reflector's influence, scattered energy coming from the surrounding walls, roof and floor of the chamber can be introduced into the QZ. And even if the major part of the energy is within the collimated beam, part of it is not captured by the AUT and can turn into reflections coming from the back-wall of the chamber. Considering these effects, RF absorbing material with a recommended reflectivity of at least -50 dB has to be laid out. This material, also called absorber layout, is frequency dependent and different studies regarding the layout pattern, e.g. Chebychev Multilevel pattern, have been developed [13].

However, in order to solve residual scattering, different error correction techniques such as background subtraction [14] or classical averaging are applied in order to improve measurement quality.

It is also significant to maintain temperature stability within the facility. This consideration will achieve relevance in terms of Dynamic Range ($DR$) of the measurement system, as this performance parameter is directly dependent from the available thermal noise power at the Antenna Under Test (AUT) (See expression 2.1).

**Reflector and feed antennas**

A CR can be build with reflectors or with a lens as collimating elements. Both of them represent the principles of transforming spherical waves into plane waves. Although lenses are proved to be a good option for high frequencies, behaviour is not as broadband as a reflector's [5]. Diverse configurations can be implemented with the reflector option. Different geometries go from a Single Reflector CR (SCR) to a Double Reflector Compact Range with cylindrical (DCPR) or double curved reflectors (CCR). The lack of symmetry due to the offset configuration of the SCR reveals itself through high cross-polar levels along the QZ [6] [7]. However, it has to be still taken in account that, as it has been mentioned in the previous subsection, the dimensions of the future range are fixed to the dimensions of the anechoic chamber found currently at the institute. Given this fact, only a SCR is a feasible option.

Whenever taking in account the reflector option for the CR layout, it has to be weighted up that the edges of the reflector will generate undesired diffractions that will manifest in form of ripple along the QZ [12]. This fact leads to the next point, the different types of reflectors. In order to minimize edge diffraction at the reflector,

different types of shape options are found. There are serrated or rolled edges [6] [7]. As the aim is to minimize diffracted fields, examining results that come from the research carried out on the topic, rolled edge performs better [15].
A supplementary error source is the reflector's surface itself. First, there is the surface accuracy. Its quality is designated via the Root Mean Square (RMS) surface error. This surface error is referred to a concrete section of the reflector and indicates how much it differs from a perfect parabola [14]. The fact that reflector's size requires this one to be mounted combining different panels, results in undesired effects within the QZ volume. As panel assembly is not perfect, it has been shown that scattering is produced. It has been proved that under certain conditions, this limitation can impact the QZ's quality [16].
To sum up, it can be established that the upper frequency limit will depend on the surface accuracy and alignment of the segments and that the lower frequency limit is determined by the scattering coming from the edges of the reflector [15].
Due to the principles of transmission-reflection behind the CR's reflector's working principle, the ideal feed that would ensure that no power is going to be transferred to the cross polarization would be an ideal Huygens source. It can be proved through Ludwig's second approach that, in practice, feeds which minimize the mentioned behaviour are corrugated horns [5]. See Figure 3.2.

Figure 3.2.: Example of corrugated horn used as CR feed. Taken from **ORBIT/FR datasheet** [17].

When talking about QZ quality, also amplitude taper levels should be kept low. As amplitude taper not only depends on amplitude taper of the feed radiation pattern itself, this should be executed by correct reflector illumination but, simultaneously, keeping spillover controlled. Note that feed spillover also generates scattering and emphasizes the need mentioned at the first point in this section, correct anechoic chamber absorber layout.
It is as well worthwile to point out that obtaining expected QZ volume also depends on the efficiency of the feed radiation pattern, in combination with the reflector system. Correct and constant illumination on the CR reflector system will guarantee desired QZ volume [18].
To conclude, it is important to mention that QZ characterization can be done in advance, before laying out the range.

This is achieved by software simulation tools like GRASP [6] or modeling techniques developed by different authors based on ray tracing and field calculation [19].

### Radio frequency (RF) instrumentation

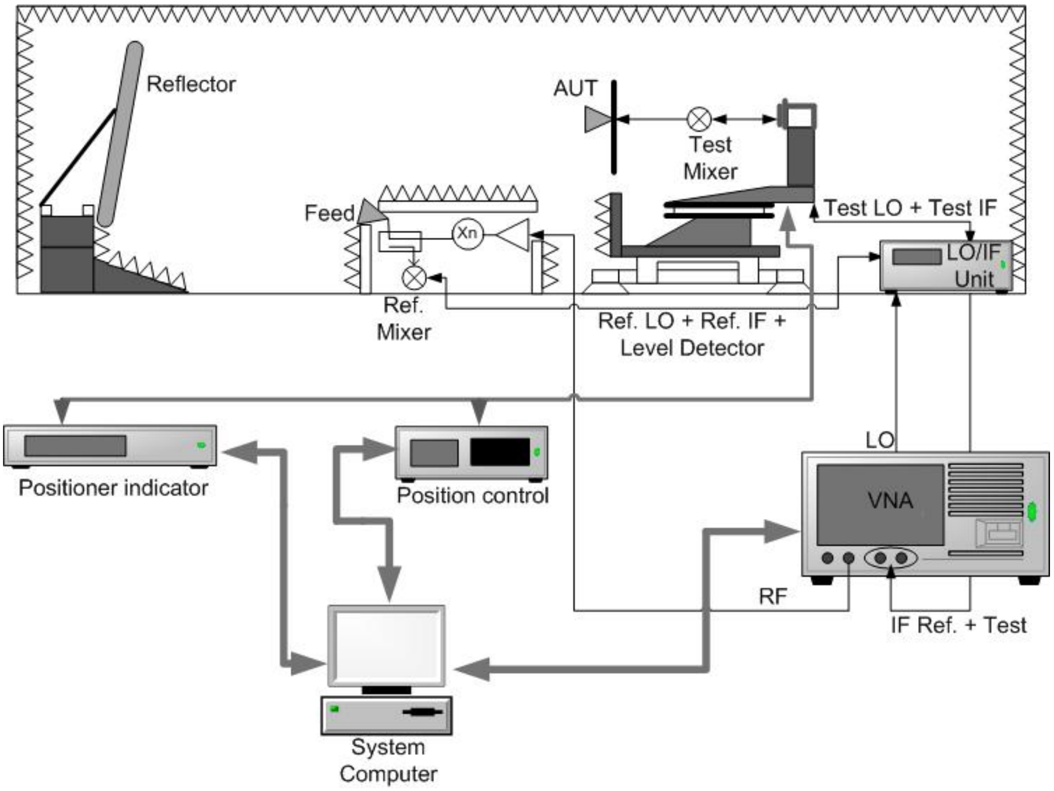


Figure 3.3.: Block diagram for a CR with remote frequency converting.

Under the denomination 'RF instrumentation' microwave receiver (or Vectorial Network Analyzer), source, cables, connectors and antennas can be found. Also frequency converting elements as mixers, multipliers or millimeterwave converters are included. Besides, required elements like couplers, amplifiers and rotary joints belong to this subsystem. See Figure 3.3.
The features and analysis of this subsystem and its performance will be developed in an exhaustive way in chapter 4. Due to the versatility of this subsystem depending on the range and the type of measure wanted to be performed, it is essential to record enough technical documentation to adapt the system settings to each environment plus permitting prediction of its performance. This record includes schematics, general proceedings description and enumerating critical points and magnitudes within the system.

### Mechanical positioners

Mechanical positioning system in this type of ranges usually implies a three axes positioning system for the AUT. First, and following classical antenna positioning coordinate system [9] , the roll over azimuth axis positioner.

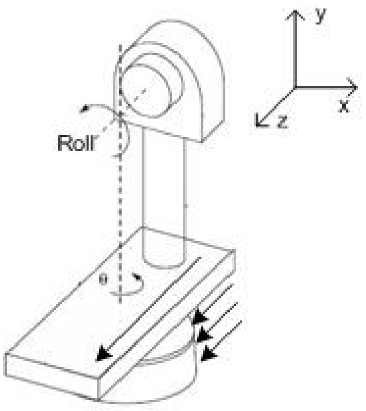


Figure 3.4.: Roll over azimuth positioner.

In this way, in addition with a slide parallel to the roll axis the exact coordinate system center, including the phase center of the AUT on the azimuth axis, can be determined and positioned [5] as Figure 3.4 shows.

At the same time, the positioned antenna, including the positioner tower, should be driven into the test zone without damaging or involving excessive complexity in terms of absorber layout modifying. Different solutions are avaiable for this issue, but for the future range at the IHF this will be done by a motor driven structure that places the whole device into the QZ as pictured in Figure 3.3 and Figure 3.4. See appendix A and **ORBIT/FR datasheet** [17] for detailed description of the future range's positioner including the layout combined with the Spherical Nearfield Range SNF.

Taking up again the RCS measurement requirements, and relating them to the positioning system, furhter considerations have to be made. Due to RCS measurements high performance demands, in terms of accuracy [2], a good ground isolation also has to be provided to avoid measurement corruption through possible vibration [14]. It is significant to bear in mind that this is also applicable to any measurement with a high precision requirement.

Finally, it worthy to mention that accuracy improvement can be achieved through techniques based on including position diversity into the measurement. This method, known as APC scanning, can be applied on both transmission and reception antenna, say positions [20]. This procedure is based on averaging the measured data for different feed positions. Thus, additional slides and/or positioners would be required plus the trade off of measurement accuracy improvement against measurement time increase.

### Control and data processing software

The required level of repeatability, speed, accuracy and efficiency of an antenna measurement system can only be reached by automated instrumentation controlled by a

software over standard bus interfaces. Data processing is also asked from the software. Taken from [9] a general functional block diagram for the software architecture can be established in Figure 3.5.
Reiterating the idea and necessity to have a versatile and adaptable measurement system in order to optimize performance, another required characteristic of the software is to ensure easy transition between different measurement settings.
Detailed description of control and data processing software is out of the scope of this work. Nevertheless, before deciding to chose a concrete option, the software provider should guarantee not only reaching required performance but also warranty, updating and maintenance services over a concrete and agreed period of time. References as **ORBIT/FR Software datasheet** [21], **March Microwave Software datasheet** [22] or **MI Technologies Software datasheet** [23] represent concrete examples of data acquisition and analysis software for antenna and RCS measurements.

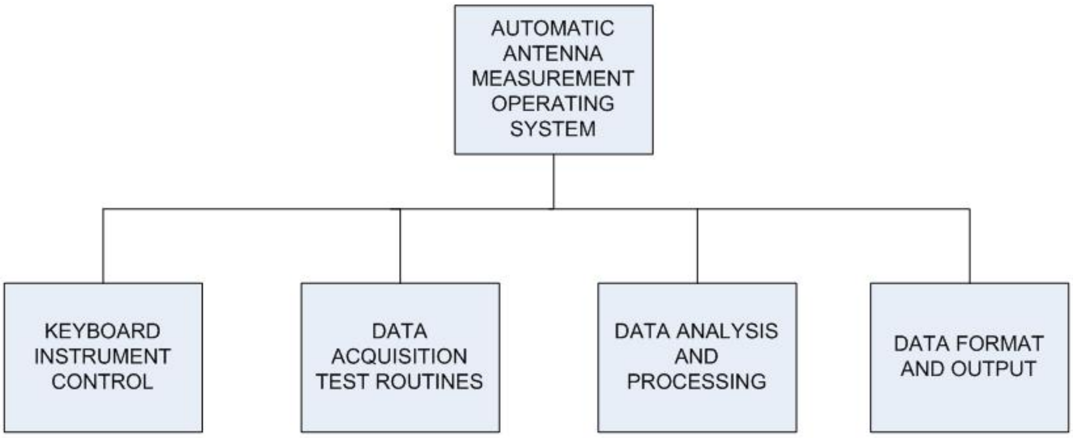


Figure 3.5.: General architecture for control and data processing software. Taken from [9].

# 4. Antenna measurement design considerations for RF instrumentation

This chapter represents one of the main targets sought in this work. Through studying each of the components building the RF instrumentation subsystem, not only the limitations of these components could be worked out, but also its possibilities in order to enhance system performance. Along the process of antenna test range configuration, deciding for a concrete component combination has a direct impact on the system performance. There will be always a trade-off between maximizing system efficiency taking maximum profit of each component without overdriving them out of their intended working state, say conditions. This is the reason why in a first stage, an approach to each of the parts configuring the RF subsystem has been carried out. Then, the analysis has been focused from the opposite perspective. Once the requirements are identified, the whole system scheme is undertaken to an evaluation with the purpose of determining if it is able to cope with the requirements. Through this procedure, the analysis pattern is determined and finally exposed in detail via an example.

## 4.1. RF instrumentation components

If the only frame of reference taken is the complete RF subsystem, this would lead to results in terms of what is to expect from the layout option chosen. Nevertheless, during the process of trying to quantify these qualities there will either show up the need to go back to single component analysis one by one, or, even important limitations of the components can be forgotten. As a consequence, the designer would present theoretical results which will possibly not coincide with real results once the system is laid out. Apart from the obvious check that the component is working within its frequency working range, the next properties should be checked for each component. This power interface related levels are:

*Damage level:* This power cannot be reached under any condition. Within an antenna range this level will be achieved rarely, and as it can be seen next, the most restrictive level is the definition that follows. However, it is worthy to check this value for passive elements, specially in an environment where maximum power transfer is requested.

*0.1 dB Compression point:* To ensure correct accuracy and predictable input-output behaviour of a non-lineal component, this one has to be fed with sufficiently small power to maintain an acceptable linearity behaviour in terms of output power. That means, that a maximum input power is specified, which ensures that the non-linear behavior operation is only a concrete margin away from being lineal. This power level is known as the "X dB Compression point" and a common criteria employed consists in specifying the 0.1 dB compression since at this level linearity errors are proved to be acceptable, apart from being within a known range [24] [25].

*Sensitivity level:* This is the minimum detectable level by a component. It is important not to confuse this value with the sensitivity of the system which will be explained in the next section.

While the components are integrated within the system, when developing a general procedure to evaluate the complete chain of RF range instrumentation performance these issues will be taken in account. If either the frequency range or the listed power levels are not respected, the input-output relation and as a consequence, the whole system performance cannot be ensured.

It is important to mention that every concrete component or component characteristic mentioned in this chapter is taken from the homonym datasheet found in the bibliography.

Concerning the performance characteristics of the components, a term definition or term distinction has to be made. If device/component attributes provided by a manufacturer are given as *Specified*, these values will be warranted as long as the device is calibrated. This would be the desirable way to obtain components characteristics. Nevertheless, as it will be seen through this work, most of the times. Attribute values are given as *Typical.* In this case, the manufacturer does not warrant that performance, even if it happens for a given confidence interval which covers majority of cases (usually for 80-90% of the cases). If the value is given as *Nominal*, that could also mean that this value is not warranted, but it corresponds to the mean or mode of that parameter. Values stated as *Measured* are values measured during design verification and far away from being warranted. Finally, it can happen that the manufacturer gives notice of *Maximum values*, this case means that these values are suitable for a worst-case frame analysis [26] [27].

*Typical* values are employed for the majority of the comparison studies made along in this work- This is because, as it has been already mentioned, these are the values commonly provided by component the manufacturers. If other type of values is given, this circumstance is mentioned in every case.

### 4.1.1. Source

Two types of sources can be distinguished within the RF Instrumentation subsystem. First, RF Source itself; second, the LO source. Even if specific considerations for LO source are exposed in subsections 4.1.4 and 4.2.4, the following considerations apply in both cases. There is a first decision to be taken, external source, say synthesizer, or not. This is one of the far reaching settlements regarding global performance as seen in chapter 6. The properties to revise when analyzing source performance are *frequency range* and *output power level*. It will be sought for that item, to be as high as possible in order to achieve the maximum power on the reception site. By doing this, the maximum system operation can be obtained, despite the system's inherent losses. Due to this reason, the source options undertaken to analysis in the frame of this work do not consider attenuation options to pull output power range down. If, as a consequence of interdisciplinary use of the source a model with attenuation option is chosen, the results of this comparison may vary slightly. Besides, due to this reason, high output power options are chosen. This reasoning also applies to possible frequency expansion options which spread frequency capabilities out of range of this study (2 GHz to 67 GHz). However, these options could be a possibility suitable to hypothetically cover the future Spherical Near Field Range SNF intended to be laid out in combination with the CR [17].
The source models compared are the listed in Table 4.1 and corresponding datasheets can be accessed by clicking on the model's name. Selection criteria to include a model into the comparison of components, is based on different proposals made by potential CR suppliers to the IHF.

Table 4.1.: Source models compared in Figure 4.1.

| **Source Model** | **Freq. Range (GHz)** | **Internal VNA Source?** |
|---|---|---|
| **Rohde&Schwarz® SMR50/60** [28] | 10 MHz to 50/60 GHz | NO |
| **Rohde&Schwarz® ZVA24** [29] | 10 MHz to 24 GHz | YES |
| **Rohde&Schwarz® ZVA50** [29] | 10 MHz to 50 GHz | YES |
| **Rohde&Schwarz® ZVA67** [29] | 10 MHZ to 70 GHz | YES |
| **Agilent E8257D PSG** [26] | 250 kHz to 67 GHz (70 GHz) | NO |
| **Agilent N5245A PNA-X** [30] | 10 MHz to 50 GHz | YES |

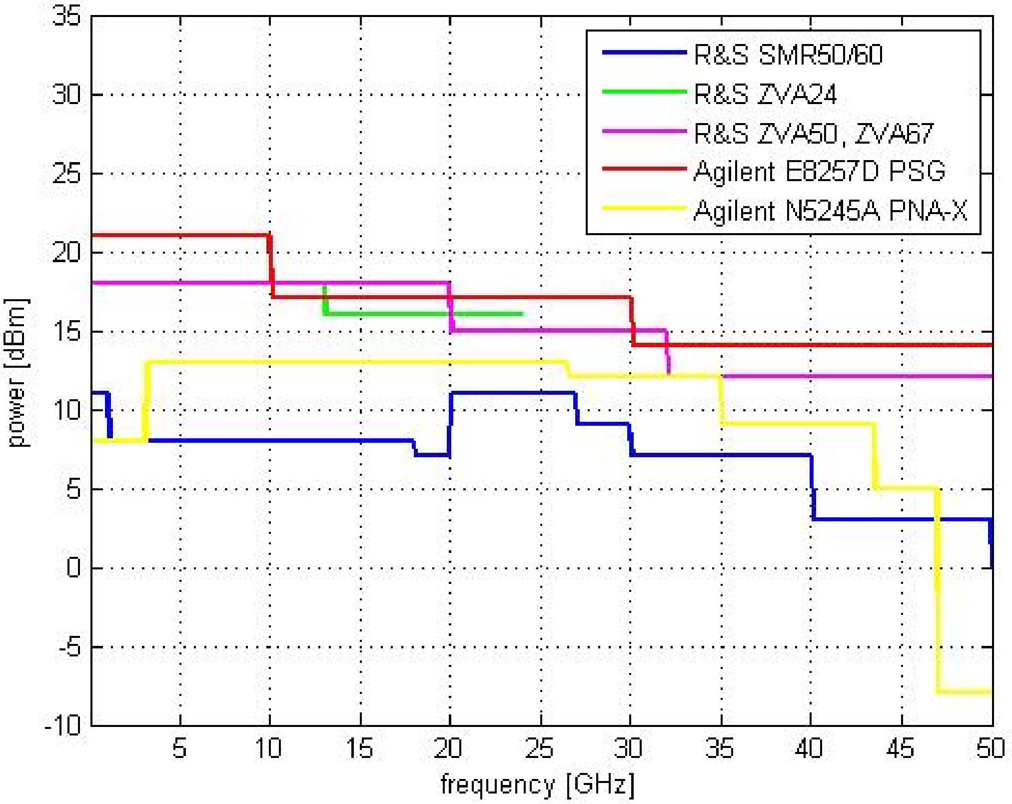


Figure 4.1.: Source model comparison

The conclusions extracted from this analysis help to indicate future behavior within the system or the other way around, they help to go back to a single component analysis when the global system performance does not reach the required level.

*Speed* in terms of frequency synthesizing is also a property to undertake to analysis, especially if the option chosen is an external source. In this case, special care has to be taken, as this component will have to be synchronized with the receiver. This reasoning points out the major relevance of receiver measurement speed which will trigger the whole measurement procedure.

### 4.1.2. Vectorial Network Analyzer

The Vectorial Network Analyzer, VNA, is the core of the system. It acts not only as a receiver. It synchronizes the measurement procedure and can also act as RF source and/or LO source by using its internal sources.
Apart from the obvious but fundamental decision of determining the frequency range to be covered by the VNA, crucial decisions or issues to consider before deciding for an analyzer are listed next.

1. Number of ports.
2. Number of independent oscillators. This decision is even more important than the number of ports, since it will determine the number of independent measurement channels.
3. IF frequency. Depending on the IF frequency chosen, the *System Sensitivity Level* and *0.1 dB Compression point* will be one or another. Even more important is to ensure that this frequency is compatible with the frequency conversion subsystem.
4. Measurement speed. Apart from the obvious importance of this attribute, it will also depend on the VNA how this speed will decrease when applying noise reduction methods like IF Bandwidth reduction (see section 4.2).
5. Direct generator/receiver access. This option allows improving the *Receiver Dynamic Range* by bypassing analyzer's internal coupler and in this way reduce the noise level, say its *Sensitivity Level.*

Examples for VNA port structures can be seen in Figure 4.2. In these figures, **Rohde&Schwarz® ZVA** [29] (ZVA24, ZVA50 or ZVA67) and **Agilent N5245A PNA-X** [30] reception blockdiagramms are shown.

As section 4.2 will explain, a given *Dynamic Range* value for a VNA will not mean that this is the available *Measurement Dynamic Range.* This would only be considering the VNA as a standalone device and without working within a complete measurement system. Apart from that, in this frame, main features for a VNA are high output power. The reason is that its internal source will commonly be used as RF source, measurement speed and a good sensitivity level to ensure correct detection when working in combination with frequency converting elements at the reception side. A comparison between different VNA's has been done in Table 4.2.

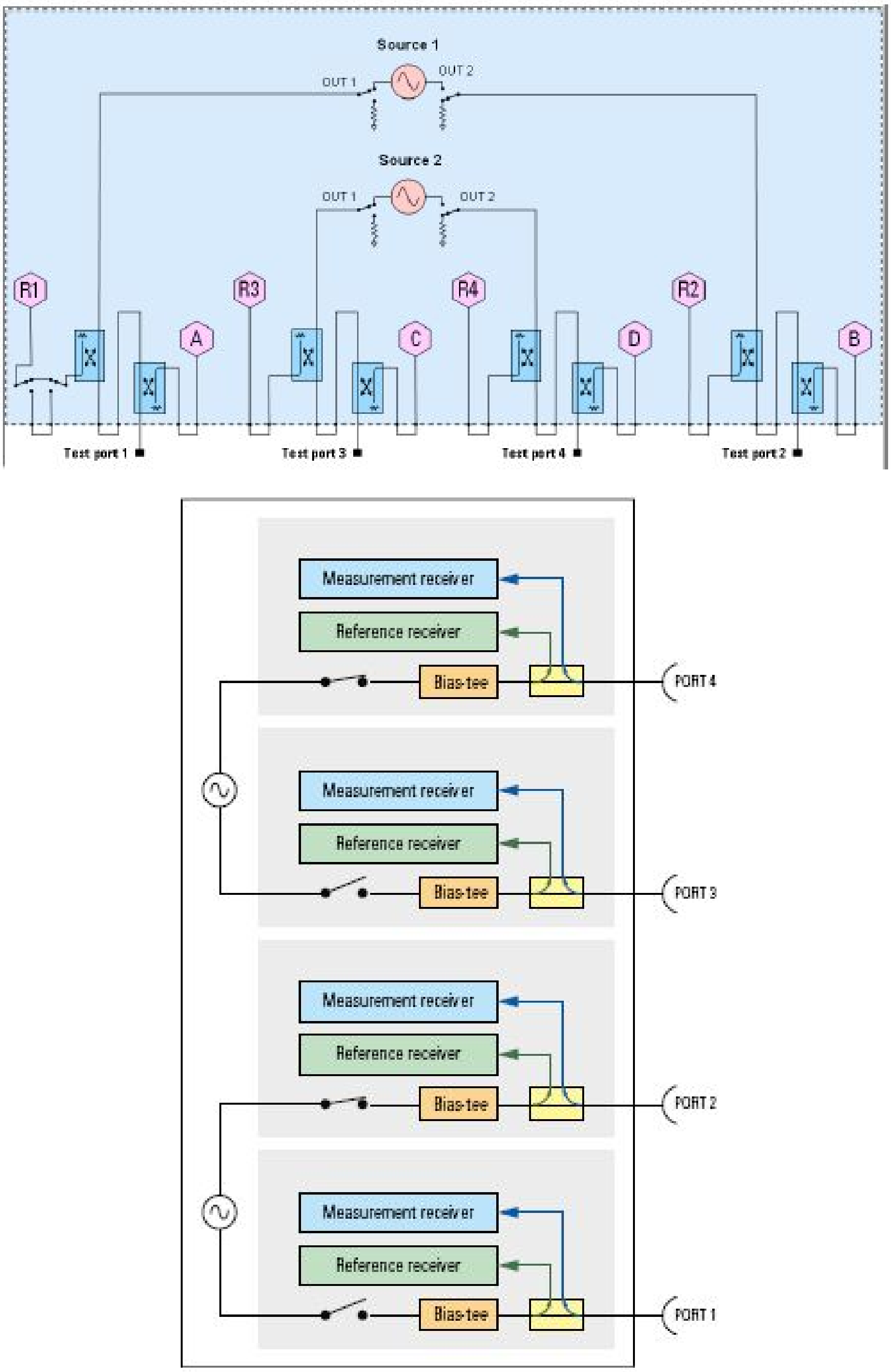


Figure 4.2.: Agilent N5245A PNA-X and Rohde&Schwarz ZVA reception blockdiagramms

Table 4.2.: Vectorial Network Analyzer performance comparison.

| **Frequency** | **2 GHz** | **50 GHz** | **67 GHz** |
|---|---|---|---|
| **Rohde&Schwarz ZVA24** | | | |
| $P_{out}$ (dBm) | 16 | - | - |
| $SensitivityLevel$ (dBm) | -130 | - | - |
| $DynamicRange$ (dB) | 145 | - | - |
| **Rohde&Schwarz ZVA50** | | | |
| $P_{out}$ (dBm) | 18 | 12 | - |
| $SensitivityLevel$ (dBm) | -130 | -115 | - |
| $DynamicRange$ (dB) | 150 | 130 | - |
| **Rohde&Schwarz ZVA67** | | | |
| $P_{out}$ (dBm) | 18 | 6 | 2 |
| $SensitivityLevel$ (dBm) | -130 | -115 | -110 |
| $Dynamic\ Range$ (dB) | 145 | 125 | 103* |
| **Agilent N5245A PNA-X** | | | |
| $P_{out}$ (dBm) | 8 | -8 | - |
| $SensitivityLevel$ (dBm) | -114 | -113 | - |
| $DynamicRange$ (dB) | 105 | 107 | - |

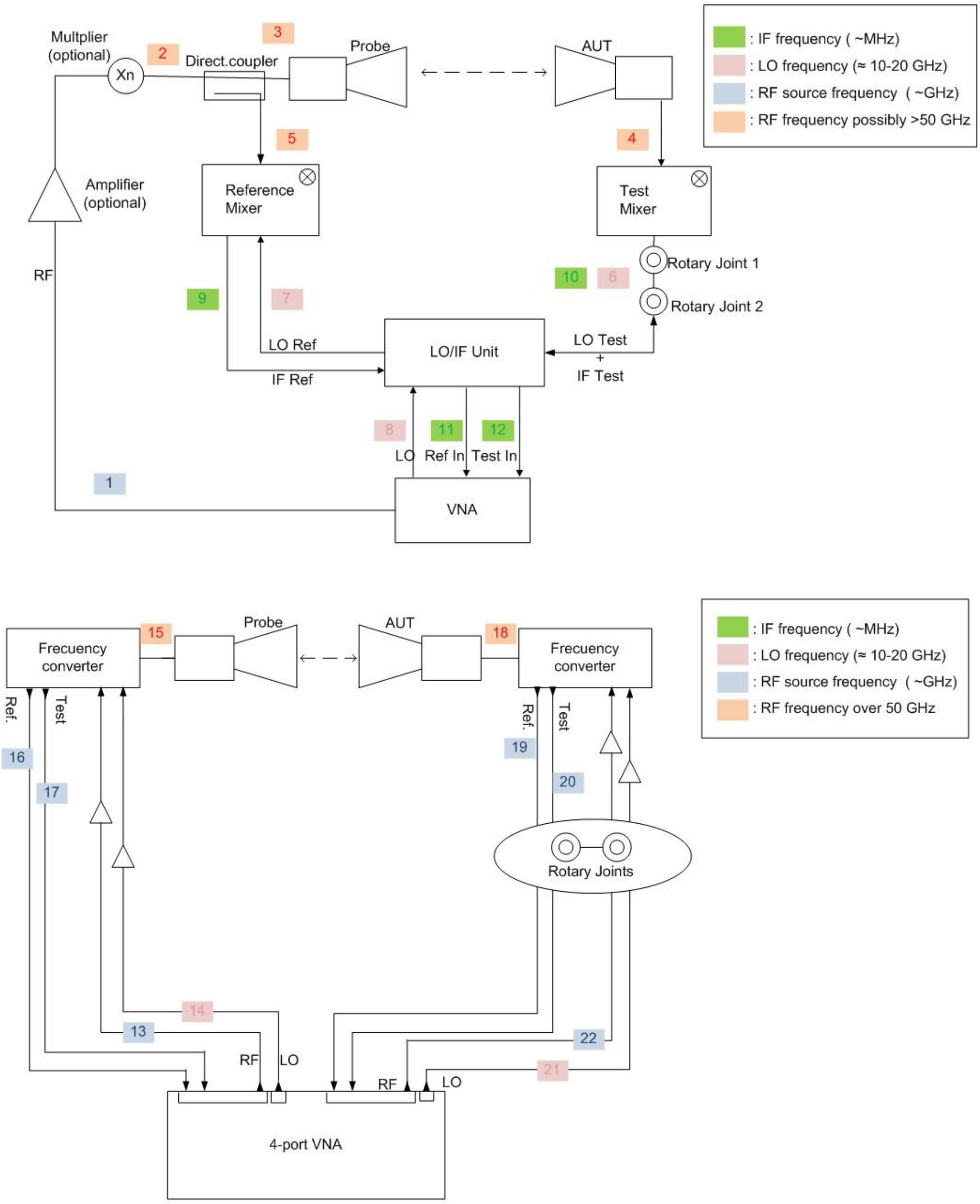


Figure 4.3.: Schematics in terms of frequency and cable paths.

### 4.1.3. Cables, connectors and rotary joints

**Cables**

Cables at RF frequencies are an important loss factor. They are distance dependent and they impact directly not only system performance, but also in the decision to settle on one system geometry or another. For example, when having a look at Figure 2.1 in chapter 2, it shows that approximately 26% of system's average inherent power loss budget at 40 GHz comes from cable losses. When having a look at Figure 4.3 (on previous page), the different cable paths can be identified.

At the same time cable needs can be summed up as seen in Table 4.3.

Table 4.3.: General cable requirements corresponding to Figure 4.3.

| **Cable Path Nr.** | **Type of cable** |
|---|---|
| 1, 13, 16, 17 | Flexible coaxial cable |
| 2, 3, 4, 5 | Flexible coaxial cable ( freq. $<$ 50 GHz) or waveguide solutions |
| 6, 14, 19, 20, 21, 22 | Semi rigid coaxial cable (able to pass rotary joints) |
| 7, 8 | Flexible coaxial cable |
| 9, 11, 12 | Flexible low frequency coaxial cable |
| 10 | Semi rigid low frequency coaxial cable (able to pass rotary joints) |
| 15, 18 | Waveguide solutions |

The main point is to determine cable losses over the frequency working range. *Cable loss* $\alpha$, expressed in dB per distance unit, can be specified in three different ways:

1. The parameter $\alpha$ is given as a list of discrete values and its corresponding discrete frequency point all over the frequency range. This is done in the **Huber+Suhner® SUCOFLEX101 datasheet** [31] and the **Huber+Suhner® SUCOFLEX104 datasheet** [32].

2. The parameter can be obtained from the equation:

$$\alpha = a\sqrt{f} + bf \tag{4.1}$$

   $f$ is frequency in GHz
   $a$ and $b$ are given by the provider. They are conductor loss coefficient and dielectric loss coefficient. These coefficients can be obtained developing classical cable loss equations for conducting and dielectric losses.
   This way of obtaining cable losses is the most exact way to obtain this attribute all over the frequency range, as it permits to calculate exact $\alpha$ value for any frequency point. An example can be found in both **Huber+Suhner® SUCOFLEX101 datasheet** [31] and **Huber+Suhner® SUCOFLEX104 datasheet** [32].

3. Another way of obtaining cable losses is through a graphic, as seen in the **Totoku Co. Ltd. datasheet** [33].

4. The less exact way to determine cable losses per meter is when the loss per distance unit is given for only a few frequency points. In this case, the way to obtain exact losses is by lineal interpolation for each frequency segment.

After evaluating different ways of analysis, a procedure for obtaining the relative exact loss values independently from how this losses are given is to solve the two term equation for $a$ and $b$ unknown and taking two frequency points. Finally, Equation 4.1 can be applied for every desired frequency point within the range. This method has been used to establish a comparison between different cable providers.
The results of this comparison can be seen in Figures 4.4 and 4.5 (on next page). The analysis compares insertion loss/attenuation for four different providers at a 25 °C temperature. It is very important to notice, as stated in the graphics legend, that different providers give losses expressed as Nominal, Typical and Maximum values before deciding for one cable provider or another.
Though, it is worth to mention that the final loss values having impact on system performance will be related to the cable length, which takes in consideration geometrical distance, possible heights and bends along the path. That is, not really cables itself but avoiding long cable distances at high frequencies will be the key factor to avoid these losses.

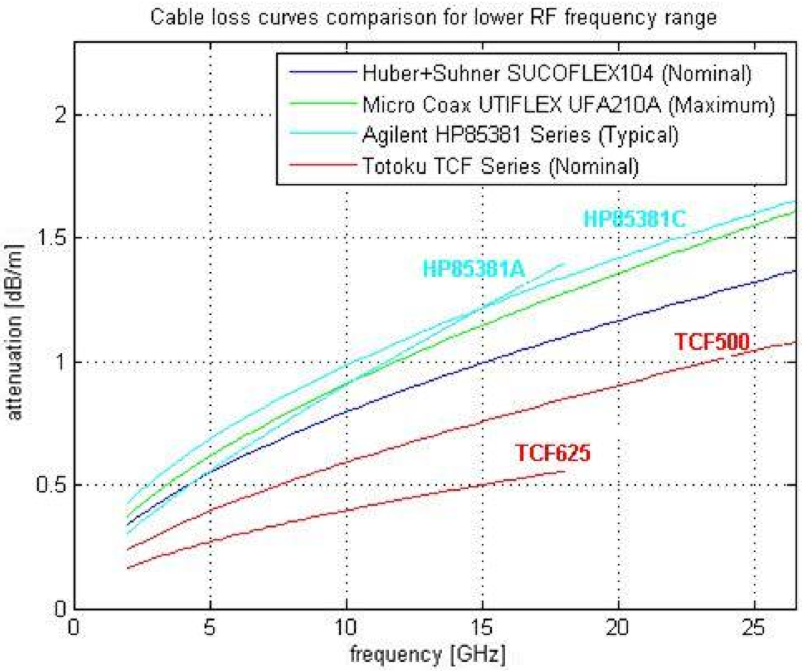


Figure 4.4.: Cable performance comparison between different providers up to 26.5 GHz.

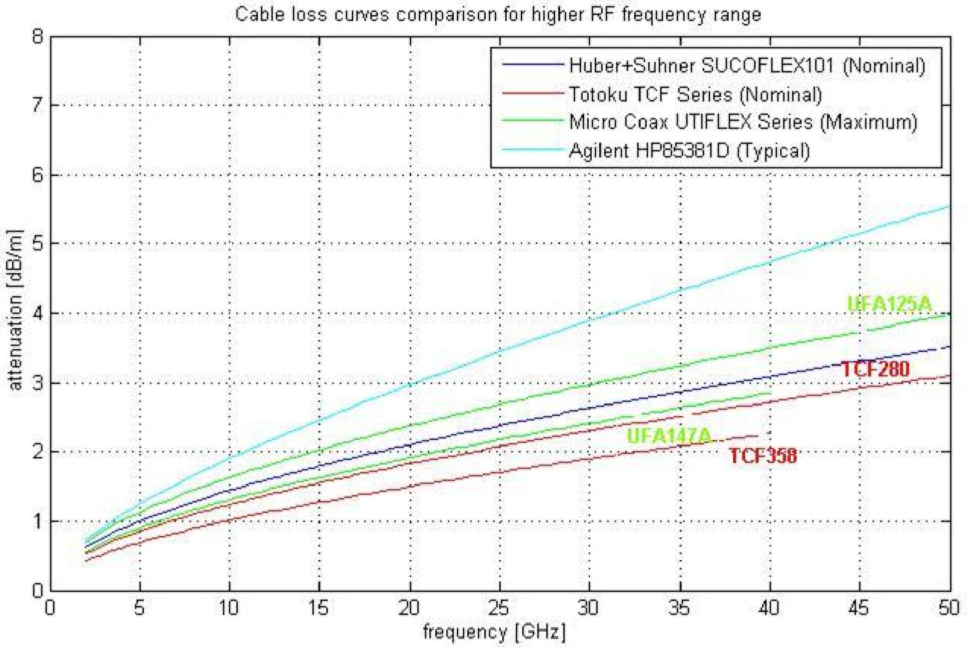


Figure 4.5.: Cable performance comparison between different providers up to 50 GHz.

### Connectors

Related to connectors, the main issues to consider is its compatibility, frequency range able to cover and risk of damage, which limits its use to system points where no frequent component exchanging happens. Figure 4.6 taken from [1] shows frequency ranges for most common used connectors while Table 4.4 states compatibility between these connectors.
Note that frequencies over 50 GHz imply the use of waveguide solutions.

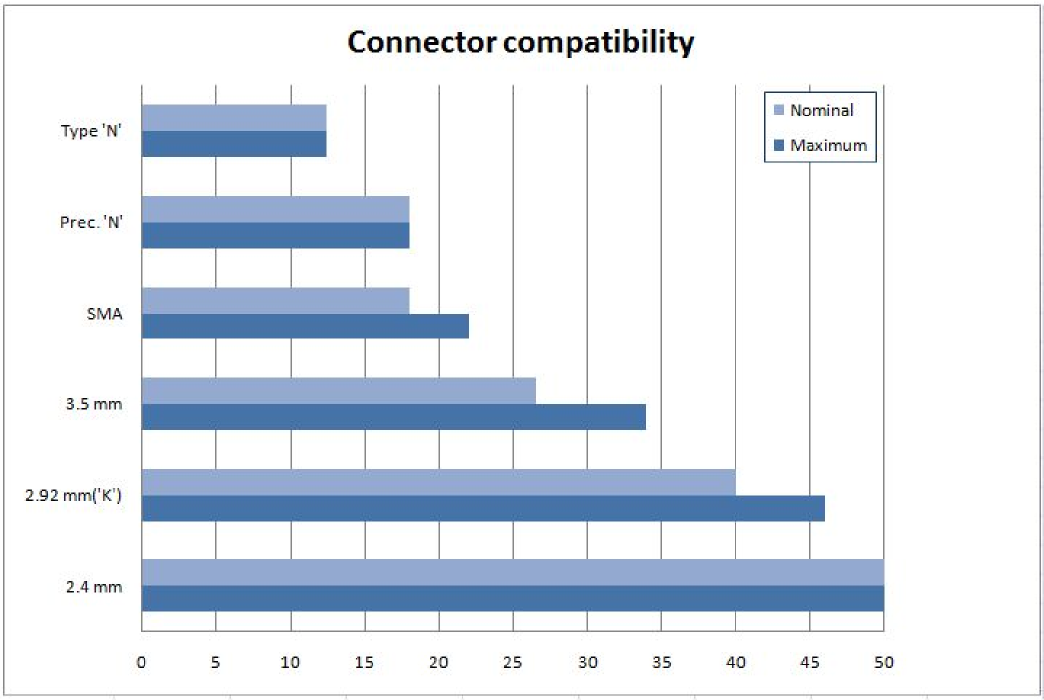


Figure 4.6.: Frequency working ranges for most common used connectors. Taken from [1].

Table 4.4.: Compatibility between most common used connectors. Taken from [1].

| | Male(Plug) | | | | |
|---|---|---|---|---|---|
| **Female (Jack)** | **'N'** | **'SMA'** | **3.5mm** | **2.92 mm** | **2.4mm** |
| **'N'** | YES | NO | NO | NO | NO |
| **'SMA'** | NO | YES | YES | YES | NO |
| **3.5mm** | NO | YES | YES | YES | NO |
| **2.92 mm** | NO | YES | YES | YES | NO |
| **2.4mm** | NO | NO | NO | NO | YES |

In order to state correctly the number of connectors and cables required for system layout, floor-plans as the one shown in Figure 4.7 (on next page) have been designed for each concrete type of range and have been included in chapter 6.

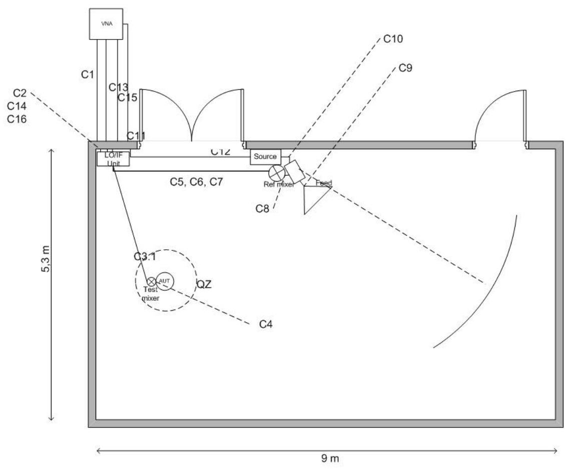
**Rotary Joints**

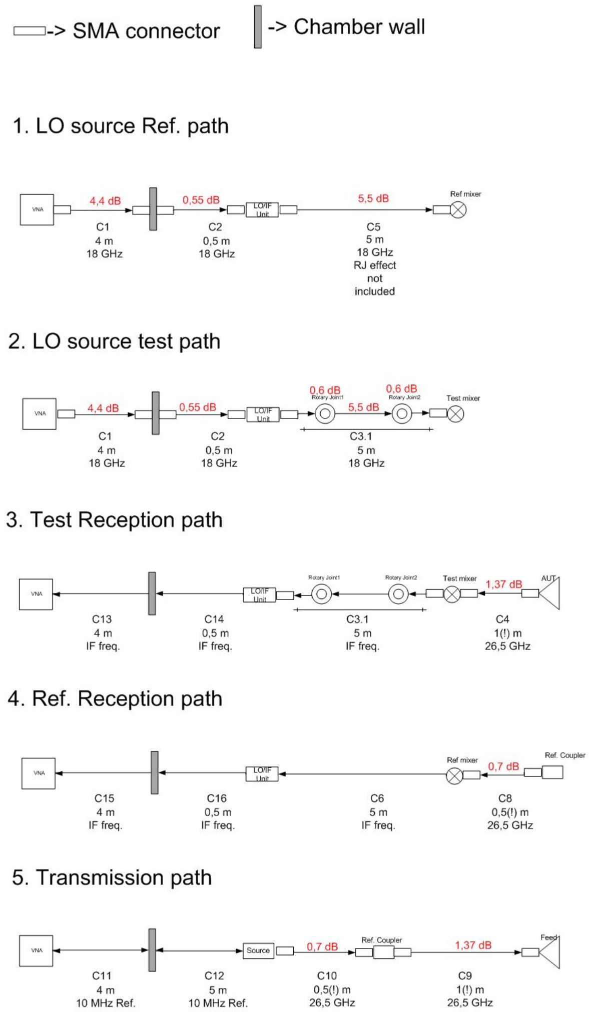
As chapter 3 illustrates, Antenna Under Test AUT will be fixed on a positioner a rotated around roll and azimuth axis. This circumstance requires the cable path coming from this component to be completely rotated around these two axes. In other words, rotary joints will be required for this path. These rotary joints will introduce a loss, but they will also require high phase stability. Usually these values are less than 1°phase fluctuation and around 0.5 dB loss per rotary joint at typical LO frequencies, around 18 GHz. This is the critical frequency to consider as it is the highest frequency passing this path as seen in Figure 4.3. Concrete values can be found in the **Spinner datasheet** [34].

Attenuation calculated for a RF frequency of 26.5 GHz and a LO frequency of 18 GHz.

Considering HUBER+SUHNER SUCOFLEX_104 Coaxial Cable.

Considering SPINNER BN835047 Rotary Joints.





C1: VNA LO source -> chamber wall.
C2: Chamber wall -> LO/IF unit
C3.1: LO/IF unit -> Test mixer
C4: Test mixer -> AUT
C5: LO/IF unit (LO) -> Ref mixer
C6: LO/IF unit (IF) -> Ref mixer
C7: LO/IF unit (Det. Level) -> Ref mixer
C8: Ref mixer -> Coupler
C9: Coupler -> Feed
C10: Source -> Coupler
C11: 10 MHz Reference (Room exterior)
C12: 10 MHz Reference (Room interior)
C13: IF Test (Chamber wall) -> VNA (Room exterior)
C14: IF Test (LO/IF Unit) -> Chamber Wall
C15:IF IF Ref (Chamber wall) -> VNA (Room exterior)
C16: IF Ref (LO/IF Unit) -> Chamber Wall

Figure 4.7.: Cable and connector losses floor-plan example.

### 4.1.4. Frequency converting elements

This type of components can be divided into three groups.

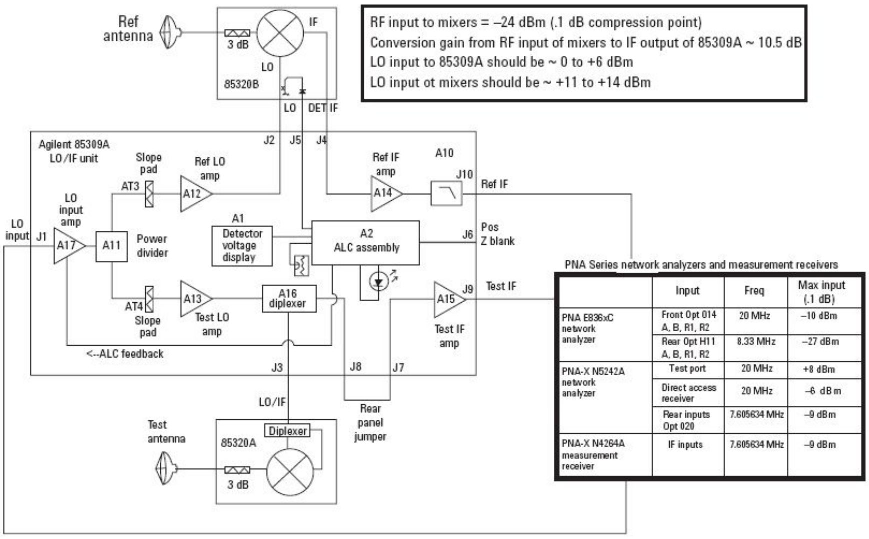
1. Multipliers
2. LO/IF Unit and Mixers
3. Frequency converters, say mmWave converters

**Multipliers**
These devices used to upconvert frequency of the incoming signal can be defined by the following attributes:

1. Required input power
2. Output power
3. Input frequency range
4. Multiplying value

Their use turns out into cable loss avoidance as the higher frequencies are not generated until the feed is nearly reached.
When analyzing system performance, the use of multipliers implies a different approach to system performance evaluation. First, it has to be ensured that the multiplier is fed with enough power all over the frequency range. As the input/output power relation for the multiplier is fixed, this multiplier's output power will be one of the most influencing factors when talking about available power at the reception side, say, *Measurement Dynamic Range.*

**LO/IF Unit and mixers**
This frequency downconverting subsystem is probably the most common found in antenna test ranges with a distributed RF system configuration. In Figure 4.8, an **Agilent HP 853209/HP85320 H50 LO/IF unit and mixer** [35] can be seen.



RF input to mixers = –24 dBm (.1 dB compression point)
Conversion gain from RF input of mixers to IF output of 85309A ~ 10.5 dB
LO input to 85309A should be ~ 0 to +6 dBm
LO input ot mixers should be ~ +11 to +14 dBm

PNA Series network analyzers and measurement receivers

| | Input | Freq | Max input (.1 dB) |
|---|---|---|---|
| PNA E836xC network analyzer | Front Opt 014<br>A, B, R1, R2 | 20 MHz | –10 dBm |
| | Rear Opt H11<br>A, B, R1, R2 | 8.33 MHz | –27 dBm |
| PNA-X N5242A network analyzer | Test port | 20 MHz | +8 dBm |
| | Direct access receiver | 20 MHz | –6 dBm |
| | Rear inputs Opt 020 | 7.605634 MHz | –9 dBm |
| PNA-X N4264A measurement receiver | IF inputs | 7.605634 MHz | –9 dBm |

Figure 4.8.: Agilent HP 853209/HP85320 H50 LO/IF unit and mixer.

Here the concept of the reference channel shows up. This reference path is used by the receiver to correct errors coming from random variations in the source power path. This reference signal can be radiated from the transmission side or coupled from it. Only coupled reference is considered for the case of a CR, due to its geometry and intrinsic high level of scattered signal inside the chamber (refer to chapter 3).

The Local Oscillator (LO) signal is the strongest signal and it is used to turn the diodes on and off. For some frequency converting systems, the LO level reaching the test mixer and the LO level reaching the reference mixer have to be the same. This is not always true, e.g.,is the case of the **NSI-RF-5943 Distributed Frequency Converter system** [36].

Connected also to the reference mixer, the Detection Level signal can be found. This level is proportional to the LO power level reaching the mixer and is used to drive the ALC (Automatic Level Control) loop. This one maintains the desired LO level regardless its frequency.

This fact is important since these mixers are usually able to perform both fundamental and harmonic mixing.

This ALC loop is found inside the LO/IF Distribution Unit. This device is in charge of distributing, controlling, levelling and filtering the signals involved to drive the non linear elements that build the mixers.

**Frequency Converters or mmWave converters**

These devices are not very common in the frame of this work, but they are a way to up- and downconvert the radiated signal. They are usually a combination of coupler, multiplier and mixer. An example of a block diagramm deduced from the **Rohde&Schwarz® ZVA-Z75 WR15 converters datasheet** [37] can be seen in Figure 4.9.

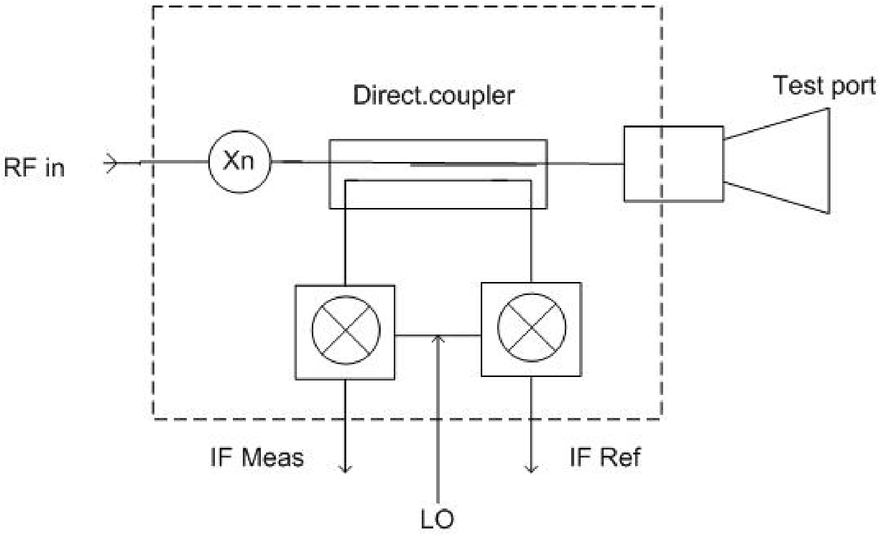


Figure 4.9.: Block diagramm example deduced from the Rohde&Schwarz WR15 converters datasheet.

A possible configuration can be seen in Figure 4.11 in section 4.2. It is important to ensure that both signal to be upconverted and LO signal reach the required level in order to perform this frequency conversion.

The signal radiated and received is conducted over the test port, which is conceived as a waveguide.

The test and reference channels at the transmission side allow to perform $S_{11}$ measurements at mmWave frequencies.

### 4.1.5. Antennas

This point involves feed antenna and the AUT, as both of them have a direct impact on the RF instrumentation chain.

**Feed**
Regarding the feed antenna, even if this component is included in the reflector-feed subsystem division presented in chapter 3, it still has an influence when working out RF instrumentation subsystem characteristics.

To evaluate system's global performance from the perspective of RF components, the feed antenna characteristics to take in account are, apart from its frequency working range, *gain* and *VSWR*. CR feeds are, as already mentioned, corrugated horns, and they cover a limited frequency range. That is why CR feeds are offered as a set of feeds covering each of them a part of the required frequency band. When evaluating feed antenna performance, three analysis steps should be performed:

1. Constant *feed antenna gain* over the desired frequency range should be present.

2. At this point, it is important to check compatibility between feed connector and the component connecting to the feed. This check can be done through floor-plans as the one pictured in Figure 4.7, through Figure 4.6 and Table 4.4.

3. *VSWR* should be considered. Its effects are equivalent to a mismatch loss ($ML$) which follows the next equation.

   $$ML = -10\log\left\{1 - \left(\frac{VSWR-1}{VSWR+1}\right)^2\right\} \tag{4.2}$$

   Otherwise, existing ***VSWR* online calculators** or equivalence tables can be found in classical microwave literature. E.g., 1.7:1 VSWR turns out into a loss of 0.3 dB. As a consequence, if feed typical gain is 13 dBi all over its frequency working range, the effective gain will be 13-0.3 = 12.7 dBi.

The example and values are taken from **ORBIT/FR datasheet** [17].

**AUT**
As the AUT is the element to characterize through the range, no further analysis has to be done on its properties. Thus, and in order to leave the system performance analysis results as general as possible, a good policy is to consider an AUT *gain* value of 0 dBi. By doing so, a theoretical reference of the measurement system can be obtained and apply this to future measurements and its results study. As a consequence, future testers working with the range should always include the expected theoretical AUT gain value into a previous analysis to determine component settings. This calculation can be easily done through the developed software tool within the frame of this work, presented in chapter 5.

### 4.1.6. Other required elements

**Coupler**

Obtaining the required reference mentioned in subsection 4.1.4 is reached through a coupling element. This coupler is a passive element with specified insertion and coupling loss values and it does not represent further difficulties. Even though, the next topics should be checked before deciding for a concrete model:

1. Frequency range of the coupler should be broad enough to cover measurement frequency range.
2. Known *coupling* and *insertion loss* all over the measurement frequency range.
3. *Connector compatibility* through aids like Table 4.4 and/or Figures 4.6 and 4.7.

The **Agilent Coupler datasheet** [38] is an example that shows coaxial coupler performance. Added to the information displayed in Figure 4.6, the statement that waveguide couplers are a feasible solution for frequencies around 50 GHz and above is underlined. Not only that this solution ensures connector compatibility, but also does not introduce significant losses.

**Amplifier**

Ensuring enough power, not only to reach desired Effective Radiated Power (*ERP*) levels, but also to feed correctly hypothetical frequency upconverting systems as seen in Figure 4.3, it can possibly require amplifying components. Implementing these along the transmission path is straightforward. As it will be seen in next section, doing this implemention will depend on available source power. Furthermore, the possible need to recover from frequency and distance dependent cable losses along the path can demand for using of amplifying elements. Apart from frequency range and amplifying/gain value itself, the attributes to evaluate when examining amplifier's performance are listed next.

- *Small signal gain flatness.* In an environment where extremely accurate performance is demanded, the gain fluctuation that is denoted by this value can be examined in two different ways. This magnitude is expressed as +/- value. Assuming the negative sign, it would be equivalent to take the cited minimum *small signal gain* specified in the amplifier's datasheet (See **Agilent Amplifier datasheet** [39]). In this case, a worst case calculation would be performed. Another valid solution is to consider this fluctuation as "variation margin" and mention this circumstance, say including it, into the final results.
- One of the most important values is the *Maximum output power*, as in some cases it can limit the transmit power. That is why when obtaining theoretical system performance, this value has to be considered as a boundary. The value that should be taken is the "Output power at maximum available input power". The other option would be taking the output power value for "1 dB Compression". Even if this is a non-lineal element, no modulation is applied on the signal's RF

frequency. As no modulation is present, reasonable no-linearities can be accepted. By doing this, the maximum output power limitation can be extended to the maximum value instead of the "1 dB Compression" value. See **Agilent Amplifier datasheet** [39]).

Power level reaching the receiver can be increased by introducing amplifiers before test and reference IF inputs. This statement is true, but it should be studied carefully since the solution would introduce noise into the measurements ( Equation 2.1). Considering the use of a Low Noise Amplifier before the RF-front-end of the system would turn out into a reduction of the RF's system sensitivity. The reason, parallel to the case of using IF amplifiers, is because the noise figure of the amplifier, $F_a$, would increase the noise power at the reception site. This is due to the increasement of the equivalent noise temperature $T$ because of rising the noise figure of the reception system, $F$, by the amplifiers own noise figure.

$$N = kTB \text{ taken from 2.1 and where } T = T_a + T_o(F - 1) \tag{4.3}$$

$T_a$ is the reception antenna temperature, K
$T_o$ is the standard noise temperature, usually 290 K
$F$ is the noise figure of reception system

As it will be seen in further sections, noise level increase means $DR$ decrease. This means that the gain introduced by the LNA should compensate the noise figure ($F$) factor. See section 4.2 for additional information regarding noise level, say sensitivity level.

## 4.2. System performance calculation

Approaching range performance analysis focusing on the whole RF subsystem is not only a basic step before settling on a concrete system layout option. It demonstrates as well that coping requirements depends on single components performance, but also on their configuration or layout geometry within the system. The parameters to consider in the frame of system requirements are mainly *Dynamic Range* (*DR*) and measurement speed. However, as it will be seen in subsection 4.2.3, the mentioned parameters have a direct influence on other parameters as measurement accuracy, range's space efficiency and cost boundaries. The specific requirements and boundaries applying to the future CR at the IHF can be found in Appendix A.

With the purpose of ensuring requirement accomplishing and correct system operation, RF subsystem has to be trialed on specific issues presented along this section.

### 4.2.1. Standard system configuration patterns

When studying different alternatives to implement the RF instrumentation, regarding design options, even if it is for a CR or not, diverse general patterns can be established. These pattern are:

- External mixing system configuration
- Frequency converter system configuration

The first one of these patterns implements the DFC system concept using external mixing. Usually, this alternative is often able to reach up to 50 GHz, even if, as it will be seen in chapter 6, some alternatives proposed to the IHF consider using mixers up to 75 GHz. Optionally, frequency upconverting elements like multipliers are used. This pattern can be seen in Figure 4.10 on next page.

The option pictured in Figure 4.11, also on next page, considers working with millimeter wave frequency converters and waveguide solutions for the RF path. Generally, these kinds of options carry more problems of mechanical nature rather than RF issues. For instance, cables coming from the AUT must be rolled around two axes, in other words, two rotary joints are required. This alternative would imply passing 4 cables through two rotary joints, which is not straightforward and should be studied carefully.

One option left is not included as a block diagram drawing due to its simplicity, and also due to the fact that it would be primarily used for lower frequencies as the ones covered, e.g. by the SNF. It considers working with neither frequency down or up converting aids, plus using the VNA's internal source.

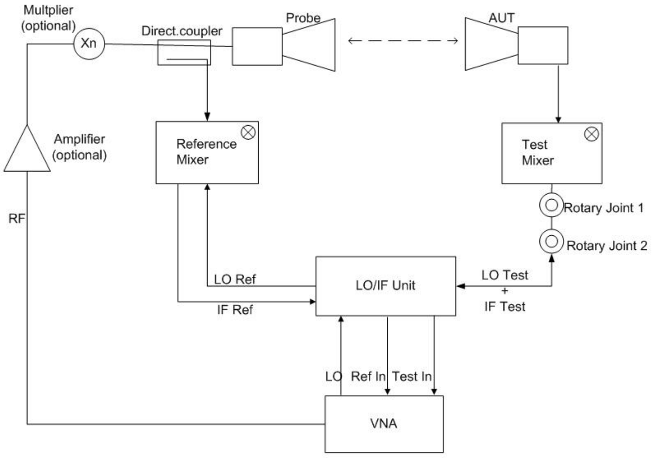


Figure 4.10.: General RF system schematic with DFC mixer system and optional multiplier.

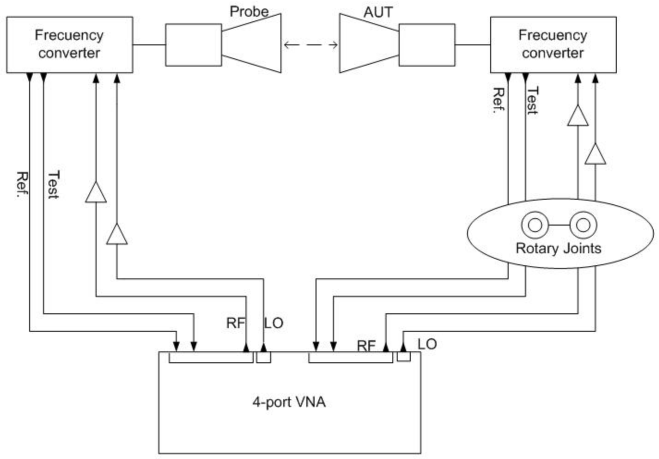


Figure 4.11.: General RF system schematic with millimeter wave frequency converters.

## 4.2.2. System inherent losses

Despite selecting high performance components and set them under optimum working conditions, this choice, will not avoid intrinsic losses found in antenna test ranges and its instrumentation system. Defined as inherent power loss budget of the system, these frequency dependent losses, can be divided into two categories:

- Cable losses
- Free-space losses

Cable losses have already been analyzed in detail in subsection 4.1.3. In any case, it is important to still stress on the importance of its effect and dependence relatedto the system geometry, as it justifies the use of remote frequency converting system configurations.
A comparison has been done for the three mentioned "standard system configuration patterns". Under the conditions, say space boundaries, that would be found in case of hypothetical layout in the future CR range at the IHF. The exact dimensions can be checked up on the anechoic chamber floor plans found in A. The results can be found in table 4.5.

Table 4.5.: Cable loss in total system's inherent power loss budget. **Huber+Suhner® SUCOFLEX101 cable** [31] and **Huber+Suhner® SUCOFLEX104 cable** [32] considered. Waveguide solutions for frequencies greater than 50 GHz.

| | **Frequency Range** | **% of Cable loss** |
|---|---|---|
| **No external frequency conversion** | 2 to 24 GHz | 11.5% at 2 GHz<br>26% at 24 GHz |
| **External mixer downconversion** | 2 to 50 GHz | 12% at 2 GHz<br>34.5% at 50 GHz |
| **External mixer plus multiplier plus multiplier** | 24 to 75 GHz | 5% at 24 GHz<br>8% at 50 GHz<br>0% at 75 GHz |
| **Frequency converters** | 50 to 75 GHz | 0% at 50 GHz<br>0% at 75 GHz |

Free-space losses are defined as the power dissipation suffered by an electromagnetic wave as a consequence of travelling along a concrete propagation path. Due to the spherical nature of the wavefront, a fraction of power is not received by the AUT. This loss is defined as [5]:

$$L_o = \left(\frac{4\pi R}{\lambda}\right)^2 \tag{4.4}$$

$R$ is the distance from radiation origin, meters
$\lambda$ is wavelength, meters

Expressing equation in dB [25]:

$$L_o = 32.45 + 20\log R + 20\log f \tag{4.5}$$

$f$ is frequency, GHz

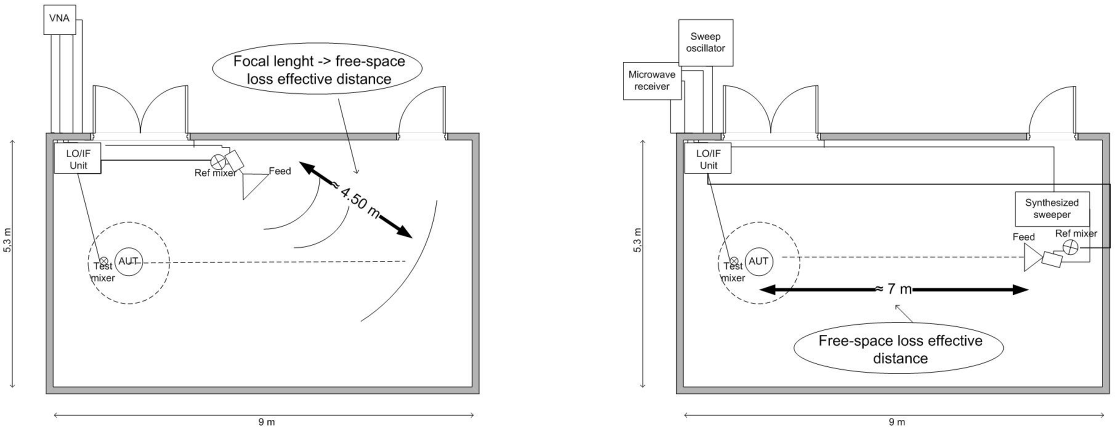


Figure 4.12.: Compact Range effective free space distance comparison schematic.

Reaching this point of the analysis, one of the advantages of the CR shows up. Note that due to beam collimation of the CR, only the plane wave path has free-space losses. Accordingly the whole loss of the system is reduced, as seen in Figure 4.12. Thus, the free-space loss will only occur along the effective free space distance. This distance will be the focal length in case of a Single Reflector CR and in case a multiple reflector system is used, its equivalent system focal length can be determined [6]. On the one hand, these schematics represent the traditional far field range length found at the IHF and, on the other hand, the hypothetical future CR laid out within IHF's anechoic chamber dimensions.
In order to evince this advantage, in Figure 4.13, comparison for two different range length free-space loss curves is provided.

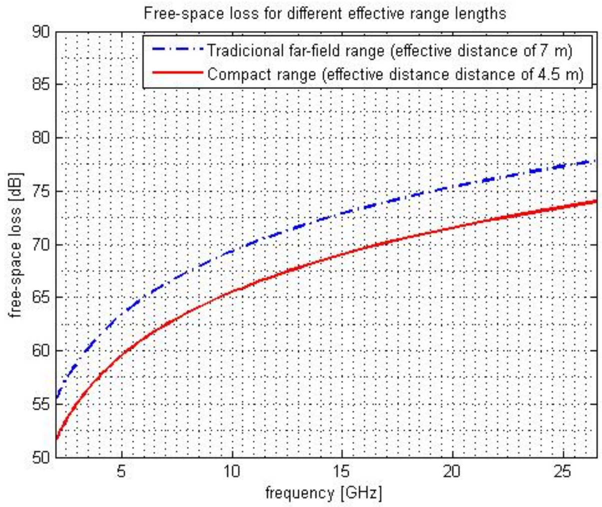


Figure 4.13.: Free-space loss comparison between the IHF traditional far-field range and the hypothetical CR.

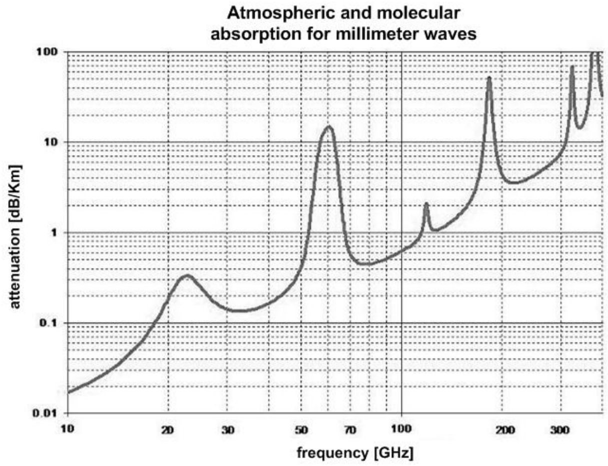


Figure 4.14.: Atmospheric and molecular absorption at millimeter wavelengths. Taken from [40].

Finally, it is important to underline that, at millimeter-wave frequencies atmospheric attenuation can be present and it is not considered in equation 4.5 [25]. Even in a controlled environment of a anechoic chamber, at certain frequencies and depending on the water vapor concentration, certain molecules can be excited causing the mentioned absorption [41]. Values start being significant when distances around 1 km are reached, even though when seeking accurate loss estimation this factor should be considered, especially at frequencies around 60 GHz. These values can be consulted in Figure 4.14.

### 4.2.3. Dynamic Range

As it has been introduced in previous chapters and sections throughout this document, no-linearities fix the level of maximum permissible signal. On the other hand, noise level determines its minimum value. So either at the input and output of a system, subsystem or component the signal power level excursion (of entrance or exit) that a system or system unit can handle is set by this two values. Nevertheless, this Dynamic Range definition, working within system global analysis, has to be carefully examined and that is the reason why definitions listed next are required.

- *Dynamic Range.* The most general and usual definition states that this magnitude is the difference between the highest power level able to be measured and the lowest level able to be detected. The criteria used is to set the maximum level at *0.1 dB Compression point* of the receiving RF frequency component. The minimum level is set to the *System Sensitivity Level.* This definition leads to a value that would be obtained by a measurement system or component, working under ideal conditions.

- *Receiver Dynamic Range.* This value refers to receiver as standalone instance and not working within a complete measurement system. The magnitude is fixed by the difference between 0.1 dB Compression at the test port and the *Receiver Sensitivity Level.* This definition can be extended to any device. This value is found in the device's corresponding datasheet, but it is important not to confuse it with the definition that follows.

- *Measurement Dynamic Range.* This definition is the most practical one, as it considers system losses affecting the power level at the reception side. It defines this magnitude as the difference between the maximum achievable power level reaching the reception side just before frequency downconversion and the *System Sensitivity Level.* Finally, to obtain a reality-corresponding value for this *Measurement Dynamic Range*, another term has to be subtracted from this value. It is the signal-to-noise ratio (SNR). This is due to the fact that desired measurement accuracy of the system is firmly related to a given SNR. At the same time, this ratio has to be related to measurement sensitivity as it acts as a fading margin for permissible measurement errors, say required measurement accuracy. Nevertheless, the specific information related to the required SNR will be found at the end of this subsection.

An example calculation showing how to obtain all these values for a concrete system is done in subsection 4.2.5. From this point onwards, if nothing else is stated, *DR* applies for *Measurement Dynamic Range.*

### *Sensitivity Level*

As it can be deduced from the definitions listed, the differentiating element between the definitions is the *Sensitivity Level*, and that is why it is fundamental to obtain the correct definition for this concept.A distinction between *Receiver Sensitivity Level* and *System Sensitivity Level* has to be made. In both cases, this value is determined through equation 2.1 applied whether to the single component, in this case the receiver, or to the whole receiving system.

The *Receiver Sensitivity Level*, or *Sensitivity Level* of any device within the RF instrumentation system is specified at RF frequency for that component and given as typical value. It can be given as an absolute value in dBm or expressed as dBm/Hz value, which is nothing else than relating the *Sensitivity Level* value to the IF bandwidth with which the system is working. For instance, if taking the **Agilent N5245A PNA-X datasheet** [30] value found on page 43 Table 16 in that document, typical test port noise floor at 10 Hz IF bandwidth is -113 dBm. Expressing this value in relation to the bandwidth would mean to express it in dB, apply equation 2.1 and obtain the value of -123 dBm/Hz.

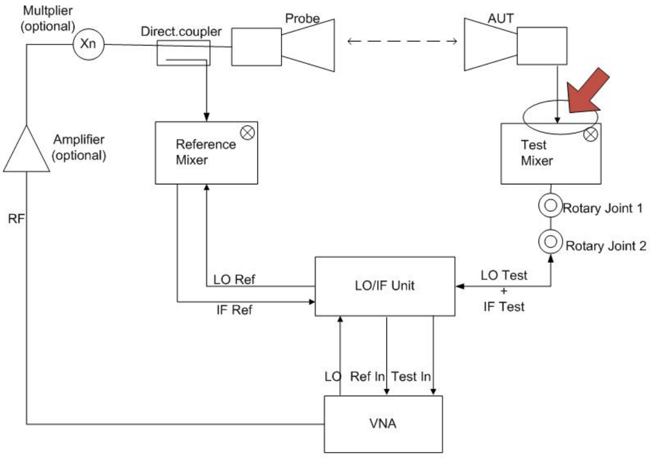


Figure 4.15.: Sensitivity Level system point to consider for *DR* calculation in case of using mixers and/or multipliers.

The *System Sensitivity Level* is not as simple as the sensitivity for a single component. The *Sensitivity Level* has to be specified at RF frequency. In other words, this value has to be obtained at the last RF point before conversion to IF frequency and considering all the components behind this point plus the AUT antenna own reception noise. This point can be identified in Figures 4.15 and 4.16.

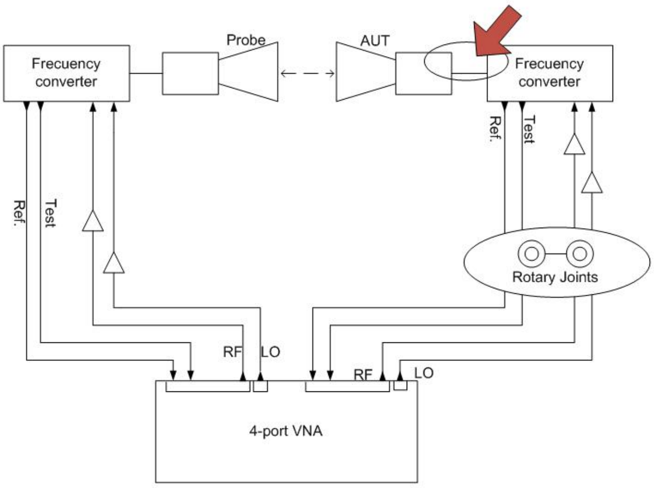


Figure 4.16.: Sensitivity Level system point to consider for *DR* calculation in case of using frequency converters.

Retaking the equation 2.1, the non-linear elements behind the RF-front-end of the circuit will increase the equivalent noise temperature ($T$). As a consequence, the procedure to obtain the *System Sensitivity Level* is not obvious and can be divided into the following steps:

1. The noise floor of the system is the goal value to obtain as it is the sensitivity of the system. Expressing equation 2.1 in a logarithmic scale:

$$\begin{aligned} N &= kTB \\ N\ [\text{dBm}] &= 30 + 10\log k + 10\log T + 10\log B = \\ &= -174 + 10\log T/T_o + 10\log B \end{aligned} \tag{4.6}$$

   It can be seen that the expression in dBm/Hz is:

$$N = -174 + 10\log T/T_o \tag{4.7}$$

   Where the key factor to 4.7 obtain, apart from $N$, is $T$.

   At the marked point in Figures 4.15 and 4.16, $T$ is the antenna noise temperature. Assuming that antenna temperature is 17 °C, say equal to standard noise temperature ($T_o = 290$ K), substituting it in 4.7, the value of -174 dBm/Hz is obtained. As it was mentioned already in section 3.2, temperature stability at 17°C will keep thermal noise power coming from the whole system, but specially from the AUT, controlled. In case that no more elements, except of the receiver, were behind this point, calculation should stop here and step 3 should be performed.

2. If more elements are found behind this point, the expression applying to the equivalent noise temperature would be:

$$T = Ta + To(F - 1) \tag{4.8}$$

In case antenna temperature is still 17°C, the final expression would be $T = T_o F$. And through $F$ the influence of the rest of the components is evinced. The elements behind this point are frequency downconverting elements like mixers, and $F$ is increased by the mixers conversion loss and bandwidth of the IF amplifier of the LO/IF unit, and possible Low Noise Amplifiers (LNA) [4]. In case that only the DFC system is found behind the AUT, the equation applying is:

$$F = L_c(t + F_{IF} - 1) \tag{4.9}$$

$L_c$ is the linear mixer's conversion loss value
$t$ is the noise temperature ratio, approximately 1
$F_{IF}$ is the noise figure for the IF amplifier of the DFC system

This equation taken from [9] applies in case that the no-linear element of the mixers is implemented as a diode mixer. If this is not the case, or in case $F_{IF}$ is not given by the supplier, the expression that applies is:

$$F \approx L_c \tag{4.10}$$

This is a good approximation as the mixers conversion loss $L_c$ will usually be around 20 dB which is a significantly higher loss as the usual $F_{IF}$ values. Consequently, this last term can be depreciated.
In case a LNA is placed before the test mixer's input, or other elements are found between the RF-front-end and the receiver, the chain noise figure formula would determine the total noise factor for the chain of elements:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}} \tag{4.11}$$

$F_n$ is the linear noise factor for the $n$-th device
$G_n$ is the linear gain for the for the $n$-th device

Again, it is important to mention that, due to the magnitude of the noise factors for the LNA and the mixers within the DFC, the dominating terms will be these cited values. In case mmWave converters are behind the antenna, its effect on the total noise factor, say noise temperature, will depend on the internal elements conforming these converters and on the given data by the supplier regarding conversion losses. It has been assumed that the noise floor of these components will usually be higher than antenna noise and that this value can be deduced through *DR* specifications for that concrete component. As it has been seen in subsection 4.1.4, it is not always complication-free to obtain this value.

If expression 4.8 is substituted in equation 4.7 the resulting equivalence is:

$$N = -174 + 10 \log \left( T_a / T_o + (F - 1) \right) \tag{4.12}$$

Assuming that AUT temperature is 17 °C, ($T_o$ = 290 K), the final resulting expression is:

$$N = -174 + 10 \log F \tag{4.13}$$

3. This level has to be compared to the *Sensitivity Level* for the element left within the reception chain, the VNA, say receiver. This means evaluating the receiver's own RF *Sensitivity Level*, as mentioned in the Agilent PNA-X *Receiver Sensitivity Level* example. This value has to be compared to the level obtained and the most restricting one will determine the final *Sensitivity Level* to consider.

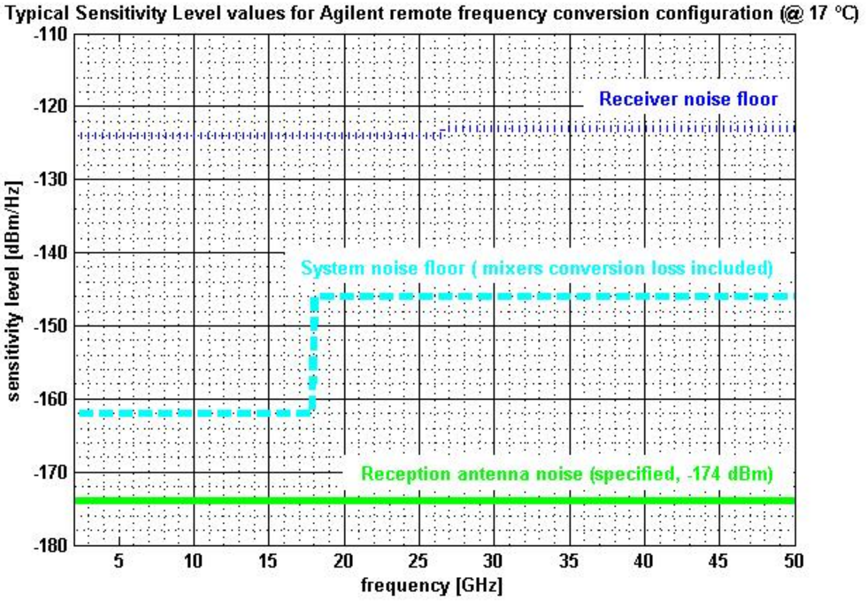


Figure 4.17.: Sensitivity Levels for Agilent remote frequency converting proposal found in appendix B with analysis performance results in chapter 6.

Figure 4.17 represents *Sensitivity Levels* for a concrete example, found in chapter 6 and in appendix B. Systems working at lower frequencies, for instance, a SNF range, can be laid out with no remote frequency converting elements on the reception side. In this case, the *System Sensitivity Level* value would still not match to the *Receiver Sensitivity Level*, and the comparison mentioned above should always be done.

To obtain the absolute *System Sensitivity Level* value, IF bandwidth $B$ in dBm has to be added, where $B$ is the receivers bandwidth. Usually, as it can be seen in datasheets **Agilent N5245A PNA-X** [30] and **Rohde&Schwarz® ZVA**, the default value for $B$ is set to 10 Hz.

***Power at the reception side,*** $P$
After determining the correct *Sensitivity Level*, the second term of the *Dynamic Range* equation, $P$ has to be determined.

$$DR = P - \text{Sensitivity Level} \tag{4.14}$$

$P$ is the power considered at the reception side and its value will depend on what *Dynamic Range* definition is required and applied.

When talking about *Dynamic Range* itself, $P$ is the most restrictive 0.1 dB compression point for the devices configuring the RF-front-end at the receiver site. Commonly, this value will be the *0.1 dB Compression point* for the mixers or the frequency converters.

If the *Receiver Dynamic Range* value is sought, apart from the fact that this value can be found in the corresponding datasheets, the $P$ value to consider is the specified *0.1 dB Compression point* at the test port of this mentioned receiver.

Finally, to obtain the *Measurement Dynamic Range*, the required $P$ is the power budget reaching the reception side, considering all losses along the system chain, starting from the signal source and ending at the RF-front-end. In next section, the general procedure is developed and in subsection 4.2.5 a complete concrete calculation example is found.
In any case, the general procedure to obtain $P$ reaching the reception RF-front-end, is based on the standard system patterns, or configurations, presented in subsection 4.2.1. Specifically, three cases have been differentiated. These cases are:

- External mixing system
- External mixing system and multiplier at transmitting side
- Frequency converter system

For each of these cases a schematic and a general expression for $P$ is included.

*External mixing system.* In this case (see Figure 4.18 on next page) $P$ represents the power reaching the test mixer's input. The procedure and expressions used to obtain this value are developed next.

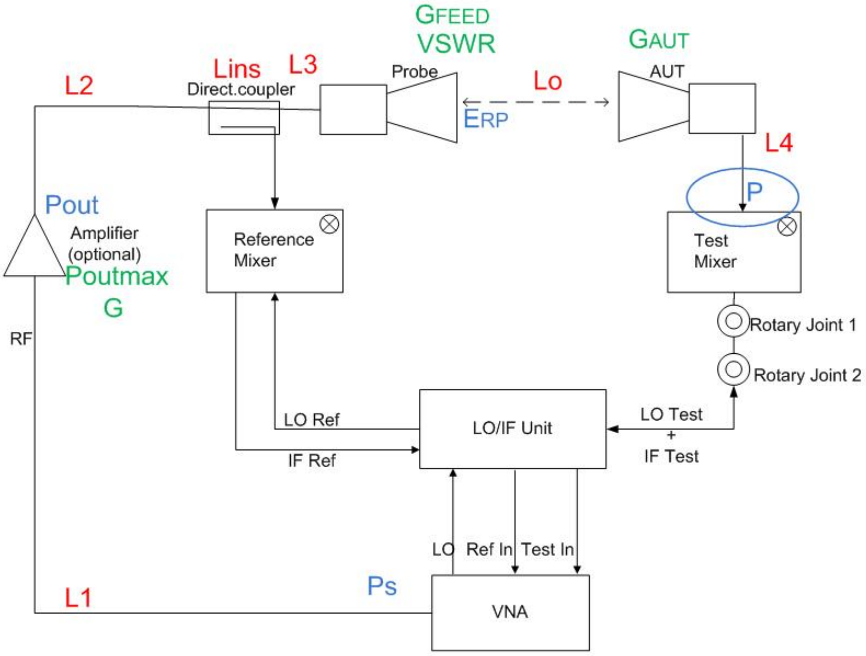


Figure 4.18.: Required power levels and specifications for reception power calculation in an external mixing system.

If an amplifier is used:

$$\begin{aligned}\text{If } P_S - L_1 + G \geq P_{outmax} \text{ then } P_{out} &= P_{outmax}\\ \text{else } P_{out} &= P_S - L_1 + G\end{aligned} \tag{4.15}$$

In case no amplifier is used:

$$P_{out} = P_S - L_1 + G \tag{4.16}$$

Now, even if an amplifier is used or not, the expression to use are:

$$ERP = P_{out} - L_2 - L_{ins} - L_3 + G_{FEED} - L_{FEEDVSWR} \tag{4.17}$$

$$P = ERP - L_o + G_{AUT} - L_4 \tag{4.18}$$

Where:
$P_S$ is the maximum available source power, dBm
$L_1$ is the cable loss for approximately 10 meters, dB
$G$ is the small signal gain of the optional chosen amplifier, dB
$P_{outmax}$ is the maximum output power for the amplifier, dBm
$P_{out}$ is the final power coming out of the optional amplifier, dBm
$L_2$ is the cable loss for approximately 1 meter, dB
$L_{ins}$ is the insertion loss for the coupler, dB
$L_3$ is the cable loss for approximately 1 meter, dB
$G_{FEED}$ is the gain for the feed, dBi
$L_{FEEDVSWR}$ is the loss resulting from the feed's VSWR, dB
$ERP$ is the effective radiated power, dBm
$L_o$ is the free-space loss for the given effective length and distance, dB
$G_{AUT}$ is the gain for the AUT, dBi
$L_4$ is the cable loss for approximately 1 meter, dB

*External mixing system and multiplier.* This context (Figure 4.19 on page 50) slightly differs from the first system configuration mentioned. Analysis can be divided into two parts. First, at the transmitting side, it has to be ensured that the multiplier is correctly fed. Second, calculate power at the test mixer, starting with the multiplier's output power. Thus, the expressions applying are below. The possible use of an amplifier is treated in an equivalent way to the case with no multiplier:

$$\begin{aligned}\text{If } P_S - L_1 + G \geq P_{outmax} \text{ then } P_{out} &= P_{outmax}\\ \text{else } P_{out} &= P_S - L_1 + G\end{aligned} \tag{4.19}$$

In case no amplifier is used:

$$P_{out} = P_S - L_1 + G \tag{4.20}$$

Now, even if an amplifier is used or not, it has to be warranted that the multiplier receives enough power:

$$\begin{aligned} \text{If } P_{out} - L_2 \leq P_{\text{in\_mult}} &\rightarrow \text{ not enough power to feed the multiplier} \\ \text{else } ERP = P_{\text{out\_mult}} - L_3 - L_{ins} &- L_4 + G_{FEED} - L_{FEEDVSWR} \\ P &= ERP - L_o + G_{AUT} - L_5 \end{aligned} \tag{4.21}$$

Where:
$P_S$ is the maximum available source power, dBm
$L_1$ is the cable loss for approximately 10 meters, dB
$G$ is the small signal gain of the optional chosen amplifier, dB
$P_{outmax}$ is the maximum output power for the amplifier, dBm
$P_{out}$ is the final power coming out of the optional amplifier, dBm
$L_2$ is the cable loss for approximately 1 meter, dB
$P_{in\_mult}$ is the required input power for the multiplier, dBm
$n$ is the frequency multiplying value for the multiplier, dBm
$P_{out\_mult}$ is the given output power for the multiplier, dBm
$L_3$ is the cable loss for approximately 1 meter, dB
$L_{ins}$ is the insertion loss for the coupler, dB
$L_4$ is the cable loss for approximately 1 meter, dB
$G_{FEED}$ is the gain for the feed, dBi
$L_{FEEDVSWR}$ is the loss resulting from the feed's VSWR, dB
$ERP$ is the effective radiated power, dBm
$L_o$ is the free-space loss for the given effective length and distance, dB
$G_{AUT}$ is the gain for the AUT, dBi
$L_5$ is the cable loss for approximately 1 meter, dB

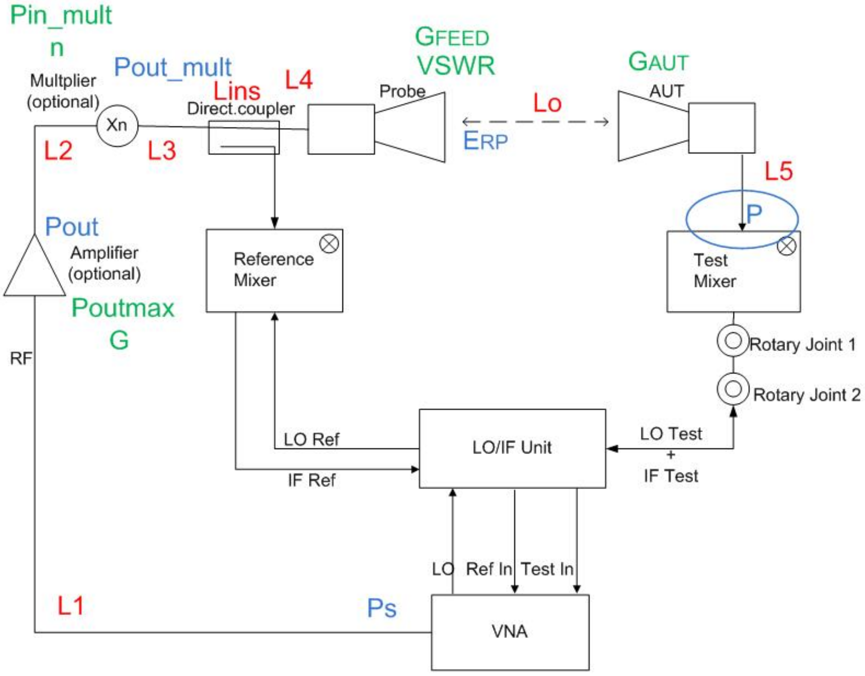


Figure 4.19.: Required power levels and specifications for reception power calculation in an external mixing system with a multiplier.

*Frequency converter system.* The last case (Figure 4.20 on next page), similar to the multiplier, has to be divided into two stages. First, checking if there is going to be enough power at the transmission side, second determine power reaching the RF front-end, in this case, the input of the receiving frequency converter. In this case, $P$ is obtained as follows:

$$\begin{aligned} \text{If } P_S - L_1 + G \geq P_{outmax} \text{ then } P_{out} &= P_{outmax} \\ \text{else } P_{out} &= P_S - L_1 + G \end{aligned} \tag{4.22}$$

In case no amplifier is used:

$$P_{out} = P_S - L_1 + G \tag{4.23}$$

Now, even if an amplifier is used or not, it has to be warranted that the frequency converter receives enough power:

$$\begin{aligned} \text{If } P_{out} - L_2 \leq P_{\mathrm{in\_conv}} \rightarrow & \text{ not enough power to feed the frequency converter} \\ \text{else } ERP &= P_{\mathrm{out\_conv}} + G_{FEED} - L_{FEEDVSWR} \\ P &= ERP - L_o + G_{AUT} \end{aligned} \tag{4.24}$$

Where:
$P_S$ is the maximum available source power, dBm
$L_1$ is the cable loss for approximately 10 meters, dB
$G$ is the small signal gain of the optional chosen amplifier, dB
$P_{outmax}$ is the maximum output power for the amplifier, dBm
$P_{out}$ is the final power coming out of the optional amplifier, dBm
$L_2$ is the cable loss for approximately 1 meter, dB
$P_{in\_conv}$ is the required input power for the frequency converter, dBm
$P_{out\_conv}$ is the given output power for the frequency converter, dBm
$G_{FEED}$ is the gain for the feed, dBi
$L_{FEEDVSWR}$ is the loss resulting from the feed's VSWR, dB
$ERP$ is the effective radiated power, dBm
$L_o$ is the free-space loss for the given effective length and distance, dB
$G_{AUT}$ is the gain for the AUT, dBi

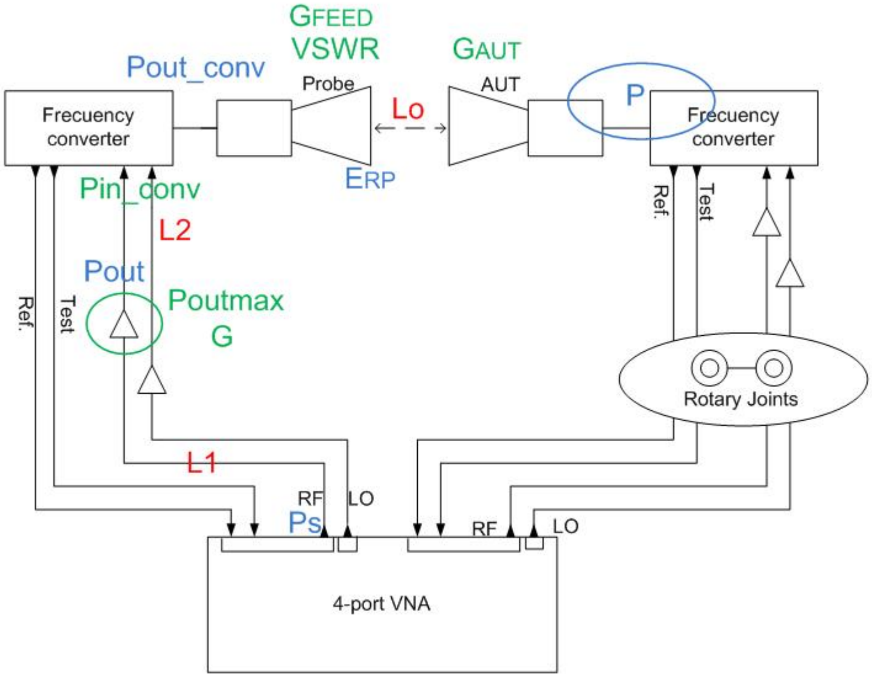


Figure 4.20.: Required power levels and specifications for reception power calculation in a frequency converter system.

***Signal to Noise Ratio SNR***

Measurement accuracy required and finally found in the measurement system has a direct impact on the *Sensitivity Level*. Possible and acceptable measurement errors have to be considered. That is why the real *System Sensitivity Level* theoretically should be increased. This is done through rising this level, say decreasing the *DR* parameter, through the Signal-to-Noise-Ratio (SNR) [25]. This ratio acts as margin considering phase and amplitude measurement errors, and can be determined through graphics like the one found in Figure 4.21. This graphic, taken from [25], represents measurement error due to noise worst-case errors. It is assumed that these errors are due to the classical Gaussian noise pattern and consequently applicable for a general case.

As a result of this concern, the realistic applicable *DR* equation has to be formulated as follows:

$$DR = P - \text{Sensitivity Level} - SNR \tag{4.25}$$

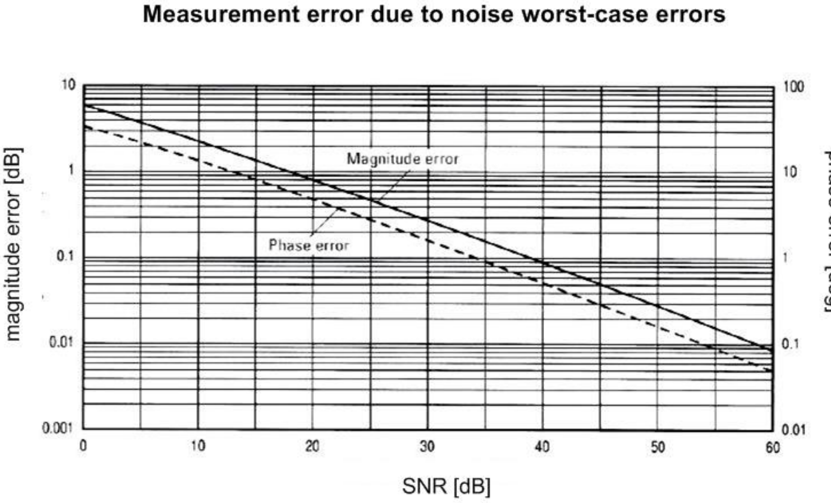


Figure 4.21.: Measurement accuracy as a function of Signal-to-Noise-Ratio (SNR). Taken from [25].

***IF Bandwidth variation and averaging***

Equation 4.25 is obtained through an analysis were following conditions apply. First, the IF bandwidth ($B$) considered is 10 Hz. Second, no averaging is performed. In case these parameters change, the stated $DR$ will also be submitted to variations. These variations can be quantified as follows.

*IF Bandwidth variation.* As it has been seen in equation 2.1, noise floor, say *System Sensitivity Level*, is dependent from $B$. If this is considered, and expressed in terms of expression 4.13, into expression 4.25, Measurement $DR$ can be defined as a function of measurement bandwidth $B$.

$$\begin{aligned} DR &= P - \text{System Sensitivity Level} - SNR \\ DR &= P - N - SNR \\ DR &= P - (-174 + 10\log F + 10\log B) - SNR \end{aligned} \tag{4.26}$$

It can be deduced from this result that, IF bandwidth variation effect on $DR$ can be written as:

$$DR_2 = DR_1 - 10\log B_2/B_1 \tag{4.27}$$

where $DR_1$ and $B_1$ are the initial values, and $DR_2$ the new value after setting bandwidth to $B_1$.

It is important to bear in mind that despite $DR$ improvement, e.g. switching from 10 Hz to 1 Hz bandwidth means 10 dB $DR$ improvement, there is going to be a loss of measurement speed due to $B$ narrowing. The exact decrease will depend on the concrete IF filter shape of the receiver [11], and has to be stated by the receiver's manufacturer.

*Averaging.* This method involves taking the measured complex vectorial data at the receiver, and average each point of a sweep with exponentially weighted coefficients [11]. Averaging signal noise will improve *System Sensitivity Level*, and simultaneously, the measurement $DR$. Commonly, the default setting when Receiver's specifications are given, is set to zero averages. The $DR$ improvement factor through averaging procedures can be expressed as [1]:

$$DR_2 = DR_1 + 10\log(\text{number of averages}) \tag{4.28}$$

Although a $DR$ enhancement is achieved through this procedure, again, there is a trade-off in terms of measurement speed to be made. Sweep speed of the receiver will be reduced by a factor equal to the number of averages selected [11]. This decrease of measurement speed is due to the additional time required by the receiver to average the selected number of traces.

Additionally it has to be pointed out that averaging will be only possible in a system configuration with a test channel and a reference channel, otherwise zero tending results can be achieved due to the random behavior of phase [11].
Generally, averaging means more measurement time increase than through applying IF bandwidth reduction, even if from the point of view of noise floor reduction the averaging method achieves higher noise reduction factors. This is why these settings should be adapted to the specific measurement aimed to be performed.

### 4.2.4. Other Critical power levels

**RF power levels**
This subsection expects to underline the importance of not only reaching the damage level of the components, but also the *0.1 dB Compression point.* That is why these power levels should be checked before laying out the measurement system. A general procedure to determine and check these power levels is presented in this section. Two different cases, following standard system configuration patterns, have been taken into account.

- External mixing system
- Frequency converter system

For each of these cases a schematic and a general expression for the RF power levels is included.

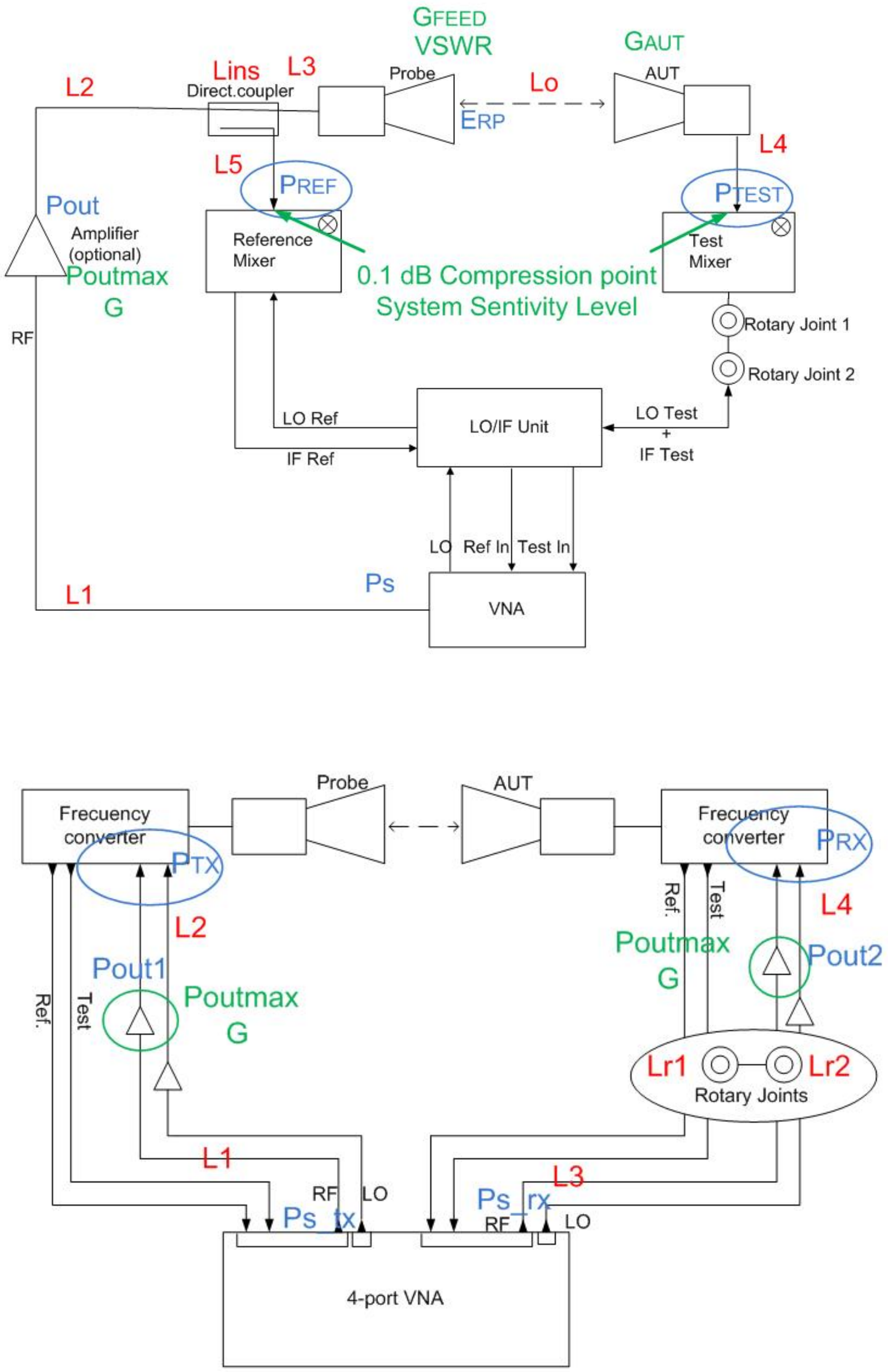


Figure 4.22.: Required power levels and specifications for RF power calculation.

*External mixing system.* In this case, (see Figure 4.22 on previous page), $P_{TEST}$ and $P_{REF}$ represent the power reaching the test and reference mixer's input. It has to be warranted that the power levels reaching mixers inputs do not overdrive them out of their linear working zone, but reach the sensitivity levels of the system, over its whole frequency working range. The procedure, equivalent to the applied to obtain the $DR$ and expressions used to obtain these power levels are developed next. In fact, as it can be seen in the expressions below, the power levels to state depend from the same factors calculated in the $DR$ calculation section. As the procedure is equal, refer to subsection 4.2.3 to obtain $P_{out}$ and $ERP$.

$$\begin{aligned} P_{TEST} &= ERP - L_o + G_{AUT} - L_4 \\ P_{REF} &= P_{out} - L_2 - L_{coup} - L_5 \end{aligned} \tag{4.29}$$

Where:
$P_{out}$ is the final power coming out of the optional amplifier, dBm
$L_2$ is the cable loss for approximately 1 meter, dB
$L_{ins}$ is the insertion loss for the coupler, dB
$L_{coup}$ is the coupling loss for the coupler, dB
$ERP$ is the effective radiated power, dBm
$L_o$ is the free-space loss for the given effective length and distance, dB
$G_{AUT}$ is the gain for the AUT, dBi
$L_4$ is the cable loss for approximately 1 meter, dB
$L_5$ is the cable loss for approximately 1 meter, dB

Now the most important check to execute is to ensure that the next inequations are accomplished:

$$\textit{System Sensitivity Level} \leq P_{TEST}, P_{REF} \leq \text{ Mixer 0.1 dB Compression Point} \tag{4.30}$$

Otherwise, correct system operation cannot be ensured. It is common that while seeking maximum power for the test channel the reference channel, say the RF input is overdriven. Under these conditions, attenuator will be required between the coupler and the reference mixer (see figure 4.22).

*Frequency converter system.* The last case (Figure 4.22 on page 56), RF power levels reaching the inputs of the converters have to be checked. These have to be within the manufacturer's given power range.

$$\begin{aligned} P_{TX} &= P_{out1} - L_2 \\ P_{RX} &= P_{out2} - L_4 - L_{r1} - L_{r2} \end{aligned} \tag{4.31}$$

$$P_{inRFmin} \leq P_{TX}, P_{RX} \leq P_{inRFmax} \tag{4.32}$$

Where:
$P_{out1}$ is the final power coming out of the optional amplifier on the transmission side, dBm
$P_{out2}$ is the final power coming out of the optional amplifier on the reception side, dBm
$L_2$ is the cable loss for approximately 1 meter, dB
$L_4$ is the cable loss for approximately 1 meter, dB
$L_{r1}$, $L_{r2}$ are the insertion loss values for the RJ, dB
$P_{inRFmin}$, $P_{inRFmax}$ are the extremes for the by the manufacturer recommended, RF input power range for the converters, dBm

**LO power levels**

The LO signal, as mentioned in subsection 4.1.4, is one of the strongest signals within the system. It is used to drive the mixers and frequency converters, depending on the system configuration. Usual frequency values for the LO are between 10 GHz and 20 GHz. These values turn out into the circumstance that special care has to be taken to warrant correct LO power levels reaching the frequency converting system, as the signal has to cover long cable paths at high frequencies. Again the division *External mixing system* and *Frequency converter system* has been done (see Figure 4.23 on next page).

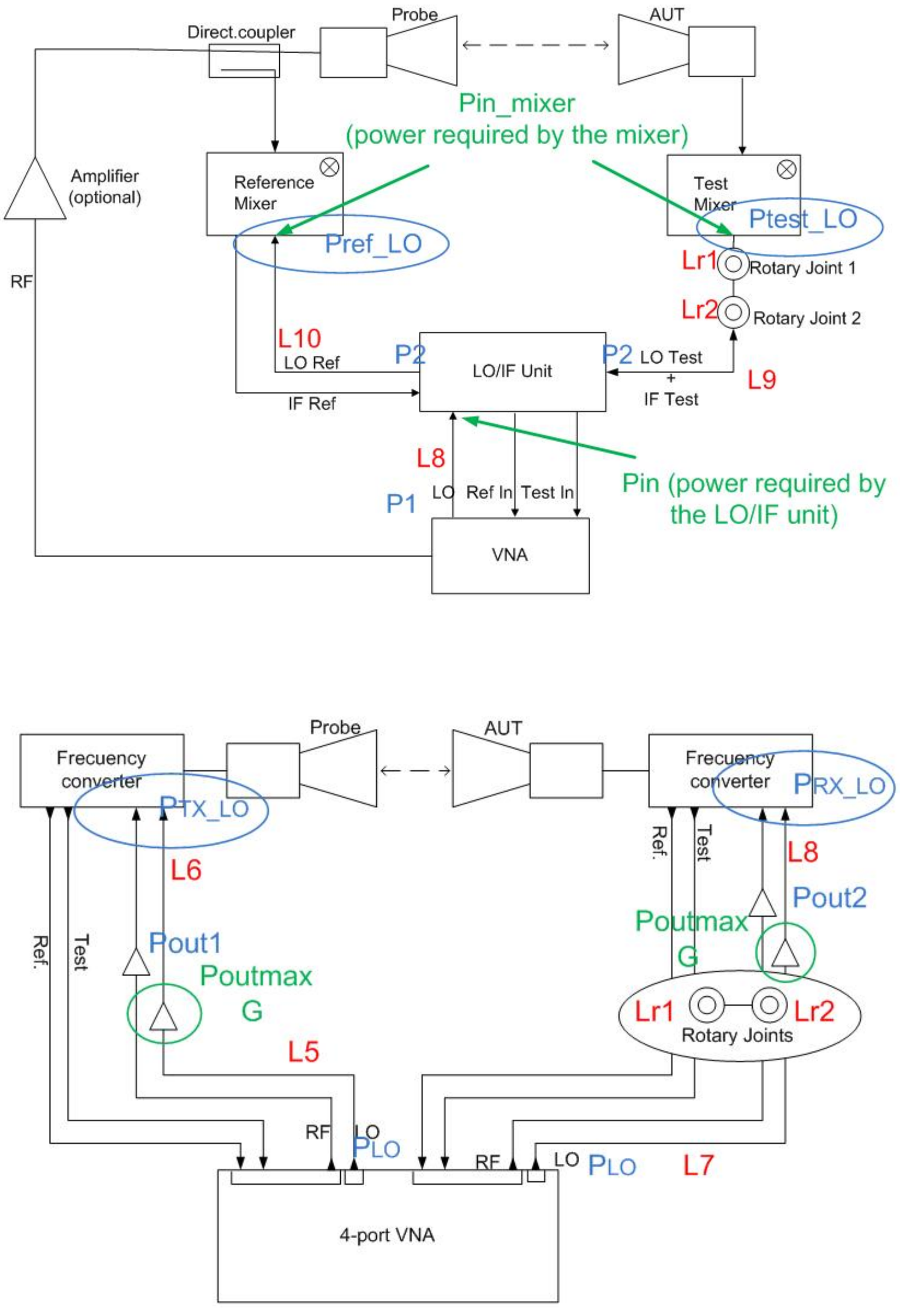


Figure 4.23.: Required power levels and specifications for LO power calculation.

*External mixing system.* In this case, additionally to the requirements in terms of LO drive power level another important fact has to be pointed out. As already alluded in subsection 4.1.4, some DFC systems require insertion losses trough reference and test channel to be the same. That is why, this item has to be checked on the corresponding datasheet. If it is the case of these kind of mixers, based on the power levels pictured in Figure 4.23, next check has to be performed.

$$L_{10} = L_9 + L_{r1} + L_{r2} \tag{4.33}$$

Where:
$L_{10}$ is the cable loss for approximately 4.5 meters, dB
$L_9$ is the cable loss for approximately 4.5 meters flexible cable, dB
$L_{r1}$, $L_{r2}$ are the insertion loss values for the RJ, dB

Usually, it can happen that due to the Rotary Joints's (RJ) insertion loss effect, to equalize power on both paths, additional cable length has to be introduced along the reference path.
Independently of what type of mixers are used, power levels reaching the LO/IF distribution unit and the mixers, have to satisfy the expressions below.

$$P_{inmin} \leq P_1 - L_8 \leq P_{inmax} \tag{4.34}$$

Where:
$P_{inmin}$, $P_{inmax}$ are the extremes for the by the manufacturer recommended, LO input power range for the LO/IF distribution unit, dBm
$L_8$ is the cable loss for approximately 4.5 meters, dB

For the mixers, there is also a recommended LO input power range which should be respected.

$$\begin{aligned} P_{inmixermin} \leq P_2 - L_9 - L_{r1} - Lr2 \leq P_{inmixermax} \text{ for the test mixer} \\ P_{inmixermin} \leq P_2 - L_{10} \leq P_{inmixermax} \text{ for the reference mixer} \end{aligned} \tag{4.35}$$

Where:
$P_{inmixermin}$, $P_{inmixermax}$ are the extremes for the by the manufacturer recommended, LO input power range for the mixers, dBm
$P_2$ is the LO/IF distribution unit's output LO power level , dB
$L_9$ is the cable loss for approximately 4.5 meters flexible cable, dB
$L_{10}$ is the cable loss for approximately 4.5 meters, dB
$L_{r1}$, $L_{r2}$ are the insertion loss values for the RJ, dB

*Frequency converter system.* In this case (Figure 4.23 on page 59), again it has to be ensured that for the given LO frequencies, there is enough power to correctly feed the frequency converters. Using the power levels defined in Figure 4.23, it has to be checked that:

$$\begin{aligned} P_{TXLO} &= P_{out1} - L_6 \\ P_{RXLO} &= P_{out2} - L_8 - L_{r1} - L_{r2} \end{aligned} \tag{4.36}$$

$$P_{inLOmin} \leq P_{TXLO}, P_{RXLO} \leq P_{inLOmax} \tag{4.37}$$

Where:
$P_{out1}$ is the final power coming out of the optional amplifier on the transmission side, dBm
$P_{out2}$ is the final power coming out of the optional amplifier on the reception side, dBm
$L_6$ is the cable loss for approximately 1 meter, dB
$L_8$ is the cable loss for approximately 1 meter, dB
$L_{r1}$, $L_{r2}$ are the insertion loss values for the RJ, dB

$P_{inLOmin}$, $P_{inLOmax}$ are the extremes for the by the manufacturer recommended, LO input power range for the converters, dBm

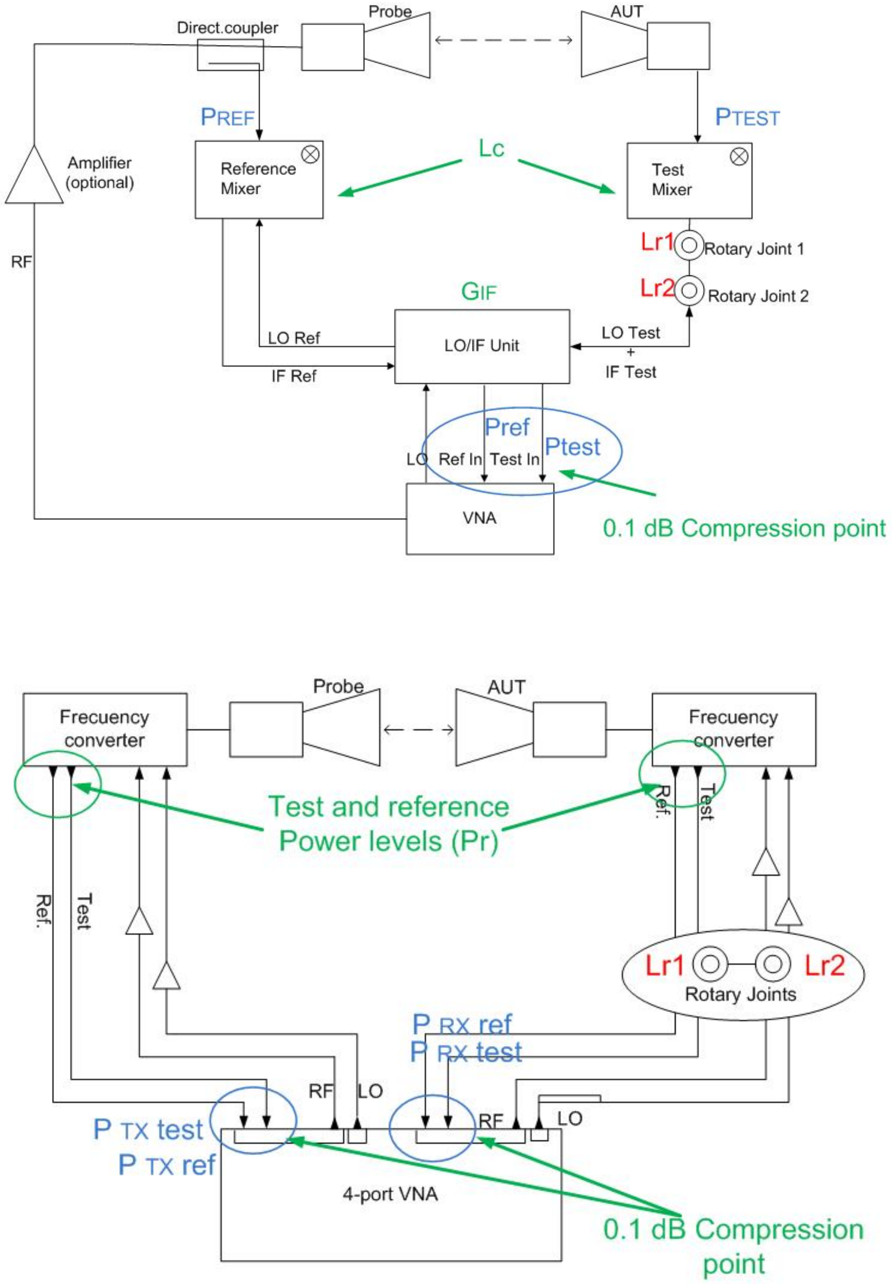


Figure 4.24.: Required power levels and specifications for IF power calculation.

### IF power levels

IF power levels are considered as the power reaching the analyzer inputs. These levels also must not exceed the specified *0.1 dB Compression level* for the analyzer inputs. Note that for all cases, as IF frequency is commonly around 10 MHz to 20 MHz, cable losses are not considered on these paths. *External mixing system.* For this kind of system (Figure 4.24 on previous page), power reaching the receiver can be determined using the power levels defined in the schematic and the following equations.

$$\begin{aligned} P_{Test} &= P_{TEST} - L_c + G_{IF} \\ P_{Ref} &= P_{REF} - L_c + G_{IF} - L_{r1} - L_{r2} \end{aligned} \tag{4.38}$$

$$P_{Test}, P_{Ref} \leq \text{ Analyzer 0.1 dB Compression Point} \tag{4.39}$$

Where:
$P_{TEST}$, $P_{REF}$ are the RF power levels reaching the mixers and calculated previously, dBm
$L_c$ is the mixers conversion loss, dB
$G_{IF}$ is the conversion gain of the LO/IF distribution unit, dB
$L_{r1}$, $L_{r2}$ are the insertion loss values for the RJ, dB

*Frequency converter system.* In this case (Figure 4.24 on previous page), an equivalent procedure to the one used for the *External mixing system* is used. Nevertheless, in this case, due to low frequencies, the test and measurement output power levels of the converters will be nearly equal to the ones reaching the receiver. The only possible differing factor can be the RJ insertion loss (around 1.2 dB).

### 4.2.5. Example

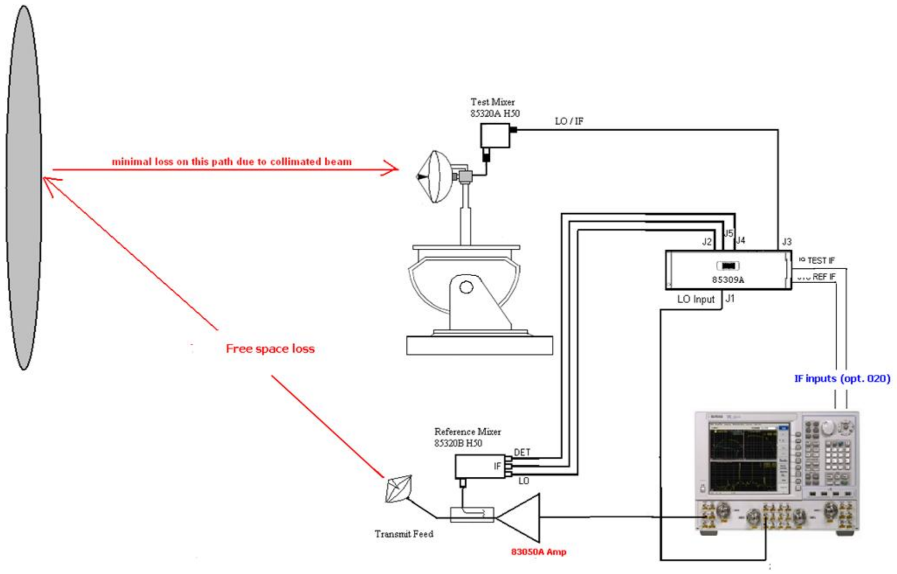


Figure 4.25.: Agilent Technologies proposal for an external mixing system.

In this section a whole example is calculated in detail for the two extreme frequencies of the defined range (2 GHz to 50 GHz). It has been divided into three parts:

- RF power levels
- LO power levels
- System Dynamic Range

Every value used and extracted from provider's supplied information is referred to its corresponding datasheet. The example analyzed is the external mixing configuration option made by Agilent Technologies to the IHF and can be seen in Figure 4.25.

***Measurement Dynamic Range***
The *Measurement Dynamic Range* corresponds to the value given by equation 4.25. Here it is seen again that a required SNR value has to be set. Additionally, the goal unknown are $P$ and the *System Sensitivity Level*, as it is the case of obtaining *Measurement Dynamic Range.*

$$DR = P - \text{Sensitivity Level} - SNR \tag{4.40}$$

First, the *Sensitivity Level* is calculated. Assuming that AUT temperature is 17 °C, equation 4.13 is used. As it is an example of external mixing, and no information is given by the provider regarding the noise figure for the IF amplifier, equation 4.9 can be replaced into equation 4.13. The resulting expression will provide the required system noise floor, say *System Sensitivity Level.*

$$N = -174 + 10\log\left(L_c\right) \tag{4.41}$$

$L_c$ is the HP85320 H50 mixer conversion loss and it is 12 dB at 2 GHz, and 28 dB at 50 GHz. These values are found in the **Agilent LO/IF unit and mixer datasheet** [35] on page 54, Table 10.

This way, the first unknown is determined:

$$\begin{aligned} N &= -162\ dBm/Hz \text{ at 2 GHz} \\ N &= -146\ dBm/Hz \text{ at 50 GHz} \end{aligned} \tag{4.42}$$

This noise level, has to be compared to the *Receiver Sensitivity Level.* In this case, the *Receiver Sensitivity Level* can be found on page 43 of the **Agilent N5245A PNA-X** [30]. It has to be expressed in dBm/Hz through the IF bandwidth value of 10 Hz. This value is -124 dBm/Hz at 2 GHz and -123 dBm/Hz at 50 GHz. In this case, system levels are more restrictive, and as a consequence, *Sensitivity Level* will correspond to the system's noise floor.

The final absolute noise level applying are:

$$\begin{aligned} N &= -152\ dBm \text{ at 2 GHz} \\ N &= -136\ dBm \text{ at 50 GHz} \end{aligned} \tag{4.43}$$

Following, power at the reception side $P$ has to be determined. Following the procedure presented for an *External mixing system* is applied.

$$\begin{aligned} \text{If } P_S - L_1 + G \geq P_{outmax} \text{ then } P_{out} &= P_{outmax} \\ \text{else } P_{out} &= P_S - L_1 + G \end{aligned} \tag{4.44}$$

$P_S$ is the Agilent N5245A PNA-X's source output power, which is 8 dBm at 2 GHz, and -8 dBm at 50 GHz. These values are found in the **Agilent N5245A PNA-X** [30] on page 7, Table 1.

$L_1$ is the cable loss for 10 meters with a Huber+Suhner® SUCOFLEX101 cable, which is 7 dB at 2 GHz, and 35.1 dB at 50 GHz. These values are found in the **Huber+Suhner® SUCOFLEX101 datasheet** [31].

$G$ is the Agilent 83050A amplifier's small signal gain, which is 21 dB all over the frequency range. These values are found in the **Agilent 83050A Amplifier datasheet** [39] on page 5.

$P_{outmax}$ is the Agilent 83050A amplifier's maximum output power, which is 20 dBm at 2 GHz, and 17 dBm at 50 GHz. These values are found in the **Agilent Amplifier datasheet** [39] on page 5.

And the power for the power coming out of the amplifier:

$$\begin{aligned} P_{out} &= 20\ dBm \text{ at } 2 \text{ GHz} \\ P_{out} &= -22.1\ dBm \text{ at } 50 \text{ GHz} \end{aligned} \tag{4.45}$$

Then, the effective radiated power is obtained:

$$ERP = P_{out} - L_2 - L_{ins} - L_3 + G_{FEED} - L_{FEEDVSWR} \tag{4.46}$$

$L_2$ is the cable loss for 1 meter with a Huber+Suhner® SUCOFLEX101 cable, which is 0.7 dB at 2 GHz, and 3.51 dB at 50 GHz. These values are found in the **Huber+Suhner® SUCOFLEX101 datasheet** [31].

$L_{ins}$ is the Agilent 87301E coupler's insertion loss, which is 2 dB all over the frequency range. These values are found in the **Agilent 87301E Coupler datasheet** [38] on page 2.

$L_3$ is the cable loss for 1 meter with a Huber+Suhner® SUCOFLEX101 cable, which is 0.7 dB at 2 GHz, and 3.51 dB at 50 GHz. These values are found in the **Huber+Suhner® SUCOFLEX101 datasheet** [31].

$G_{FEED}$ is the ORBIT/FR feed's gain, which is 13 dBi all over its specified range. These values are found in the **ORBIT/FR datasheet** [17] on page 50.

$L_{FEEDVSWR}$ is the loss derived from the ORBIT/FR feed's VSWR, which is 0.3 dB (1.7:1) at 2 GHz, and 0.07 dB (1.3:1), say null, at 50 GHz. These values are found in the **ORBIT/FR datasheet** [17] on page 50 and using the ***VSWR* online calculators**.

In this case,

$$\begin{aligned} ERP &= 29.3\ dBm \text{ at 2 GHz} \\ ERP &= -18.1\ dBm \text{ at 50 GHz} \end{aligned} \tag{4.47}$$

Using expression for $P$:

$$P = ERP - L_o + G_{AUT} - L_4 \tag{4.48}$$

$L_o$ is the free-space loss value for the given range and frequencies, obtained through expression $L_o = 32.45+20\log R+20\log f$, which is 52 dB at 2 GHz and 80 dB at 50 GHz.

$G_{AUT}$ is set to the 0 dBi, following the line of argument exposed in subsection 4.1.5.

$L_4$ is the cable loss for 1 meter with a Huber+Suhner® SUCOFLEX101 cable, which is 0.7 dB at 2 GHz, and 3.51 dB at 50 GHz. These values are found in the **Huber+Suhner® SUCOFLEX101 datasheet** [31].

Finally, the power reaching the receiver RF-front-end is:

$$\begin{aligned} P &= -23.4\ dBm \text{ at 2 GHz} \\ P &= -101.6\ dBm \text{ at 50 GHz} \end{aligned} \tag{4.49}$$

Now, a SNR value has to be fixed. Using the graphic displayed in Figure 4.21, a SNR is chosen that set magnitude and phase measurement error to approximately 1 dB and 10°respectively. This value is around 15 dB.
Consequently, using expression 4.40, the $DR$ values are:

$$\begin{aligned} DR &= 113.6\ dB \text{ at 2 GHz} \\ DR &= 19.4\ dB \text{ at 50 GHz} \end{aligned} \tag{4.50}$$

Results can be put together as shown in Table 4.6 and Figure 4.26.

Table 4.6.: *Measurement Dynamic Range* calculation power levels for Agilent Technologies proposal with an external mixing system from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | **50 GHz** |
|---|---|---|
| $P_S$ (dBm) | 8 | -8 |
| $L_1$ (dB) | (-)7 | (-)35.1 |
| $G$ (dB) | 21 | 21 |
| $P_{out}$ (dBm) | 20 | -22.1 |
| $L_2$ (dB) | (-)0.7 | (-)3.51 |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | (-)0.7 | (-)3.51 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | 0 |
| $ERP$ (dBm) | 29.3 | -18.1 |
| $L_o$ (dB) | (-)52 | (-)80 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.7 | (-)3.51 |
| $P$ (dBm) | -23.4 | -101.61 |
| $N$ (dBm) | (-)-152 | (-)-136 |
| $SNR$ (dB) | (-)15 | (-)15 |
| $DR$ (dB) | 113.6 | 19.39 |

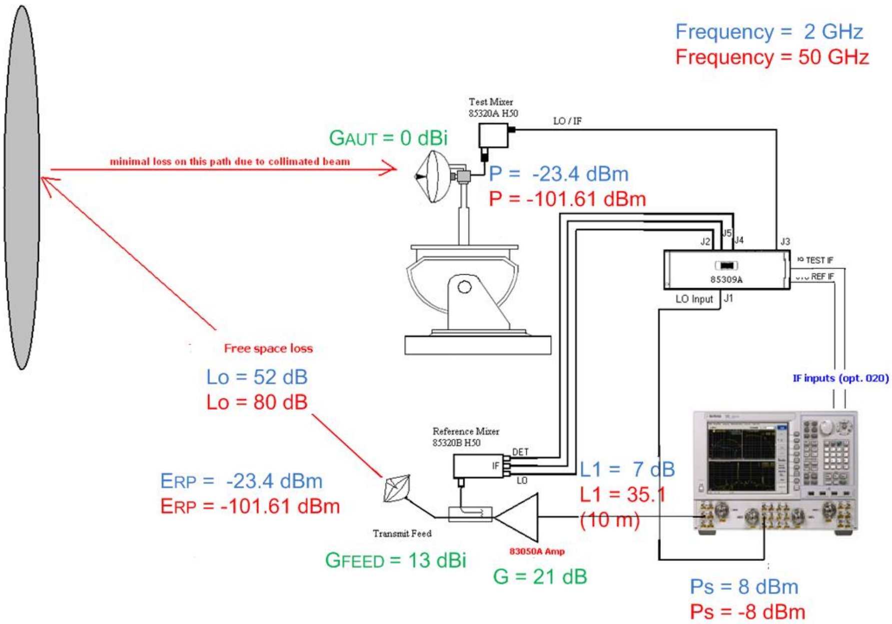


Figure 4.26.: Agilent Technologies proposal for external mixing configuration with performance analysis results.

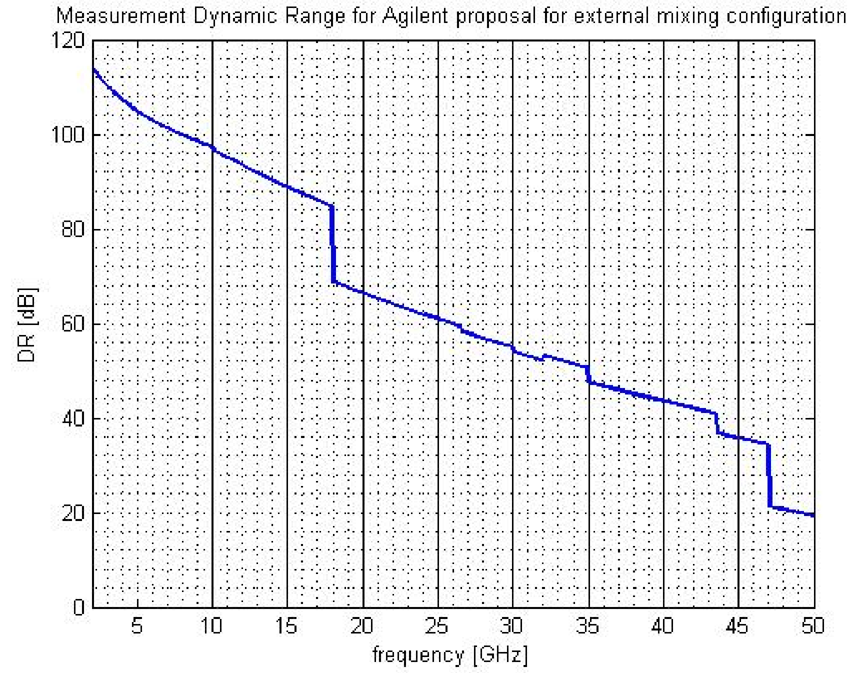


Figure 4.27.: Dynamic Range for Agilent Technologies proposal.

These values could be improved through IF bandwidth narrowing or averaging 4.27 4.28, with the consequent speed measurement decrease.
As it is required to know *DR* all over the frequency range defined, these calculations can be generalized for every frequency point through MATLAB® scripts and plotted as seen in Figure 4.27.

***RF power levels***
To obtain these levels, expressions presented in subsection 4.2.4 apply.

$$\begin{aligned} P_{TEST} &= ERP - L_o + G_{AUT} - L_4 \\ P_{REF} &= P_{out} - L_2 - L_{coup} - L_5 \end{aligned} \tag{4.51}$$

Where:
$ERP$ can be obtained as for the *DR* example calculation, and it is 29.3 dBm at 2 GHz and -18.1 dBm at 50 GHz.

$L_o$ is the free-space loss value for the given range and frequencies, obtained through expression $L_o = 32.45 + 20 \log R + 20 \log f$, which is 52 dB at 2 GHz and 80 dB at 50 GHz.

$G_{AUT}$ is set to the 0 dBi, following the line of argument exposed in subsection 4.1.5.

$L_4$ is the cable loss for 1 meter with a Huber+Suhner® SUCOFLEX101 cable, which is 0.7 dB at 2 GHz, and 3.51 dB at 50 GHz. These values are found in the **Huber+Suhner® SUCOFLEX101 datasheet** [31].

$P_{out}$ can be obtained as for the *DR* example calculation, and it is 20 dBm at 2 GHz and -22.1 dBm at 50 GHz.

$L_2$ is the cable loss for 1 meter with a Huber+Suhner® SUCOFLEX101 cable, which is 0.7 dB at 2 GHz, and 3.51 dB at 50 GHz. These values are found in the **Huber+Suhner® SUCOFLEX101 datasheet** [31].

$L_{coup}$ is the Agilent 87301E coupler's coupling loss, which is 10 dB all over the frequency range. These values are found in the **Agilent Coupler datasheet** [38] on page 2.

$L_5$ is the cable loss for 1 meter with a Huber+Suhner® SUCOFLEX101 cable, which is 0.7 dB at 2 GHz, and 3.51 dB at 50 GHz. These values are found in the **Huber+Suhner® SUCOFLEX101 datasheet** [31].

The maximum power level which has to be respected is found in **Agilent LO/IF unit and mixer datasheet** [35] on page 54. On the other hand, the minimum is defined by the *System Sensitivity Level* obtained in the *DR* calculation example.

$$\begin{aligned}\text{Maximum level}: 0.1\text{ dB Compression point} &= -24\ dBm\\ \text{Minimum level}: N &= -162\ dBm \text{ at 2 GHz}\\ \text{Minimum level}: N &= -146\ dBm \text{ at 50 GHz}\end{aligned} \tag{4.52}$$

As the resulting power levels are:

$$\begin{aligned}P_{TEST} &= -23.4\ dBm \text{ at 2 GHz}\\ P_{TEST} &= -101.6\ dBm \text{ at 50 GHz}\\ P_{REF} &= 8.6\ dBm \text{ at 2 GHz}\\ P_{REF} &= -39.1\ dBm \text{ at 50 GHz}\end{aligned} \tag{4.53}$$

In conclusion, an attenuator will be required for the reference path for the lower part of the frequency range. Otherwise, the reference mixer will be driven out of its linear working zone. At the test path, situation is similar but only for 0.6 dB and for 2 GHz. These results are based on theoretical, worst case situation calculation using most of the times typical values. That is why in practice, this little overdriving situation may vary. It is more important to consider by the future tester the circumstance that AUT gain has been considered 0. That means, that source power must be turned down as the AUT expected gain value increases. A good option to state optimal settings is using a software tool as the one presented in the next chapter.

The results for the most relevant system points can be seen in Figure 4.28. To sum up and generalize results for all over the frequency range, table 4.7 and graphic 4.29 have been included on next page.

Table 4.7.: RF power level calculation for Agilent Technologies proposal for an external mixing system from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | **50 GHz** |
|---|---|---|
| $P_S$ (dBm) | 8 | -8 |
| $L_1$ (dB) | (-)7 | (-)35.1 |
| $G$ (dB) | 21 | 21 |
| $P_{out}$ (dBm) | 20 | -22.1 |
| $L_2$ (dB) | (-)0.7 | (-)3.51 |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | (-)0.7 | (-)3.51 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | 0 |
| $ERP$ (dBm) | 29.3 | -18.1 |
| $L_o$ (dB) | (-)52 | (-)80 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.7 | (-)3.51 |
| $P_{TEST}$ (dBm) | -23.4 | -101.61 |
| $L_{coup}$ (dB) | (-)10 | (-)10 |
| $L_5$ (dB) | (-)0.7 | (-)3.51 |
| $P_{REF}$ (dBm) | 8.6 | -39.1 |
| $Minimum$ (dBm) | -152 | -136 |
| $Maximum$ (dBm) | -24 | -24 |

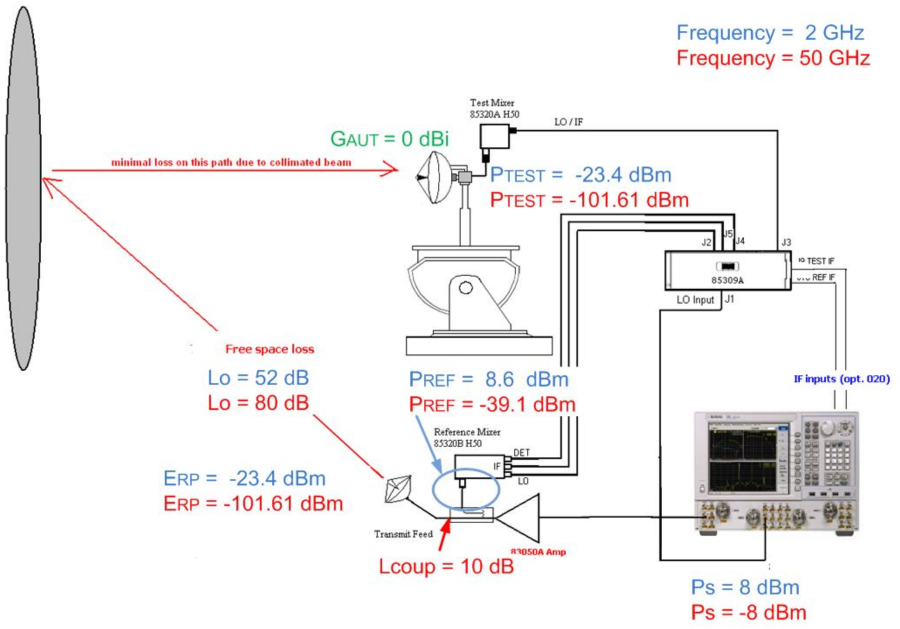


Figure 4.28.: Agilent Technologies proposal for external mixing configuration with RF power levels analysis results.

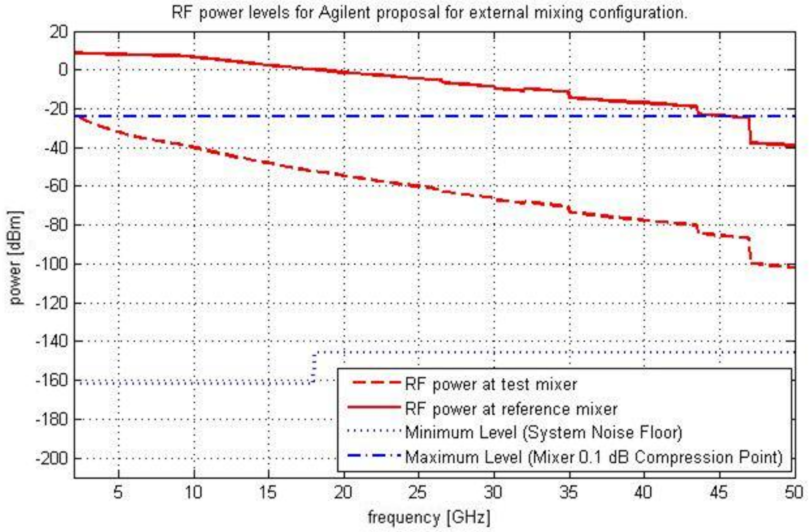


Figure 4.29.: RF power levels for Agilent Technologies proposal.

***LO power levels***

For LO power level calculation, LO maximum frequency has to be used. It is found in the corresponding **Agilent LO/IF unit and mixer datasheet** [35] on page 47. In this case, the maximum frequency is 18 GHz.

Then, the mixer models have to be identified and determined if they require having same losses for both test and reference LO paths. In the example analyzed, mixers require to have the same loss as it is stated in the Agilent configuration guide [25]: "*This is to ensure that the insertion losses through the reference and test mixer module LO paths are the same.*". Consequently, the next check is performed.

$$\begin{aligned} \text{Check if } L_{10} &= L_9 + L_{r1} + L_{r2} \\ L_{10} &= 5\ dB \text{ at 18 GHz} \\ L_9 + +L_{r1} + L_{r2} &= 8.2\ dB \text{ at 18 GHz} \end{aligned} \tag{4.54}$$

Where:

$L_{10}$ is the cable loss for 4.5 meters with a Huber+Suhner® SUCOFLEX104 cable, which loss is 5 dB at 18 GHz. This value is found in the **Huber+Suhner® SUCOFLEX104 datasheet** [32].

$L_9$ is the cable loss for 4.5 meters with a Micro Coax® MIL-DTL-17/129 semi-rigid coaxial cable, which loss is 7 dB at 18 GHz. This value is found in the **Micro Coax® MIL-DTL-17/129 semi-rigid coaxial cables datasheet** [42] on page 14.

$L_{r1}$, $L_{r2}$ are the Spinner BN 83-50-47 RJ's insertion loss for each one of them, which is 0.6 dB all over the frequency range. These values are found in the **Spinner datasheet** [34] on page 15.

It can be seen that additional cable will have to be considered for the reference path in order to even the insertion loss for both paths. In this case the extra cable length would be approximately 3 meter (1.1 dB/m insertion loss at 18 GHz) of a **Huber+Suhner® SUCOFLEX104 cable** [32]. This way the losses on the path would be 8.2 dB.

Next, LO levels are determined using the next expressions already presented in subsection 4.2.4.

$$\begin{aligned} \text{Check if } P_{inmin} &\leq P_1 - L_8 \leq P_{inmax} \\ 0\ dBm &\leq P_1 - L_8 \leq 6\ dBm \\ P_1 &= 13dBm\ dBm \text{ at 18 GHz} \\ L_8 &= 5\ dB \text{ at 18 GHz} \end{aligned} \tag{4.55}$$

Where:
$P_{inmin}$, $P_{inmax}$ are the extremes for the by the manufacturer recommended, LO input power range for the Agilent 85309 LO/IF distribution unit, these values are 0 dBm and 6 dBm, and can be found in the **Agilent LO/IF unit and mixer datasheet** [35] on page 48.

$P_1$ is Agilent N5245A PNA-X's maximum source output power, which is 13 dBm at 18 GHz. This value is found in the **Agilent N5245A PNA-X** [30] on page 7, Table 1.

$L_8$ is the cable loss for 4.5 meters with a Huber+Suhner® SUCOFLEX104 cable, which loss is 5 dB at 18 GHz. This value is found in the **Huber+Suhner® SUCOFLEX104 datasheet** [32].

This way, it has been found out, that due to system configurations, there is no need to use the maximum output power of the VNA for the LO source.
The recommended LO input levels for the mixers are also being checked and obtained through previously calculated losses.

$$\begin{aligned} \text{Check if } P_{inmixermin} \leq P_2 - L_9 - L_{r1} - Lr2 \leq P_{inmixermax} \text{ for the test mixer} \\ P_{inmixermin} \leq P_2 - L_{10} \leq P_{inmixermax} \text{ for the reference mixer} \end{aligned} \tag{4.56}$$

$$\begin{aligned} \text{Check if } 12\ dBm \leq P_2 - 8.2dB \leq 17\ dBm \text{ for the test mixer} \\ 12\ dBm \leq P_2 - 8.2dB \leq 17\ dBm \text{ for the reference mixer} \\ P_2 = 19dBm\ dBm \end{aligned} \tag{4.57}$$

Where:
$P_{inmixermin}$, $P_{inmixermax}$ are the extremes for the by the manufacturer recommended, LO input power range for the Agilent 85320 H50 mixers, these values are 12 dBm and 17 dBm, and can be found in the **Agilent LO/IF unit and mixer datasheet** [35] on page 48.

$P_2$ is the Agilent 85309 LO/IF distribution unit's output LO power level, this value is 19 dBm, and can be found in the **Agilent LO/IF unit and mixer datasheet** [35] on page 47.

Here it can be seen how additional 2 dB are required. This could be solved either trying to place the LO/IF distribution unit in a way to reduce cable distance, or introducing amplifiers on the paths. Another option would be trying to find semi-rigid cables with a lower insertion loss parameter.
These power levels can be found in Figure 4.30 on next page. To sum up, table 4.7 has been included.

Table 4.8.: LO power level calculation for Agilent Technologies proposal for an external mixing system.

| **Frequency** | **18 GHz** |
|---|---|
| $P_1$ (dBm) | 13 |
| $L_8$ (dB) | (-)5 |
| $P_1$-$L_8$ (dBm) | 8 |
| *Minimum* (dBm) | 0 |
| *Maximum* (dBm) | 6 |
| $L_{10}$ (dB) | (-)5 |
| $L_9$ (dB) | (-)7 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $L_9$- $L_{r1}$ - $L_{r2}$ (dB) | (-)8.2 |
| Loss applying, $L$ (dB) | (-)8.2 |
| $P_2$ (dBm) | 19 |
| $P_2$ - $L$ (dBm) | 10.8 |
| *Minimum* (dBm) | 12 |
| *Maximum* (dBm) | 18 |

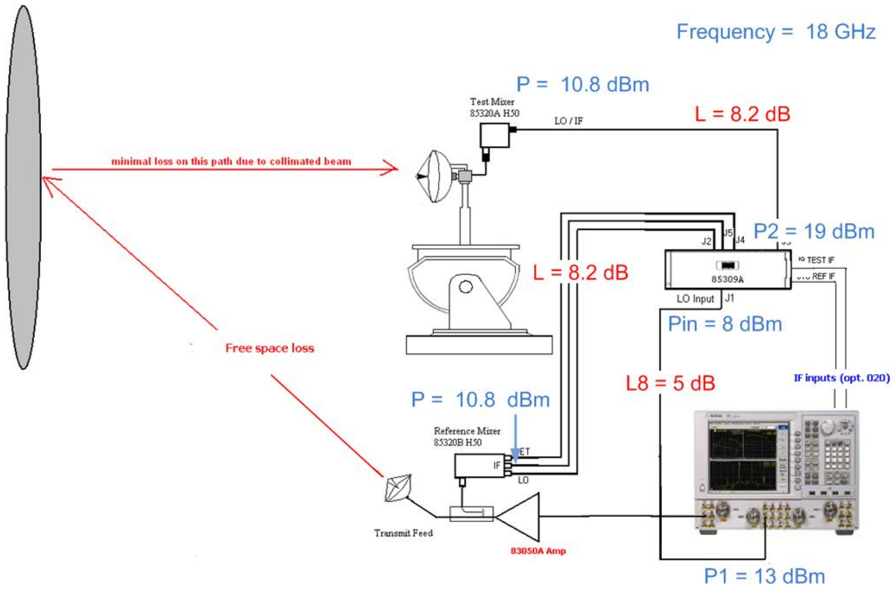


Figure 4.30.: Agilent Technologies proposal for external mixing configuration with LO power levels analysis results.

***IF power levels***

Last power levels left to check are the IF power levels reaching the receiver. As it is to check if they exceed a value, this calculation is done for the worst case for this frame of work. That means, using values at the lowest RF frequency. Taking the expressions from subsection 4.2.4, the calculation check is performed.

$$\begin{aligned} P_{Test} &= P_{TEST} - L_c + G_{IF} \\ P_{Ref} &= P_{REF} - L_c + G_{IF} - L_{r1} - L_{r2} \\ P_{Test}, P_{Ref} &\leq \text{ Analyzer 0.1 dB Compression Point} \end{aligned} \tag{4.58}$$

$$\begin{aligned} P_{Test} &= -11 \text{ dBm} \\ P_{Ref} &= -12.2 \text{ dBm} \\ P_{Test}, P_{Ref} &\leq \text{ Analyzer 0.1 dB Compression Point} \end{aligned} \tag{4.59}$$

Where:

*Analyzer 0.1 dB Compression Point* is the Agilent N5245A PNA-X's maximum accepted input level, which is -9 dBm for the offered 020 option. It is found in the **Agilent N5245A PNA-X** [30] on page 61, Table 31.

$P_{TEST}$, $P_{REF}$ are the RF power levels reaching the mixers calculated previously, for the RF power level check and, for the worst case, and assuming the required attenuation is included, these values are set to -24 dBm

$L_c$ is the HP85320 H50 mixer conversion loss and it is 12 dB at 2 GHz. This values is found in the **Agilent LO/IF unit and mixer datasheet** [35] on page 54, Table 10.

$G_{IF}$ is the Agilent 85309 LO/IF distribution unit's IF small signal channel gain, the maximum value of 25 dB is taken, to consider this a worst case calculation. It can be found in the **Agilent LO/IF unit and mixer datasheet** [35] on page 47, Table 10.

$L_{r1}$, $L_{r2}$ are the Spinner BN 83-50-47 RJ's insertion loss for each one of them, which is 0.6 dB all over the frequency range. These values are found in the **Spinner datasheet** [34] on page 15.

It can be seen that values, even if it has been performed a worst case calculation, are in range. Once more, results are also stated in the system schematic in 4.31 and in the table 4.9 on next page.

Table 4.9.: IF power level calculation for Agilent Technologies proposal for an external mixing system.

| **Frequency (worst case)** | **IF = 7.606 MHz, RF = 2 GHz** |
|---|---|
| $P_{TEST}$ (dBm) | -24 |
| $P_{REF}$ (dBm) | -24 |
| $L_c$ (dB) | (-)12 |
| $G_{IF}$ (dB) | 25 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $P_{Test}$ (dBm) | -11 |
| $P_{Ref}$ (dBm) | -12.2 |
| *Analyzer 0.1 dB Compression Point* (dBm) | -9 |

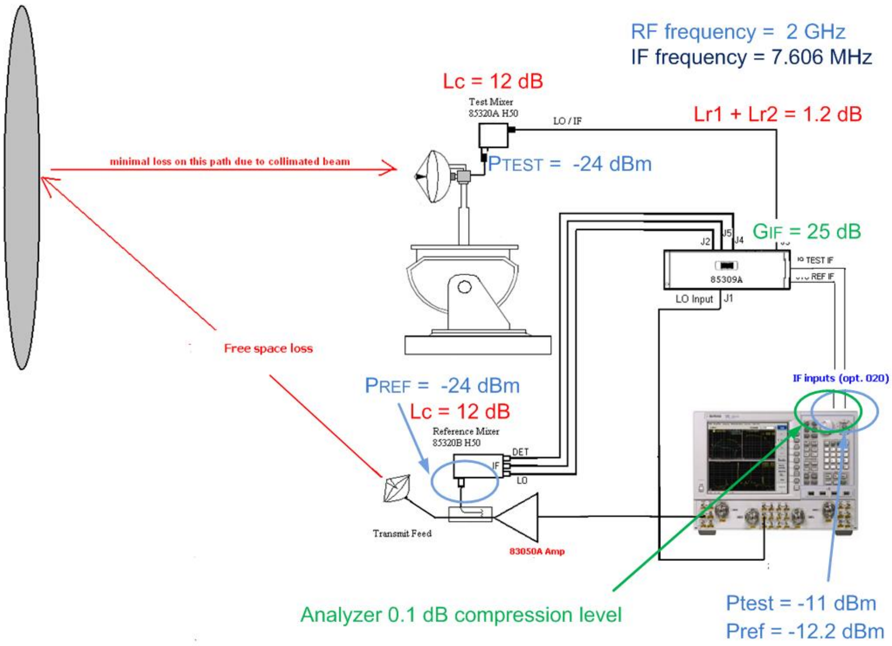
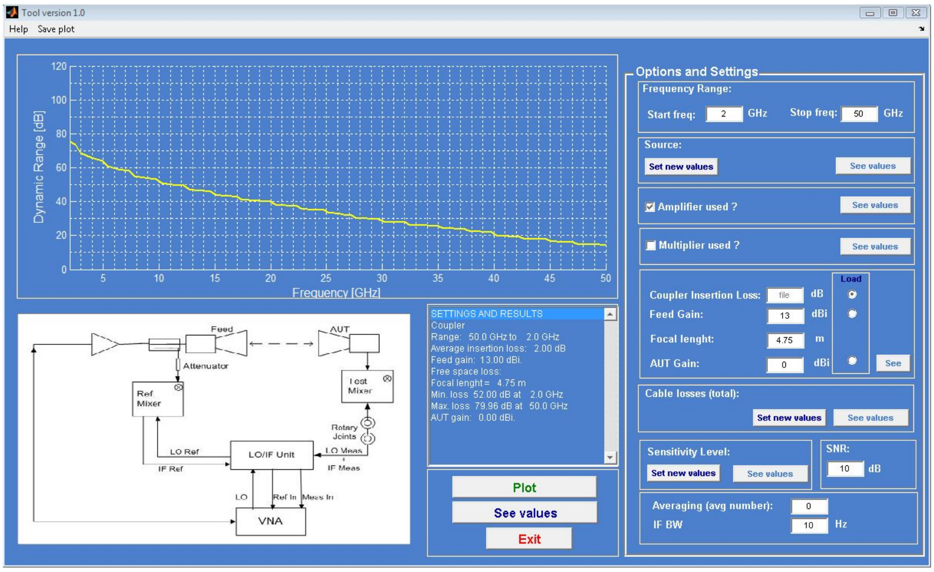


Figure 4.31.: Agilent Technologies proposal for external mixing configuration with IF power levels analysis results.

# 5. Software Tool development

As it has been seen in previous chapters, system performance analysis is not straightaway. A considerable number of variables have to be taken into account and different checks have to be performed. In order to ease and generalize the procedure of evaluating system performance analysis, a MATLAB® based software tool has been developed. It allows the user to introduce the required system characteristics and the frequency range to be analyzed. The software uses this data to discretize the frequency span and to obtain the *Measurement Dynamic Range DR* and critical power levels all over the mentioned frequency interval (subsections 4.2.3 and 4.2.4). In this manner, not only the graphics for the mentioned system attributes, but also obtain the power levels on the interesting, say critical, system points for concrete frequency values within the defined range can be obtained.
The philosophy of this program is based on user interaction through MATLAB® GUI's (Graphic User Interface), which allow introducing all the required data. Once this is done, GUI's are programmed to, through classical MATLAB® scripts, calculate the required system characteristics.



```
SETTINGS AND RESULTS
Coupler
Range:   50.0 GHz to    2.0 GHz
Average insertion loss:   2.00 dB
Feed gain:  13.00 dBi.
Free space loss:
Focal lenght =   4.75 m
Min. loss  52.00 dB at    2.0 GHz
Max. loss  79.96 dB at   50.0 GHz
AUT gain:   0.00 dBi.
```

Frequency Range:
Start freq: 2 GHz
Stop freq: 50 GHz
Source:
☑ Amplifier used ?
☐ Multiplier used ?
Coupler Insertion Loss: file dB ●
Feed Gain: 13 dBi ○
Focal lenght: 4.75 m
AUT Gain: 0 dBi ○
Cable losses (total):
Sensitivity Level:
SNR: 10 dB
Averaging (avg number): 0
IF BW 10 Hz

Figure 5.1.: Software Tool version 1.0 main window.

The user interface is divided into two principal windows, say GUI's. The first one (Figure 5.1), acts like a classical RF device panel, but applying for the whole system. Through it, the system can be defined and the settings can be introduced. Then, it can be chosen if *DR* wants to be calculated, if critical power levels want to be known or if concrete power levels for concrete system points are wanted. In this case, a second GUI shows up and pictures the power levels on the system schematic (Figure 5.2).

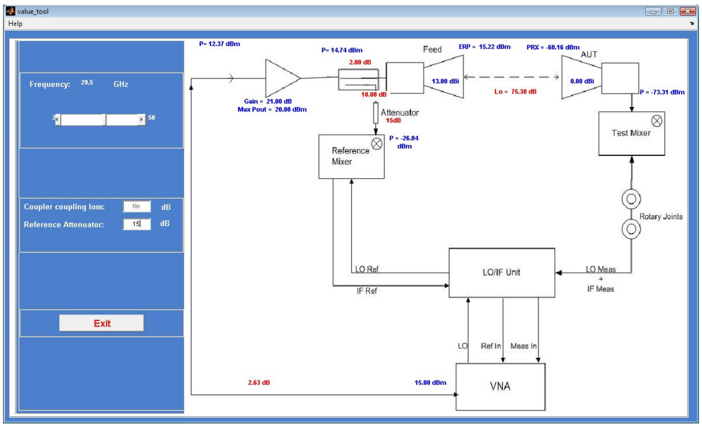
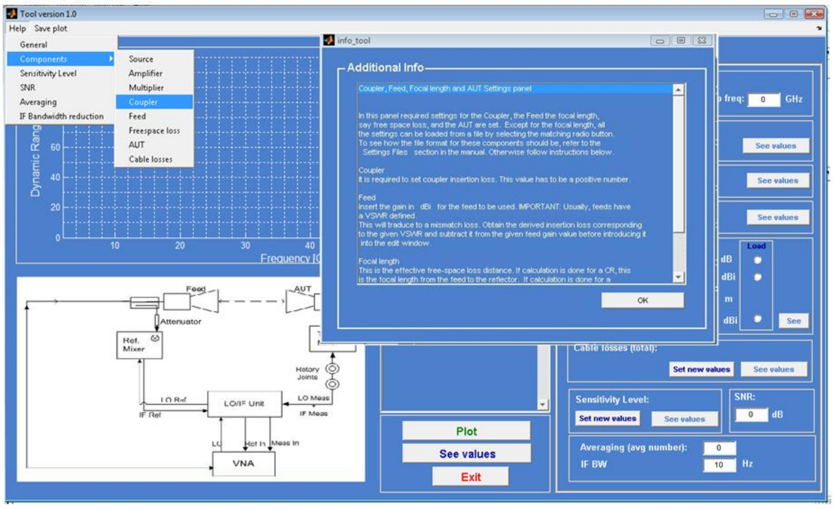

Frequency: 29.5 GHz
Coupler coupling loss: file dB
Reference Attenuator: 15 dB

Figure 5.2.: Software Tool version 1.0 power level calculation window.

Secondary GUI's can possibly show up, in order to ease data input or the act as user "Help" environment (Figure 5.3). Data input can be done through classical edit windows appearing in a sub GUI (Figure 5.4, or loading it from a *.txt* file. The file format is accurately defined in software's instruction manual found in appendix C.


Coupler, Feed, Focal length and AUT Settings panel

In this panel required settings for the Coupler, the Feed the focal length,
say free space loss, and the AUT are set. Except for the focal length, all
the settings can be loaded from a file by selecting the matching radio button.
To see how the file format for these components should be, refer to the
Settings Files section in the manual. Otherwise follow instructions below.

Coupler
It is required to set coupler insertion loss. This value has to be a positive number.

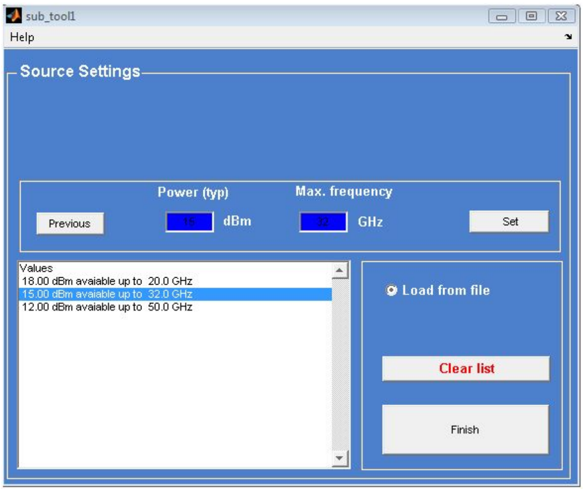
Feed
Insert the gain in dBi for the feed to be used. IMPORTANT: Usually, feeds have
a VSWR defined.
This will traduce to a mismatch loss. Obtain the derived insertion loss corresponding
to the given VSWR and subtract it from the given feed gain value before introducing it
into the edit window.

Focal length
This is the effective free-space loss distance. If calculation is done for a CR, this
is the focal length from the feed to the reflector. If calculation is done for a

freq: 0 GHz
SNR: 0 dB
Averaging (avg number): 0
IF BW 10 Hz

Figure 5.3.: Software Tool version 1.0 "Help" environment.

Internally, the program works with data matrices in which every column is a point of the discrete frequency span. Every row corresponds to a value or setting required for the calculation (Figure 5.5). These matrices are used by the scripts to calculate the required feature. The calculation is based on the procedure developed in chapter 4.



Power (typ): 15 dBm

Max. frequency: 32 GHz

Values
18.00 dBm avaiable up to  20.0 GHz
15.00 dBm avaiable up to  32.0 GHz
12.00 dBm avaiable up to  50.0 GHz

Figure 5.4.: Software Tool version 1.0 settings introduction sub GUI.

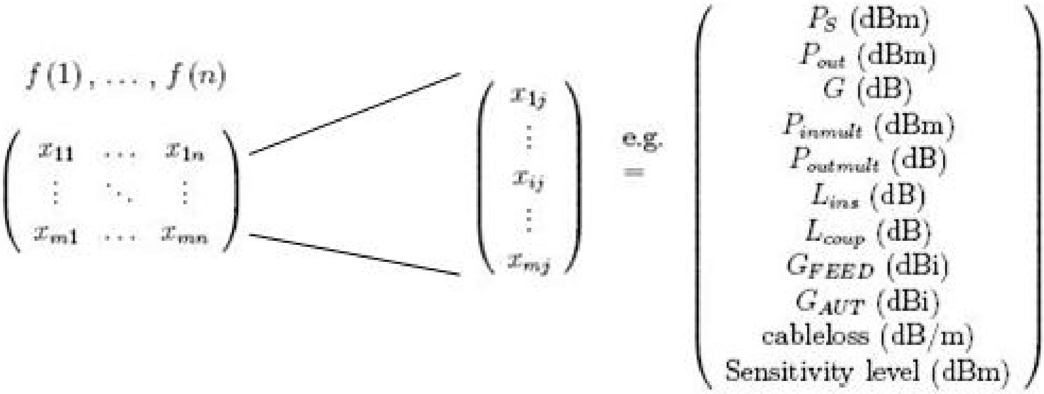


Figure 5.5.: Data matrix example for software Tool version 1.0 with $n$ frequency points.

Apart from the calculation scripts itself, there are other scripts in the program intended to execute other type of tasks. There are scripts to act as error check for the input data and notice it to the user before the calculation is performed. Another type of scripts used in the program manages the graphic input environment. Finally, the last type of scripts carry out tasks in terms of transforming data to the calculation format or to the user's display format. A script hierarchy can be found in the code documentation found in appendix C.

Even if the developed software fulfills all the specified requirements in a first stage, there are some issues left open that could be improved and considered as future work proposals. These topics are:

- Allow the user to charge values for a concrete system component using different files, instead of changing the file for every case.
- Allow the user to introduce different cable paths depending on the path.
- Develop additional system performance attribute calculation, for instance, measurement speed.
- Include plotting options for RF, LO and IF power levels.
- Include the ”Frequency converter system” standard configuration pattern.

As the program source code and detailed code documentation is at hand and due to the programs own nature, new requirements, mentioned topics left open, and possible improvements could be easily introduced.

# 6. Results

This chapter intends to offer the reader a global overview on the results once the different proposals were analyzed following the patterns exposed in chapter 4.
First, analysis pattern has been applied to the traditional far field range currently found at the IHF.
Then, aiming to obtain a reliable performance comparison, proposals have been divided depending on what general system pattern they follow (see chapter 4), and this way contrast results between them.
It has been assumed that the CR supplier will be ORBIT/FR, since at the stage this work has been developed, it was the most potential supplier. In case this situation changes, in order to make result actualization easier, analysis pattern in chapter 4 and Software Tool v1.0 (see chapter 5) have been left as general as possible.
For each of these mentioned system patterns, *Measurement Dynamic Range DR* is calculated for the extreme values of the system's frequency range and then plotted all over the frequency span.
For each of these comparisons, conclusions and result interpretation are included.
For detailed information regarding each of the proposals, refer to Appendix B.

## 6.1. IHF traditional Far Field Test Range

In order to obtain a first approach to system analysis and performance evaluation, and to underline the need to refurbish the current antenna test range found at the IHF, performance analysis of the mentioned range has been carried out.
It is a traditional far field range whose system follows the general system pattern of an external mixing configuration. The range is intended to work within 2 GHz and 50 GHz, although the current cable layout only permits to run and analyze the range up to 26.5 GHz.
The system is made up of an HP 8530 Microwave receiver, an HP 83621A Sweep oscillator, an HP 83651A Synthesized sweeper, and the HP 853209/HP85320 H50 LO/IF unit and mixer.
Cable lengths have been measured as accurate as the system layout permitted and both cable length and cable model itself, when not available, are assumed under approximations.

Unlike the case of CR proposal analysis, not all of the datasheets employed could be referred since some of them, due to the age of the range, are no longer available. In some cases, specifications were included in the specific manuals belonging to the internal documents of the IHF.
As this analysis is meant to be an approach to system analysis and out of the main scope of this work, not all the datasheets have been referred.

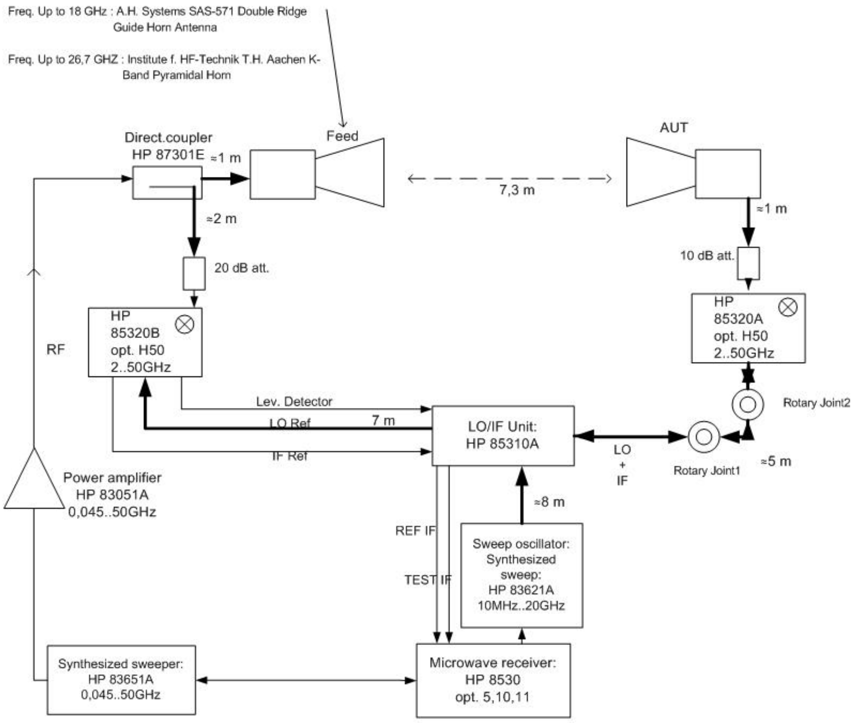


Figure 6.1.: IHF traditional Far Field Test Range.

### Measurement Dynamic Range

Table 6.1.: *Measurement Dynamic Range* calculation power levels for IHF's traditional Far Field Range with an external mixing system from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | **26.5 GHz** |
|---|---|---|
| $P_S$ (dBm) | -20 | -20 |
| $L_1$ (dB) | - | - |
| $G$ (dB) | 23 | 23 |
| $P_{out}$ (dBm) | 3 | 3 |
| $L_2$ (dB) | - | - |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | (-)0.43 | (-)1.68 |
| $G_{FEED}$ (dBi) | 9 | 15 |
| $L_{FEEDVSWR}$ (dB) | - | - |
| $ERP$ (dBm) | 9.57 | 14.32 |
| $L_o$ (dB) | (-)55.7 | (-)78.2 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.43 | (-)1.68 |
| *Test attenuator* (dB) | (-)10 | (-)10 |
| $P$ (dBm) | -56.6 | -75.54 |
| $N$ (dBm) | (-)-152 | (-)-136 |
| $SNR$ (dB) | (-)15 | (-)15 |
| $DR$ (dB) | 80.4 | 45.45 |

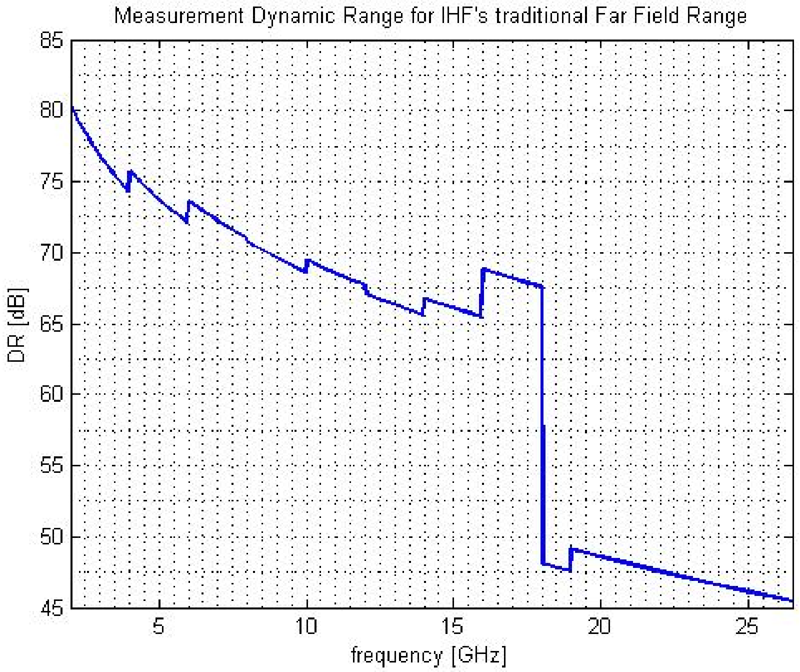


Figure 6.2.: Dynamic Range for IHF's traditional Far Field Range with an external mixing system.

### *RF power levels*

For this range, the layout in terms of RF power levels has been done properly, as the mixers are not overdriven out of their linear working zone thanks to the attenuators placed at their inputs.

Table 6.2.: RF power level calculation for IHF's traditional Far Field Range with an external mixing system from 2 GHz to 26.5 GHz.

| **Frequency** | **2 GHz** | **26.5 GHz** |
|---|---|---|
| $P_S$ (dBm) | -20 | -20 |
| $L_1$ (dB) | - | - |
| $G$ (dB) | 23 | 23 |
| $P_{out}$ (dBm) | 3 | 3 |
| $L_2$ (dB) | - | - |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | (-)0.43 | (-)1.68 |
| $G_{FEED}$ (dBi) | 9 | 15 |
| $L_{FEEDVSWR}$ (dB) | - | - |
| $ERP$ (dBm) | 9.57 | 14.32 |
| $L_o$ (dB) | (-)55.7 | (-)78.2 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.43 | (-)1.68 |
| *Test attenuator* (dB) | (-)10 | (-)10 |
| $P_{TEST}$ (dBm) | -56.6 | -75.54 |
| $L_{coup}$ (dB) | (-)10 | (-)10 |
| $L_5$ (dB) | (-)0.85 | (-)4 |
| *Ref attenuator* (dB) | (-)20 | (-)20 |
| $P_{REF}$ (dBm) | -27.85 | -31 |
| $Minimum$ (dBm) | -152 | -136 |
| $Maximum$ (dBm) | -24 | -24 |

### *LO power levels*

Table 6.3.: LO power level calculation for IHF's traditional Far Field Range with an external mixing system.

| **Frequency** | **18 GHz** |
|---|---|
| $P_1$ (dBm) | 13 |
| $L_8$ (dB) | (-)10.6 |
| $P_1$-$L_8$ (dBm) | 2.4 |
| $Minimum$ (dBm) | 0 |
| $Maximum$ (dBm) | 6 |
| $L_{10}$ (dB) | (-)11.4 |
| $L_9$ (dB) | (-)10.2 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $L_9$- $L_{r1}$ - $L_{r2}$ (dB) | (-)11.4 |
| Loss applying, $L$ (dB) | (-)11.4 |
| $P_2$ (dBm) | 21.4 |
| $P_2$ - $L$ (dBm) | 10 |
| $Minimum$ (dBm) | 12 |
| $Maximum$ (dBm) | 18 |

### *IF power levels*

Table 6.4.: IF power level calculation for IHF's traditional Far Field Range with an external mixing system.

| **IF Frequency** | (Lowest RF frequency) |
|---|---|
| $P_{TEST}$ (dBm) | -24 |
| $P_{REF}$ (dBm) | -24 |
| $L_c$ (dB) | (-)12 |
| $G_{IF}$ (dB) | 25 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $P_{Test}$ (dBm) | -11 |
| $P_{Ref}$ (dBm) | -12.2 |
| *Analyzer 0.1 dB Compression Point* (dBm) | -10 |

List of components used for this proposal and its evaluation:

- Agilent HP 8530 Microwave receiver
- HP 83621A Sweep oscillator (external LO source)
- HP 83651A Synthesized sweeper (external source)
- Agilent HP85381 Series cable
- Rosenberger UFA210B cable
- **Agilent 83051A Amplifier** [39]

- **Agilent 87301E Coupler** [38]
- Feeds:
  1. A.H. Systems SAS-571 Ridge Guide Horn Antenna
  2. IHF own production K-Band Pyramidal Horn
- AUT considered 0 dBi
- **Agilent HP 853209/HP85320 H50 LO/IF unit and mixer** [35]
- SNR considered is 15 dB (1 dB magnitude error and 10°phase error)
- **Spinner BN 83-50-47 Rotary Joints** [34]
- **Micro Coax® MIL-DTL-17/129 semi-rigid coaxial cables** [42]

An interesting fact about this system is the circumstance that both source and the LO source work under minimum power conditions. This fact turns out into a debatable issue when weighting up the presence of the amplifier at the transmission side, but also when LO power levels are evaluated as they are below the recommended minimum. Obviously this does not mean that the system is not working, as all these calculations are approximated, although it can give an idea about possible operating error sources. In this case it is also evinced that traditional Far Field ranges will suffer more free-space loss as CR basically because of its direct-line-of-sight concept which turns out into higher free-space loss values.

## 6.2. Proposals considering external mixing

This type of proposals follow the general system configuration pattern presented in chapter 4 and shown in Figure 6.3. The ORBIT/FR proposal would follow the same pattern but including a multiplier at the transmission side (see Figure 6.4).

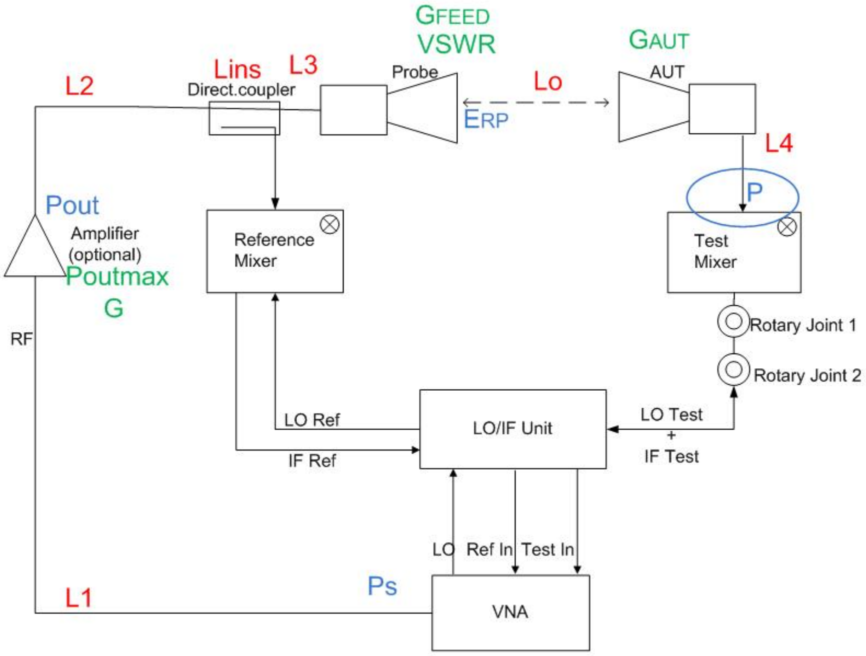


Figure 6.3.: External mixing standard system configuration pattern.

As seen in graph 6.5 the Agilent and ORBIT/FR proposals perform better. Nevertheless, the Rohde&Schwarz® does not include an amplifier at the transmission side. Including one would be a feasible option to improve the DR around 20 dB.
Besides, the output power limitations, at high frequencies, of the **Agilent N5245A PNA-X** [30] are evinced.
On the other hand, it is worthwile to mention and to consider the circumstance of how the ORBIT/FR option performs better for higher frequencies. This situation is due to the fact that frequency upconversion is carried out attached to the feed. In other words, around 10 meters of cable path at high frequencies are avoided.

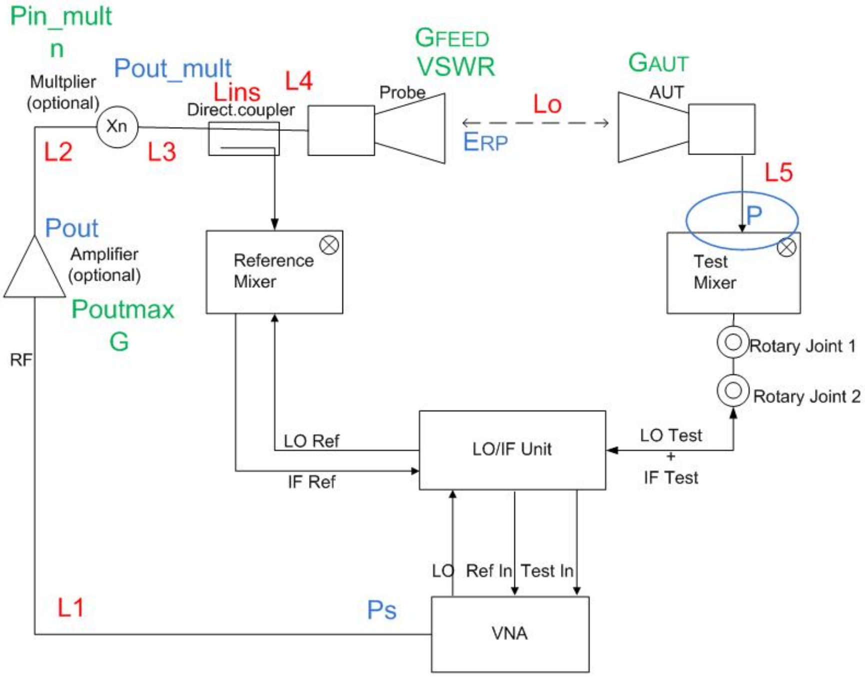


Figure 6.4.: External mixing standard system configuration pattern (including multiplier).

Table 6.5.: *Measurement Dynamic Range* calculation power levels for proposals with an external mixing system from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | | | **50 GHz** | | |
|---|---|---|---|---|---|---|
| **Supplier** | **Agilent** | **Rohde&Schwarz** | **ORBIT/FR** | **Agilent** | **Rohde&Schwarz** | **ORBIT/FR** |
| $P_S$ (dBm) | 8 | 18 | 18 | -8 | 6 | - |
| $L_1$ (dB) | (-)7 | (-)7 | (-)7 | (-)35.1 | (-)35.1 | - |
| $G$ (dB) | 21 | 0 | 21 | 21 | 0 | - |
| $P_{out}$ (dBm) | 20 | 11 | 20 | -22.1 | -29.1 | 8 |
| $L_2$ (dB) | (-)0.7 | (-)0.7 | (-)-0.7 | (-)3.51 | (-)3.51 | - |
| $L_{ins}$ (dB) | (-)2 | (-)2 | (-)2 | (-)2 | (-)2 | (-)2 |
| $L_3$ (dB) | (-)0.7 | 0 | (-)-0.7 | (-)3.51 | 0 | (-)3.51 |
| $G_{FEED}$ (dBi) | 13 | 13 | 13 | 13 | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | (-)0.3 | (-)0.3 | 0 | 0 | 0 |
| $ERP$ (dBm) | 29.3 | 21 | 29.3 | -18.1 | -21.6 | 15.5 |
| $L_o$ (dB) | (-)52 | (-)52 | (-)52 | (-)80 | (-)80 | (-)80 |
| $G_{AUT}$(dBi) | 0 | 0 | 0 | 0 | 0 | 0 |
| $L_4$ (dB) | (-)0.7 | (-)0.7 | (-)0.7 | (-)3.51 | (-)3.51 | (-)3.51 |
| $P$ (dBm) | -23.4 | -31.7 | -23.4 | -101.61 | -105.1 | -68 |
| $N$ (dBm) | (-)-152 | (-)-152 | (-)-152 | (-)-136 | (-)-155 | (-)-136 |
| $SNR$ (dB) | (-)15 | (-)15 | (-)15 | (-)15 | (-)15 | (-)15 |
| $DR$ (dB) | 113.6 | 105.3 | 113.6 | 19.39 | 34.9 | 53 |

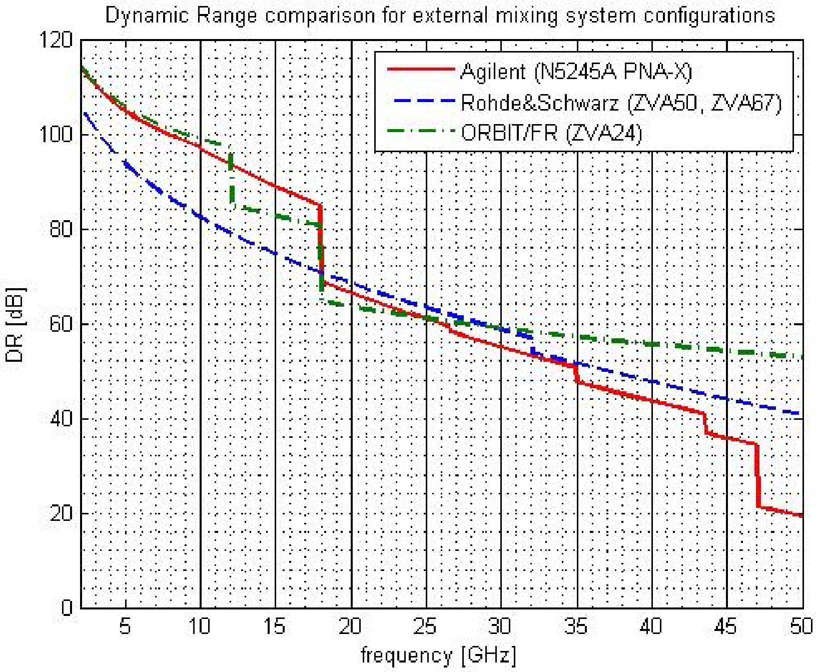


Figure 6.5.: Dynamic Range comparison for external mixing system configurations.

## 6.3. Proposals considering frequency converters

These proposals consider using frequency converters attached to the transmission and reception antenna (see Figure 6.6). This means that both frequency upconversion and downconversion are carried out inside the chamber, avoiding high frequencies travelling along long cables.

These solutions proposed by Agilent and Rohde&Schwarz® are compared to a proposal made by ORBIT/FR using high frequency multipliers and mixers. In any case, when reaching 50 GHz, waveguide solutions must be implemented as neither cables nor connectors will be practicable at that frequencies.

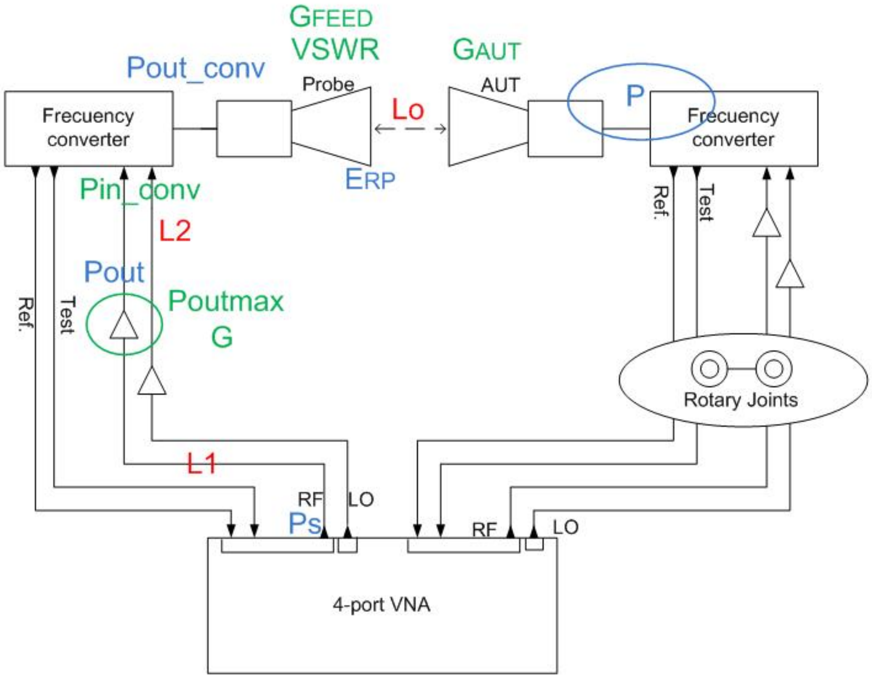


Figure 6.6.: Frequency converter standard system configuration pattern.

Frequency converters perform dramatically worst than other solutions. The reason is its high noise floor. This noise floor has been used under several assumptions, as none of the converters manufactures stated concrete values regarding the sensitivity level or power input-output relation when these devices work within a concrete system layout. Apart from this circumstance, there is an issue left to overcome. As it can be seen in the schematic (6.6), a frequency converter attached to the AUT will mean passing 4 cables through 2 rotary joints. This circumstance could generate a mechanical problem.

Table 6.6.: *Measurement Dynamic Range* calculation power levels for proposals with an frequency converter system or a multiplier from 50 GHz to 75 GHz.

| **Frequency** | **50 GHz** | | | **75 GHz** | | |
|---|---|---|---|---|---|---|
| **Supplier** | **Agilent** | **Rohde&Schwarz** | **ORBIT/FR** | **Agilent** | **Rohde&Schwarz** | **ORBIT/FR** |
| $P_{out\_conv}$ (dBm) | 7 | 4 | - | 7 | 4 | - |
| $P_{out\_mult}$ (dBm) | - | - | 8 | - | - | 8 |
| $L_{ins}$ (dB) | 0 | 0 | 0 | 0 | 0 | 0 |
| $G_{FEED}$ (dBi) | 13 | 13 | 13 | 13 | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | 0 | 0 | 0 | 0 | 0 | 0 |
| $ERP$ (dBm) | 20 | 17 | 21 | 20 | 17 | 21 |
| $L_o$ (dB) | (-)80 | (-)80 | (-)80 | (-)83.5 | (-)83.5 | (-)83.5 |
| $G_{AUT}$(dBi) | 0 | 0 | 0 | 0 | 0 | 0 |
| $P$ (dBm) | -60 | -63 | -59 | -63.5 | -66.5 | -62.5 |
| $N$ (dBm) | (-)-95 | (-)-101 | (-)-137 | (-)-95 | (-)-101 | (-)-137 |
| $SNR$ (dB) | (-)15 | (-)15 | (-)15 | (-)15 | (-)15 | (-)15 |
| $DR$ (dB) | 20 | 23 | 63 | 16.5 | 19.5 | 59.5 |

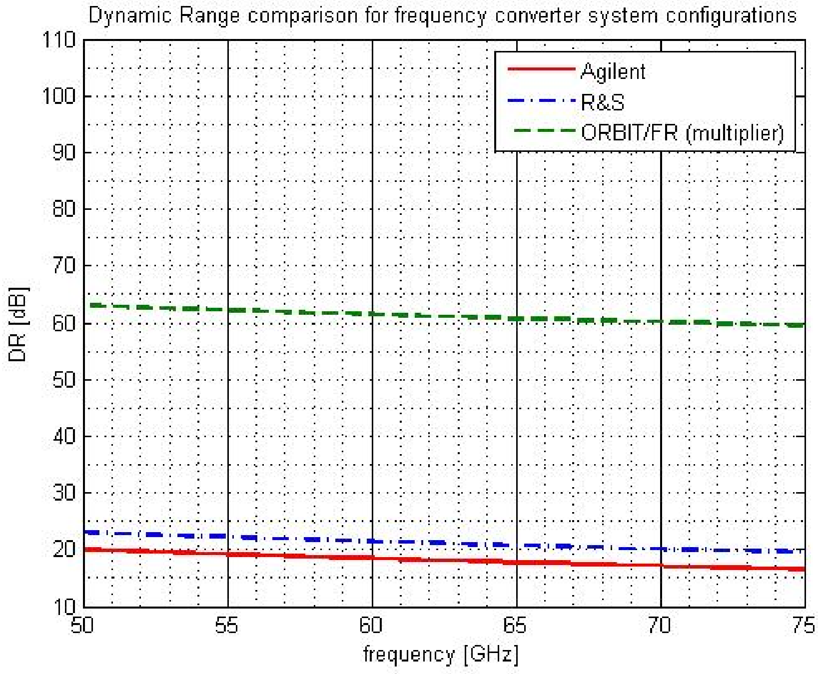


Figure 6.7.: Dynamic Range comparison for frequency converter and multiplier system configurations.

## 6.4. Proposals without external frequency conversion

This type of configuration has not been mentioned when talking about standard configuration system patterns due to its simplicity. However, apart from being the type of system to implement the Spherical Nearfield Range SNF, this option is feasible for the lower part of the frequency range as it can be seen when analyzing one of the Rohde&Schwarz® proposals (see Figure 6.8).

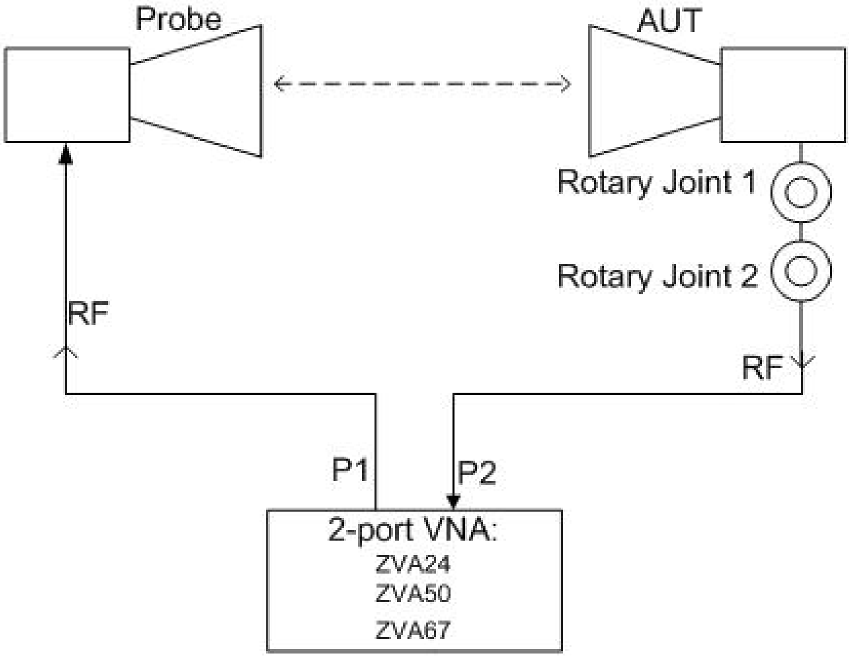


Figure 6.8.: Rohde&Schwarz proposal for no external frequency conversion system configuration.

Table 6.7.: *Measurement Dynamic Range* calculation power levels for Rohde&Schwarz proposal with no external frequency conversion and different VNA's.

| **Frequency** | **2 GHz** | **2 GHz** | **2 GHz** | **24 GHz** | **50 GHz** | **70 GHz** |
|---|---|---|---|---|---|---|
| **VNA** | **ZVA24** | **ZVA50** | **ZVA67** | **ZVA24** | **ZVA50** | **ZVA67** |
| $P_S$ (dBm) | 18 | 18 | 18 | 16 | 12 | 6 |
| $L_1$ (dB) | (-)3 | (-)7 | (-)7 | (-)12.9 | (-)35.1 | - |
| $G_{FEED}$ (dBi) | 13 | 13 | 13 | 13 | 13 | - |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | (-)0.3 | (-)0.3 | 0 | 0 | - |
| $ERP$ (dBm) | 27.7 | 23.7 | 23.7 | 16.1 | -10.1 | - |
| $L_o$ (dB) | (-)52 | (-)52 | (-)52 | (-)73.6 | (-)80 | - |
| $G_{AUT}$(dBi) | 0 | 0 | 0 | 0 | 0 | - |
| $L_2$ (dB) | (-)3 | (-)7 | (-)7 | (-)12.9 | (-)35.1 | - |
| $L_{r1}$ (dB) | (-)0.6 | (-)0.6 | (-)0.6 | (-)0.6 | (-)0.6 | - |
| $L_{r2}$ (dB) | (-)0.6 | (-)0.6 | (-)0.6 | (-)0.6 | (-)0.6 | - |
| $P$ (dBm) | -28.5 | -36.5 | -36.5 | -71.6 | -126.4 | - |
| $P_{max}$ (dBm) | 15 | 10 | 10 | 10 | 3 | 3 |
| $N$ (dBm) | (-)-130 | (-)-130 | (-)-130 | (-)-130 | (-)-115 | - |
| $SNR$ (dB) | (-)15 | (-)15 | (-)15 | (-)15 | (-)15 | - |
| $DR$ (dB) | 86.5 | 78.5 | 78.5 | 43.4 | -26.4 | - |

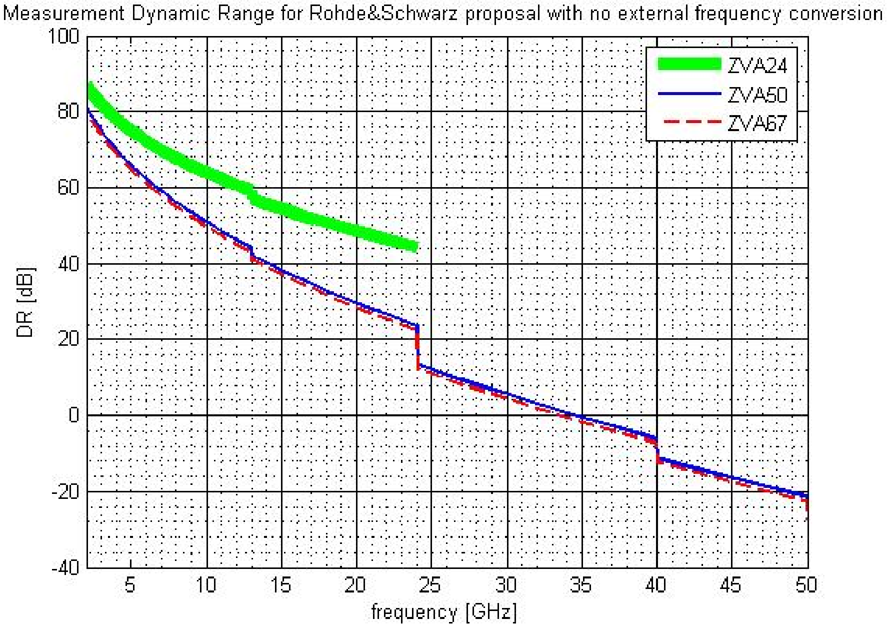


Figure 6.9.: Dynamic Range comparison for Rohde&Schwarz proposal with no external frequency conversion system configuration and different VNA's.

It is essential to mention that due to practical considerations regarding physical space and component exchange between different test environments at the anechoic chamber the IHF, in a first stage, only considers working with internal VNA source.

Finally, it is important to point out that LNA high frequency amplifiers could be an option to rise the available power at the reception side. Apart from the cost factor, this solution should be carefully considered, as it would also increase the noise floor of the system retaking again the idea of the need to implement the LNA only if its gain compensates the resulting equivalent noise figure ($F$) of the system.

# A. Appendix 1 - IHF Compact Range requirements and boundaries

This appendix is included in order to ease the reader's understanding of the different assumptions made for the calculations found in this work. Furthermore, the requirements intended to be covered by the future range are found in this appendix. The values for these requirements are taken from the IHF's internal documents. The requirements are summed up in table A.1. It is important to mention that these requirements may change over time. Nevertheless, the analysis procedure has been exposed in general terms in order to be adapted to these possible future changes.

Table A.1.: IHF Requirements for the future Compact Range CR and Spherical Nearfield Range SNF.

| **Requirement** | |
|---|---|
| Room size [m] | $9.0 \times 5.3 \times 5.3$ |
| Frequency Range [GHz] | 0.8 - 2 (SNF) and 2 - 67 (CR) |
| Amplitude ripple in the QZ [dB] | 0.35 |
| Phase ripple in the QZ [°] | 3 |
| Amplitude taper [dB] | 0.5 |
| Maximum AUT weight [kg] | 100 |
| Positioner rotation axis accuracy [°] | 0.01 |
| Positioner slide translation accuracy [mm] | 0.01 |
| Software | SNF transformations and RCS measurements |
| RF instrumentation | |
| | Vectorial measurement technique |
| | 3 independent measurement channels |
| Measurement Dynamic Range [dB] | $\geq$50 (80 RCS) |
| Measurement speed | $\geq$ 50000data points/$s$ |

As it was also mentioned in chapter 2, chapter 4 and chapter 6 there are many assumptions made in terms of distance when evaluating system's inherent losses (see chapter 4). That is why an approximated theoretical distances floor plan included (see Figure A.1) is attached. There are also floor plans included for different system configurations. These system configurations are:

1. External mixing configuration (Figure A.2)
2. External mixing configuration and optional multiplier (Figure A.3)
3. External mixing and external source configuration (Figure A.4)
4. Frequency converter configuration (Figure A.5)
5. No external frequency conversion configuration (Figure A.6)
6. RCS system configuration (Figure A.7)

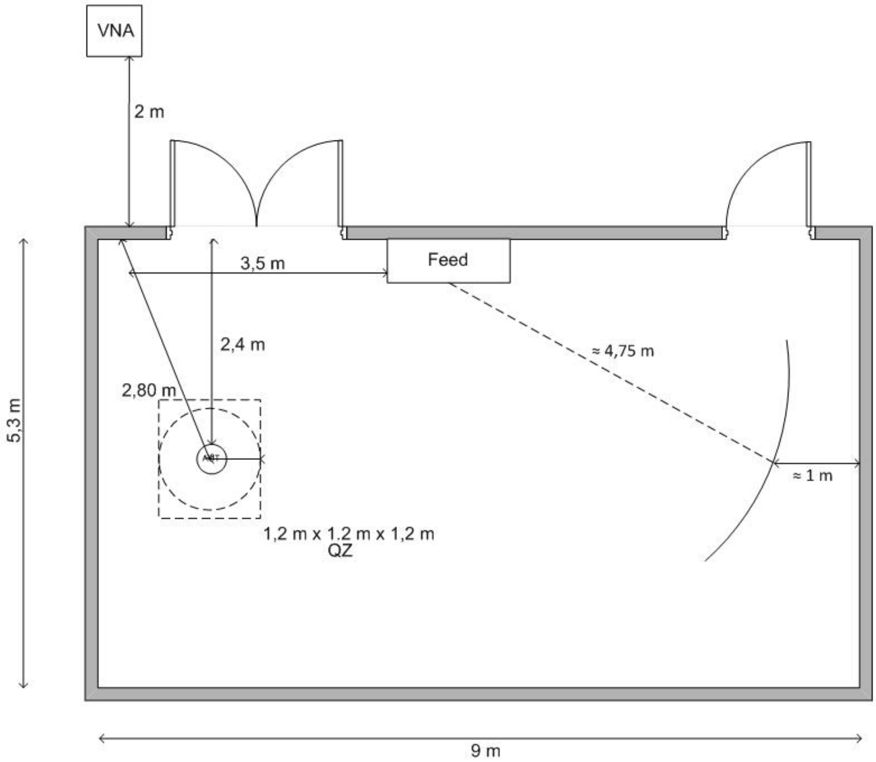
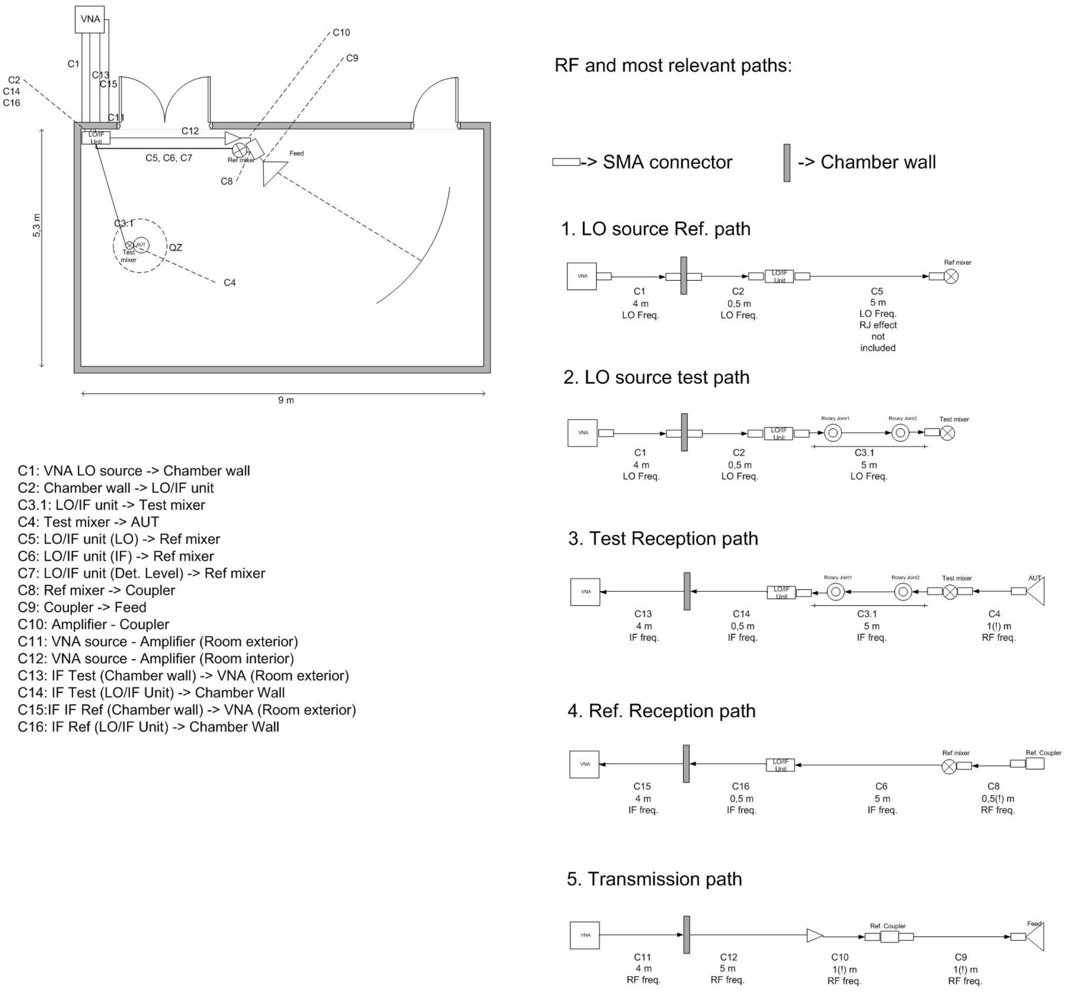


Figure A.1.: Theoretical geometric distances found in the anechoich chamber.



C1: VNA LO source -> Chamber wall
C2: Chamber wall -> LO/IF unit
C3.1: LO/IF unit -> Test mixer
C4: Test mixer -> AUT
C5: LO/IF unit (LO) -> Ref mixer
C6: LO/IF unit (IF) -> Ref mixer
C7: LO/IF unit (Det. Level) -> Ref mixer
C8: Ref mixer -> Coupler
C9: Coupler -> Feed
C10: Amplifier - Coupler
C11: VNA source - Amplifier (Room exterior)
C12: VNA source - Amplifier (Room interior)
C13: IF Test (Chamber wall) -> VNA (Room exterior)
C14: IF Test (LO/IF Unit) -> Chamber Wall
C15:IF IF Ref (Chamber wall) -> VNA (Room exterior)
C16: IF Ref (LO/IF Unit) -> Chamber Wall

RF and most relevant paths:

1. LO source Ref. path

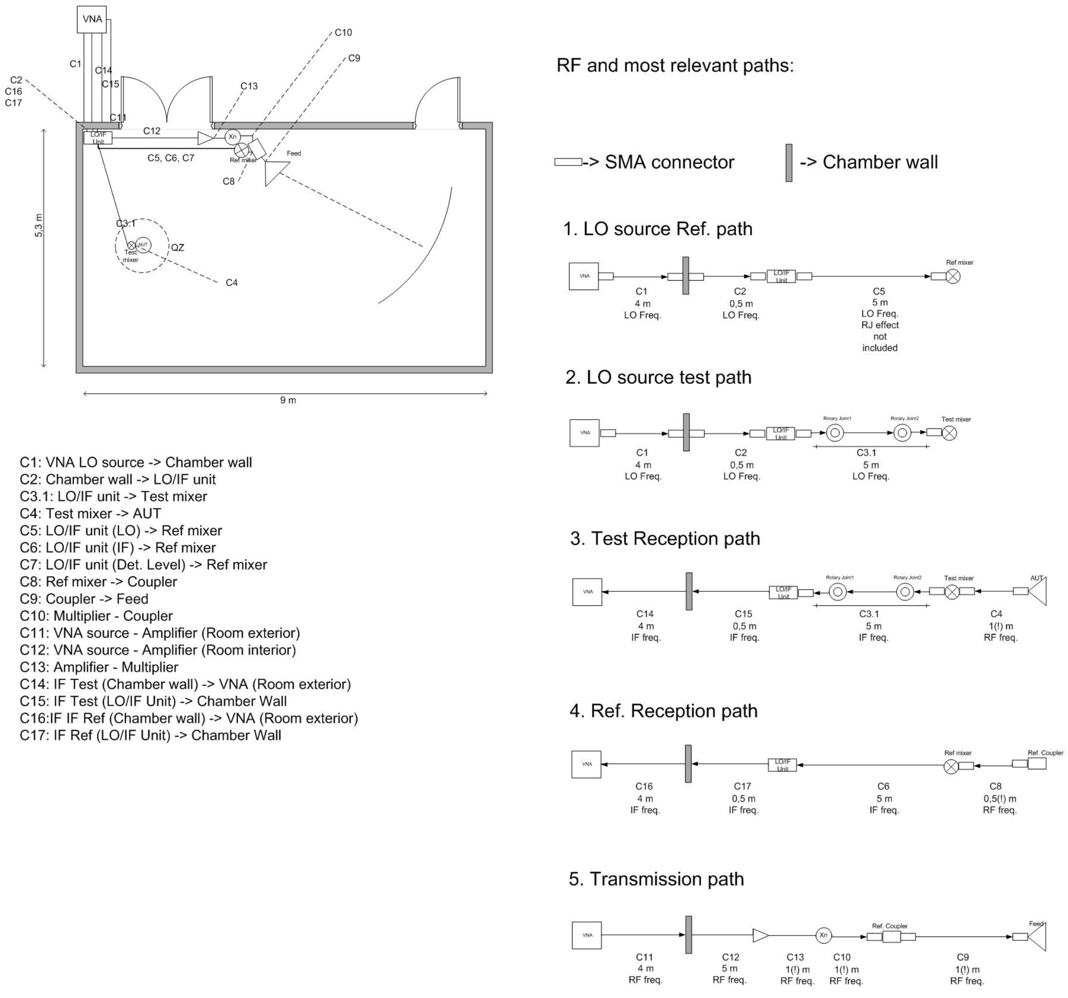
2. LO source test path

3. Test Reception path

4. Ref. Reception path

5. Transmission path

Figure A.2.: External mixing configuration floor-plan example.



C1: VNA LO source -> Chamber wall
C2: Chamber wall -> LO/IF unit
C3.1: LO/IF unit -> Test mixer
C4: Test mixer -> AUT
C5: LO/IF unit (LO) -> Ref mixer
C6: LO/IF unit (IF) -> Ref mixer
C7: LO/IF unit (Det. Level) -> Ref mixer
C8: Ref mixer -> Coupler
C9: Coupler -> Feed
C10: Multiplier - Coupler
C11: VNA source - Amplifier (Room exterior)
C12: VNA source - Amplifier (Room interior)
C13: Amplifier - Multiplier
C14: IF Test (Chamber wall) -> VNA (Room exterior)
C15: IF Test (LO/IF Unit) -> Chamber Wall
C16:IF IF Ref (Chamber wall) -> VNA (Room exterior)
C17: IF Ref (LO/IF Unit) -> Chamber Wall

Figure A.3.: External mixing configuration and optional multiplier floor-plan example.

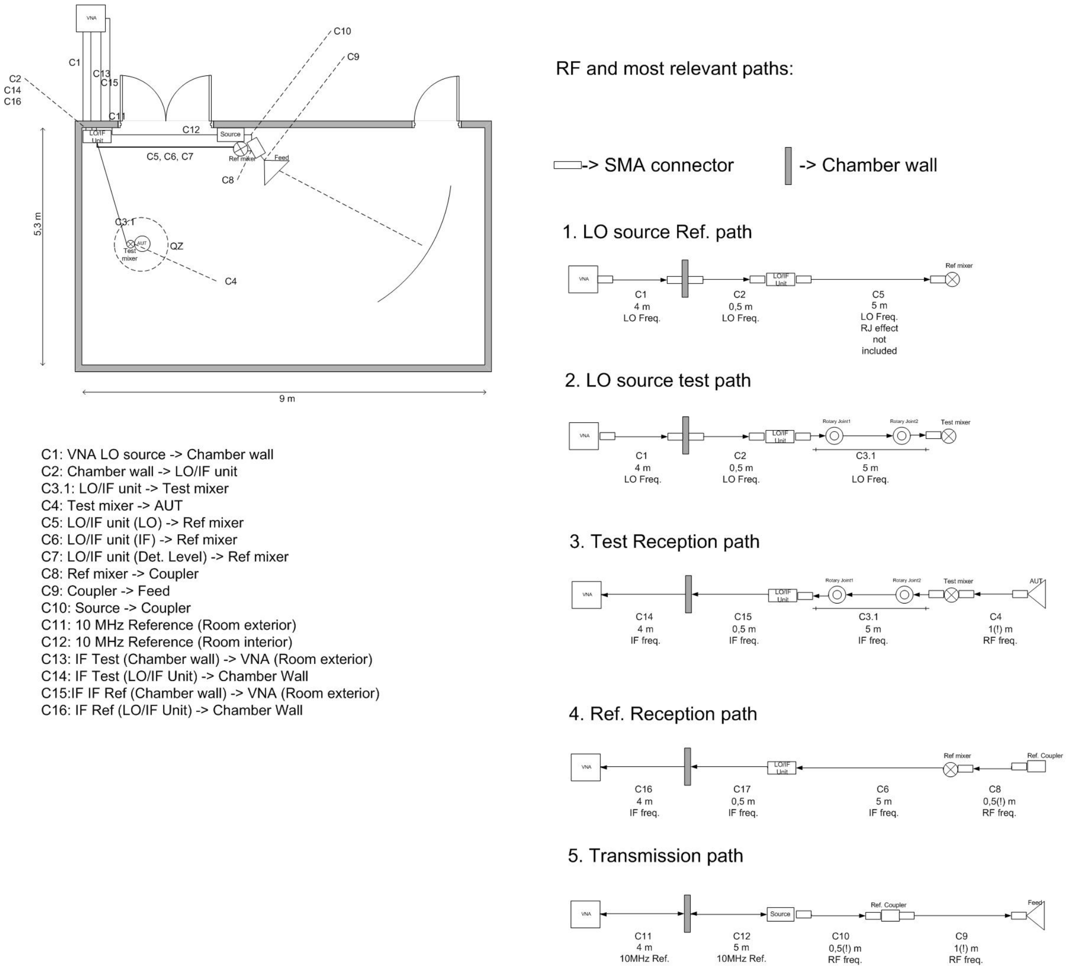


Figure A.4.: External mixing and external source configuration floor-plan example.

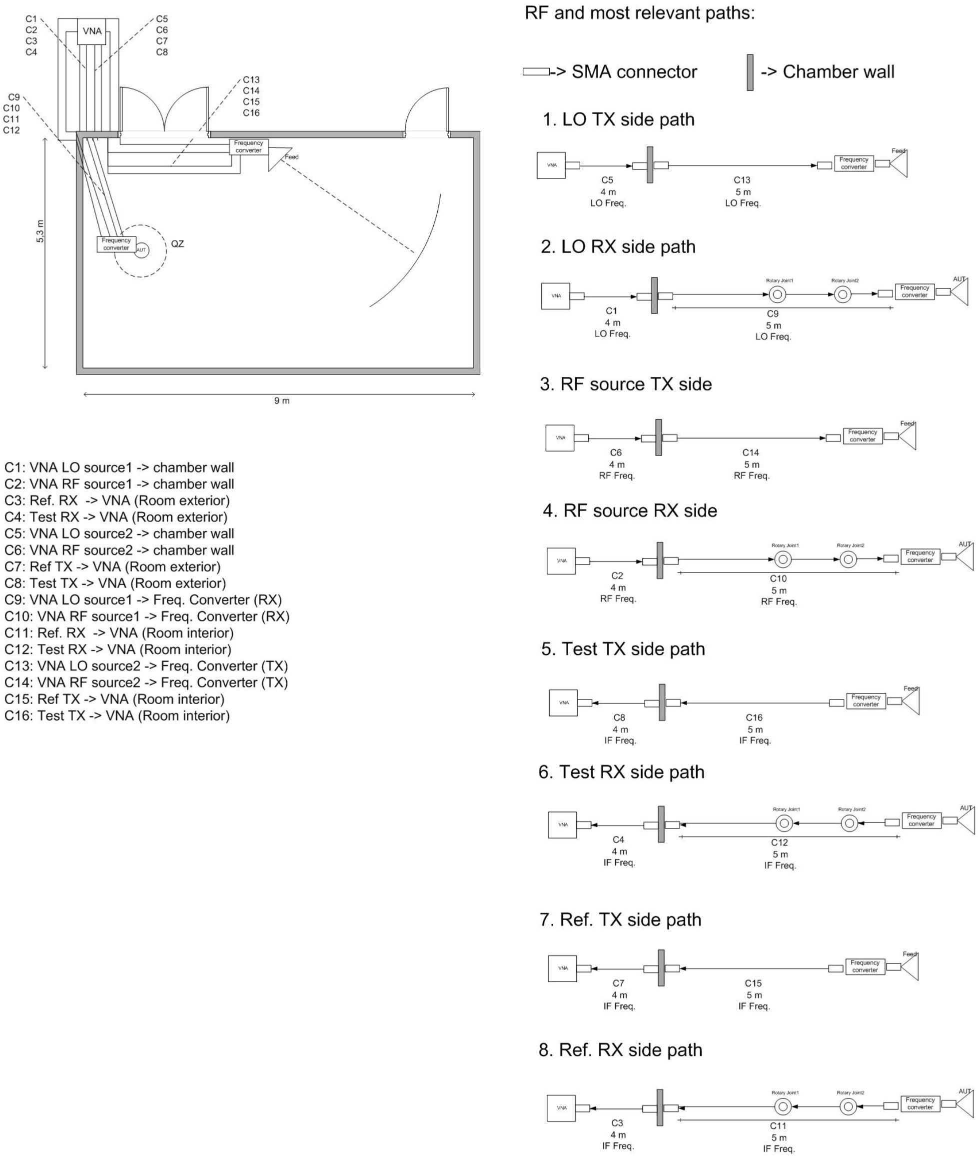
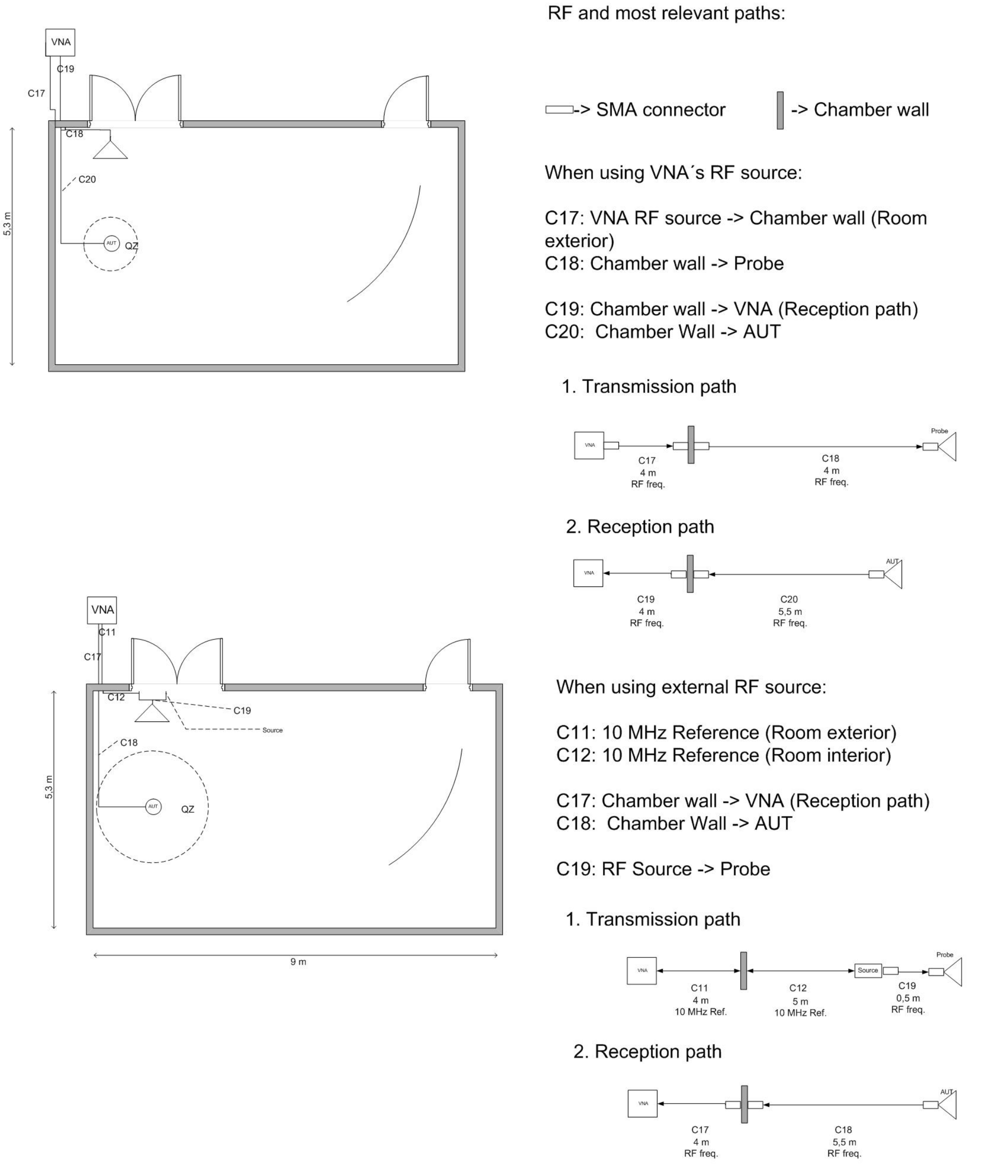


Figure A.5.: Frequency converter configuration floor-plan example.


RF and most relevant paths:

-> SMA connector

-> Chamber wall

When using VNA´s RF source:

C17: VNA RF source -> Chamber wall (Room exterior)
C18: Chamber wall -> Probe

C19: Chamber wall -> VNA (Reception path)
C20:  Chamber Wall -> AUT

1. Transmission path

2. Reception path

When using external RF source:

C11: 10 MHz Reference (Room exterior)
C12: 10 MHz Reference (Room interior)

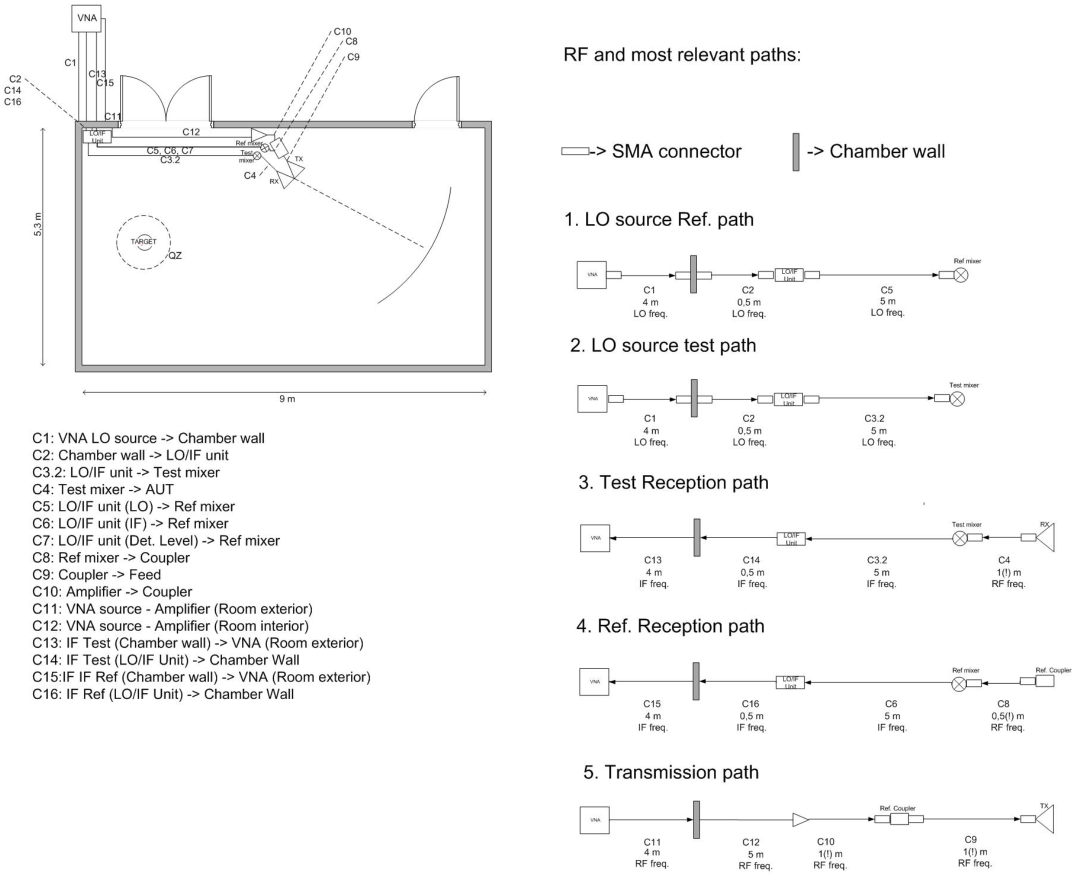
C17: Chamber wall -> VNA (Reception path)
C18:  Chamber Wall -> AUT

C19: RF Source -> Probe

1. Transmission path

2. Reception path

Figure A.6.: No external frequency conversion configuration floor-plan example.



C1: VNA LO source -> Chamber wall
C2: Chamber wall -> LO/IF unit
C3.2: LO/IF unit -> Test mixer
C4: Test mixer -> AUT
C5: LO/IF unit (LO) -> Ref mixer
C6: LO/IF unit (IF) -> Ref mixer
C7: LO/IF unit (Det. Level) -> Ref mixer
C8: Ref mixer -> Coupler
C9: Coupler -> Feed
C10: Amplifier -> Coupler
C11: VNA source - Amplifier (Room exterior)
C12: VNA source - Amplifier (Room interior)
C13: IF Test (Chamber wall) -> VNA (Room exterior)
C14: IF Test (LO/IF Unit) -> Chamber Wall
C15:IF IF Ref (Chamber wall) -> VNA (Room exterior)
C16: IF Ref (LO/IF Unit) -> Chamber Wall

Figure A.7.: RCS system configuration floor-plan example.

# B. Appendix 2 - Different layout options

In addition to the example presented in chapter 4 and to the results presented in chapter 6, in this section, the different layout options coming from different suppliers are presented. System performance calculation has been done in each case.
Apart from the traditional far field system found at the IHF, which has been analyzed in section 6.1 in chapter 6, the different layout options analyzed are listed next:

1. Agilent Technologies proposals
    a) External mixing proposal
    b) Frequency converter proposal
2. Rohde&Schwarz®
    a) No external frequency conversion
    b) External mixing proposal (using NSI frequency downconversion system)
    c) Frequency converter proposal
3. ORBIT/FR proposals
    a) No multiplier proposal (using ZVA24 VNA and Agilent Technologies downconversion system)
    b) Multiplier proposal (using ZVA24 VNA, Agilent Technologies downconversion system, and ORBIT/FR multipliers)
    c) Multiplier proposal (using ZVA24 VNA and ORBIT/FR multipliers and mixers)

For additional information regarding power levels and system attributes nomenclature refer to chapter 4, section 4.2.

# B.1. Agilent Technologies proposals

## B.1.1. Agilent Technologies external mixing proposal

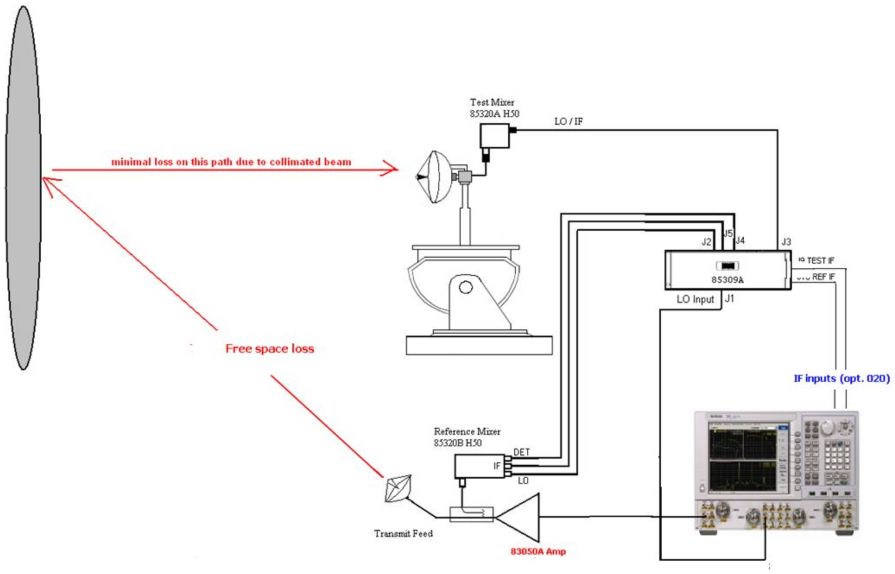


Figure B.1.: Agilent Technologies proposal for an external mixing system.

The proposal considers using the **Agilent N5245A PNA-X** [30] and the **Agilent LO/IF unit and mixers** [35]. It is intended to work from 2 GHz to 50 GHz.

### *Measurement Dynamic Range*

Table B.1.: *Measurement Dynamic Range* calculation power levels for Agilent Technologies proposal with an external mixing system from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | **50 GHz** |
|---|---|---|
| $P_S$ (dBm) | 8 | -8 |
| $L_1$ (dB) | (-)7 | (-)35.1 |
| $G$ (dB) | 21 | 21 |
| $P_{out}$ (dBm) | 20 | -22.1 |
| $L_2$ (dB) | (-)0.7 | (-)3.51 |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | (-)0.7 | (-)3.51 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | 0 |
| $ERP$ (dBm) | 29.3 | -18.1 |
| $L_o$ (dB) | (-)52 | (-)80 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.7 | (-)3.51 |
| $P$ (dBm) | -23.4 | -101.61 |
| $N$ (dBm) | (-)-152 | (-)-136 |
| $SNR$ (dB) | (-)15 | (-)15 |
| $DR$ (dB) | 113.6 | 19.39 |

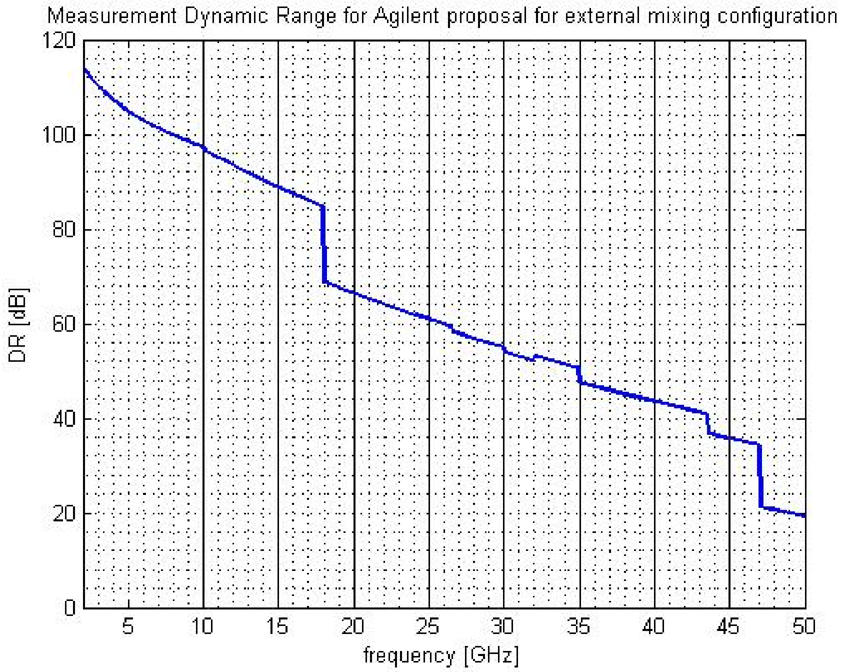


Figure B.2.: Dynamic Range for Agilent Technologies proposal with external mixing configuration.

### RF power levels

Table B.2.: RF power level calculation for Agilent Technologies proposal for an external mixing system from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | **50 GHz** |
|---|---|---|
| $P_S$ (dBm) | 8 | -8 |
| $L_1$ (dB) | (-)7 | (-)35.1 |
| $G$ (dB) | 21 | 21 |
| $P_{out}$ (dBm) | 20 | -22.1 |
| $L_2$ (dB) | (-)0.7 | (-)3.51 |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | (-)0.7 | (-)3.51 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | 0 |
| $ERP$ (dBm) | 29.3 | -18.1 |
| $L_o$ (dB) | (-)52 | (-)80 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.7 | (-)3.51 |
| $P_{TEST}$ (dBm) | -23.4 | -101.61 |
| $L_{coup}$ (dB) | (-)10 | (-)10 |
| $L_5$ (dB) | (-)0.7 | (-)3.51 |
| $P_{REF}$ (dBm) | 8.6 | -39.1 |
| $Minimum$ (dBm) | -152 | -136 |
| $Maximum$ (dBm) | -24 | -24 |

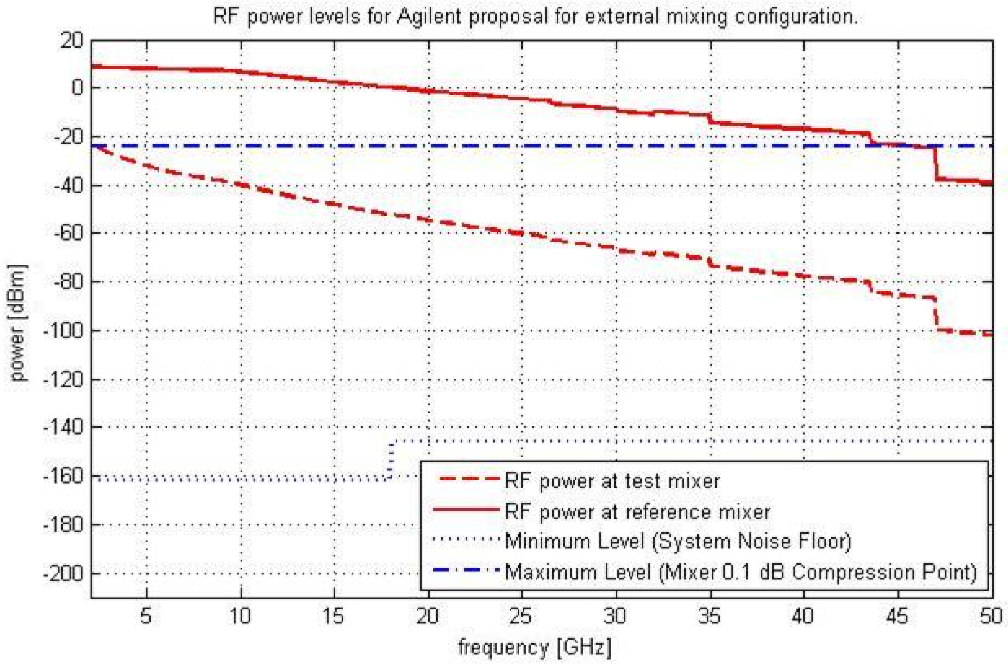


Figure B.3.: RF power levels for an Agilent Technologies proposal with external mixing configuration.

### *LO power levels*

Table B.3.: LO power level calculation for Agilent Technologies proposal for an external mixing system.

| **Frequency** | **18 GHz** |
|---|---|
| $P_1$ (dBm) | 13 |
| $L_8$ (dB) | (-)5 |
| $P_1$-$L_8$ (dBm) | 8 |
| *Minimum* (dBm) | 0 |
| *Maximum* (dBm) | 6 |
| $L_{10}$ (dB) | (-)5 |
| $L_9$ (dB) | (-)7 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $L_9$- $L_{r1}$ - $L_{r2}$ (dB) | (-)8.2 |
| Loss applying, $L$ (dB) | (-)8.2 |
| $P_2$ (dBm) | 19 |
| $P_2$ - $L$ (dBm) | 10.8 |
| *Minimum* (dBm) | 12 |
| *Maximum* (dBm) | 18 |

### *IF power levels*

Table B.4.: IF power level calculation for Agilent Technologies proposal for an external mixing system.

| **Frequency (worst case)** | **IF = 7.606 MHz, RF = 2 GHz** |
|---|---|
| $P_{TEST}$ (dBm) | -24 |
| $P_{REF}$ (dBm) | -24 |
| $L_c$ (dB) | (-)12 |
| $G_{IF}$ (dB) | 25 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $P_{Test}$ (dBm) | -11 |
| $P_{Ref}$ (dBm) | -12.2 |
| *Analyzer 0.1 dB Compression Point* (dBm) | -9 |

List of components used for this proposal and its evaluation:

- **Agilent N5245A PNA-X** [30]
- **Huber+Suhner® SUCOFLEX101 cable** [31]
- **Huber+Suhner® SUCOFLEX104 cable** [32]
- **Agilent 83050A Amplifier** [39]
- **Agilent 87301E Coupler** [38]
- **ORBIT/FR Feed** [17]

- AUT considered 0 dBi
- **Agilent HP 853209/HP85320 H50 LO/IF unit and mixer** [35]
- SNR considered is 15 dB (1 dB magnitude error and 10°phase error)
- **Spinner BN 83-50-47 Rotary Joints** [34]
- **Micro Coax® MIL-DTL-17/129 semi-rigid coaxial cables** [42]

## B.1.2. Agilent Technologies frecuency converter configuration proposal

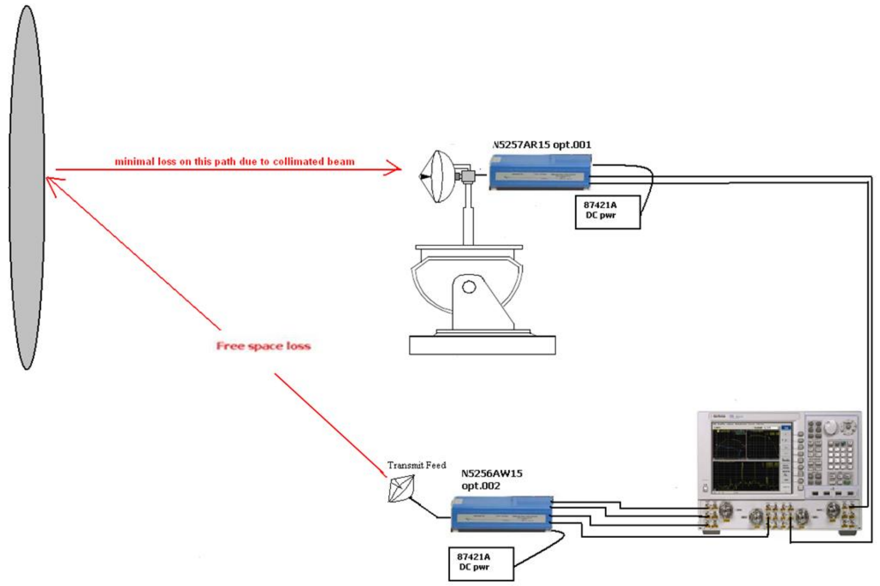


Figure B.4.: Agilent Technologies proposal for frequency converter system configuration.

The proposal considers using the **Agilent N5245A PNA-X** [30] and the **Agilent mmWave converters** [43] (also see **Agilent mmWave converters Technical's Overwiev** [44]). It is intended to work from 50 GHz to 75 GHz.

### *Measurement Dynamic Range*

Table B.5.: *Measurement Dynamic Range* calculation power levels for Agilent Technologies proposal with a frequency converter system configuration from 50 GHz to 75 GHz.

| **Frequency** | **50 GHz** | **75 GHz** |
|---|---|---|
| $P_{out\_conv}$ (dBm) | 7 | 7 |
| $L_{ins}$ (dB) | 0 | 0 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | 0 | 0 |
| $ERP$ (dBm) | 20 | 20 |
| $L_o$ (dB) | (-)80 | (-)83.5 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $P$ (dBm) | -60 | -63.5 |
| $N$ (dBm) | (-)-95 | (-)-95 |
| $SNR$ (dB) | (-)15 | (-)15 |
| $DR$ (dB) | 20 | 16.5 |

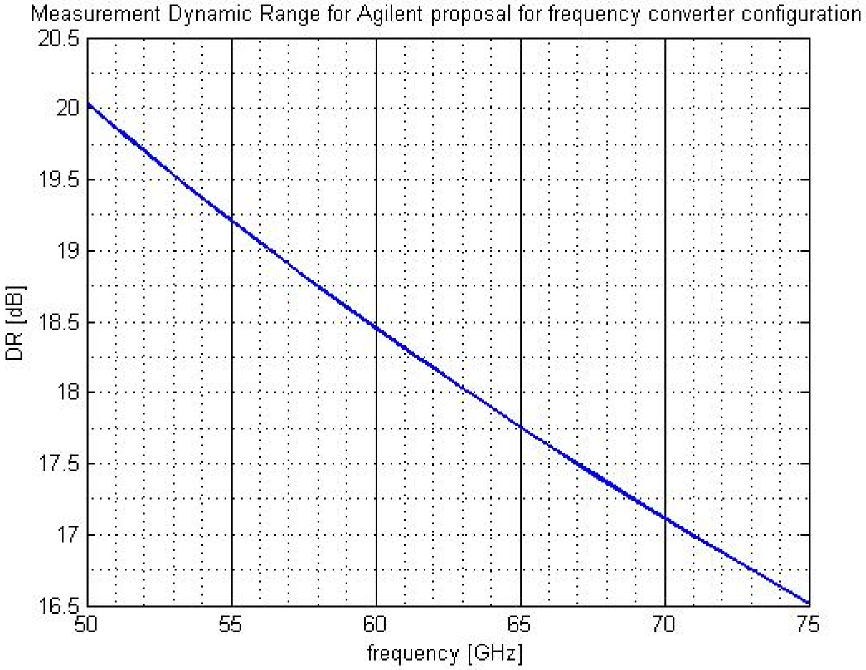


Figure B.5.: Dynamic Range for Agilent Technologies frequency converter proposal.

***RF power levels***

Note that in this case the RF power levels are the ones to be up- and downconverted. Due to the lack of information, it has been assumed that the RF frequency is approximately between 12 GHz and 20 GHz, this is why a value of 15 has been taken for calculations.

There is also a lack of information regarding the specifications for maximum input power at the RF inputs.

It can be appreciated that for any case, due to the long cable distance between VNA and the converters, amplifiers will be required.

Table B.6.: RF power level calculation for Agilent Technologies proposal for frequency converter system configuration from 50 GHz to 75 GHz.

| **Frequency** | **15 GHz** |
|---|---|
| $P_{out1}$ (dBm) | 13 |
| $P_{out2}$ (dBm) | 13 |
| $L_{r2}$(dB) | (-)0.6 |
| $L_{r1}$(dB) | (-)0.6 |
| $L_2$ (dB) | (-)10 |
| $L_4$ (dB) | (-)10 |
| $P_{TX}$ (dBm) | 3 |
| $P_{RX}$ (dBm) | 1.8 |
| $P_{inRFmin}$ (dBm) | 5 |
| $P_{inRFmax}$ (dBm) | - |

### *LO power levels*

Note that in this case the LO power levels are the ones to be up- and downconvert. Due to the lack of information, it has been assumed that the LO frequency is approximately between 12 GHz and 20 GHz, this is why a value of 15 has been taken for calculations.
Also note that there is a lack of information regarding the specifications for maximum input power at the LO inputs.
It can be appreciated that for any case, due to the long cable distance between VNA and the converters, amplifiers will be required.

Table B.7.: LO power level calculation for Agilent Technologies proposal for frequency converter system configuration from 50 GHz to 75 GHz.

| **Frequency** | **15 GHz** |
|---|---|
| $P_{out1}$ (dBm) | 13 |
| $P_{out2}$ (dBm) | 13 |
| $L_{r2}$(dB) | (-)0.6 |
| $L_{r1}$(dB) | (-)0.6 |
| $L_6$ (dB) | (-)10 |
| $L_8$ (dB) | (-)10 |
| $P_{TXLO}$ (dBm) | 3 |
| $P_{RXLO}$ (dBm) | 1.8 |
| $P_{inLOmin}$ (dBm) | 5 |
| $P_{inLOmax}$ (dBm) | - |

### *IF power levels*

For this system configuration the IF levels of the converters are nearly equal (except for the loss associated to the Rotary Joints) to the ones reaching the receiver and adapted to the VNA's inputs (see chapter 4 section 4.2.4). The only requirement to consider is chosing the correct VNA option in order to match the IF frequency (8.33 MHz in this case) (see **Agilent mmWave converters Technical's Overwiev** [44] page 7).

List of components used for this proposal and its evaluation:

- **Agilent N5245A PNA-X** [30]
- **Huber+Suhner® SUCOFLEX104 cable** [32]
- **ORBIT/FR Feed** [17]
- AUT considered 0 dBi
- **Agilent mmWave N5256/7 converters** [44]
- SNR considered is 15 dB (1 dB magnitude error and 10°phase error)
- **Spinner BN 83-50-47 Rotary Joints** [34]

# B.2. Rohde&Schwarz proposals

## B.2.1. Rohde&Schwarz no external frequency conversion proposal

Since there are no mixers and other frequency converting elements, the VNA will be the main component defining system performance. In this case, it will determine the *DR* by its *Sensitivity Level* and also the maximum input by its *0.1 dB Compression point*, defined as $P_{max}$.
In this case it will also depend on the VNA chosen. There are three options (ZVA24, ZVA50 and ZVA67). An analysis for each of them has been made.
For all options, the direct generator/receiver access option has been assumed (see chapter 4 subsection sec42-ss2).
Important to note in this case is how the option considering the use of the ZVA67 is not feasible due to the cable losses and the operating frequency range of the cables and connectors itself.

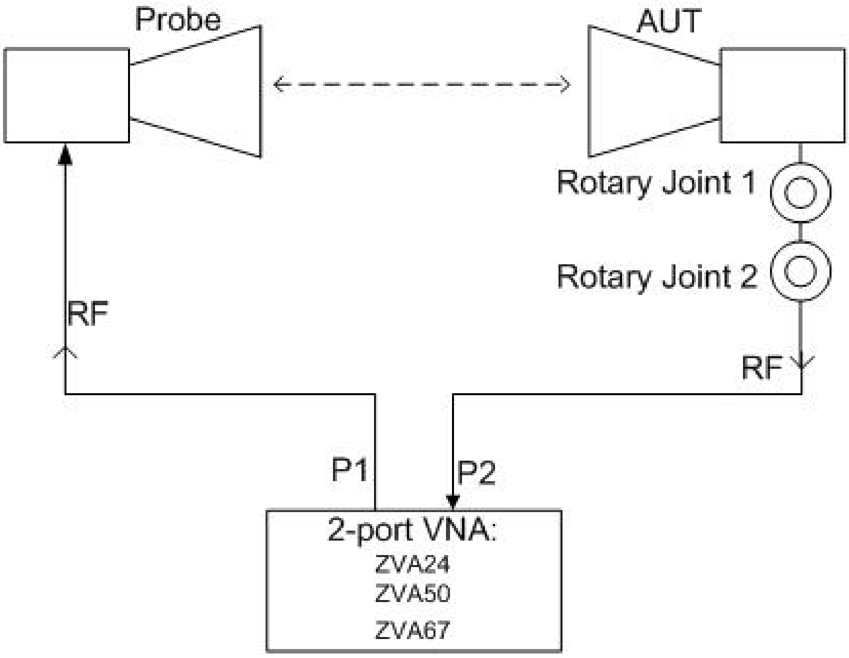


Figure B.6.: Rohde&Schwarz proposal for no external frequency conversion system configuration.

### *Measurement Dynamic Range*

Table B.8.: *Measurement Dynamic Range* calculation power levels for Rohde&Schwarz proposal with no external frequency conversion and different VNA's.

| **Frequency** | **2 GHz** | **2 GHz** | **2 GHz** | **24 GHz** | **50 GHz** | **70 GHz** |
|---|---|---|---|---|---|---|
| **VNA** | **ZVA24** | **ZVA50** | **ZVA67** | **ZVA24** | **ZVA50** | **ZVA67** |
| $P_S$ (dBm) | 18 | 18 | 18 | 16 | 12 | 6 |
| $L_1$ (dB) | (-)3 | (-)6.2 | (-)6.2 | (-)12.9 | (-)35.1 | - |
| $G_{FEED}$ (dBi) | 13 | 13 | 13 | 13 | 13 | - |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | (-)0.3 | (-)0.3 | 0 | 0 | - |
| $ERP$ (dBm) | 27.7 | 23.7 | 23.7 | 16.1 | -10.1 | - |
| $L_o$ (dB) | (-)52 | (-)52 | (-)52 | (-)73.6 | (-)80 | - |
| $G_{AUT}$(dBi) | 0 | 0 | 0 | 0 | 0 | - |
| $L_2$ (dB) | (-)3 | (-)6.2 | (-)6.2 | (-)12.9 | (-)35.1 | - |
| $L_{r1}$ (dB) | (-)0.6 | (-)0.6 | (-)0.6 | (-)0.6 | (-)0.6 | - |
| $L_{r2}$ (dB) | (-)0.6 | (-)0.6 | (-)0.6 | (-)0.6 | (-)0.6 | - |
| $P$ (dBm) | -28.5 | -36.5 | -36.5 | -71.6 | -126.4 | - |
| $P_{max}$ (dBm) | 15 | 10 | 10 | 10 | 3 | 3 |
| $N$ (dBm) | (-)-130 | (-)-130 | (-)-130 | (-)-130 | (-)-115 | - |
| $SNR$ (dB) | (-)15 | (-)15 | (-)15 | (-)15 | (-)15 | - |
| $DR$ (dB) | 86.5 | 80.1 | 80.1 | 43.4 | -26.4 | - |

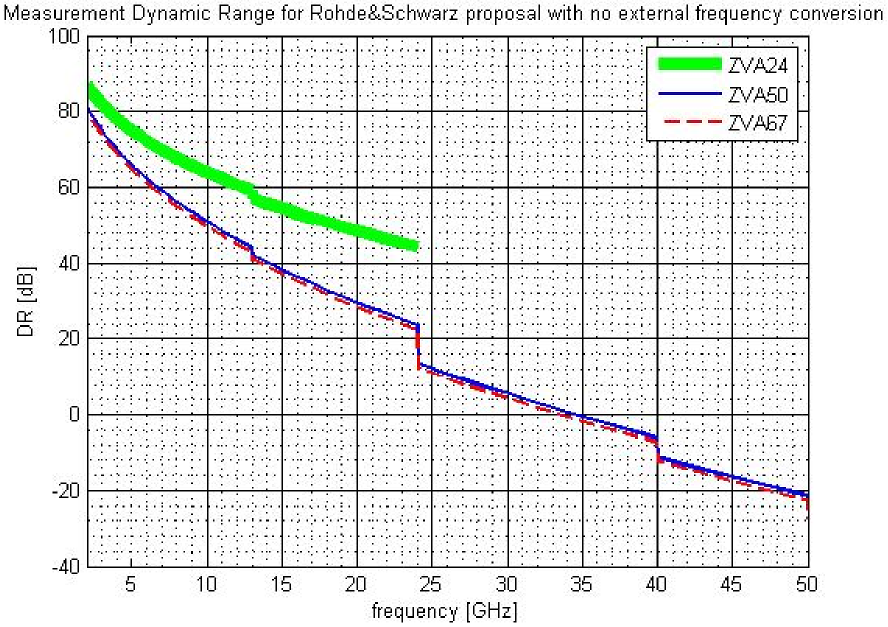


Figure B.7.: Dynamic Range comparison for Rohde&Schwarz proposal with no external frequency conversion system configuration and different VNA's.

List of components used for this proposal and its evaluation:

- **Rohde&Schwarz® ZVA24** [29]
- **Rohde&Schwarz® ZVA50** [29]
- **Rohde&Schwarz® ZVA67** [29]
- **Huber+Suhner® SUCOFLEX101 cable** [31]

- **Huber+Suhner® SUCOFLEX104 cable** [32]
- **ORBIT/FR Feed** [17]
- AUT considered 0 dBi
- SNR considered is 15 dB (1 dB magnitude error and 10°phase error)
- **Spinner BN 83-50-47 Rotary Joints** [34]

## B.2.2. Rohde&Schwarz external mixing proposal

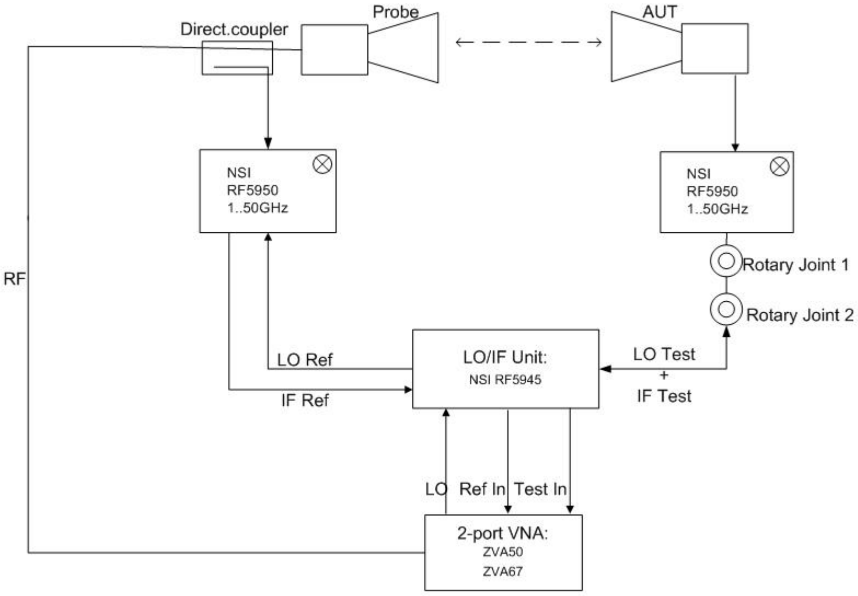


Figure B.8.: Rohde&Schwarz proposal for external mixing system configuration.

The proposal considers using the **Rohde&Schwarz® ZVA50** [29] or the **Rohde&Schwarz® ZVA67** [29].
It is intended to work from 2 GHz to 50 GHz.
In this case it is important to mention that, first of all, these results could be improved by including an amplifier within the system configuration. Concretely, at the transmission side, located at the coupler's input.
Next, some assumptions had to be made due to a lack of information regarding the **NSI-RF-5943 Distributed Frequency Converter system** [36] specifications when working in combination with a Rohde&Schwarz® VNA.

### *Measurement Dynamic Range*

Table B.9.: *Measurement Dynamic Range* calculation power levels for Rohde&Schwarz proposal with an external mixing system from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | **50 GHz** |
|---|---|---|
| $P_S$ (dBm) | 18 | 12 |
| $L_1$ (dB) | (-)7 | (-)35.1 |
| $G$ (dB) | 0 | 0 |
| $P_{out}$ (dBm) | 11 | -23.1 |
| $L_2$ (dB) | (-)0.7 | (-)3.51 |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | 0 | 0 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | 0 |
| $ERP$ (dBm) | 21 | -15.61 |
| $L_o$ (dB) | (-)52 | (-)80 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.7 | (-)3.51 |
| $P$ (dBm) | -31.7 | -99.1 |
| $N$ (dBm) | (-)-152 | (-)-155 |
| $SNR$ (dB) | (-)15 | (-)15 |
| $DR$ (dB) | 105.3 | 40.9 |

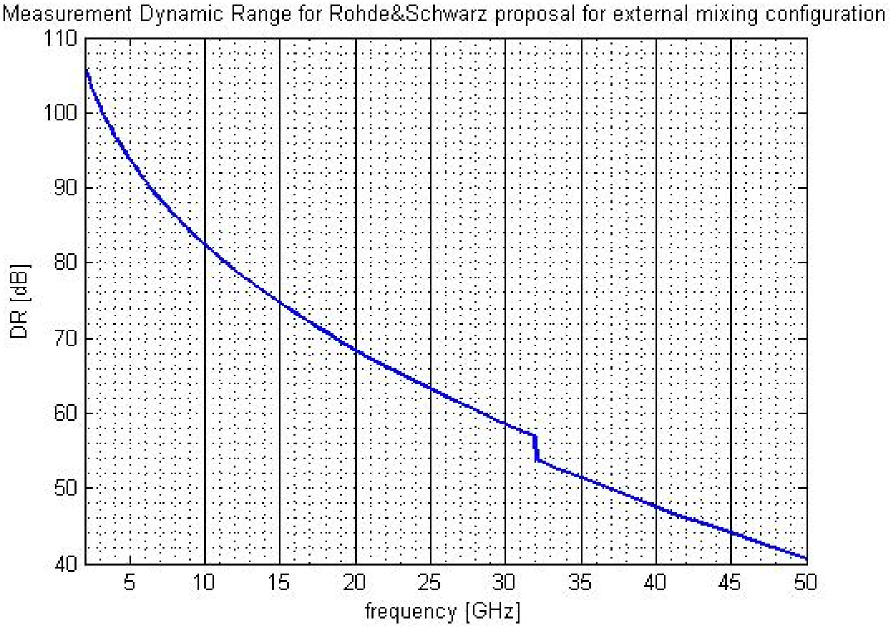


Figure B.9.: Dynamic Range for Rohde&Schwarz proposal with external mixing configuration.

***RF power levels***

At this point it is very important to mention that an attenuator will be required for the lower part of the frequency range. This one should be placed before the reference mixer's input in order to not overdrive this component.

Table B.10.: RF power level calculation for Rohde&Schwarz proposal for an external mixing system from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | **50 GHz** |
|---|---|---|
| $P_S$ (dBm) | 18 | 12 |
| $L_1$ (dB) | (-)7 | (-)35.1 |
| $G$ (dB) | 0 | 0 |
| $P_{out}$ (dBm) | 11 | -23.1 |
| $L_2$ (dB) | (-)0.7 | (-)3.51 |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | 0 | 0 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | 0 |
| $ERP$ (dBm) | 21 | -15.6 |
| $L_o$ (dB) | (-)52 | (-)80 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.7 | (-)3.51 |
| $P_{TEST}$ (dBm) | -31.7 | -99.1 |
| $L_{coup}$ (dB) | (-)10 | (-)10 |
| $L_5$ (dB) | (-)0.7 | (-)3.51 |
| $P_{REF}$ (dBm) | -0.4 | -40.1 |
| $Minimum$ (dBm) | -152 | -155 |
| $Maximum$ (dBm) | -26 | -17 |

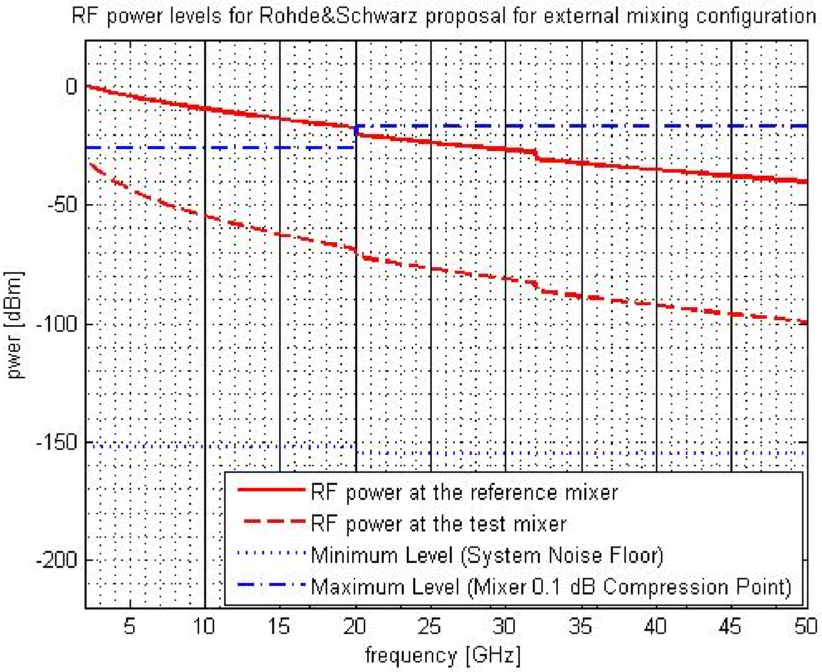


Figure B.10.: RF power levels for a Rohde&Schwarz proposal with external mixing configuration.

***LO power levels***

In this case it is important to mention that for the mixing system used in this proposal, special conditions apply. In the **NSI-RF-5943 Distributed Frequency Converter system** [36] no cable loss and length restrictions are found. In other words, the LO levels for the test and the reference path do not have to be the same (see chapter 4). It can be also noticed how the LO source (VNA's internal source) does not have to work at maximum output power.

Table B.11.: LO power level calculation for Rohde&Schwarz proposal for an external mixing system.

| **Frequency** | **20 GHz** |
|---|---|
| $P_1$ (dBm) | 15 |
| $L_8$ (dB) | (-)5.2 |
| $P_1$-$L_8$ (dBm) | 9.8 |
| *Minimum* (dBm) | 5 |
| *Maximum* (dBm) | 5 |
| $L_{10}$ (dB) | (-)5.2 |
| $L_9$ (dB) | (-)7.2 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $P_2$ (dBm) | 15 |
| $P_{LOtest}$ (dBm) | 6.6 |
| $P_{LOref}$ (dBm) | 9.8 |
| *Minimum* (dBm) | -20 |
| *Maximum* (dBm) | - |

**IF power levels**

It has to be mentioned that the *0.1 Compression point* in this case is given as *Maximum nominal input level* and not specified expressly fot the IF frequency.

List of components used for this proposal and its evaluation:

Table B.12.: IF power level calculation for Rohde&Schwarz proposal for an external mixing system.

| **Frequency (worst case)** | **IF = not specified, RF = 2 GHz** |
|---|---|
| $P_{TEST}$ (dBm) | -26 |
| $P_{REF}$ (dBm) | -26 |
| $L_c$ (dB) | (-)- |
| $G_{IF}$ (dB) | 16 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $P_{Test}$ (dBm) | -11.2 |
| $P_{Ref}$ (dBm) | -10 |
| *Analyzer 0.1 dB Compression Point* (dBm) | 10 (RF freq) |

- **Rohde&Schwarz® ZVA50** [29]
- **Rohde&Schwarz® ZVA67** [29]
- **Huber+Suhner® SUCOFLEX101 cable** [31]
- **Huber+Suhner® SUCOFLEX104 cable** [32]
- **ORBIT/FR Feed** [17]
- AUT considered 0 dBi
- **NSI-RF-5943 Distributed Frequency Converter system** [36]
- SNR considered is 15 dB (1 dB magnitude error and 10°phase error)
- **Spinner BN 83-50-47 Rotary Joints** [34]

## B.2.3. Rohde&Schwarz frequency converter proposal

The proposal considers using the **Rohde&Schwarz® ZVA** [29] (ZVA24, ZVA50 or ZVA67) and the **Rohde&Schwarz® ZVA-Z75 WR15** [37] frequency converter.
It is intended to work from 50 GHz to 75 GHz.

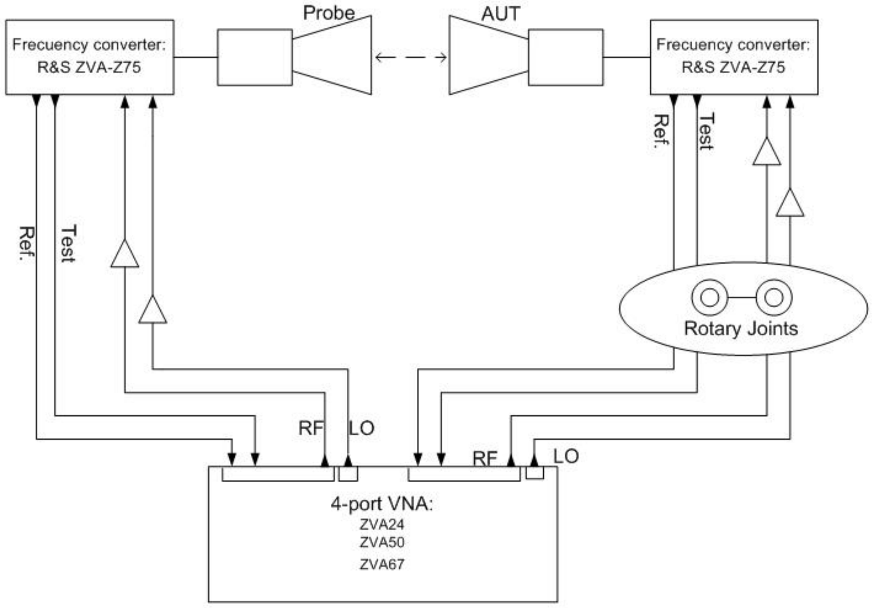


Figure B.11.: Rohde&Schwarz proposal for frequency converter system configuration.

### *Measurement Dynamic Range*

Table B.13.: *Measurement Dynamic Range* calculation power levels for Rohde&Schwarz proposal with a frequency converter system configuration from 50 GHz to 75 GHz.

| **Frequency** | **50 GHz** | **75 GHz** |
|---|---|---|
| $P_{out\_conv}$ (dBm) | 4 | 4 |
| $L_{ins}$ (dB) | 0 | 0 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | 0 | 0 |
| $ERP$ (dBm) | 17 | 17 |
| $L_o$ (dB) | (-)80 | (-)83.5 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $P$ (dBm) | -63 | -66.5 |
| $N$ (dBm) | (-)-101 | (-)-101 |
| $SNR$ (dB) | (-)15 | (-)15 |
| $DR$ (dB) | 23 | 19.5 |

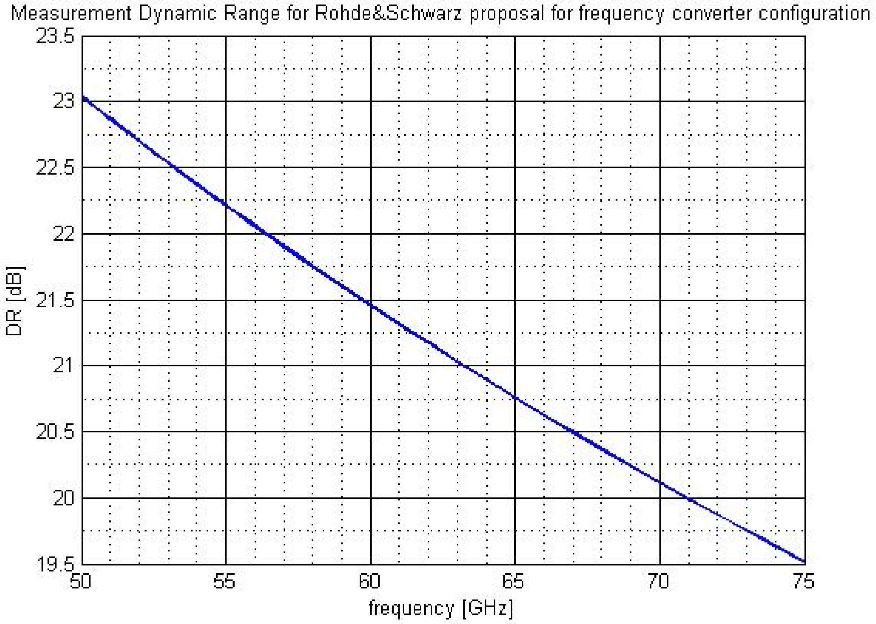


Figure B.12.: Dynamic Range for Rohde&Schwarz frequency converter proposal.

***RF power levels and LO power levels***

In this case both critical parameters are going to be calculated simultaneously. This is due to the circumstance that for the **Rohde&Schwarz® ZVA-Z75 WR15** [37] converter both signals have the same power and frequency requirements. At the same time, within the system configuration, they suffer equivalent losses (see Figure B.11). In a first stage, it has been assumed that there are no amplifiers placed between the VNA and the converters, and this way realize, that no amplifiers are required in order to compensate cable losses.

Table B.14.: RF and LO power level calculation for Rohde&Schwarz proposal for frequency converter system configuration from 50 GHz to 75 GHz.

| **Frequency** | 8.33 GHz | 12.5 GHz |
|---|---|---|
| $P_{out1}$ (dBm) | 18 | 18 |
| $P_{out2}$ (dBm) | 18 | 18 |
| $L_{r2}$(dB) | (-)0.6 | (-)0.6 |
| $L_{r1}$(dB) | (-)0.6 | (-)0.6 |
| $L_2$ (dB) | (-)7.3 | (-)9 |
| $L_4$ (dB) | (-)7.3 | (-)9 |
| $P_{TX}$ (dBm) | 10.7 | 9 |
| $P_{RX}$ (dBm) | 9.5 | 7.8 |
| $P_{inRFmin}$ (dBm) | 5 | 5 |
| $P_{inRFmax}$ (dBm) | 10 | 10 |

***IF power levels***

For this system configuration the IF levels of the converters are nearly equal (except for the loss associated to the Rotary Joints) to the ones reaching the receiver and are adapted to the VNA's inputs (see chapter 4 section 4.2.4). The only requirement to consider is to chose the correct VNA option in order to match the IF frequency.

List of components used for this proposal and its evaluation:

- **Rohde&Schwarz® ZVA** [29] (ZVA24, ZVA50 or ZVA67)
- **Huber+Suhner® SUCOFLEX104 cable** [32]
- **ORBIT/FR Feed** [17]
- AUT considered 0 dBi
- **Rohde&Schwarz® ZVA-Z75 WR15 converters** [37]
- SNR considered is 15 dB (1 dB magnitude error and 10°phase error)
- **Spinner BN 83-50-47 Rotary Joints** [34]

# B.3. ORBIT/FR proposals

## B.3.1. ORBIT/FR no multiplier proposal (using ZVA24 VNA and Agilent Technologies downconversion system and ORBIT/FR multipliers)

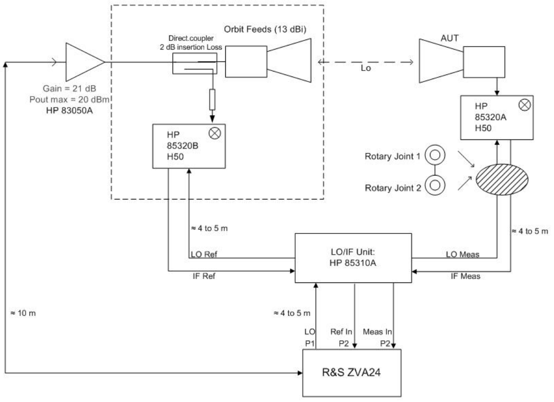


Figure B.13.: ORBIT/FR proposal for no multiplier (using ZVA24 VNA and Agilent Technologies downconversion system) system configuration.

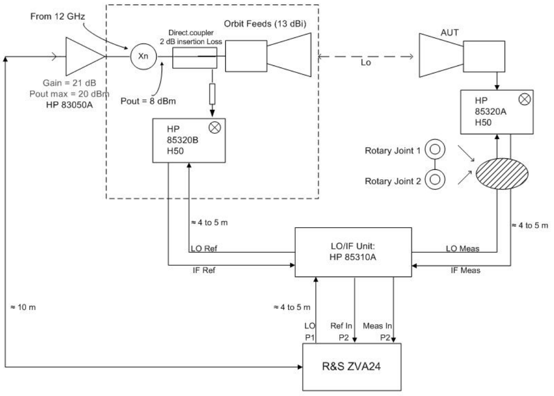


Figure B.14.: ORBIT/FR proposal for multiplier (using ZVA24 VNA, Agilent Technologies downconversion system, and ORBIT/FR multipliers) system configuration.

The last two options represent one layout proposal in one, where until 12 GHz no multipliers are used and then x2, x4, and x6 multipliers are used to cover the whole frequency range (2 GHz to 75 GHz).
This is implemented using the **Rohde&Schwarz® ZVA24** [29] and the **Agilent HP 853209/HP85320 H50 LO/IF unit and mixer** [35]. The multipliers used are ORBIT/FR own defined multipliers. These multipliers where specified as follows:

| **Multiplier specifications** | |
|---|---|
| Required input power: | 12 dBm |
| Output power: | 8 dBm |
| Input frequency range: | (depending on the type of multiplier it would reach from approximately 11 GHz to 24 GHz) |
| Multiplying value: | x2, x4, x6 |

***Measurement Dynamic Range***

Table B.15.: *Measurement Dynamic Range* calculation power levels for ORBIT/FR proposal with an Agilent Technologies external mixing system and multipliers from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | **50 GHz** |
|---|---|---|
| $P_S$ (dBm) | 18 | - |
| $L_1$ (dB) | (-)7 | - |
| $G$ (dB) | 21 | - |
| $P_{out}$ (dBm) | 20 | 8 |
| $L_2$ (dB) | (-)0.7 | - |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | (-)-0.7 | (-)3.51 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | 0 |
| $ERP$ (dBm) | 29.3 | 15.5 |
| $L_o$ (dB) | (-)52 | (-)80 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.7 | (-)3.51 |
| $P$ (dBm) | -23.4 | -68 |
| $N$ (dBm) | (-)-152 | (-)-136 |
| $SNR$ (dB) | (-)15 | (-)15 |
| $DR$ (dB) | 113.6 | 53 |

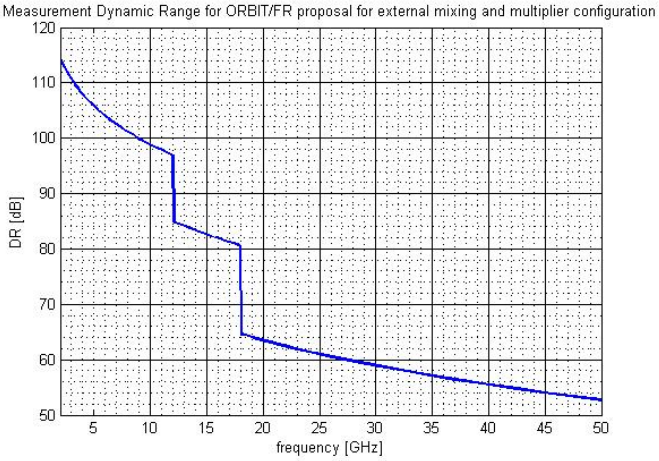


Figure B.15.: Dynamic Range for ORBIT/FR proposal with an Agilent Technologies external mixing system and multipliers configuration.

***RF power levels***

Considering the results it can be stated that an attenuator is required before the reference mixer's input. This is due to the fact that, at the lower part of the frequency range, cable losses are low. For the higher part of the frequency range it is because the multiplier has a very high output power (8 dBm) all over its working range.
It can be also stated that throught the amplifier (21 dB gain and 20 dBm maximum output power) at the transmission side, cable losses will be compensated (maximum 22.3 dB at 24 GHz). That means that the multiplier will obtain the required input power all over its frequency working range.

Table B.16.: RF power level calculation for ORBIT/FR proposal with an Agilent Technologies external mixing system and multipliers from 2 GHz to 50 GHz.

| **Frequency** | **2 GHz** | **50 GHz** |
|---|---|---|
| $P_S$ (dBm) | 18 | - |
| $L_1$ (dB) | (-)7 | - |
| $G$ (dB) | 21 | - |
| $P_{out}$ (dBm) | 20 | 8 |
| $L_2$ (dB) | (-)0.7 | - |
| $L_{ins}$ (dB) | (-)2 | (-)2 |
| $L_3$ (dB) | (-)-0.7 | (-)3.51 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | (-)0.3 | 0 |
| $ERP$ (dBm) | 29.3 | 15.5 |
| $L_o$ (dB) | (-)52 | (-)80 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $L_4$ (dB) | (-)0.7 | (-)3.51 |
| $P_{TEST}$ (dBm) | -23.4 | -68 |
| $L_{coup}$ (dB) | (-)10 | (-)10 |
| $L_5$ (dB) | (-)0.7 | (-)3.51 |
| $P_{REF}$ (dBm) | 8.6 | -5.51 |
| $Minimum$ (dBm) | -152 | -136 |
| $Maximum$ (dBm) | -24 | -24 |

### *LO power levels*

In this option, due to the high output power of the ZVA24, this power setting can be set lower and, by doing this, do not exceed the maximum permitted value for the LO source (see B.17).

Table B.17.: LO power level calculation for ORBIT/FR proposal with an Agilent Technologies external mixing system and multipliers.

| **Frequency** | **18 GHz** |
|---|---|
| $P_1$ (dBm) | 16 |
| $L_8$ (dB) | (-)5 |
| $P_1$-$L_8$ (dBm) | 11 |
| *Minimum* (dBm) | 0 |
| *Maximum* (dBm) | 6 |
| $L_{10}$ (dB) | (-)5 |
| $L_9$ (dB) | (-)7 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $L_9$- $L_{r1}$ - $L_{r2}$ (dB) | (-)8.2 |
| Loss applying, $L$ (dB) | (-)8.2 |
| $P_2$ (dBm) | 19 |
| $P_2$ - $L$ (dBm) | 10.8 |
| *Minimum* (dBm) | 12 |
| *Maximum* (dBm) | 18 |

### *IF power levels*

Table B.18.: IF power level calculation for ORBIT/FR proposal with an Agilent Technologies external mixing system and multipliers.

| **Frequency (worst case)** | **IF = not specified, RF = 2 GHz** |
|---|---|
| $P_{TEST}$ (dBm) | -24 |
| $P_{REF}$ (dBm) | -24 |
| $L_c$ (dB) | (-)12 |
| $G_{IF}$ (dB) | 25 |
| $L_{r1}$ (dB) | (-)0.6 |
| $L_{r2}$ (dB) | (-)0.6 |
| $P_{Test}$ (dBm) | -11 |
| $P_{Ref}$ (dBm) | -12.2 |
| *Analyzer 0.1 dB Compression Point* (dBm) | 15 (RF freq) |

List of components used for this proposal and its evaluation:

- **Rohde&Schwarz® ZVA24** [29]
- **Huber+Suhner® SUCOFLEX101 cable** [31]
- **Huber+Suhner® SUCOFLEX104 cable** [32]
- **Agilent 83050A Amplifier** [39]

- **Agilent 87301E Coupler** [38]
- ORBIT/FR multiplier (see B.3.1) for more information
- **ORBIT/FR Feed** [17]
- AUT considered 0 dBi
- **Agilent HP 853209/HP85320 H50 LO/IF unit and mixer** [35]
- SNR considered is 15 dB (1 dB magnitude error and 10°phase error)
- **Spinner BN 83-50-47 Rotary Joints** [34]
- **Micro Coax® MIL-DTL-17/129 semi-rigid coaxial cables** [42]

## B.3.2. ORBIT/FR multiplier proposal (using ZVA24 VNA and ORBIT/FR multipliers and mixers)

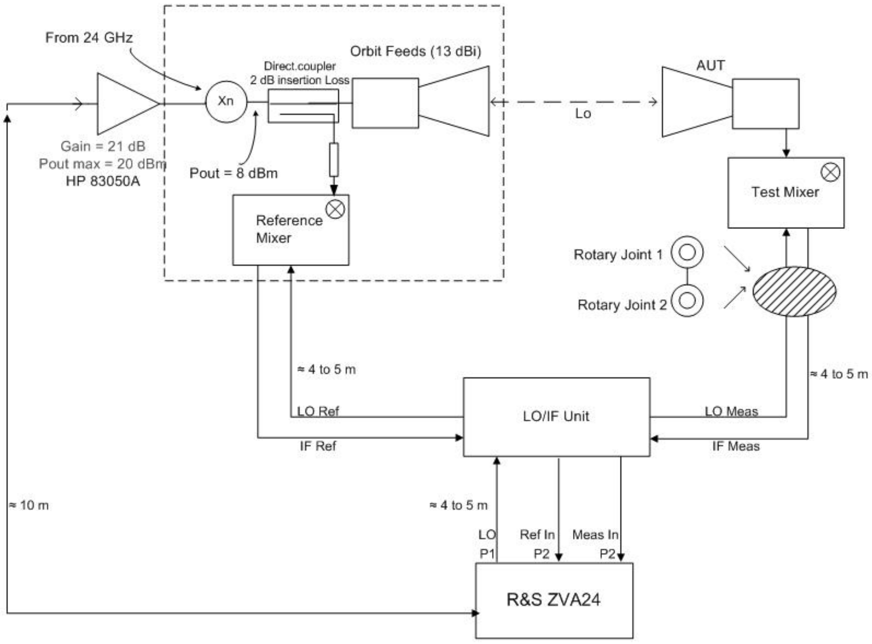


Figure B.16.: ORBIT/FR proposal for multiplier (using ZVA24 VNA and ORBIT/FR multipliers and mixers) system configuration.

This last option considers using own ORBIT/FR multipliers but also own mixers. Due to this circumstance, the only specifications available, apart from the multiplier's (see B.3.1) are the mixer's conversion loss, which is 27 dB ± 3 dB.

### *Measurement Dynamic Range*

Table B.19.: *Measurement Dynamic Range* calculation power levels for ORBIT/FR proposal with an Agilent Technologies external mixing system and multipliers from 2 GHz to 50 GHz.

| **Frequency** | **50 GHz** | **75 GHz** |
|---|---|---|
| $P_{out\_conv}$ (dBm) | - | - |
| $P_{out\_mult}$ (dBm) | 8 | 8 |
| $L_{ins}$ (dB) | 0 | 0 |
| $G_{FEED}$ (dBi) | 13 | 13 |
| $L_{FEEDVSWR}$ (dB) | 0 | 0 |
| $ERP$ (dBm) | 21 | 21 |
| $L_o$ (dB) | (-)80 | (-)83.5 |
| $G_{AUT}$(dBi) | 0 | 0 |
| $P$ (dBm) | -59 | -62.5 |
| $N$ (dBm) | (-)-137 | (-)-137 |
| $SNR$ (dB) | (-)15 | (-)15 |
| $DR$ (dB) | 63 | 59.5 |

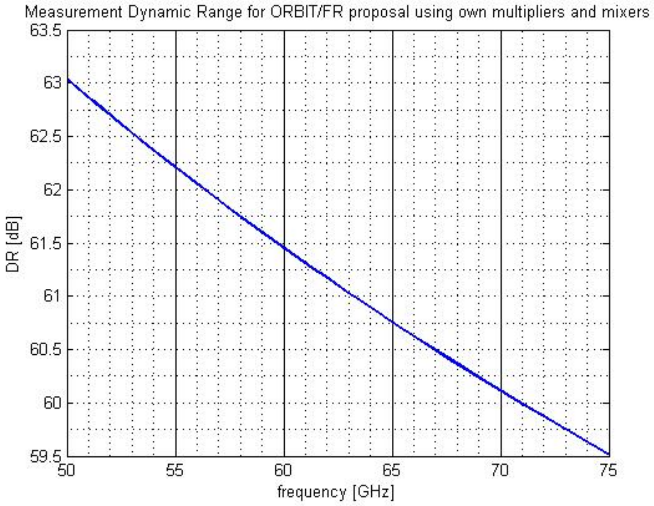


Figure B.17.: Dynamic Range for ORBIT/FR proposal with external mixing system and multipliers configuration.

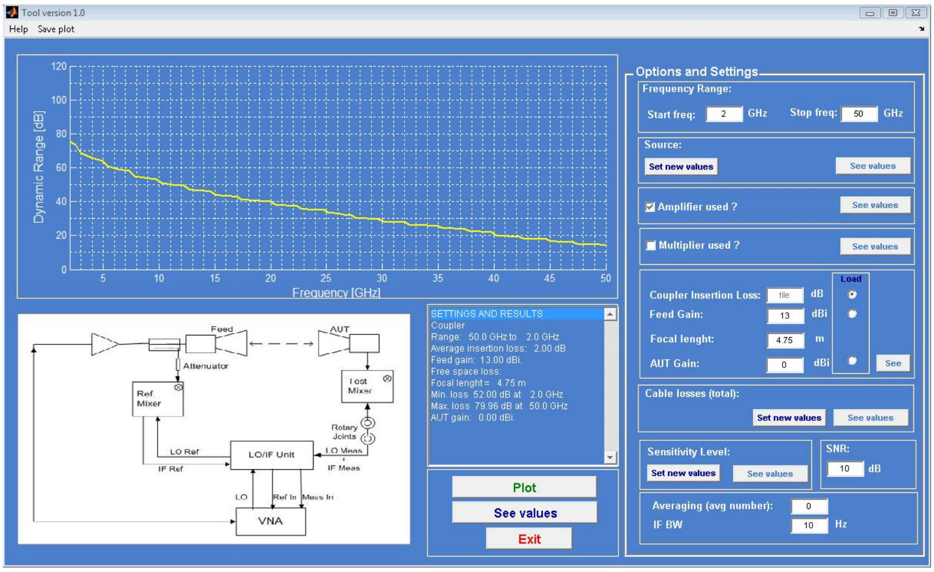
***RF power levels, LO power levels, IF power levels***
Due to the lack of information regarding the frequency downconverting system, these power levels could not be stated within the frame of this work.
Nevertheless, it can be also stated for this option that, throught the amplifier (21 dB gain and 20 dBm maximum output power) at the transmission side, cable losses will be compensated (maximum 22.3 dB at 24 GHz). That means that the multiplier will obtain the required input power all over its frequency working range.

List of components used for this proposal and its evaluation:

- **Rohde&Schwarz® ZVA24** [29]
- **Huber+Suhner® SUCOFLEX104 cable** [32]
- **Agilent 83050A Amplifier** [39]
- **Agilent 87301E Coupler** [38]
- ORBIT/FR multiplier (see B.3.1) for more information
- **ORBIT/FR Feed** [17]
- AUT considered 0 dBi
- ORBIT/FR mixers
- SNR considered is 15 dB (1 dB magnitude error and 10°phase error)

# C. Appendix 3 - Software Tool instruction manual

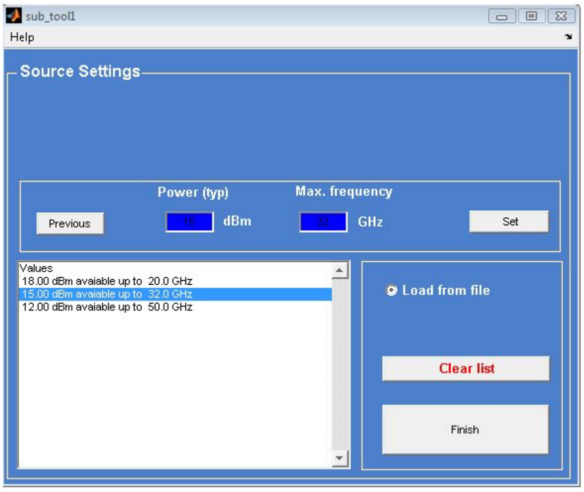
The Software Tool v1.0 software is a MATLAB® based software, developed to calculate system performance in terms of *Dynamic Range* (*DR*) and at the same time determine critical power levels along the system.
It is very important not to forget that the power levels and settings required for the mentioned calculations must be defined all over the considered frequency range. Internally, the program will establish/save each of these systems attributes for every discrete point of the defined frequency span.
The program consists of four different types of GUI windows.



```
SETTINGS AND RESULTS
Coupler
Range:   50.0 GHz to    2.0 GHz
Average insertion loss:   2.00 dB
Feed gain:  13.00 dBi.
Free space loss:
Focal lenght =   4.75 m
Min. loss  52.00 dB at   2.0 GHz
Max. loss  79.96 dB at   50.0 GHz
AUT gain:   0.00 dBi.
```

Start freq: 2 GHz
Stop freq: 50 GHz
☑ Amplifier used ?
☐ Multiplier used ?
Coupler Insertion Loss: file dB ●
Feed Gain: 13 dBi ○
Focal lenght: 4.75 m
AUT Gain: 0 dBi ○
SNR: 10 dB
Averaging (avg number): 0
IF BW 10 Hz

Figure C.1.: Software Tool version 1.0 main window.



sub_tool1

Help

**Source Settings**

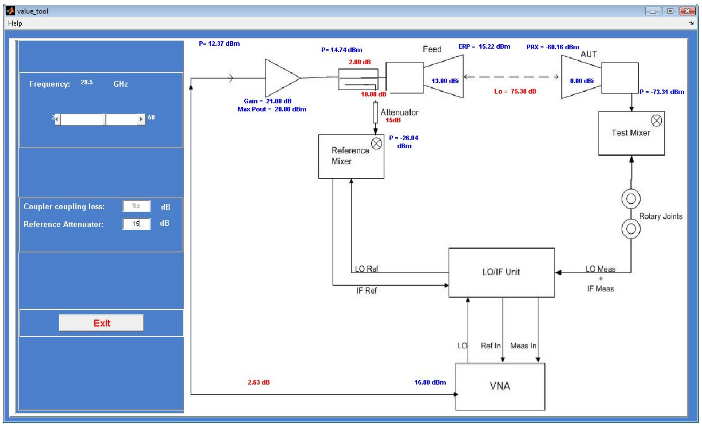
Power (typ): 15 dBm

Max. frequency: 32 GHz

Values
18.00 dBm avaiable up to 20.0 GHz
15.00 dBm avaiable up to 32.0 GHz
12.00 dBm avaiable up to 50.0 GHz

○ Load from file

Figure C.2.: Software Tool version 1.0 settings introduction sub GUI.



value_tool

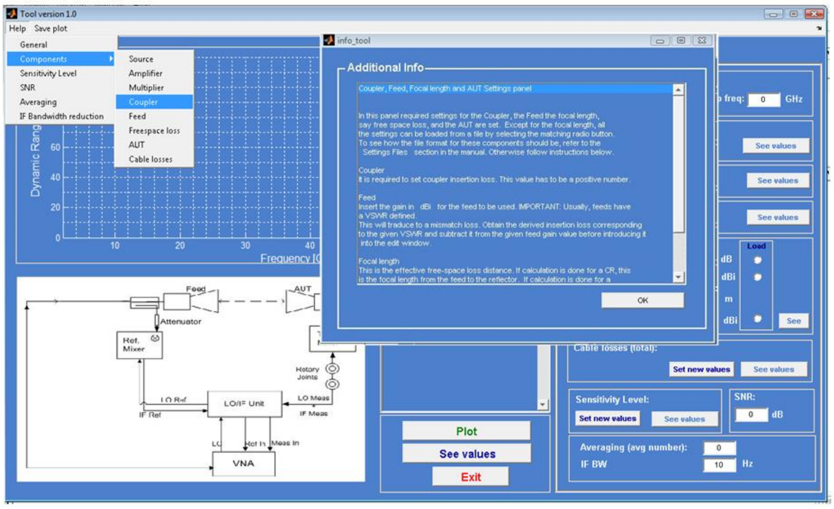
Help

Frequency: 29.5 GHz

Coupler coupling loss: file dB

Reference Attenuator: 15 dB

Figure C.3.: Software Tool version 1.0 power level calculation window.



Coupler, Feed, Focal length and AUT Settings panel

In this panel required settings for the Coupler, the Feed the focal length, say free space loss, and the AUT are set. Except for the focal length, all the settings can be loaded from a file by selecting the matching radio button. To see how the file format for these components should be, refer to the Settings Files section in the manual. Otherwise follow instructions below.

Coupler
It is required to set coupler insertion loss. This value has to be a positive number.

Feed
Insert the gain in dBi for the feed to be used. IMPORTANT: Usually, feeds have a VSWR defined.
This will traduce to a mismatch loss. Obtain the derived insertion loss corresponding to the given VSWR and subtract it from the given feed gain value before introducing it into the edit window.

Focal length
This is the effective free-space loss distance. If calculation is done for a CR, this is the focal length from the feed to the reflector. If calculation is done for a

freq: 0 GHz

SNR: 0 dB

Averaging (avg number): 0

IF BW 10 Hz

Figure C.4.: Software Tool version 1.0 "*Help*" environment.

- Main window: all required system settings for *DR* calculation are set in this window (see Figure C.1).
- Settings introduction sub GUI window: in this type of windows the settings for different components and attributes of the system are introduced (see Figure C.2).
- Power level calculation window: in this window, power levels for each discrete frequency point of the selected range can be checked (see Figure C.3).
- "*Help*" environment window: This type of window will show up every time the *Help* function menu is selected (see Figure C.4).

The *DR* definition applied for calculation follows the expression:

$$DR = P - \text{Sensitivity Level} - SNR \tag{C.1}$$

Where:
$P$ is the the available power reaching the reception side, dBm
*Sensitivity Level* is the *System Sensitivity Level* defined as the noise floor of the system, dBm
$SNR$ is the Signal to Noise Ratio. It is considered in order to avoid possible measurement accuracy errors

Refer to the matching subsections in order to obtain additional information.

**IMPORTANT:** Settings for the following components, source, amplifier, multiplier, coupler, feed, AUT, cables and the *System Sensitivity Level*, are saved in homonym `.txt` files. In this way, settings used for a previous software execution can be reused, refreshed or overwritten.

## Main window

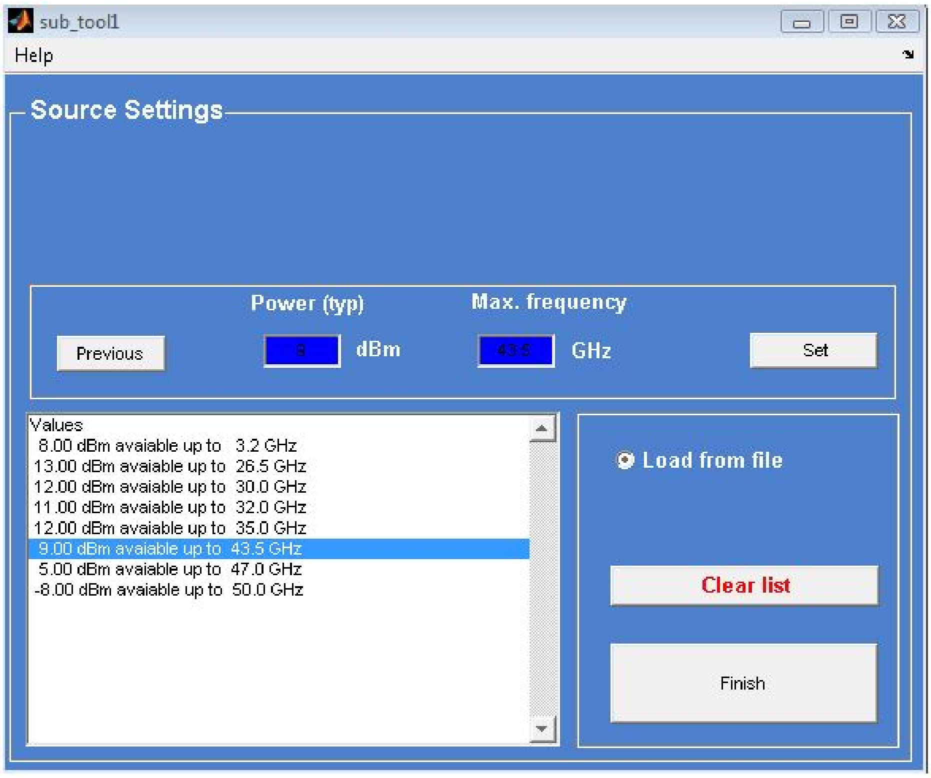
### Frequency Range

Here, the frequency range for which the system performance has to be calculated is selected. Every time one of the extreme values of the range is actualized, say introduced, the plot with the *DR* results will be refreshed. The program will generate an error if:

- The input is not a number.
- No input is given at all.
- Values are 0 or below 0.
- Start frequency is greater than stop frequency.

**IMPORTANT:** This frequency range is the RF frequency range of the system. For example, if multipliers are used, this is the frequency range that will be finally transmitted on the transmission side and received on the reception side before down-conversion.
Use this panel to reduce the frequency span if, once results are plotted, more precision is required in order to examine them.

**Source panel**
In the "Source" panel on the main GUI, settings for the source can be looked up by pushing the "See values" button. In this way, the current set attributes in terms of power and frequency for the source, even if it is the internal VNA's source, will be displayed on the information panel in the main window.



Power (typ) 9 dBm

Max. frequency 43.5 GHz

```
Values
 8.00 dBm avaiable up to   3.2 GHz
13.00 dBm avaiable up to  26.5 GHz
12.00 dBm avaiable up to  30.0 GHz
11.00 dBm avaiable up to  32.0 GHz
12.00 dBm avaiable up to  35.0 GHz
 9.00 dBm avaiable up to  43.5 GHz
 5.00 dBm avaiable up to  47.0 GHz
-8.00 dBm avaiable up to  50.0 GHz
```

Figure C.5.: Software Tool version 1.0 Source's "Settings introduction sub GUI window".

If current settings should be actualized or even overwritten, select the "Set new values" button. By doing this, the "Settings introduction sub GUI window" for the source will show up (see Figure C.5).

**Source settings introduction sub GUI window**
Source settings can be loaded from a file or introduced manually.

To introduce them manually, insert the source output power and the maximum frequency for which the source can achieve this power level. E.g, if in a datasheet the manufacturer states that the source will typically generate 16 dBm from 13 GHz to 24 GHz, insert: 16 and 24.

To save the values, push the "Set" button. The settings that are going to be saved on the `.txt` file will appear on the information display found in this sub GUI. Repeat this procedure until the whole frequency range is specified, otherwise, the program will generate an error advising about a frequency compatibility conflict.

If a correction has to be done, push the "Previous" button until the desired value is highlighted on the display. Then, insert the new values and push the "Set" button to save the actualized settings.

In case they are loaded from a file, push the "Load from file" radio button. The settings located on the file will appear on the display. In case the settings want to be actualized, proceed as explained above when a correction should be done by using the "Previous" button.

To see how the file format for this component should be, refer to the "Settings Files" section in the manual.

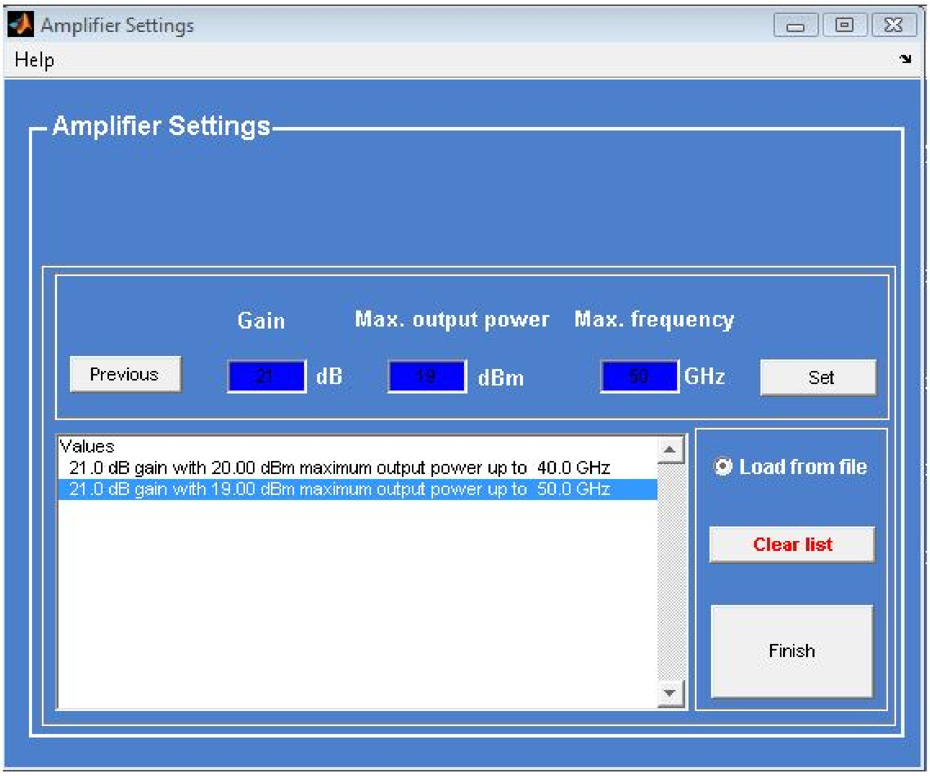
If none of the settings found in the file/display match the current requirements, the "Clear list" button can be used in order to start from the beginning defining the component's specifications.

Finally, by pushing the "Finish" button, all the settings defined and shown in the display will be written and saved on the `Source.txt` file and used by the program for the calculations.

These settings can be checked at anytime on the main GUI by pushing the "See values" button on the Source panel in the main GUI.

### Amplifier panel

In case an amplifier is used in the system configuration, select the check box found on the "Amplifier" panel on the main GUI.
If the current amplifier settings found on the homonym `.txt` file want to be used by the user or checked before overwrite them, select "No" when the question box shows up. The current settings are going to appear on the information display on the main GUI.



Gain 21 dB
Max. output power 19 dBm
Max. frequency 50 GHz

```
Values
 21.0 dB gain with 20.00 dBm maximum output power up to  40.0 GHz
 21.0 dB gain with 19.00 dBm maximum output power up to  50.0 GHz
```

Figure C.6.: Software Tool version 1.0 Amplifier's "Settings introduction sub GUI window".

If the current settings should be actualized or even overwritten, select the "Yes" button. In this way, the "Settings introduction sub GUI window" for the amplifier will show up (see Figure C.6).

**Amplifier settings introduction sub GUI window**
Amplifier settings can be loaded from a file or introduced manually.

To introduce them manually, insert the amplifier gain, the amplifier maximum output power and the maximum frequency for which the amplifier's frequency operation range is defined. E. g, if in a datasheet the manufacturer states that the amplifier has a small signal gain of 21 dB, with a maximum output power of 20 dBm up to 40 GHz, insert: 21, 20, and 40.

**IMPORTANT:** The value that should be taken for the amplifier's maximum output power is the "Output power at maximum available input power" this value should be used instead of the output power value for "X dB Compression". Even if this is a non-lineal element, no modulation is applied on the signal's RF frequency. As no modulation is present, reasonable no linearities can be accepted. In this way, the maximum output power limitation can be extended to the maximum value instead of the "1 dB Compression".

To save the values, push the "Set" button. The settings that will be saved on the `.txt` file will appear on the information display found in this sub GUI. Repeat this procedure until the whole frequency range is specified, otherwise, the program will generate an error advising about a frequency compatibility conflict.

If a correction has to be done, push the "Previous" button until the desired value is highlighted on the display. Then, insert the new values and push the "Set" button to save the actualized settings.

In case they are loaded from a file, push the "Load from file" radio button. The settings located on the file will appear on the display. In case the settings want to be actualized proceed as explained above when a correction should be done by using the "Previous" button.

To see how the file format for this component should be, refer to the "Settings Files" section in the manual.

If none of the settings found in the file/display match the current requirements, the "Clear list" button can be used in order to start from the beginning defining the component's specifications.

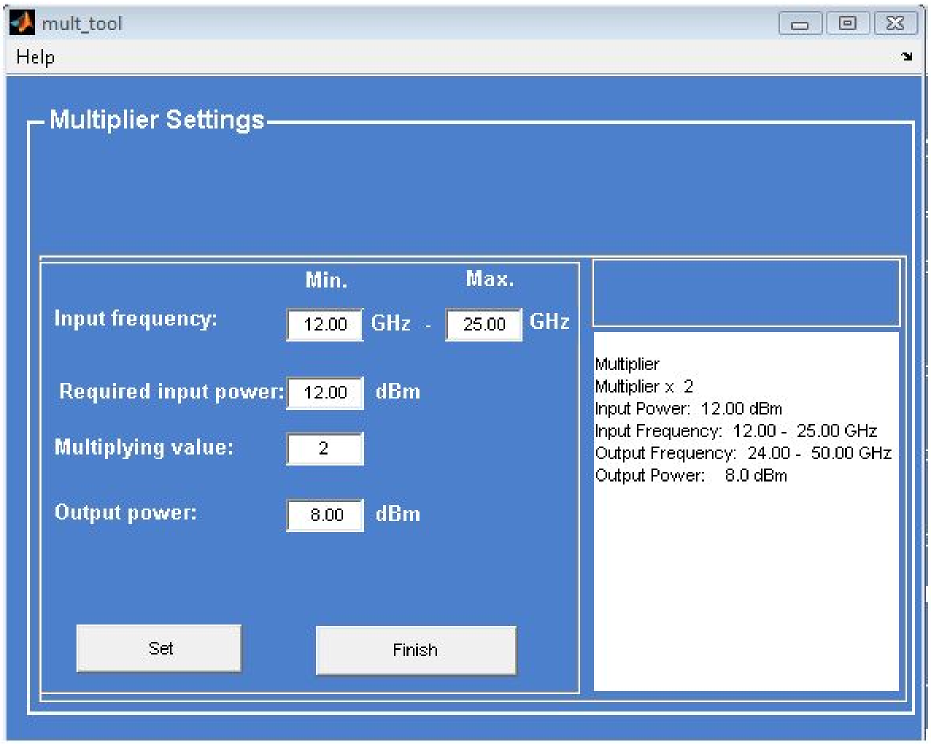
Finally, by pushing the "Finish" button, all the settings defined and shown in the display will be written and saved on the `Amp.txt` file and used by the program for the calculations.

Anytime, these settings can be checked on the main GUI by pushing the "See values" button on the Amplifier panel in the main GUI Anytime it can be renounced to the use of an amplifier by deselecting the checkbox. Even though, settings will still be saved on the file for future executions.

### Multiplier panel

In case a multiplier is used in the system configuration, select the check box found on the "Multiplier" panel on the main GUI.

If the current amplifier settings found on the homonym `.txt` file want to be used or checked before overwrite them, select "No" when the question box shows up. The current settings will appear on the information display on the main GUI.



Input frequency: 12.00 GHz - 25.00 GHz

Required input power: 12.00 dBm

Multiplying value: 2

Output power: 8.00 dBm

Multiplier
Multiplier x 2
Input Power: 12.00 dBm
Input Frequency: 12.00 - 25.00 GHz
Output Frequency: 24.00 - 50.00 GHz
Output Power: 8.0 dBm

Figure C.7.: Software Tool version 1.0 Multiplier's "Settings introduction sub GUI window".

If current settings should be actualized or even overwritten, select the "Yes" button. In this way, the "Settings introduction sub GUI window" for the multiplier will show up (see Figure C.7).

**Multiplier settings introduction sub GUI window**
Multiplier settings, due to their simplicity are introduced manually in any case. Nevertheless, the settings used in previous executions will appear on the GUI.
If the user wants to use a file, refer to "Settings Files" section in the manual.

In case they require being refreshed, this procedure can be done introducing directly on the corresponding edit windows.

The multiplier can be defined through the following settings:

- Input frequency range.
- Required input power.
- Frequency multiplying value.
- Output power.

The output frequency range resulting from the multiplying value and the input frequency range is displayed on the sub GUI information panel once the "Set" button is pushed. This frequency range should match the selected frequency range on the main window, otherwise a frequency compatibility conflict error will be generated.

**IMPORTANT:** To save the values, push the "Set" button. If not, the settings that have been introduced/refreshed will not be saved on the `.txt` file, and as a consequence, not considered for the program's calculations.

Finally, by pushing the "Finish" button, the program returns to the main window of the program.

These settings can be checked whenever the user wants on the main GUI by pushing the "See values" button on the Multiplier panel in the main GUI It can be renounced at anytime to the use of a multiplier by deselecting the checkbox. Even though, settings will still be saved on the file for future executions.

Coupler Insertion Loss: file dB ●

Feed Gain: 13 dBi ○

Focal lenght: 4.75 m

AUT Gain: 0 dBi ○

Figure C.8.: Software Tool version 1.0 Coupler, Feed, Free-space loss and AUT panel.

### Coupler, Feed, Focal length and AUT Settings panel

In this panel required settings for the Coupler, the Feed, the focal length, say free space loss, and the AUT are set. Except for the focal length, all the settings can be loaded from a file by selecting the matching radio button (see Figure C.8). To see how the file format for these components should be, refer to the "Settings Files" section. Otherwise follow instructions below.

### Coupler

It is required to set coupler insertion loss. This value has to be a positive number. Typical values for this attribute are around 2 dB for coaxial couplers and can be considered 0 dB in case waveguide couplers are used.

### Feed

Insert the gain in dBi for the feed to be used.

**IMPORTANT:** Usually, feeds have a VSWR defined. This is translated to a mismatch loss. Obtain the derived insertion loss corresponding to the given VSWR and subtract it from the given feed gain value before introducing it into the edit window. Typical feed gain values are usually between 10 dB and 15 dB.

### Focal length

This is the effective free-space loss distance. If the calculation is done for a Compact Range (CR), this is the focal length from the feed to the reflector. If the calculation is done for a traditional Far Field Range, this is the direct line-of-sight distance between Feed and AUT. The formula that will define free-space loss is:

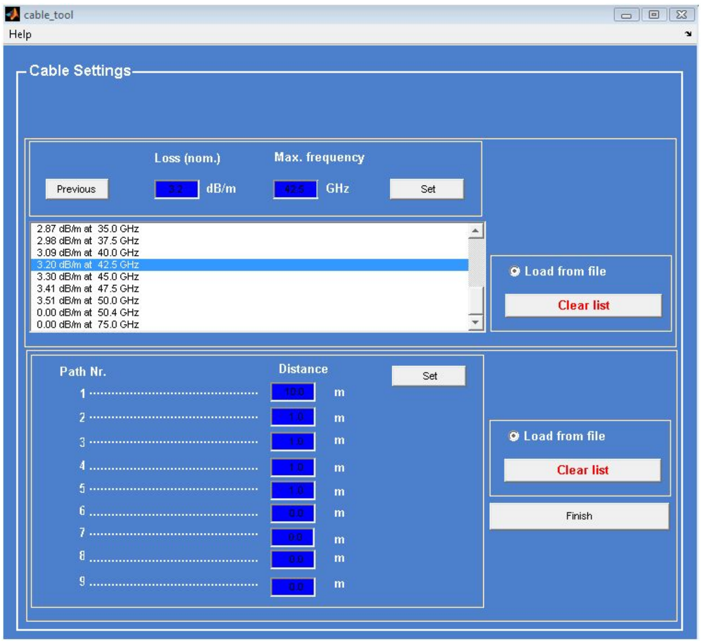
$$Lo = 32.45 + 20log(d[\mathrm{m}]) + 20log(f[\mathrm{GHz}]) \qquad \text{(C.2)}$$

### AUT

Same reasoning as for the Feed applies in this case. Insert the expected AUT gain value. If the system performance in general terms is analyzed, this value should be left zero. After setting all the data required, even if it is from a file or not, this information can be displayed on the display panel by pushing the "See values" button.

### Cable losses panel

In the "Cable losses" panel on the main GUI, settings for the cables can be looked up by pushing the "See values" button. Inhis way, the current set attributes in terms of losses in dB/m for a given frequency will be displayed on the information panel in the main window.



Loss (nom.) 3.2 dB/m Max. frequency 42.5 GHz

```
2.87 dB/m at  35.0 GHz
2.98 dB/m at  37.5 GHz
3.09 dB/m at  40.0 GHz
3.20 dB/m at  42.5 GHz
3.30 dB/m at  45.0 GHz
3.41 dB/m at  47.5 GHz
3.51 dB/m at  50.0 GHz
0.00 dB/m at  50.4 GHz
0.00 dB/m at  75.0 GHz
```

| Path Nr. | Distance |
|---|---|
| 1 | 10.0 m |
| 2 | 1.0 m |
| 3 | 1.0 m |
| 4 | 1.0 m |
| 5 | 1.0 m |
| 6 | 0.0 m |
| 7 | 0.0 m |
| 8 | 0.0 m |
| 9 | 0.0 m |

Figure C.9.: Software Tool version 1.0 Cable losses' "Settings introduction sub GUI window".

If current settings should be actualized or even overwritten, select the "Set new values" button. This way, the "Settings introduction sub GUI window" for the cable losses will show up (see Figure C.9).

**Cable losses settings introduction sub GUI window**
Cable losses settings have to be defined divided into two parts. First, the cable itself has to be defined by specifying the cable loss in dB/m all over the frequency range. These settings can be loaded from a file or introduced manually.

To introduce them manually insert the nominal attenuation in dB/m and the frequency for that value. This attenuation is going to be used for all the frequency points before the next specified attenuation/frequency pair of values. E. g, if in a datasheet the manufacturer states that the cable will typically have an attenuation of 1.63 dB/m at 12.5 GHz insert: 1.63 and 12.5.

To save the values, push the "Set" button. The settings that will be saved on the `.txt` file will appear on the information display found in this sub GUI. Repeat this procedure until the whole frequency range is specified, otherwise, the program will generate an error advising about a frequency compatibility conflict.

If a correction has to be done, push the "Previous" button until the desired value is highlighted on the display. Then, insert the new values and push the "Set" button to save the actualized settings.

In case they are loaded from a file, push the "Load from file" radio button. The settings located on the file will appear on the display. In case the settings want to be actualized proceed as explained above when a correction should be done by using the "Previous" button.

To see how the file format for this component should be, refer to the "Settings Files" section in the manual.

If none of the settings found in the file/display match the current requirements the "Clear list" button can be used in order to start from the beginning defining the component's specifications.

Second the distance, say effective length for the different cable paths found in the system has to be defined. Any possible path within the system has been numbered (see Table C.1 and Figure C.10).

Table C.1.: Software Tool v1.0 cable path numbering.

| Number | Path description |
|---|---|
| 1 | Source to transmission side (Amplifier's input, if any). |
| 2 | Amplifier (if any) to transmission side (Multiplier's input (if any)). |
| 3 | Multiplier (if any) to transmission side. |
| 4 | Coupler's output to feed antenna's input. |
| 5 | AUT's output to reception side (test mixer's input). |
| 6 | Coupler's coupling output to reference mixer's input. |
| 7, 8, 9 | Not programmed in this version. Possible future use for LO and IF cable paths. |

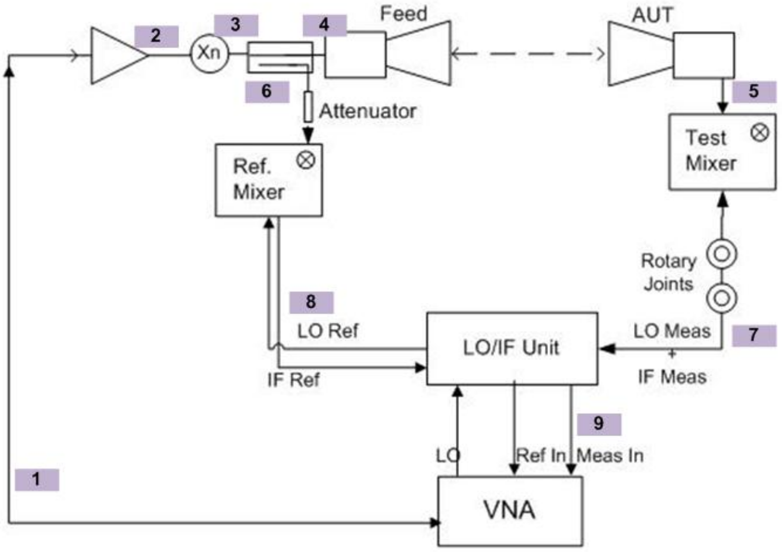


Figure C.10.: Software Tool v1.0 cable path numbering.

These cable paths can be introduced manually or loaded from a file.

To see how the file format for this setting should be, refer to the "Settings Files" section in the manual.

Manual introduction is done by editing the corresponding edit windows. In case the path distances are loaded from a file, this load is done selecting the "Load from file" radio button.

In case settings want to be actualized by the user, overwrite them directly on the edit windows.

If none of the settings found in the file/display match the current requirements the "Clear list" button can be used in order to start from the beginning defining the component's specifications.

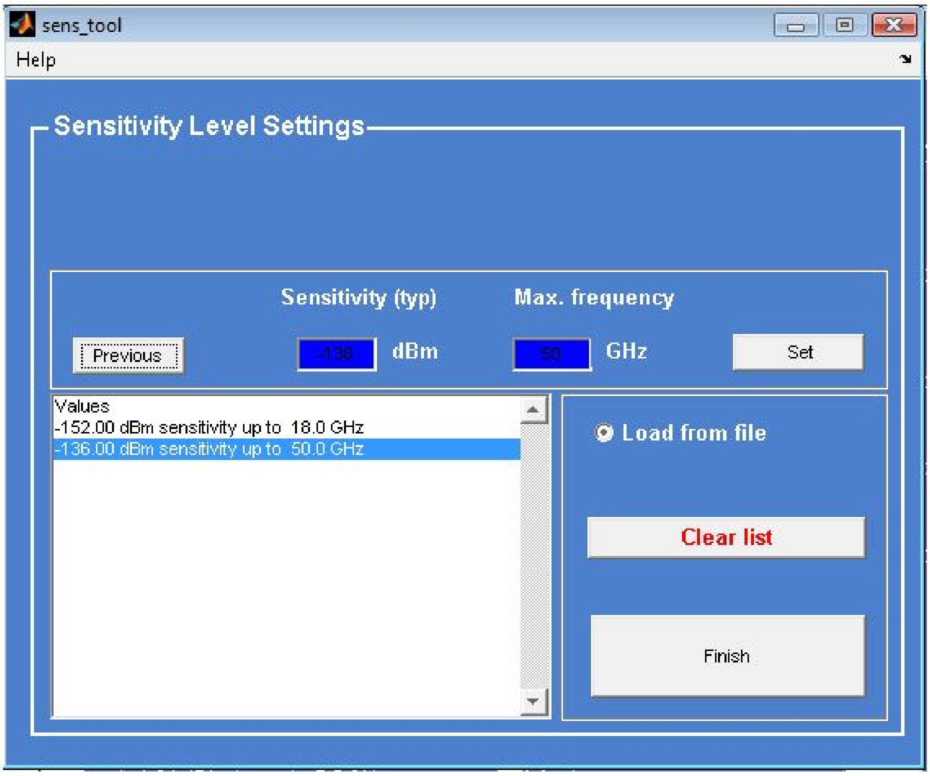
**IMPORTANT:** To save the values, push the "Set" button. If not, the settings previously introduced/refreshed will not be saved on the `.txt` file. As a consequence, they would not be considered for the program's calculations.

Finally, by pushing the "Finish" button, all the settings defined and shown on the display will be written and saved on the `distance.txt` and `cable.txt` files and used by the program for the calculations.

These settings can be checked at anytime on the main GUI by pushing the "See values" button on the Cable losses panel in the main GUI.

***Sensitivity Level* panel**

In the "*Sensitivity Level*" panel on the main GUI, the settings for the *Sensitivity Level* can be looked up by pushing the "See values" button. By doing this, the current set level in terms of power and frequency will be displayed on the information panel in the main window.



Sensitivity (typ) -136 dBm

Max. frequency 50 GHz

Values
-152.00 dBm sensitivity up to 18.0 GHz
-136.00 dBm sensitivity up to 50.0 GHz

Figure C.11.: Software Tool v1.0 *Sensitivity Level*'s "Settings introduction sub GUI window".

If current settings should be actualized or even overwritten, select the "Set new values" button. This way, the "Settings introduction sub GUI window" for the *Sensitivity Level* will show up (see Figure C.11).

**_Sensitivity Level_ settings introduction sub GUI window**
*Sensitivity Level* settings can be loaded from a file or introduced manually.

The *Sensitivity Level* is defined as the noise floor of the system. It is specified at the last RF point before conversion to IF frequency and considering all the components behind this point plus the AUT antenna own reception noise.

The noise floor can be obtained through following expression using the IF bandwidth B:

$$\begin{aligned} N &= kTB \\ N[\mathrm{dBm}] &= 30 + 10logk + 10logT + 10logB = \\ &= -174 + 10logT/To + 10logB \end{aligned} \tag{C.3}$$

Where

$$T = Ta + To(F-1) \tag{C.4}$$

Is the equivalent noise temperature.
Assuming that the testing environment is at 17 degree Celsius, the expression would be:

$$N = -174 + 10logF + 10logB \tag{C.5}$$

$F$ is the noise factor of the reception chain, and if no LNA amplifiers are placed before the frequency downconverting system (mixers), this value can be approximated by the conversion loss. If other elements are before the frequency conversion stage, the chain noise figure formula would determine the total noise factor for the chain of elements.

To introduce the values manually insert the sensitivity power level and the maximum frequency for which this level will be maintained. E. g, -136 dBm up to 50 GHz, insert: -136 and 50.

To save the values, push the "Set" button. The settings that will be saved on the `.txt` file will appear on the information display found in this sub GUI. Repeat this procedure until the whole frequency range is specified, otherwise, the program will generate an error advising about a frequency compatibility conflict.

In case a correction has to be done, push the "Previous" button until the desired value is highlighted on the display. Then, insert the new values and push the "Set" button to save the actualized settings.

In case they are loaded from a file, push the "Load from file" radio button. The settings found on the file will appear on the display. In case settings want to be actualized proceed as explained above when a correction should be done by using the "Previous" button.

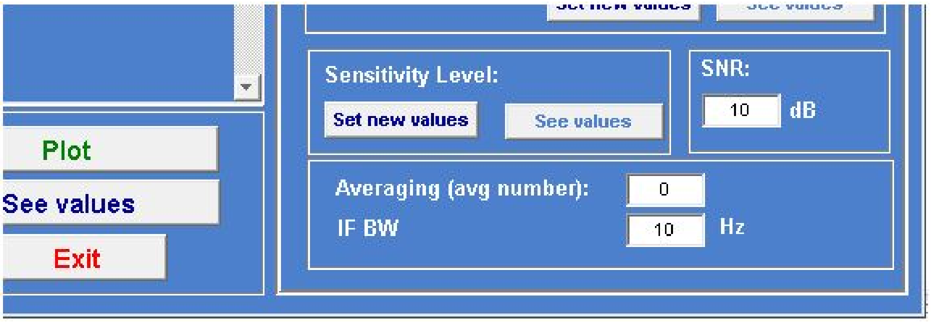
To see how the file format for this setting should be, refer to the "Settings Files" section in the manual.

If none of the settings found in the file/display match the current requirements the "Clear list" button can be used in order to start from the beginning defining the component's specifications.

Finally, by pushing the "Finish" button, all the settings defined and shown in the display will be written and saved on the `Sens.txt` file and used by the program for the calculations.

Anytime, these settings can be checked on the main GUI by pushing the "See values" button on the *Sensitivity Level* panel in the main GUI.

**Signal to Noise Ratio ($SNR$)**
The measurement accuracy required and finally found in the measurement system, has a direct impact on the *Sensitivity Level.* Possible and acceptable measurement errors have to be considered. That is why the real *System Sensitivity Level* theoretically should be increased. This is carried out through rising this level, say decreasing the $DR$ parameter, through the Signal-to-Noise-Ratio ($SNR$). This ratio acts as a margin considering phase and amplitude measurement errors, and can be determined through graphics as the one found in the program's folder called "SNR" or the one on page 18 in the document found at **http://cp.literature.agilent.com/litweb/pdf/5968-6759E.pdf**.



SNR: 10 dB

Averaging (avg number): 0

IF BW 10 Hz

Figure C.12.: Software Tool v1.0 editing windows for *SNR*, averaging and bandwidth reduction.

The chosen value for the calculation can be specified by editing the corresponding edit window on the main GUI (see Figure C.12).

The program will generate a warning in case this value is left 0. It will neither accept negative values or values which are not a number.

**Averaging**
This method involves taking the measured complex vectorial data at the receiver and average each point of a sweep with exponentially weighted coefficients.

Averaging signal noise will improve *System Sensitivity Level* and simultaneously, the measurement $DR$. Commonly, the default setting when the Receiver's specifications are given, is set to zero averages. The $DR$ improvement factor through averaging procedures can be expressed as:

$$DR_2 = DR_1 + 10 \log (\text{number of averages}) \tag{C.6}$$

**IMPORTANT:** Averaging means a decrease of measurement speed due to the additional time required by the receiver to average the selected number of traces.

The chosen value for the calculation can be specified by editing the corresponding edit window on the main GUI (see Figure C.12).

**Bandwidth reduction**
Noise floor, say *System Sensitivity Level*, is dependent from the receiver's bandwidth $B$. If this is considered, *Measurement DR* can be defined as a function of $B$.

$$\begin{aligned} DR = P - \text{System Sensitivity Level} - SNR \\ DR = P - N - SNR \\ DR = P - (-174 + 10 \log F + 10 \log B) - SNR \end{aligned} \tag{C.7}$$

It can be deduced from this result that, IF bandwidth variation effect on $DR$ can be written as:

$$DR_2 = DR_1 - 10 \log B_2/B_1 \tag{C.8}$$

**IMPORTANT:** There is going to be a loss of measurement speed due to $B$ narrowing. The exact decrease will depend on the concrete IF filter shape of the receiver, and has to be stated by the receiver's manufacturer.

**"Plot pushbutton"**
Once all the system specifications and required characteristics are defined, the *Measurement DR* can be calculated and plotted all over the specified frequency range.

If there are components and/or parameters not defined for the range, frequency compatibility errors will be generated.

In case of not enough or too much power to feed the multiplier, power warnings will be generated.

In case settings are left to 0 for the coupler, the feed, the AUT or the $SNR$ value, warnings will show up in order to ensure that this is done intentionally by the user.

Everytime one of the systems settings or characteristics is changed, the plot will be erased and the "Plot" pushbutton should be pushed again in order to obtain the actualized plot.

**"See values" tool/pushbutton**
There is the option to obtain the exact value of the power levels and main losses within the system for a concrete frequency. These can be obtained by pushing the "See values" button. In this way, the power level calculation window will show up (see Figure C.2).

Each of these values will be refreshed any time the slider button is triggered. The slider permits to choose a frequency within the selected range in the main window.

Power reaching the inputs of the test and reference mixer is calculated in this window. It has to be warranted that the power levels reaching mixers inputs do not overdrive them out of their linear working zone, but they do reach the sensitivity levels of the system, over its whole frequency working range. These levels can be checked with this program's function.

For the reference path, it is required to specify the coupler's coupling loss and by this way determine the power reaching the reference mixer's input. It is commonly required to place an attenuator at this point. The attenuation value will also have to be specified in the corresponding edit window.

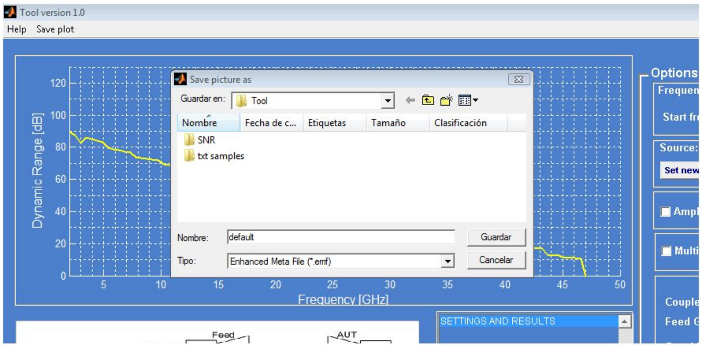
### *Save plot* menu

This function found in the main window allows saving the plot displayed (see Figure C.13). This can be done using three different formats. These formats are: `.emf`, `.bmp`, and `.fig`.

### *Help* menu

By selecting a concrete section from the *Help* menu, the matching information window will appear (see Figure C.4 and Figure C.14).

The "*Help* environment menu" provides additional information regarding the components and settings required for system performance calculation.



Guardar en: Tool

Nombre: default

Tipo: Enhanced Meta File (*.emf)

Figure C.13.: Software Tool v1.0 *Save plot* menu.

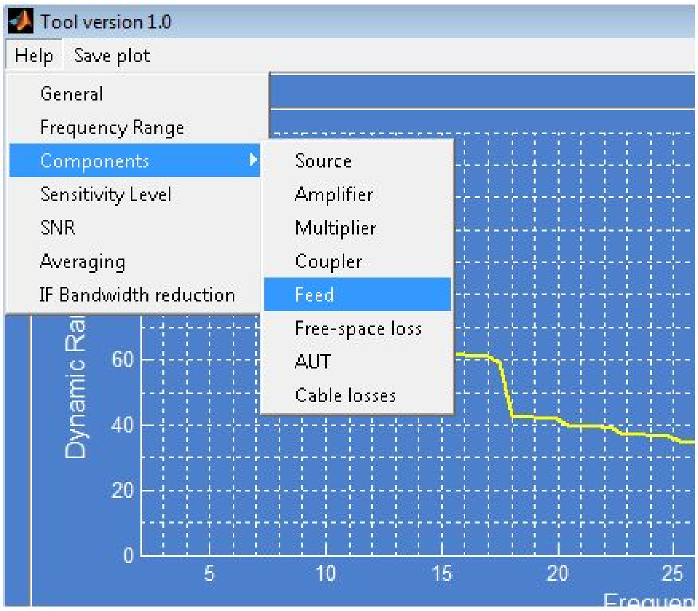


Figure C.14.: Software Tool v1.0 *Help* menu.

## Setting files section

Settings for the following components, source, amplifier, multiplier, coupler, feed, AUT, cables and the *System Sensitivity Level* are saved in homonym `.txt` files. By doing this, the settings used for a previous software execution can be reused, refreshed or overwritten.

Each of these files can be generated externally, outside the program's MATLAB® running environment, or by introducing the data manually through the "Settings introduction sub GUI windows".

It is very important to respect the file data format and file names required (see Table C.2). Otherwise, the program is not going to be able to correctly calculate the required system performance evaluation parameters.

These files should be placed directly into the program's main folder.

Table C.2.: Software Tool version 1.0 settings files format.

| **Component** | **File Name** | **Format** | | |
|---|---|---|---|---|
| Source | `Source.txt` | Max Freq [GHz] | Power [dBm] | |
| Amplifier | `Amp.txt` | Max Freq [GHz] | Max Output Power [dBm] | Gain [dB] |
| Multiplier | `Mult.txt` | Min Input Freq [GHz] | Max Input Freq [GHz] | Req. Input Power [dBm] |
| | | ... | Multiplying value | Output Power [dBm] |
| Coupler | `Coupler.txt` | Min Freq [GHz] | Max Freq [GHz] | Insertion Loss [dB] |
| | | ... | Coupling Loss [dB] | |
| Feed | `Feed.txt` | Min Freq [GHz] | Max Freq [GHz] | Gain [dBi] |
| AUT | `AUT.txt` | Min Freq [GHz] | Max Freq [GHz] | Gain [dBi] |
| Cable losses | | | | |
| Cable loss | `Cable.txt` | Freq [GHz] | Nominal Attenuation [dB/m] | |
| Distance | `distance.txt` | Distance [m] | | |
| Sensitivity Level | `Sens.txt` | Max Freq [GHz] | Power [dBm] | |

**IMPORTANT:** Except for the multiplier and the distance file, all the other files can have up to 256 rows defining the parameters within the frequency range.

**File examples**

`Source.txt` file can be written as:

| | |
|---|---|
| 13 | 18 |
| 24 | 16 |
| 50 | 14 |
| 70 | 13 |
| … | … |

Which would mean that there are 18 dBm available up to 13 GHz, 16 dBm available up to 24 GHz, 14 dBm available up to 50 GHz and 13 dBm available up to 70 GHz.

`Multiplier.txt` file can be written as:

| | | | | |
|---|---|---|---|---|
| 12 | 25 | 12 | 2 | 8 |

Which would mean that the multiplier has a frequency input range going from 12 GHz to 25 GHz and it requires an input power of 12 dBm. It will multiply frequencies by 2 and generate an output power of 8 dBm.

`distance.txt` file can be written as:

| |
|---|
| 10 |
| 1 |
| 1 |
| 0.5 |
| 0.5 |
| 0 |
| 0 |
| 0 |
| 0 |

Where every value corresponds to a cable distance, following the numbering exposed in the cable losses section in this manual.

Or for the `Feed.txt` file:

| | | |
|---|---|---|
| 2 | 25 | 15 |
| 25 | 50 | 13 |
| 50 | 75 | 15 |
| ... | ... | ... |

Which would mean that the feed has a gain of 15 dBi between 2 GHz and 25 GHz, 13 dBi gain between 25 GHz and 50 GHz and 15 dBi between 50 and 75 GHz.

# D. Appendix 4 - Software Tool code documentation

In order to ease future software use, updating and improvement of the software Tool version 1.0 presented in chapter 5, code documentation is included.

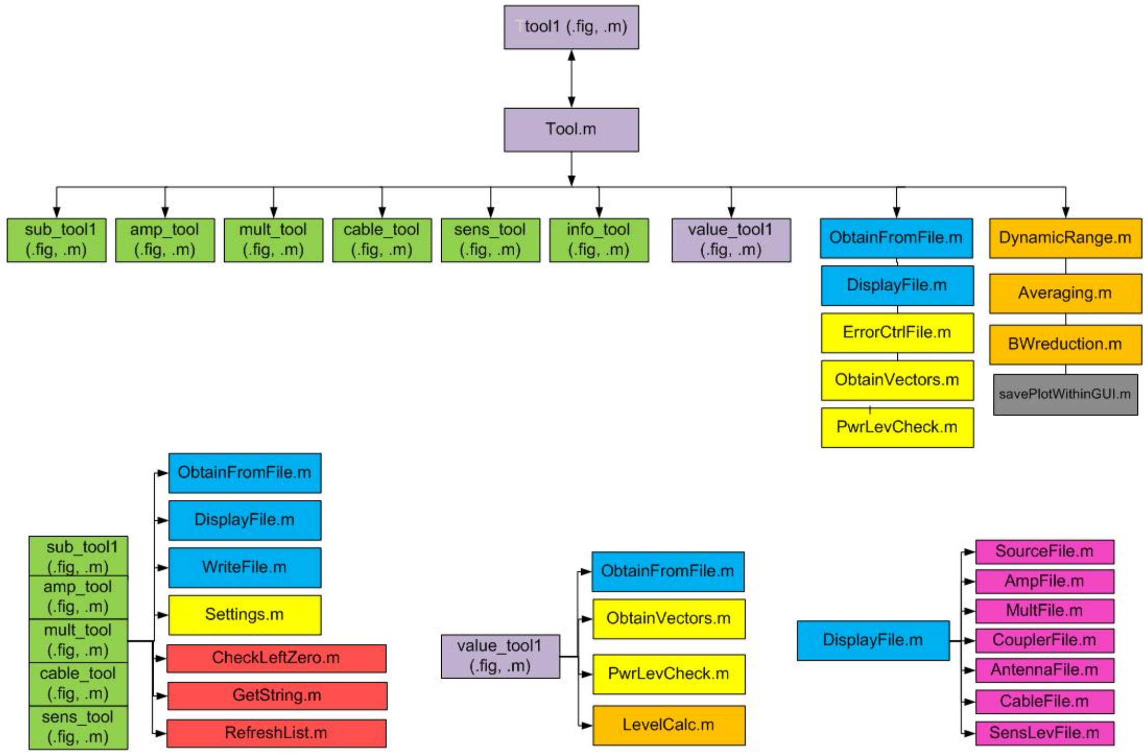


Figure D.1.: Software Tool version 1.0 script hierarchy.

Table D.1.: Software Tool version 1.0 script description.

| **File name** | **Extension** | **Description** |
|---|---|---|
| tool1 | *.fig*,*.m* | Main GUI, *DR* results |
| value_tool | *.fig*,*.m* | Sub GUI, power level calculation |
| Tool | *.m* | Main file |
| sub_tool1 | *.fig*,*.m* | Sub GUI, source settings |
| amp_tool | *.fig*,*.m* | Sub GUI, optional amplifier settings |
| mult_tool | *.fig*,*.m* | Sub GUI, optional multiplier settings |
| cable_tool | *.fig*,*.m* | Sub GUI, cable settings |
| sens_tool | *.fig*,*.m* | Sub GUI, Sensitivity Level settings |
| info_tool | *.fig*,*.m* | Sub GUI, Help environment |
| ObtainFromFile | *.m* | Obtains settings from the file for a given component |
| WriteFile | *.m* | Writes settings in the file for a given component |
| DisplayFile | *.m* | Displays settings file for a given component |
| Settings | *.m* | Introduces new inputs into the parameter vectors |
| ObtainVectors | *.m* | Generates data matrix from parameter vectors |
| ErrorCtrlFile | *.m* | Checks errors in parameter vectors |
| PwrLevCheck | *.m* | Checks interface compatibility in parameter vectors |
| SourceFile | *.m* | Generates Source settings string from file data |
| AmpFile | *.m* | Generates Amplifier settings string from file data |
| MultFile | *.m* | Generates Multiplier settings string from file data |
| CouplerFile | *.m* | Generates Coupler string from file data |
| AntennaFile | *.m* | Generates Antenna string from file data |
| CableFile | *.m* | Generates Cable string from file data |
| SensLevFile | *.m* | Generates Sensitivity Level string from file data |
| CheckLeftZero | *.m* | Eliminates possible left zeros in the input strings |
| GetString | *.m* | Generates string from new input values from the Sub GUI |
| RefreshList | *.m* | Actualizes values in the info string displayed in the Sub GUI |
| DynamicRange | *.m* | *DR* calculation |
| Averaging | *.m* | *DR* with averaging calculation |
| BWreduction | *.m* | *DR* with *BW* reduction calculation |
| LevelCalc | *.m* | Power level calculation file |
| savePlotWithinGUI | *.m* | Allows saving plotted results |

As the software is based on MATLAB® GUI's, or in other words, *.fig* files, these files are linked to its homonym, *.m* extension file. At the same time, these scripts call up other *m*-files in order to calculate the required values. In order to ease software understanding a list of all the files included and required by the program is attached (see table D.1. The way these files are related can be seen in diagram D.1. A brief description of the code and its operation within the program is also done for each *m*-file.

### ***tool1.m***

`function varargout = tool1(varargin)`

This script is self generated when creating the *tool1.fig* MATLAB® figure. This figure is the main GUI and no functions are launched, say executed, from this file, as this is the task performed by the *Tool.m* file.

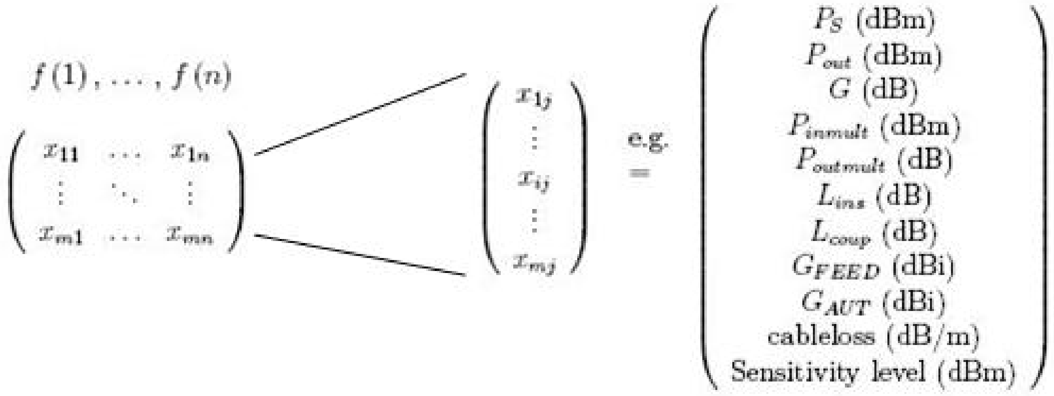


Figure D.2.: Data matrix example for software Tool version 1.0 with $n$ frequency points.

### ***value_ tool.m***

`function varargout = value_tool(varargin)`

This script obtains the concrete power levels for the selected system settings in the main GUI. It works with the same data matrix as the one used in *Tool.m*. But here, it uses a single frequency point in each case, say, a single colummn of the data matrix (see Figure D.2). The functions in this script are described next.

`function value_tool_OpeningFcn(hObject, eventdata, handles, varargin)`

The system configuration is obtained from the main GUI in order to charge the matching schematic picture. Then, all the system settings are obtained from the main GUI or from the corresponding file (*ObtainFromFile.m*) depending on which option is chosen by the user. Afterwards, settings are checked for error by the *ErrorCtrlFile*. All the variables used in this script are global, as they are going to be required by nearly every function. They are defined via the handles structure.

`function valedit1_Callback(hObject, eventdata, handles)`

This is the Callback function for the slider in which the frequency point to calculate is selected. Every time there is a change in the selected frequency value, all the calculated values are refreshed.

Before, in case it is the first time this function is executed, the error flag found in the variable `handles.errorflag` is checked. If an error appears while performing error check for the values set in the main GUI, an error *Msgbox* will show up.

If not, settings are converted into the system's data matrix, which will be generated for the given frequency range (see D.2).
Then, the interface compatibility between parameter vectors check is performed with the *PwrLevCheck.m* file.
Afterwards, *LevelCalc.m* is executed for the selected frequency point, and settings coming from the main GUI, also using the settings found on the current GUI (`handles.att` and `handles.coupling`). In this way, the power levels for a concrete frequency point, say column of the data matrix, are obtained. These values are set on the text windows along the picture of the system.

`function edit2_Callback(hObject, eventdata, handles)`
This function is equivalent to `function valedit1_Callback(hObject, eventdata, handles)`. The code is equivalent, but in this case, it is the calbback function for edit window used for the attenuator's attenuation value (`handles.att`). That means, that every time the attenuation value is changed, power levels on the block diagram will be refreshed.

`function edit3_Callback(hObject, eventdata, handles)`
This function is equivalent to `function valedit1_Callback(hObject, eventdata, handles)`. The code is equivalent but in this case, it is the callback function for edit window used for the coupler's coupling loss value (`handles.coupling`). That means, that every time the coupling loss value is changed, power levels on the block diagram will be refreshed.

`function valexit_Callback(hObject, eventdata, handles)`
This function asks the user for closing confirmation via a Message Box *MssgBox*. If the user chooses to exit this GUI, the figure is closed.

***Tool.m***
`function Tool(action,info)`
This is the main script within the program. It is intended to act as main spine of the flowchart pattern of this tool. From this script all the actions done/coming from the main GUI are managed launching other scripts, sub GUI's or just compiling data for further calculations.
The arguments for the header are:

- `action:` string used as main switch argument between different actions. Default case (no input value assigned to action) takes the `'start'` action.
- `info:` number used only in case `'info'` action is executed. Depending on its value, different information is displayed on the *info_ tool.fig* sub GUI.

While global variables are:

- `ctrl:` struct variable containing all handles of all objects in the main GUI.
- `f:` vector containing set frequency range for which the *DR* and power level calculation is going to be done.

- `current_plot:` variable set to 0 when there is no plot pictured. If there is one, it contains the handle number of the current plot. It helps out to administrate plot refreshing actions.

The programming philosophy in this script is based on a switch which will execute different actions, depending on what action is performed on the main GUI. The cases are listed next:

- `case 'start':` Main figure of the program is opened and its handles are obtained and saved into the ctrl struct variable. Axes for the future plot are labeled, sized and initialized. X-axis is set to its default value and will be adjusted in a later point of the program once the frequency range is chosen.
  Global variables are initialized. `current_plot` is set to 0.
  The `ctrl.displaypanel`, in which information concerning the components is displayed on the Main GUI *tool1.fig*, is initialized with its title.
  Also the images are obtained/charged on the GUI.

- `case 'refresh':` This action is executed every time any of the determinant parameters for the plot object are changed. Basically, these parameters are the start and stop frequencies.
  If there is already a plot, it is erased. Then, the new frequency vector
  `f = linspace(start_freq, end_freq)` is determined. Finally, according to this vector, the x-axis is refreshed.

- `case 'sub':` Action executed every time the pushbutton *'Set source power'* is pushed (callback function for this pushbutton). It is the way to execute the sub GUI which will obtain the `.txt` file with the source power setting. Executing this GUI means overwriting possible already existing settings.
  First, a message box (*Msgbox*) shows up asking if the possible current settings should be overwritten. If *'Yes'*, *sub_ tool1.m* is executed. If *'No'*, an equivalent code fragment to `'seesource'` case is executed.

- `case 'seesource':` Callback function for pushbutton *'See values'* found in the source subpanel on the main GUI. This action overwrites the information on the displaypanel and shows the settings, in this case, for the source (input argument for *DisplayFile.m* file/function is *'Source'*). It actualizes the string of the displaypanel via the `function display = DisplayFile(liststring,input)` found in *DisplayFile.m.*

- `case 'amp':` Action executed every time the amplifier checkbox is activated or deactivated. If it is activated, it will execute the sub GUI which will obtain the `.txt` file with the amplifier settings. Executing this GUI means overwriting possible already existing settings. First, the system schematic shown in the main GUI is actualized. New picture will include amplifier or not.
  Then, a *Msgbox* shows up asking if the possible current settings should be overwritten. If *'Yes'*, *amp_ tool.m* is executed. If *'No'*, an equivalent code fragment to `'seeamp'` case is executed.

- `case 'seeamp':` Callback function for pushbutton *'See values'* found in the amplifier subpanel on the main GUI. This action overwrites the information on the display panel and shows the settings, in this case, for the amplifier (input argument for *DisplayFile.m* file/function is *'Amp'*). It actualizes the string of the displaypanel via the `function display = DisplayFile(liststring,input)` found in *DisplayFile.m*.
- `case 'mult':` This case is equivalent to the amplifier's case, but applying for the multiplier. In this case *mult_ tool.m* is executed.
- `case 'seemult':` This case is equivalent to the amplifier's case but applying for the multiplier. In this case, the input argument for the *DisplayFile.m* file/function is *'Mult'*.
- `case 'loadcoup':` When it is selected by the user to load coupler settings from file or not (Callback function for radio button *'Load from File'* found in the coupler subpanel in the main GUI), the edition window on the GUI is enabled or disenabled. The plot display and the information on the display panel in the main GUI are actualized.
- `case 'loadfeed':` This case is equivalent to the coupler's case but applying for the feed settings.
- `case 'loadaut':` This case is equivalent to the coupler's case, but applying for the AUT settings.
- `case 'seerxtx':` Callback function for pushbutton *'See'* found in the coupler subpanel in the main GUI. Displays on the main GUI's display panel the setting for the coupler, feed and AUT plus the free-space loss for the selected frequency range extremes.
- `case 'cable':` This case is equivalent to the source's case, but applying for the cable loss settings. In this case *cable_ tool.m* is executed.
- `case 'seecable':` This case is equivalent to the source's case but applying for the cable loss settings.In this case, input argument for the *DisplayFile.m* file/function is *'Cable'*.
- `case 'sens':` This case is equivalent to the source's case but applying for the Sensitivity Level settings. In this case *sens_ tool.m* is executed.
- `case 'seesens':` This case is equivalent to the source's case, but applying for the Sensitivity Level settings. In this case, input argument for the *DisplayFile.m* file/function is *'Sens'*.
- `case 'snr':` Actualizes plot display in the main GUI when user refreshes the Signal to Noise SNR value.
- `case 'plot':` Callback function for pushbutton *'Plot'* found in the main GUI. Settings for each component are obtained through the *ObtainFromFile.m* file or directly from the GUI. This choice depends on the component and the options chosen by the user.

Then error check is performed for these settings executing *ErrorCtrlFile.m*.
Afterwards, data matrix is generated for the given frequency range and the given parameter vectors executing the *ObtainVectors.m* file.
Then, the interface compatibility between parameter vectors check is performed with the *PwrLevCheck.m* file.
Finally, if all the checks are correctly passed, *DynamicRange.m* is executed and results plotted on the display. If the corresponding options are chosen, *Averaging.m* and *BWreduction.m* are also executed.

- `case 'avg'`: Actualizes plot display in the main GUI when user refreshes the number of averages value. An error *Msgbox* is displayed if the introduced value is not a valid number.
- `case 'bw'`: Actualizes plot display in the main GUI when user refreshes the IF bandwidth value. An error *Msgbox* is displayed if the introduced value is not a valid number.
- `case 'value'`: First, it is checked that the selected frequency range is correct. Say, no 0 or not consistent values. Then the *value_tool.m* is executed.
- `case 'info'`: Callback function for pushbutton *'Help'* found all over the program. It launches *info_tool.m* with the corresponding information. The information is defined by the `info` variable and this value will depend on the point of the program the callback function has been executed, say, what type of help is required. The required information is obtained from a `.txt` file where the instructions are found.
- `case 'save'`: Callback function for menu option *'Save plot'* to the format chosen by the user.
- `case 'exit'`: Callback function for pushbutton *'Exit'*. In this case, *Msgbox* shows up asking user for exiting confirmation. If *'Yes'* is chosen, the program will close all figures.

***sub_tool1.m***

`function varargout = setsourcepower(varargin)`

This *m*-file corresponds to the sub GUI *sub_tool-fig.* Through this
mboxGUI the user introduces settings corresponding to the source. In this case, the global variables are defined via the handles structure.
For this script, the programming philosophy is based on callback functions. For any item found in a GUI, e.g. button, edit window, etc. a callback function can be programmed. This function will be launched when the user acts on the item. The functions found in the script are listed next.

`function sub_tool1_OpeningFcn(hObject, eventdata, handles, varargin)`
In this function struct variable containing all handles of all objects in the main GUI is obtained. Then, additional global variables are defined and initialized. These global variables are:

- `handles.power:` Is the vector containing the output power levels for the source. It is initialized to 0.
- `handles.frequencies:` Is the vector containing the $n$-th maximum frequency for which the source reaches the output power defined in the $n$-th position of the `handles.power` vector.
- `handles.counter:` Is a variable containing the position on the vectors to be edited next.
- `handles.prevfreq` and `handles.prevpwr:` These variables are used to save values to be compared with new values and determine if there has been a setting update/correction.

Settings are also done in order to allow button activation via hot keys.

`function set_Callback(hObject, eventdata, handles)`
Callback function for pushbutton *'Set'*. In this function it is checked that there is data in the edit windows. If this data has been edited by the user, these string variables are converted into double values to later introduce them into the parameter vector.
Additionally, the string values are saved before conversion (`freqStr`, `pwrStr`) in order to add them to the display element on the GUI.
Then, it is checked if it is the first time that this `handles.counter` position has been edited, say that it is not the case of a correction.
If it is the first time the position is edited, the string to display with the new values has to be created. This is done with the *GetString.m* function. Before, the already saved string format values (`freqStr`, `pwrStr`) are checked for possible left zeros and if it is the case, these are erased (*CheckLeftZero.m*). Afterwards, the new string is added to the display aid on the GUI.
Else, if that position has been already edited, the display aid's string array is actualized (*RefreshList.m*).
Then, the new values are introduced in the parameter vectors executing the *Settings.m* file.
Finally, the `handles.counter` value is updated.

`function previous_Callback(hObject, eventdata, handles)`
Callback function for pushbutton *'Previous'*. This routine is used to select previous edited positions. By doing this, it allows the user to correct already introduced values. The `handles.counter` is decreased and 'old' values are saved in `handles.prevfreq` and `handles.prevpwr` variables. In this way, it can be checked if actualizing the list is required once the user selects setting these new values.

`function srcload_Callback(hObject, eventdata, handles)`
Callback function for the radio button *'Load from file'*. It allows the user to take settings directly from a `.txt` file. These settings are obtained from the corresponding file executing *ObtainFromFile.m*.
Then it is checked if there are settings on the file.
If there are settings, these are the ones introduced into the `handles.frequencies` and `handles.power` vectors. The new string array is also created for the display aid found in the GUI executing *GetString.m*.

`function srcclear_Callback(hObject, eventdata, handles)`
Callback function for the pushbutton *'Clear list'*. This one will clear the display aid found in the GUI in order to let the user start introducing new values from the beginning. That is why here, `handles.counter` is set to the initial value 1.

`function finish_Callback(hObject, eventdata, handles)`
Callback function for the pushbutton *'Finish'*. In this routine, the edited data is written on the matching `.txt` file. In this case, the *Source.txt* file (*WriteFile.m*).
If file writing has been successful, the new settings are displayed on the main GUI. Else error *MsgBox* will appear, plus an error message on the MATLAB® prompt. Finally, the sub GUI is closed.

`function hotKeyfunct(src,evnt)`
This part of the code associates a key to a concrete callback function. In this case, it executes the callback for the *'Set'* pushbutton by pressing the enter key.

***amp_ tool1.m*, *mult_ tool1.m*, *cable_ tool1.m*, *sens_ tool1.m***

```
function varargout = amp_tool(varargin)
function varargout = mult_tool(varargin)
function varargout = cable_tool(varargin)
function varargout = sens_tool(varargin)
```

These *m*-files correspond to the homonym *fig*-file. Their code is equivalent to code found in *subtool.fig* but adapted to each of the components.

***info_ tool.m***

`function varargout = info_tool(varargin)`
This file corresponds to the sub GUI *info_ tool.fig*. This one will appear any time a *'Help'* pushbutton is activated. It will show a string in order to act as help tool within the program. The switching between different helping cases is done from the *Tool.m* file. The GUI is called also from this last file.

***ObtainFromFile.m***

`function [matrix] = ObtainFromFile(component)`
Through this script, component settings already found on a file can be obtained. Depending on the selected `component` value, one or another path and name are used to open the file.
If the file could be opened successfully, the settings for the given component are read

and saved into a matrix. In this matrix, every row corresponds to a frequency point while every column stands for a different attribute of the component.
As the number of attributes varies from one component to another, a switch is done with the `component` parameter in order to adapt `matrix` size to the component characteristics.

***WriteFile.m***
`function SP = WriteFile(paramatrix,component)`
Following the pattern used in the scrip described above, this file will open one or another path depending on the component chosen.
It will write down the values found in the `paramatrix`. Once the file has been written, this one is closed.
`SP` acts as an error indicator in case an error is produced while file opening, writing or closing.

***DisplayFile.m***
`function display = DisplayFile(liststring,input)`
This function generates a string from values coming from a concrete component. `liststring` contains the string array already displayed on the information panel. Depending on the component selected through `input` variable, the function opens the corresponding file, reads the values and closes the file. Then it is checked if the file is empty or not.
If the file is empty, `'No settings'` will be the new string to show.
Else, depending on the component a new type of string is generated through the matching *m*-file. For instance, if multiplier settings are to be displayed, the *MultFile.m* will be executed (see table D.1).
Finally, it is checked if there is already displayed data on the display, say in `liststring`, in order to correctly introduce it in the string array.

***Settings.m***
`function [outputvector] = Settings(paramvector,counter,inputvector)`
This function is called when new input values coming from the GUI, (`inputvector`), must be inserted into the corresponding parameter vector.

***ObtainVectors.m***
`function [f,n,Mastervec] = ObtainVectors(f,srcmatrix,ampmatrix,multmatrix, coupler,coupling,feed,aut,cablematrix,sensmatrix)`
This file will generate the global system data matrix (`Mastervec`) from the parameter vectors for each system component. It will take the discrete frequency range `f` and generate a matrix in which every column is a point of the frequency span and every row corresponds to a value or setting required for the calculation (Figure D.2).
The number of points used to define the frequency span is set to 100. Nevertheless, if there is a component setting with more defined frequency points, this will be the new number of discrete points. This value is returned through the `n` variable.

***ErrorCtrlFile.m***

`function [errorstr, errorflag] = ErrorCtrlFile(f,srcmatrix, ampmatrix,ampcheck,multmatrix,multcheck,coupler,feed,focal,aut, cablematrix,distance,sensmatrix,snr)`

This file checks possible errors found in the parameter vectors. It indicates if there is an error through the `errorflag` and indicates the type of error returning the `errorstr` variable. Every time an error is found the function actualizes the output variables and finishes execution.

First, it is checked if there is a frequency range value conflict with `f`. If not, the next check is performed.

Second, it is checked that no variable, say parameter vector is empty. If it is not the case, next check is performed.

Third, it is checked that no negative distances or SNR values have been introduced.

Finally, the frequency compatibility check is performed in order that no component is out of range. Also that components frequency ranges match between them is proved.

Additionally, if any error is found, an error *Msgbox* will show up.

***PwrLevCheck.m***

`function [powerstr,powerflag] = PwrLevCheck(f,Mastervec,focal,distance,att)`

This function checks interface compatibility between components, focused on the optional multiplier found in the system, since this component is the one which mostly requires correct power feeding for proper operation. In this file the frequency range is scanned point by point. For each point, losses regarding distance, as cable loss, are calculated. Then, it is evaluated if the settings found in the input variables match the component requirements specified in `Mastervec`. It indicates if there is a warning through the `powerflag` and it indicates the type of warning or power level incompatibility returning the `powerstr` variable. Every time an incompatibility is found, the function actualizes the output variables but does not finishes execution.

***SourceFile.m**, **AmpFile.m**, **MultFile.m**, **CouplerFile.m**, **AntennaFile.m**, **CableFile.m**, **SensLevFile.m***

```
function [newstring] = SourceFile(col1,col2)
function [newstring] = AmpFile(col1,col2,col3)
function [newstring] = MultFile(col1,col2,col3,col4,col5)
function [newstring] = CouplerFile(col1,col2,col3,col4)
function [newstring] = AntennaFile(col1,col2,col3)
function [newstring] = CableFile(matrix)
function [newstring] = SensLevFile(col1,col2)
```

These files are used by the *DisplayFile.m* function to generate the components corresponding string. This string will be displayed in order to let the user know which settings are set for that component.

***CheckLeftZero.m***

`function [outstring] = CheckLeftZero(instring)`

This function eliminates possible zeros that can be introduced by the user when typing the desired values along the program. The typed data is used always twice by the program. On the one side, to convert the data to numerical format in order to use it in the calculations. On the other sied, as a string variable to display to the user. This second case is when the need to erase possible zeros on the left shows up. For the first case it is not required, as the math program manages this circumstance by itself.

***GetString.m***
`function [STR] = GetString(string,component,inputvector)`
Similar to the *SourceFile.m*, *AmpFile.m*,etc, this file generates strings to display. But in this case, these values are obtained directly from an edit window instead of coming from a file `inputvector` and they are added to a string array coming from a display aid found in the corresponding sub GUI.

***RefreshList.m***
`function [newlist] = RefreshList(list,counter,`
`component,oldvaluesvec,newvaluesvec)`
This function has the same function as *GetString.m* but in this case, it actualizes values and strings in a list, instead of simply adding it.

***DynamicRange.m***
`function [DR] = DynamicRange(f,Mastervec,focal,distance,snr)`
This is a classical MATLAB® function which calculates the *DR* as exposed in chapter 4. It calculates the value for all over the defined frequency range, `f`, using the settings found in `Mastervec`. Additional information for free-space loss and cable loss calculation is found in `focal` and in `distance`. The required SNR is also given through the input variable `snr`.
The result of executing this function will be a $n$-point vector plotted in the main GUI.

***Averaging.m***
`function outdr = Averaging(indr, avg)`
This function calculates the effect of averaging on the DR.

***BWreduction.m***
`function outdr = BWreduction(indr,bw)`
This function calculates the effect of IF bandwidth reduction on the DR.

***LevelCalc.m***
`function [ValueVector] = LevelCalc(f,Mastervec,multvalue,focal,distance,att)`
This is a classical MATLAB® function which calculates the power levels for the critical system points. It calculates the value for a selected point belonging to the defined frequency range, `f`, using the settings found in `Mastervec`. Additional information for free-space loss, cable loss calculation and attenuation before the reference mixer is found in `focal`, `distance`, and `att`.

### *savePlotWithinGUI.m*

`function savePlotWithinGUI(axesObject, legendObject)`

This function allows saving plotted data on the *DR* to *.emf*, *.bmp*, or *.fig* file. Function extracted from [45].

# List of Figures

# List of Tables

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