

GENERATION OF RADAR SIGNALS FOR MULTI-ANTENNA RECEIVERS

Products:

- ▶ R&S®SMW200A
- ▶ R&S®SMA100B
- ▶ R&S®Pulse Sequencer RF software
- ▶ R&S®RF Ports Alignment software
- ▶ R&S®ZNA
- ▶ R&S®ZNB
- ▶ R&S®RTP
- ▶ R&S®RTO

Florian Gerbl | 1GP | Version 0E | 12.2021

<https://www.rohde-schwarz.com/appnote/1gp125>

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1 Overview

EW receivers are tested in the lab at RF to discover problems before flight testing. This eliminates cost and schedule risk. Flight testing can cost tens of thousands of dollars per hour and must be scheduled many months in advance. In contrast, using test equipment to test at RF might require a certain upfront cost but provides a readily-accessible capability to simulate radar threats at RF for a long time. This application note explains how the angle-of-arrival (AoA) capabilities of EW receivers can be tested with commercial off-the-shelf (COTS) RF test equipment. Topics covered are the generation of scenarios, instrument setup, and setup calibration. We will use a radar warning receiver (RWR) as a proxy for a generic EW receiver in this application note.

2 Background

A radar warning receiver (RWR) must be able to find the direction of a threat. This is done by estimating the angle of arrival (AoA) of a signal that is emitted by a threat. An RWR has multiple receive ports. The receive ports are connected to different antennas that may have different locations and orientations.

A signal that is emitted by a threat arrives at the antennas at different times and from different angles. Amplitude, time and phase differences between the signals carry information about the AoA. In the presence of multiple threats, the RWR needs to sort the emitters based on their radiated signals. The AoA is the primary sorting parameter. Therefore, testing the RWR's capability of estimating the AoA is a must.

Testing may cover various layers - from RF hardware to algorithms. RF signals can be provided to the device under test (DUT) over the air (radiated) or using cables (conducted).

This application note is focused on conducted test cases, and on how to generate multiple RF signals in order to test the direction finding capabilities of RWRs. Figure 1 shows the basic idea of the Pulse Sequencer RF software and SMW200A vector signal generators acting as a radar simulator. This R&S radar simulator provides the RWR under test with signals that it would otherwise receive in a real-world scenario. This approach is very flexible, and it gives you full control over the scenario. You can easily modify and refine the scenarios as required throughout the development cycle of the RWR.

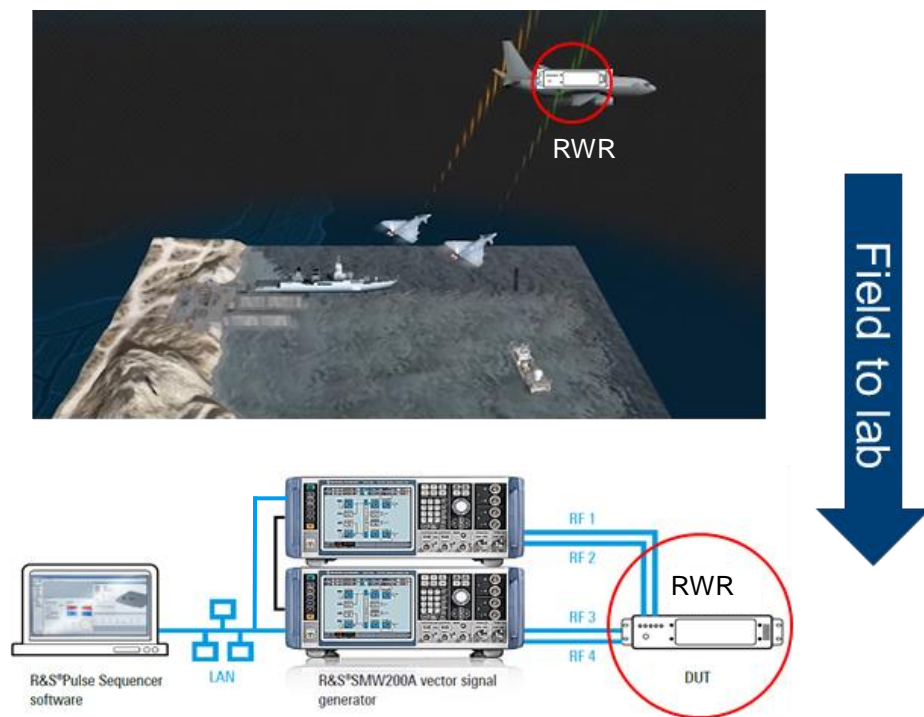


Figure 1: The R&S Pulse Sequencer RF software together with R&S SMW200A vector signal generators provides the RWR under test (circled in red) with signals as if the RWR was operated in a real-world scenario.

3 Organization of this application note

Instead of placing the RWR and its antennas in a real RF environment during expensive flight tests (Figure 2),



Figure 2: RWR under test in a real RF environment

we can define the desired scenario in the R&S Pulse Sequencer RF software (Figure 3),

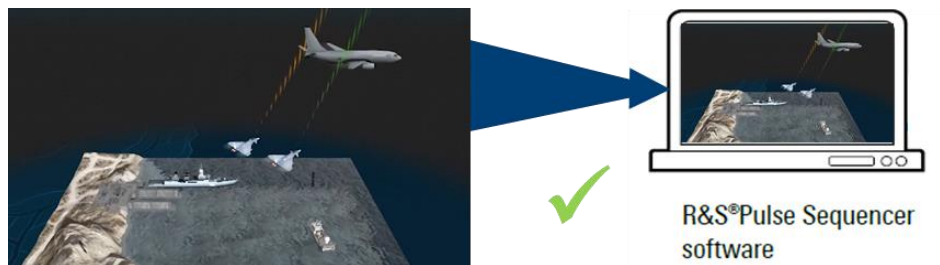


Figure 3: Modeling the scenario in R&S Pulse Sequencer RF software

generate the corresponding RF signals using R&S vector signal generators with a number of RF paths, and inject these signals into the receiver ports of the RWR (Figure 4).



Figure 4: Simulating a real world RF environment in the lab

A very important step is the calibration of the setup to make sure the signals have the desired time, amplitude and phase relation at the input ports of the RWR (Figure 5).



Figure 5: Making sure the signals are aligned at a defined reference plane

Thus, this application note covers the topics

- ▶ Defining the scenario using R&S Pulse Sequencer RF software (s. section 5)
- ▶ Setting up the instruments (s. section 6)
- ▶ Calibrating the setup. Why and how? (s. section 7)
- ▶ Testing the DUT (s. section 8)

In case you want to use your own scenario simulator instead of Pulse Sequencer RF software, the SMW200A is a perfect fit as well. In this case, software options (SMW-K503, SMW-K504) activate high performance PDW streaming interfaces in the SMW200A. You might want to read application note [1] first and then proceed with section 6 of this application note.

4 Direction Finding Principles

Direction finding (DF) receivers can have one or multiple receive ports. Depending on the number of receive ports, different methods are used to determine the direction of arrival of a signal.

We focus on multi-port receivers.

The receive ports are connected to different antennas that may have different locations and orientations.

A signal emitted from a certain direction arrives at the antennas at different times, from different angles and with different amplitudes, e.g. depending on the directivity of the antennas.

Amplitude, time and phase differences between the signals carry information about the angle of arrival (AoA) and thus they can be used for direction finding.

Well-known DF techniques are:

- ▶ Amplitude monopulse
- ▶ Time difference of arrival (TDOA)
- ▶ Interferometry

Multiple techniques can be used in combination within one receiver.

The following sections describe how to create Pulse Sequencer RF scenarios that contain the necessary amplitude, time and phase differences between the individual ports, and how to set up and calibrate the instruments according to the requirements of the DUT.

5 Defining the scenario using R&S Pulse Sequencer RF software

The R&S Pulse Sequencer RF software is a powerful radar simulation software. There are lots of resources on how to use it at [2]. This application note comes with several R&S Pulse Sequencer RF examples (requires software version 2.3 or higher) that may serve as starting points for your own application.

Make sure R&S Pulse Sequencer RF (available for download free of charge from [2]) is installed on your PC.

In order to open one of the examples in Pulse Sequencer RF, go to File -> Import Repository Archive... (or simply double-click on the file in Windows Explorer) and follow the instructions.

In each of the following examples, there is a receiver placed right in the origin of a map. This receiver is a placeholder for your RWR under test (Figure 6).

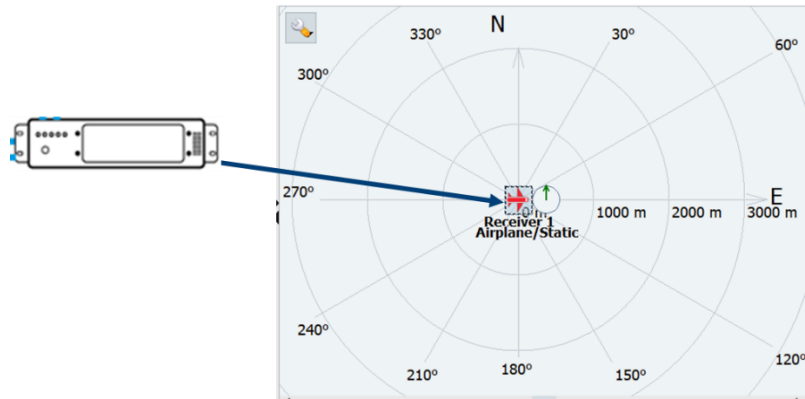


Figure 6: The receiver on the map is a placeholder for the RWR under test

The receiver can be static or following a trajectory, and there can be one or more static or moving emitters. The receiver can have a number of ports and antennas with individual positions, attitudes and patterns.

The Pulse Sequencer RF software automatically calculates the signals pulse by pulse that each of the receiver's ports would receive based on the distance between emitter and receiver, their relative attitudes and the antenna patterns.

Generating these signals with a setup of signal generators according to section 6 that has been calibrated according to section 7 will provide your RWR under test with the signals that it would receive in the real environment that you have modelled in the Pulse Sequencer RF software.

In order to get the most realistic timing differences between the ports, which are most important in TDOA based DF algorithms, you have to select the receiver model "TDOA". For most realistic phase differences, which are important for interferometric techniques, you have to choose the receiver model "Interferometer".

5.1 Example 1: Static receiver, one static emitter

Scenario 1 contains one **static receiver** and one **static emitter** (Figure 7).

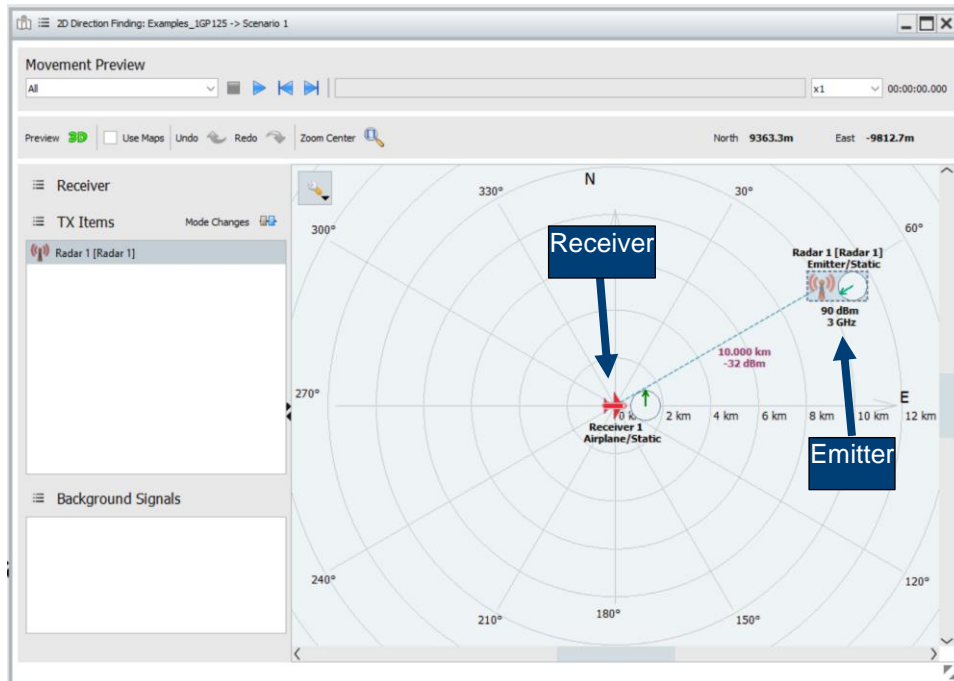


Figure 7: Locations of receiver and emitter

The emitter is placed at a relative bearing of 60° in a distance of 10 km from the receiver.

The receiver has four antennas attached to it. They have cardioid patterns with a half power beam width (HPBW) of 78°. The angular spacing between two adjacent antennas is 90° in azimuth (Figure 8).

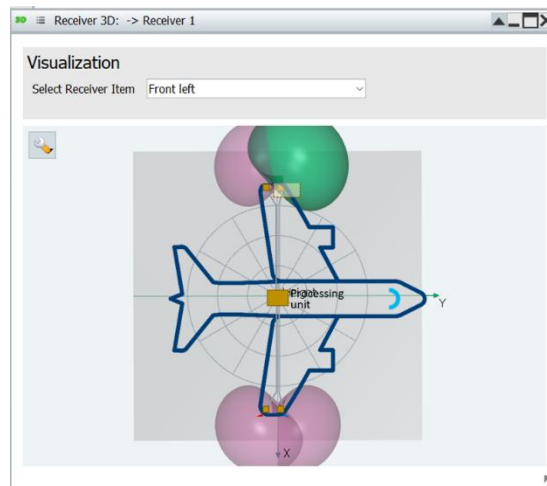


Figure 8: Screenshot of Pulse Sequencer RF with the defined antenna patterns and an aircraft overlaid.

The antenna configuration is based on a typical antenna distribution on an aircraft. It might be used for amplitude monopulse or TDOA direction estimation or a combination thereof.

The signals that the receiver would receive at its ports are calculated by clicking on the "Calculate" button (Figure 9). Make sure multithreading is enabled in order to speed up calculation. This is done at Signal Calculation -> Config -> Output -> Optimize Calculation Speed -> Enable multithreading.

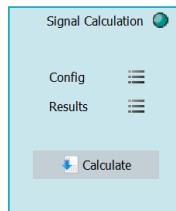


Figure 9: Button for starting signal calculation

The parameters of the resulting pulses per receiver port and emitter can be displayed by clicking on Signal Calculation -> Config -> View and choosing the desired combination of receiver port and emitter - in this case the receiver port "Front left" and the emitter "Radar 1" (Figure 10).

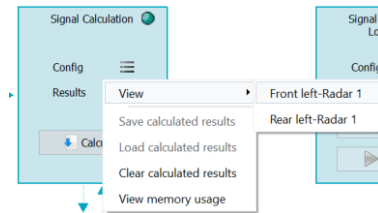


Figure 10: How to view results of the calculation

The parameters can be displayed graphically or as a table as shown in Figure 11.

Signal Preview: Examples_1GP125/Scenario 1(Front right - Radar 1)

Navigation: Start position 0 s, Cursor position 0 s

Display: Ant.-Emit.: Front right - Radar 1

Range: 200 us, 11 visible / 11 total

	TOA	Level	PW	Freq	Phase	Type	MOP	Param	Marker[4321]
1	0.000 000 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011
2	0.000 020 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011
3	0.000 040 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011
4	0.000 060 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011
5	0.000 080 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011
6	0.000 100 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011
7	0.000 120 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011
8	0.000 140 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011
9	0.000 160 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011
10	0.000 180 000 000 s	0.00 dB	1 us	0 Hz	209.56	Real time	UNMOD		0011

Figure 11: Table showing pulse parameters

The scenario can easily be modified to meet the needs of your application.

How to stimulate your DUT with signals from the scenario is described in sections 6 ff.

5.2 Example 2: Static receiver, one emitter moving along a line

This scenario is very similar to the previous one. The main difference is that it has a **moving emitter** instead of a static one. The trajectory is a line. You can see a preview of the movement (Figure 13) of the emitter by clicking on the play button (Figure 12).

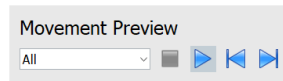


Figure 12: Click on the blue triangle to start the preview

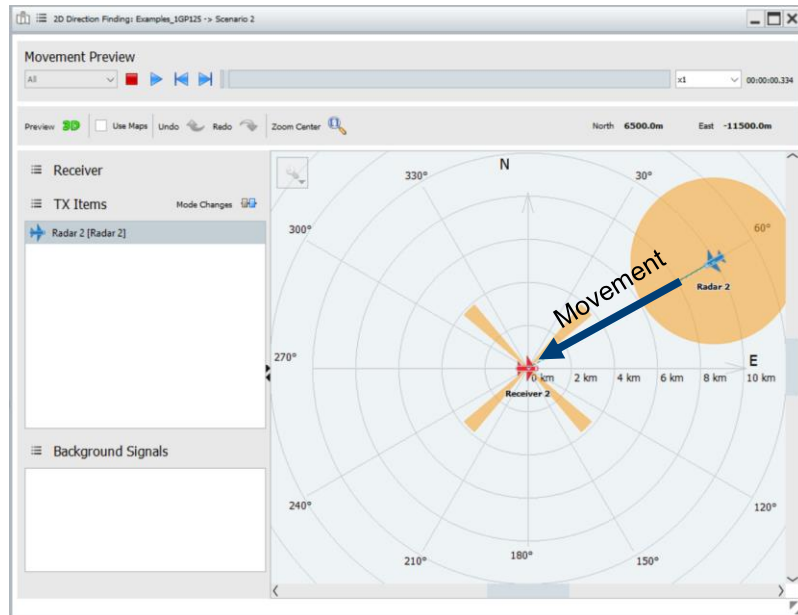
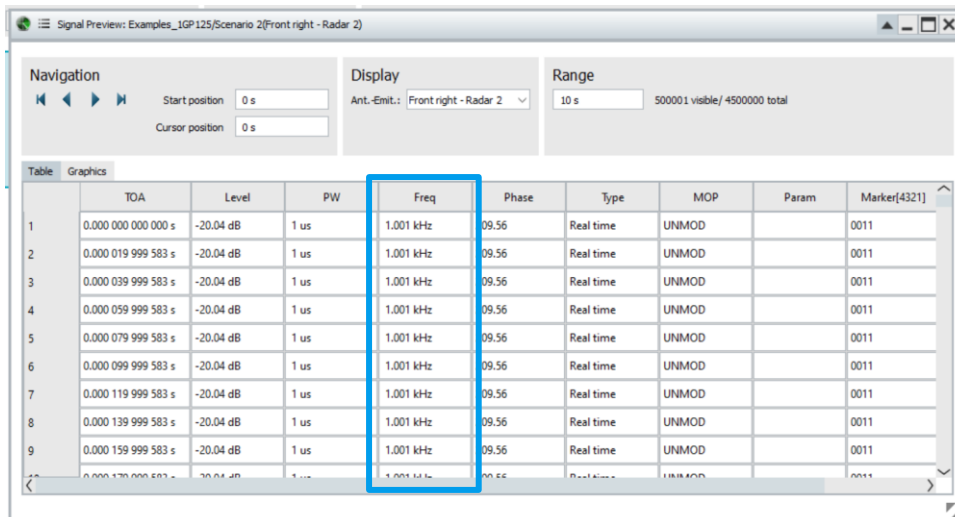


Figure 13: Movement of the emitter on a straight line towards the receiver

Since the emitter is moving, the received signals will be Doppler shifted. You can check the Doppler shift in the result table (Figure 14). Note, however, that in case of multiple emitters with different frequencies, the offset frequencies in the result table contain both the emitter's frequency offset from the scenario's center frequency and the Doppler shift. The displayed level (in dB) is just a relative value. It is not an absolute level in dBm.



	TOA	Level	PW	Freq	Phase	Type	MOP	Param	Marker[4321]
1	0.000 000 000 000 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011
2	0.000 019 999 583 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011
3	0.000 039 999 583 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011
4	0.000 059 999 583 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011
5	0.000 079 999 583 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011
6	0.000 099 999 583 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011
7	0.000 119 999 583 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011
8	0.000 139 999 583 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011
9	0.000 159 999 583 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011
10	0.000 179 999 583 s	-20.04 dB	1 us	1.001 kHz	09.56	Real time	UNMOD		0011

Figure 14: Table showing pulse parameters, in particular the frequency offsets

How to stimulate your DUT with signals from this scenario is described in sections 6 ff.

5.3 Example 3: Static receiver, one emitter moving along an arc

This scenario is very similar to the previous one. The main difference is that the emitter **moves along an arc** with radius 10 km around the receiver (Figure 15).

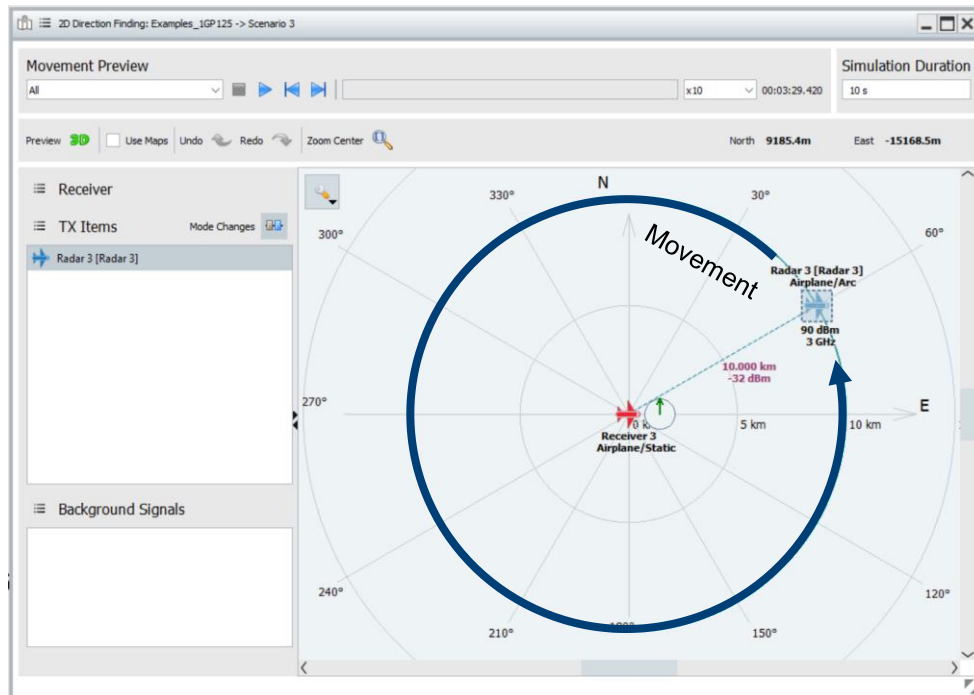


Figure 15: Movement of the emitter on an arc around the receiver

There is a 3D preview available (Figure 16)

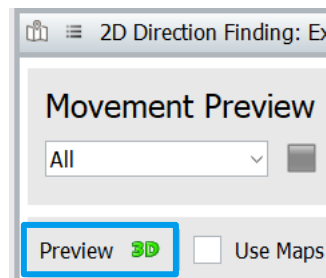


Figure 16: Access to the 3D preview

that even shows the amplitude of the chosen signal as the emitter moves around the receiver (Figure 17).

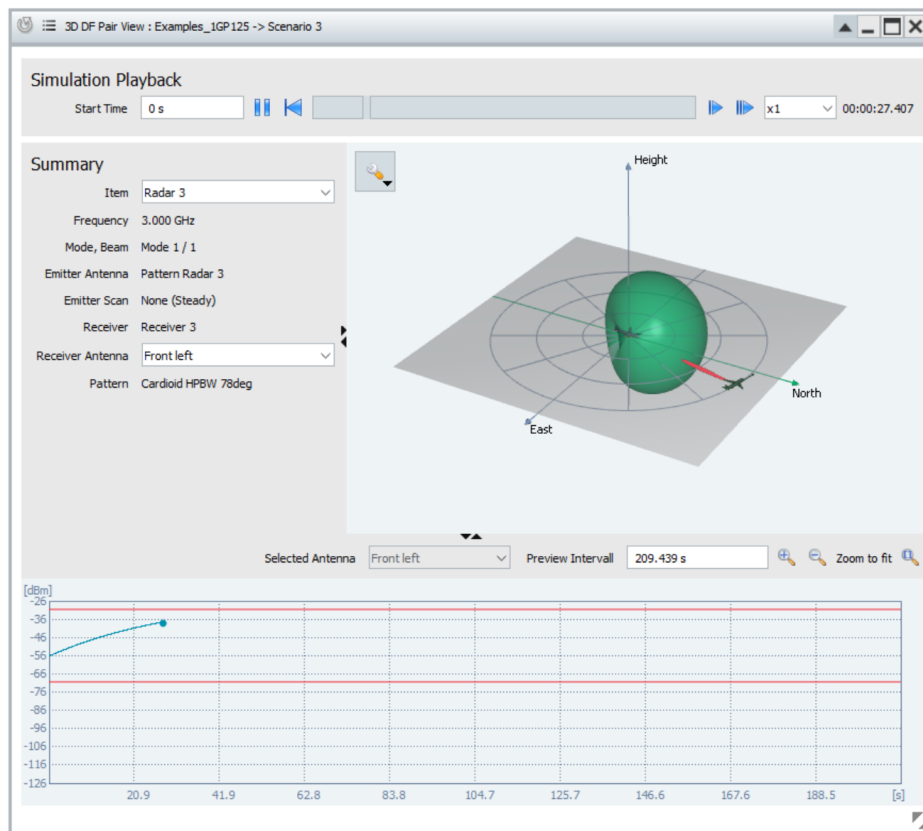


Figure 17: The plot on the bottom shows the amplitude of the received signal as emitter moves along its trajectory

How to stimulate your DUT with signals from this scenario is described in sections 6 ff.

5.4 Example 4: Static receiver with closely spaced antennas, one emitter moving along an arc

This scenario is very similar to the previous one. The main difference is that the receiver has a **uniform linear antenna array** with an element spacing of 50 mm according to half a wavelength at 3 GHz (Figure 18). This array might be used together with an interferometric DF algorithm.

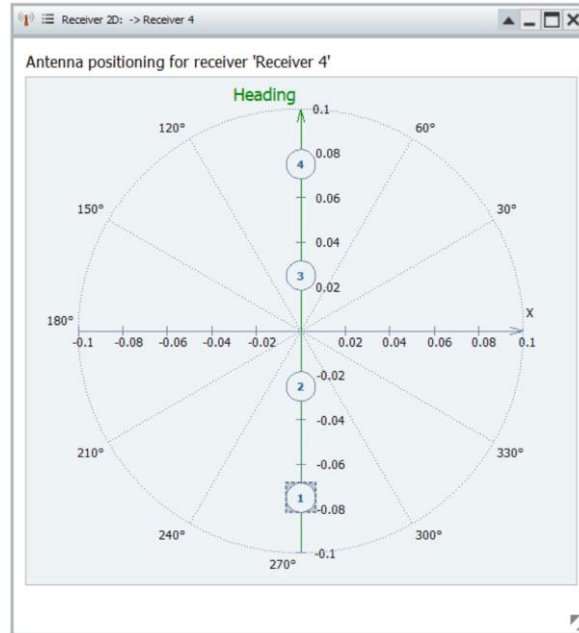


Figure 18: Locations of the antennas, indicated by the numbers 1, 2, 3 and 4 (circled)

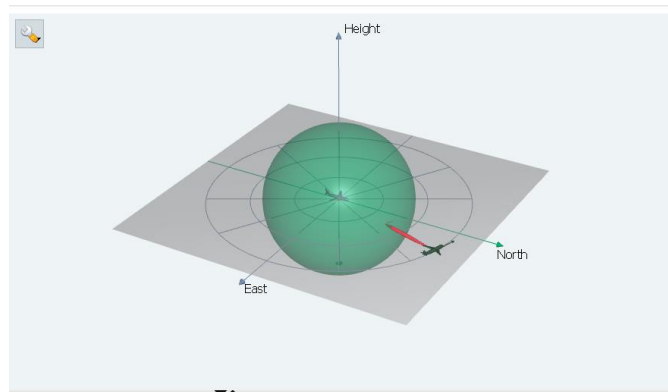


Figure 19: 3D preview of one antenna pattern

As the emitter moves around the receiver (Figure 19), the phases of the signals at the receiver inputs and also the phase differences between the receiver inputs change (Figure 20, Figure 21).

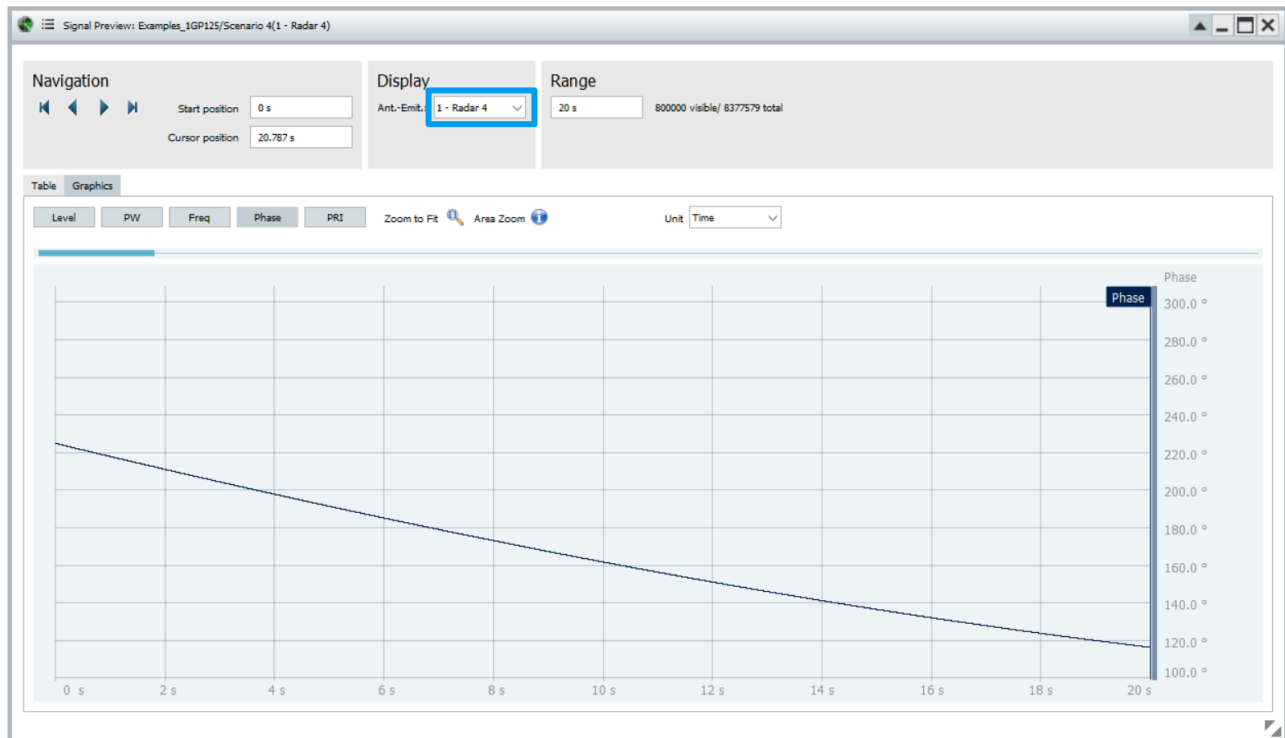


Figure 20: Phase of the signal at antenna 1 versus time as the emitter ("Radar 4" of Pulse Sequencer example Scenario 4) moves along its trajectory

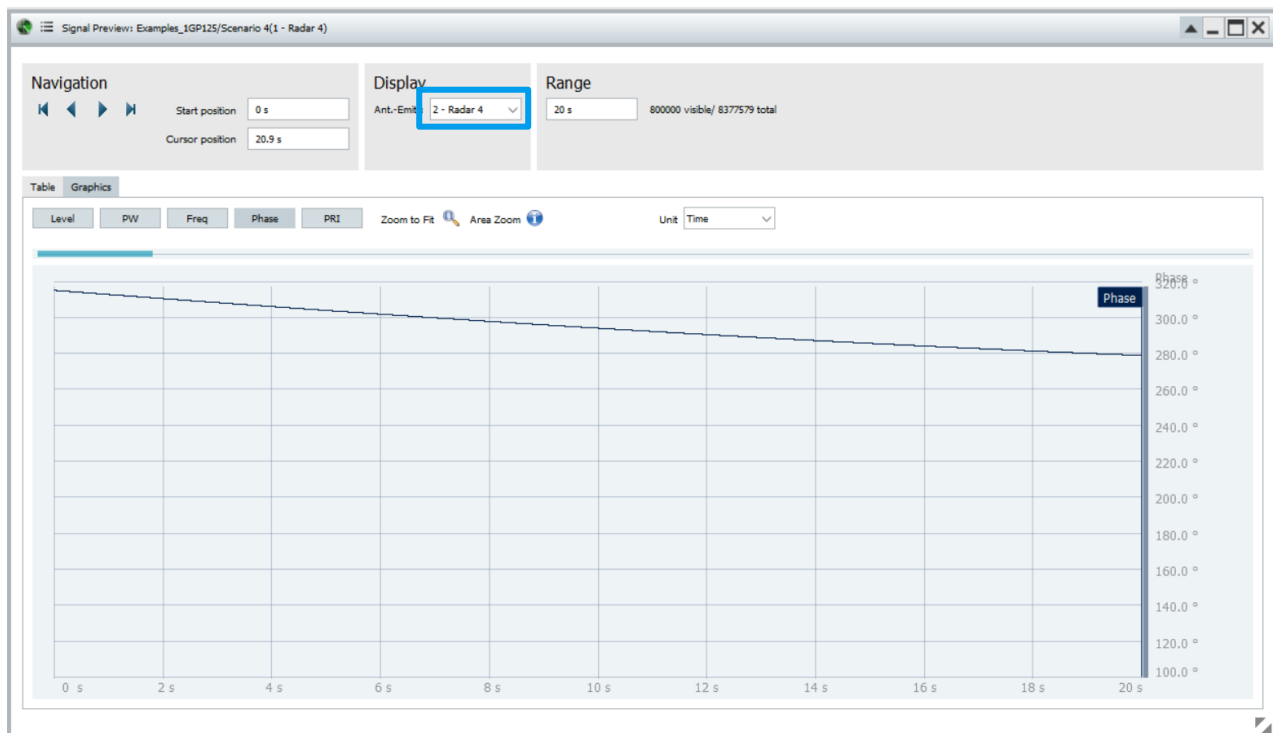


Figure 21: Phase of the signal at antenna 2 versus time as the emitter ("Radar 4" of Pulse Sequencer example Scenario 4) moves along its trajectory

The phase differences between the signals carry information on the angle of arrival. Therefore, these signals can be used to test interferometric receivers.

How to stimulate your DUT with signals from this scenario is described in sections 6 ff.

5.5 More complex scenarios

Scenarios needed for testing can be more complex than shown in the previous examples. The Pulse Sequencer RF software offers a lot more features and possibilities in order to bring reality into the lab. A few examples.

- ▶ The receiver can be moving as well.
- ▶ There can be hundreds of emitters with hundreds of different modes.
- ▶ PDW lists containing custom PDWs from real emitters can be imported and assigned to emitters.
- ▶ Pulse on pulse situations can be simulated.
- ▶ Arbitrary trajectories for receiver and emitters can be imported from files.
- ▶ Trajectories have 6 degrees of freedom (DoF).
- ▶ There is a variety of predefined parametrized antenna patterns, and custom antenna patterns can be imported.
- ▶ There is a variety of antenna scans available.

Please refer to [2] for additional information.

5.6 Verifying the scenario

R&S Pulse Sequencer RF offers a reporting feature that shows, for each pulse, the simulated AoA, among many other relevant parameters. This can be used to verify the AoA over time. The feature can be enabled under Scenario -> Signal Calculation -> Config -> Reporting. Further verification possibilities are described in [3]. For a visual comparison, Pulse Sequencer RF can animate the movement of the emitters on the map while the signals are being generated in the signal generators (Figure 35 and Figure 47).

6 Setting up the instruments

Figure 22 shows a setup with 4 RF paths that generates the signals for 4 RWR input ports. Each of the instruments' RF paths can contain the signals of a single emitter or even multiple emitters that are operating simultaneously. Pulses from different emitters that are overlapping in time, which is often called "pulse on pulse" or "co-pulse", can be handled by multiple wideband baseband generator boards (SMW-B9) and fading simulator boards (SMW-B15). More details on that are given in [3].



Figure 22: Setup with 4 RF paths to simulate multiple emitters with AoA at 4 RWR input ports, including two SMW200A vector signal generators, an SMA100B analog signal generator as LO source and a ZNB vector network analyzer for RF ports alignment.

The setup can be easily scaled to the required number of RWR input ports and thus RF paths by adding SMW200As¹ (Figure 23).

In order to synchronize the individual RF paths among multiple SMW200As, several cable connections are necessary. The left part of Figure 23 shows the wiring of the example setup from Figure 22.

¹ When using more than one SMW200A in the setup, it is recommended to use SMW200As with serial numbers ≥ 107000 for maximum phase stability. SMW200As with lower serial numbers can be retrofitted with a new wideband baseband main module (SMW-B13XT; DACW revision ≥ 6.00) to get the same performance. You can look up the revision using the SMW200A's GUI under System Config -> Setup -> Instrument Assembly -> Hardware Config -> Baseband Assembly in the line "DACW".

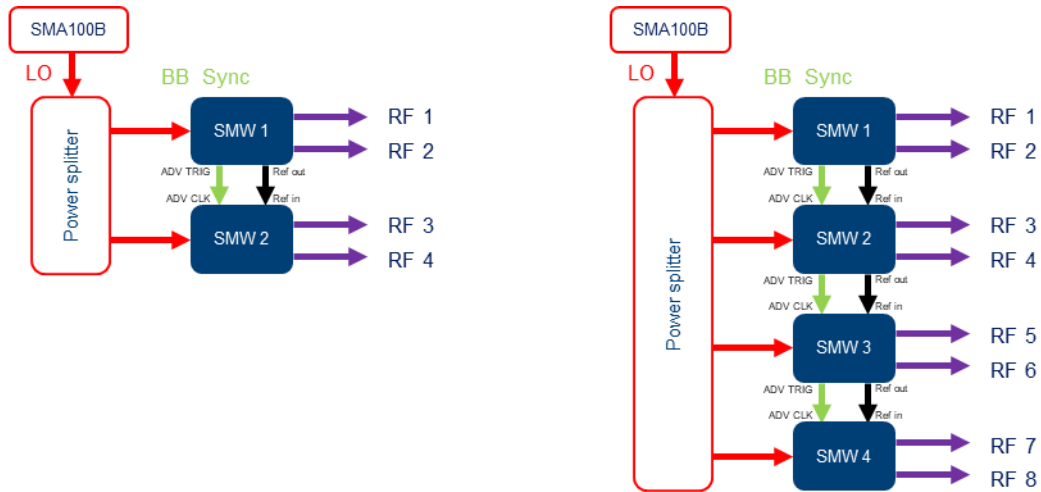


Figure 23: Required connections for exemplary setups with 4 RF paths (left) and 8 RF paths (right) with a star distribution of the LO signal that is generated by an SMA100B

The power splitters need to cover the frequency range from the lowest desired operating frequency (minimum 200 MHz for phase coherence in SMW200A) up to 6.5 GHz (or the highest desired operating frequency, whichever is **lower**). Examples of suitable power splitters are Mini-Circuits®ZFRSC-183-S+ (2-way) and Mini-Circuits®ZN4PD-5R183-S+ (4-way), both of which have a specified lower frequency of 500 MHz and an upper frequency of more than 6.5 GHz. The most critical signal paths with respect to phase stability are the LO signal distribution (red arrows in Figure 23) the baseband (BB) sync signal distribution (green arrows) and the RF signals (purple arrows).

When planning your setup, this guideline will help you maximize phase stability:

- ▶ Allow instruments to warm up properly.
- ▶ Keep ambient temperature as constant as possible.
- ▶ Use phase stable cables for LO, baseband synchronization and RF paths (e.g. semi-rigid cables where possible and R&S®ZV-Z19x where flexibility is needed)
- ▶ Keep the cables as short as possible.
- ▶ Use symmetries:
 - cables of equal types in all branches
 - cables of equal lengths in all branches
 - route cables such that all branches see equal temperature
 - star distribution of the local oscillator (LO) signal provided by an SMA100B
- ▶ Avoid vibration.

If phase stability between the RF paths is not required for your application and the setup is calibrated according to section 7.2 using Pulse Sequencer RF's built-in feature, the LO signal distribution is not necessary.

How Pulse Sequencer RF software needs to be configured with and without shared LO signal is covered in sections 7.2 and 8.

7 Calibrating the setup

7.1 Why do we need to calibrate the setup?

The Pulse Sequencer RF software calculates the signals with amplitude, timing and phase relations as they would occur at the RWR input ports.

Just connecting the SMW200A's RF paths to the RWR's input ports might not yield the desired relations at the RWR's input ports. There might be unintentional amplitude, timing and phase differences between the individual signals at the RWR's input ports (Figure 24) caused by the

- ▶ internal structure of the signal generators as well as
- ▶ cables and components used to connect the DUT.

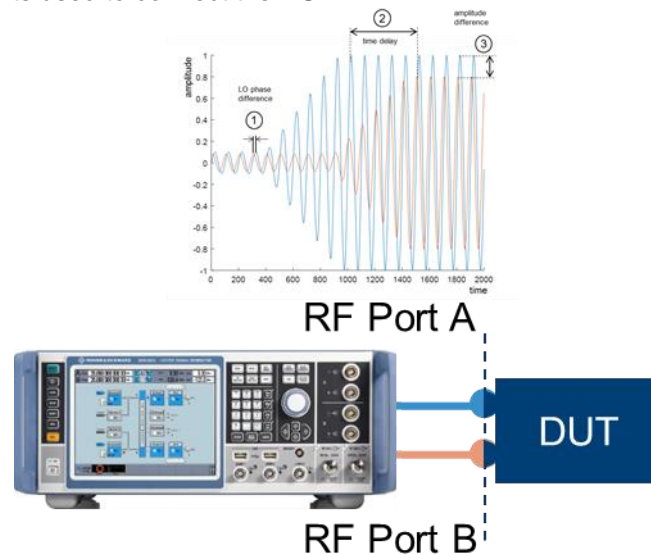


Figure 24: The diagram shows possible misalignment of two signals at the inputs of the DUT with respect to amplitude, time and phase

Radar warning receivers exploit amplitude, timing and/or phase differences between the signals from different antennas to estimate the angle of arrival. Therefore, it is necessary to eliminate all unwanted contributions on amplitude, time and phase along the RF paths. The goal is to align the signals at a certain reference plane. The consequence is that when you play identical signals in the baseband entities of the SMW200As, the signals will be aligned at the defined reference plane, that means with identical amplitude, time and/or phase. When you intentionally change amplitude, time or phase differences, these changes will become effective at the reference plane. In other words, the amplitude, time and phase differences that are calculated by the Pulse Sequencer RF for a given scenario will become effective exactly at the defined reference plane. We will assume the reference plane to be at the input ports of the RWR (Figure 25).

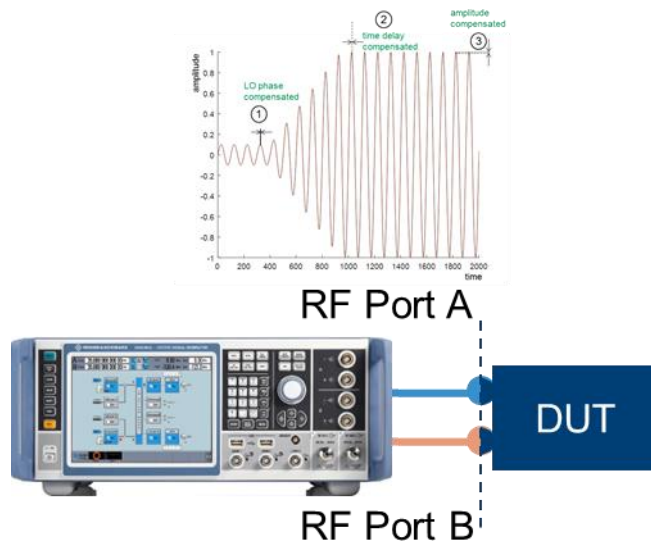


Figure 25: The diagram shows perfect alignment of two signals at the input ports of the DUT with respect to amplitude, time and phase

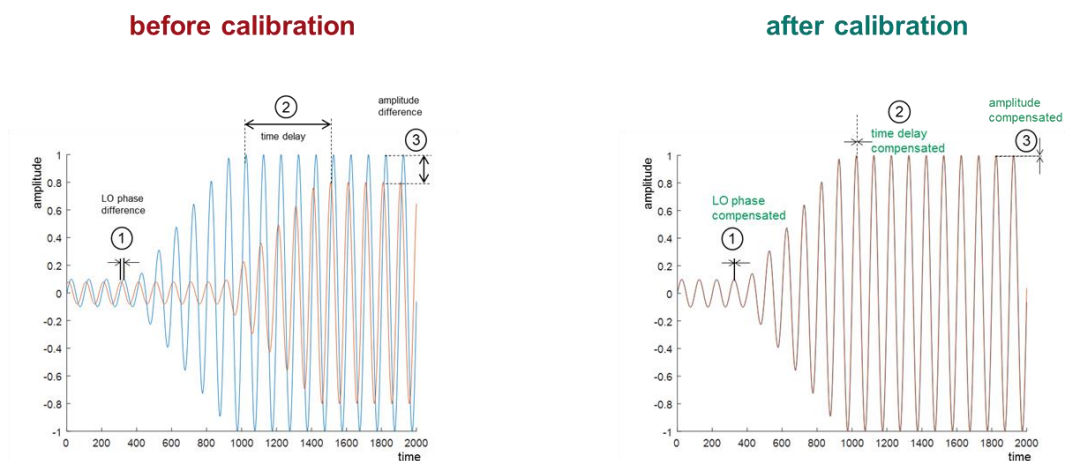


Figure 26: Comparison of amplitude, time and phase differences before and after calibration

Figure 26 shows a comparison of amplitude, time and phase differences between two signals before and after calibration.

The following table gives is a rough overview over available calibration methods and their use cases.

Method	What is calibrated?	Suitable for
R&S Pulse Sequencer's built-in feature	<ul style="list-style-type: none"> Amplitude at scenario's center frequency Time differences at one selected frequency 	Simple scenarios and setups for receivers using <ul style="list-style-type: none"> Amplitude monopulse Time difference of arrival (TDOA)
R&S RF Ports Alignment option	Each of <ul style="list-style-type: none"> Amplitude Time differences Phase differences over user-definable frequency and amplitude range	Complex scenarios and setups for receivers using <ul style="list-style-type: none"> Amplitude monopulse Time difference of arrival (TDOA) Interferometry

Please refer to the information in the following sections for more details on which method to choose and how to apply it.

7.2 Amplitude and timing calibration using R&S Pulse Sequencer RF's built-in feature, an NRP power sensor and an oscilloscope

In case only amplitude and timing calibration are necessary, the setup can be calibrated using an NRP power sensor and an oscilloscope following the guideline in [4] in the sections "Compensating Time Delays" and "Compensating Path Loss". This works with all R&S vector signal generators that are supported by Pulse Sequencer RF, e.g. SMW200A, SMBV100B, SGT100A.

The Pulse Sequencer RF level adjustment feature compensates the path losses in the individual propagation paths (and makes their amplitudes equal) at the center frequency of the Pulse Sequencer RF scenario only. Even if you run a Pulse Sequencer RF level adjustment over a certain frequency range, the level in each path will be corrected by one single offset value, namely the value that was measured for the center frequency of the current scenario. Another value from the level adjustment measurement only gets effective if you run a scenario at another center frequency. Only one single value of the level adjustment measurement curve is effective at a time - the one at the center frequency of the scenario.

This means that if you want to calibrate the setup for a single scenario, you only need to do the calibration for one frequency point - the center frequency of your scenario.

For offset frequencies within the RF modulation bandwidth of the signal generator, there remains an uncertainty per RF path given by its I/Q modulation RF frequency response (see datasheet of the respective signal generator) and additionally the frequency response of the signal path between the signal generator outputs and the DUT inputs.

The frequency response of each signal generator path within its modulation bandwidth can be flattened using the IQ optimization mode "High Quality" or "High Quality Table", which can be selected in Pulse Sequencer RF software.

- High Quality mode gives best flatness. It uses a short test signal to measure the current frequency response and compensates it. The test signal is present at the RF output.
- High Quality Table mode is faster and avoids the test signal while still providing a very flat frequency response (based on frequency response measurements during last internal adjustments).

The frequency responses of the signal paths between the signal generators' outputs and the DUT's inputs will remain uncompensated. In case this is a limitation for your application, or if you need a calibration also with respect to phase differences between the DUT's input ports, the solution described in section 7.3 is the right choice.

7.3 Amplitude, time and phase calibration using R&S RF Ports Alignment option

The R&S RF Ports Alignment (RFPAL) option (SMW-K545) together with the R&S®RFPAL PC software allows you to calibrate a setup of one or multiple SMW200As with regard to amplitude, time and phase differences between RF paths very conveniently.

RFPAL makes use of an R&S vector network analyzer to measure the amplitude, time and phase differences of all paths to the reference path, which is RF A of the primary SMW200A. If needed, the absolute level accuracy at the reference plane can be improved using an R&S power sensor. The measured data are processed into correction data which are transferred to the SMW200As. Embedding and deembedding of components in the setup can be done using S-parameters. The SMW200As apply the correction data and S-parameters in real time. Therefore, RFPAL can be used with any baseband standard, and in particular with the Extended Sequencer in Pulse Sequencer mode (SMW-K502) and in PDW streaming mode (SMW-K503, SMW-K504).

Steps to achieve a calibrated setup include

- ▶ Set up the instruments
- ▶ Download the RF Ports Alignment (RFPAL) software from [5] and install it on a PC running Microsoft Windows.
- ▶ Configure the setup in the RFPAL software
- ▶ Choose calibration parameters (frequencies, modulation bandwidth and levels)
- ▶ Perform the calibration
- ▶ Validate the calibration with the Quick Check feature

Each of these steps is described in detail in the RFPAL user manual [6]. In particular, proper choice of the calibration parameters (frequencies, modulation bandwidth and levels) is covered in the manual in sections "Setting Appropriate Calibration Frequencies and Modulation Bandwidth" and "Setting Appropriate Calibration Levels".

A video on getting started with RFPAL is available at [7].

7.4 Influence of parameter variations on AoA simulation

Section 6 gives recommendations on how to obtain maximum phase stability. Here, we will discuss the influence of varying amplitude, time and phase differences on the simulated angle of arrival – and thus why it is important to keep amplitude, time and phase differences stable enough.

7.4.1 Amplitude monopulse

One method to estimate the angle of arrival is the amplitude monopulse method (see e.g. section 2.3 of [8]). Figure 27 shows the patterns of four antennas with an angular spacing of 90° between adjacent antennas. A signal from an emitter at azimuth angle α is intercepted by the antennas with different amplitudes according to their antenna patterns and the incident angle. The AoA can be estimated based on the ratio of the amplitudes of the two strongest signals.

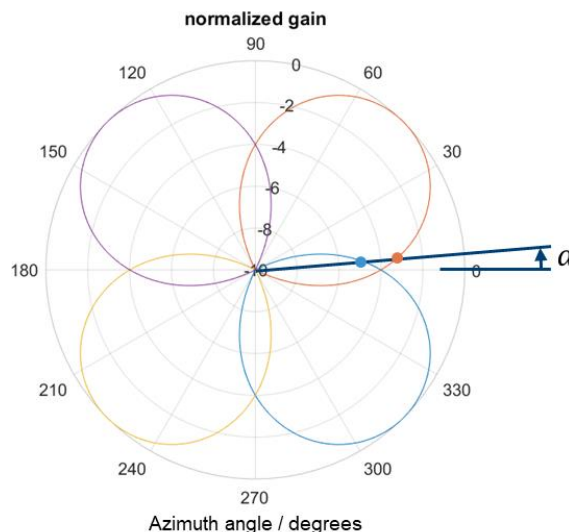


Figure 27: Antenna patterns and their influence on the received signal strength depending on AoA

As an example, we assume two antennas with Gaussian shaped patterns with normalized gain $G(\alpha)$ according to

$$G(\alpha) = e^{-4(\ln 2) \frac{\alpha^2}{\alpha_{\text{HPBW}}^2}}$$

When two of these antennas are arranged such that their boresight directions are spaced by α_s , the ratio R in decibels of the powers received through the antennas is

$$R = 80 \cdot \log_{10}(2) \cdot \frac{\alpha \cdot \alpha_s}{\alpha_{\text{HPBW}}^2} \text{ dB.}$$

Figure 28 shows the ratio R as a function of the incident angle for two antennas with Gaussian patterns, half power beam widths of 78° and an angular spacing of 90° between the antennas.

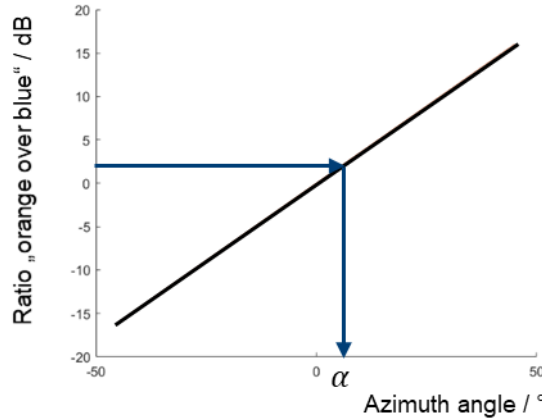


Figure 28: Estimating the azimuth angle based on the ratio of the signals received with the "orange" and the "blue" antenna pattern (cp. Figure 27). Azimuth angle limited to the region from -45° to 45° where "orange" and "blue" antenna deliver maximum power amongst all 4 antennas.

The inverse of this relation can be used to estimate the AoA from the amplitude ratio. Solving the previous equation for α yields

$$\alpha = \frac{R}{\text{dB}} \cdot \frac{\alpha_{\text{HPBW}}^2}{80 \cdot \log_{10}(2) \cdot \alpha_s}$$

The derivative

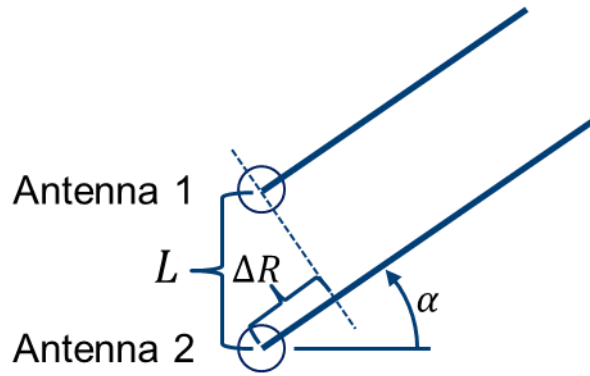
$$\frac{d\alpha}{dR} = \frac{1}{\text{dB}} \cdot \frac{\alpha_{\text{HPBW}}^2}{80 \cdot \log_{10}(2) \cdot \alpha_s}$$

gives the sensitivity of the AoA estimation on variations of R . It allows to determine the error of the AoA estimation based on an error of the measurement of R . For the antenna configuration assumed above, 1 dB error in the amplitude ratio R translates into 2.8° error of the AoA estimation. Similarly, 0.5 dB error in the amplitude ratio R translates into 1.4° error of the AoA estimation in the given example.

The estimation error of a particular DUT may also depend on the number of antennas, on the antenna patterns and on the actual algorithm that is being used. Therefore, the given numbers are to be understood as an example only.

7.4.2 Time difference of arrival (TDOA)

Depending on the angle of arrival and the spacing between two antennas, a signal from an emitter is intercepted by two antennas at different times (Figure 29). From the time difference, the angle of arrival can be estimated.



$$\Delta R \rightarrow \Delta t$$

Figure 29: Different ranges from the emitter to antenna 1 and antenna 2 yield different times of arrival that are a function of the AoA and the antenna spacing

As an example, we assume two antennas spaced by a distance L . Under the plane wave assumption, the angle of arrival is identical for both antennas and denoted α . Trigonometry tells us that the range difference is

$$\Delta R = L \cdot \sin(\alpha),$$

and therefore, the time difference of arrival is

$$\Delta t = \frac{\Delta R}{c} = \frac{L \cdot \sin(\alpha)}{c},$$

where c is the speed of light. The inverse of this relation can be used to estimate the AoA from the time difference of arrival. Solving the previous equation for α yields

$$\alpha = \arcsin\left(\frac{\Delta t \cdot c}{L}\right).$$

The derivative

$$\frac{d\alpha}{d\Delta t} = \frac{c}{L \cos(\alpha)}$$

gives the sensitivity of the AoA estimation on variations of Δt . It allows to determine the error of the AoA estimation based on an error of the measurement of the time difference of arrival. The sensitivity depends on the antenna spacing as well as on the actual angle of arrival.

Figure 30 shows the sensitivity in degrees AoA per nanosecond time difference as a function of the actual AoA (α), for three different antenna spacings (5 m, 10 m, 20 m). In other words, the plot shows the AoA error that results from 1 ns error in the time difference of arrival measurement. An example: For an antenna spacing of 10 m, we have to read off the orange trace. The sensitivity depends on the actual AoA (α). For an AoA (α) of 20°, the sensitivity is approximately 1.8°/ns. This means that a timing error of 0.5 ns translates into an angle error of 0.9° in the given example.

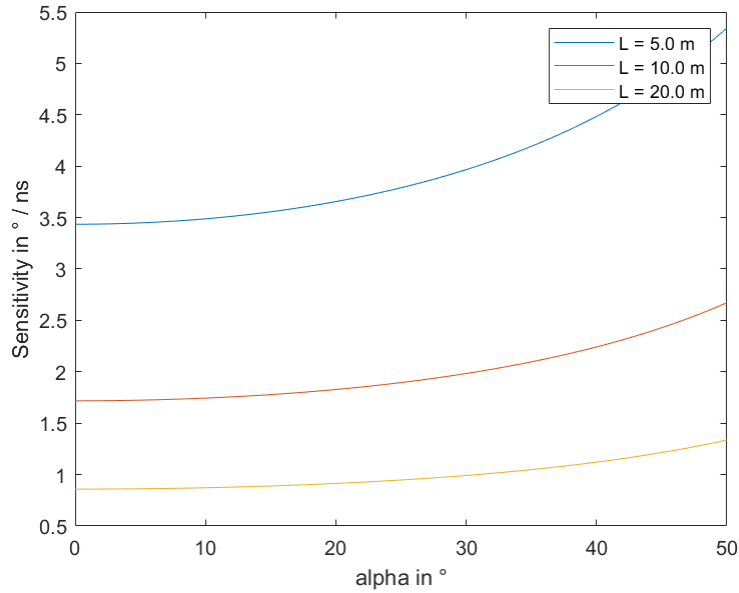
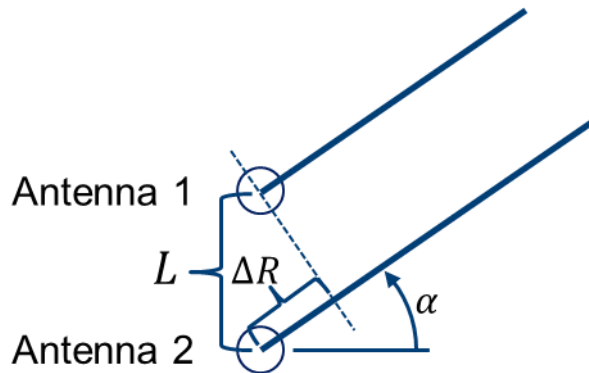


Figure 30: Sensitivity in degrees AoA per nanosecond time difference as a function of the actual AoA (α), for three different antenna spacings (5m, 10 m, 20 m)

The sensitivity of a particular DUT may also depend on the number of antennas and on the actual algorithm that is being used. Therefore, the given numbers are to be understood as an example only.

7.4.3 Interferometry

Depending on the angle of arrival, the spacing between multiple antennas and the frequency, a signal from an emitter is intercepted by different antennas with different phases (Figure 31). From the phase difference, the angle of arrival can be estimated using a variety of different algorithms. For only 2 antennas, the apparent AoA changes when the phase difference between the two signals is changed unintentionally.



$$\Delta R \rightarrow \Delta \varphi$$

Figure 31: Different ranges from the emitter to antenna 1 and antenna 2 yield a phase difference that is a function of the AoA and the antenna spacing

As an example, we assume two antennas spaced by a distance L . Under the plane wave assumption, the angle of arrival is identical for both antennas and denoted α . Trigonometry tells us that the range difference is

$$\Delta R = L \cdot \sin(\alpha),$$

and therefore, the phase difference is

$$\Delta\varphi = \frac{2\pi}{\lambda} \cdot \Delta R = \frac{2\pi}{\lambda} \cdot L \cdot \sin(\alpha)$$

where λ is the wavelength of the emitted signal. The inverse of this relation can be used to estimate the AoA from the observed phase difference. Solving the previous equation for α yields

$$\alpha = \arcsin\left(\frac{\lambda \cdot \Delta\varphi}{2\pi L}\right).$$

The derivative

$$\frac{d\alpha}{d\Delta\varphi} = \frac{\lambda}{2\pi L \cos(\alpha)}$$

gives the sensitivity of the AoA estimation on variations of $\Delta\varphi$. It allows to determine the error of the AoA estimation based on an error of the measurement of the phase difference. The sensitivity depends on the wavelength and the antenna spacing as well as on the actual angle of arrival.

Figure 32 shows the sensitivity in degrees AoA per degree phase error as a function of the actual AoA (α), for two antennas that are spaced by half a wavelength. In other words, the plot shows the AoA error that results from 1° error in the phase difference measurement. An example: For an AoA (α) of 30°, we read off a sensitivity of approximately 0.37 degrees angle error per degree phase error. This means that we get an angle error of 0.74° for a phase error of 2° in the given example.

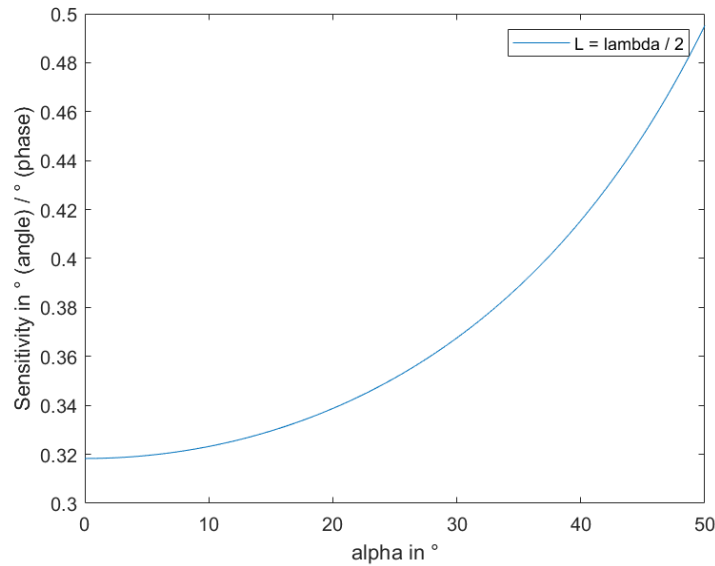


Figure 32: Sensitivity in degrees AoA per degree phase error as a function of the actual AoA (α), for two antennas that are spaced by half a wavelength

The sensitivity of a particular DUT may also depend on the number of antennas and on the actual algorithm that is being used. Therefore, the given numbers are to be understood as examples only.

8 Testing the DUT

After the calibration is done and the DUT is connected, the playback of the scenario can be started from within R&S Pulse Sequencer RF software.

8.1 Using Pulse Sequencer RF's built-in level adjustment feature

In case you are using Pulse Sequencer RF's built-in level adjustment feature (see section 7.2) make sure that level correction is enabled (Figure 33),

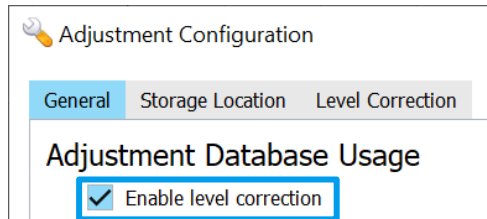


Figure 33: Make sure level correction is enabled

the Baseband Sync Mode is set to "Common Trigger", the Sync Roles are chosen properly and "Use High Quality Mode" is enabled, with the desired mode ("High Quality" or "High Quality Table", cp. section 7.2) chosen from the list (Figure 34).

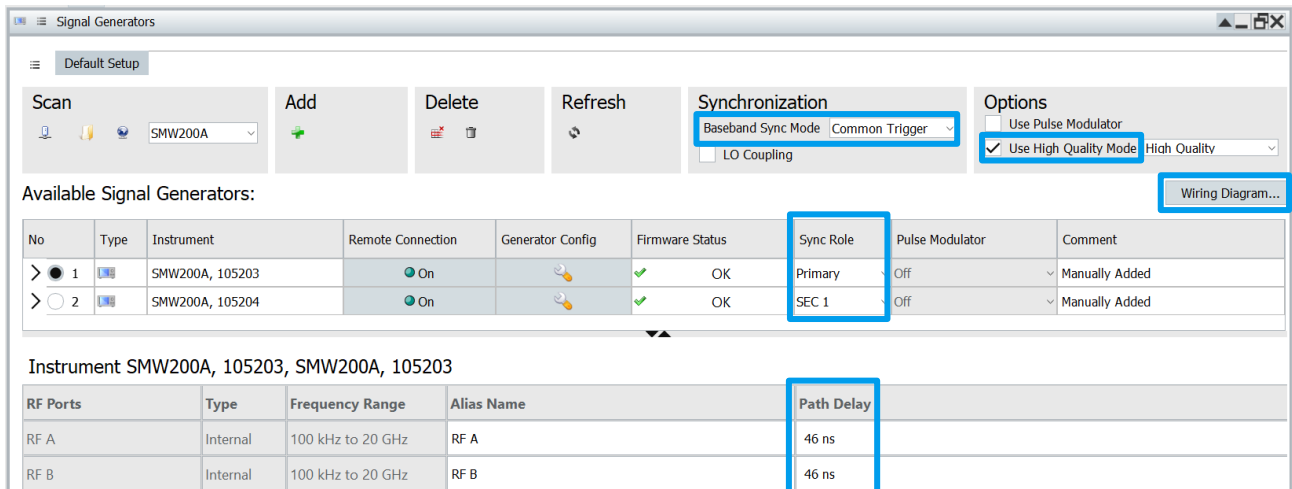


Figure 34: Important settings: Baseband Sync Mode, Use High Quality Mode, Sync Role, Path Delay, and access to Wiring Diagram

Also make sure that the wiring of your setup conforms to the wiring diagram that is accessible via the respective button.

Next, go to the scenario that you want to play.

If you want to watch the emitters moving on the map while the signals are generated, enable "Start preview after trigger" (Figure 35).

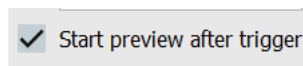


Figure 35: When "Start preview after trigger" is enabled, the movement of the emitters will be displayed while the signals are generated

Now you can advance through the workflow pressing the buttons "Calculate", "Interleave" (in case interleaving is enabled for the scenario), and "Run", which will eventually start signal generation (Figure 36).

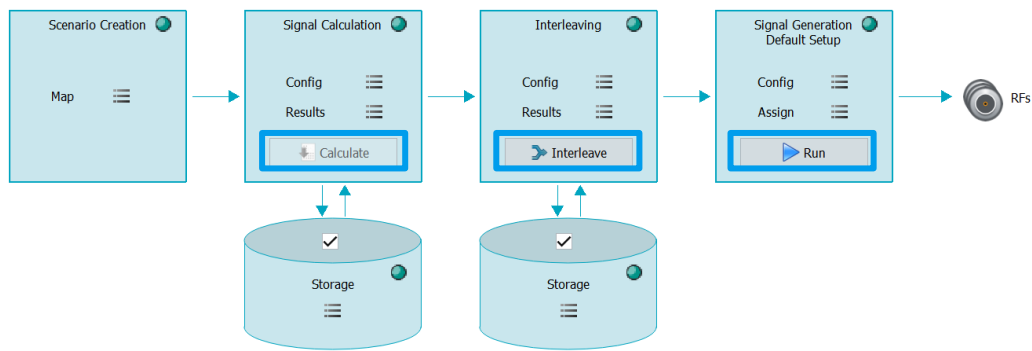


Figure 36: Workflow from left to right: Scenario Creation, Signal Calculation, Interleaving, Signal Generation

Figure 37 shows the amplitudes of the pulses generated for the scenario shown in Figure 15 (with modified PRI), where an emitter moves around the receiver at a constant distance.

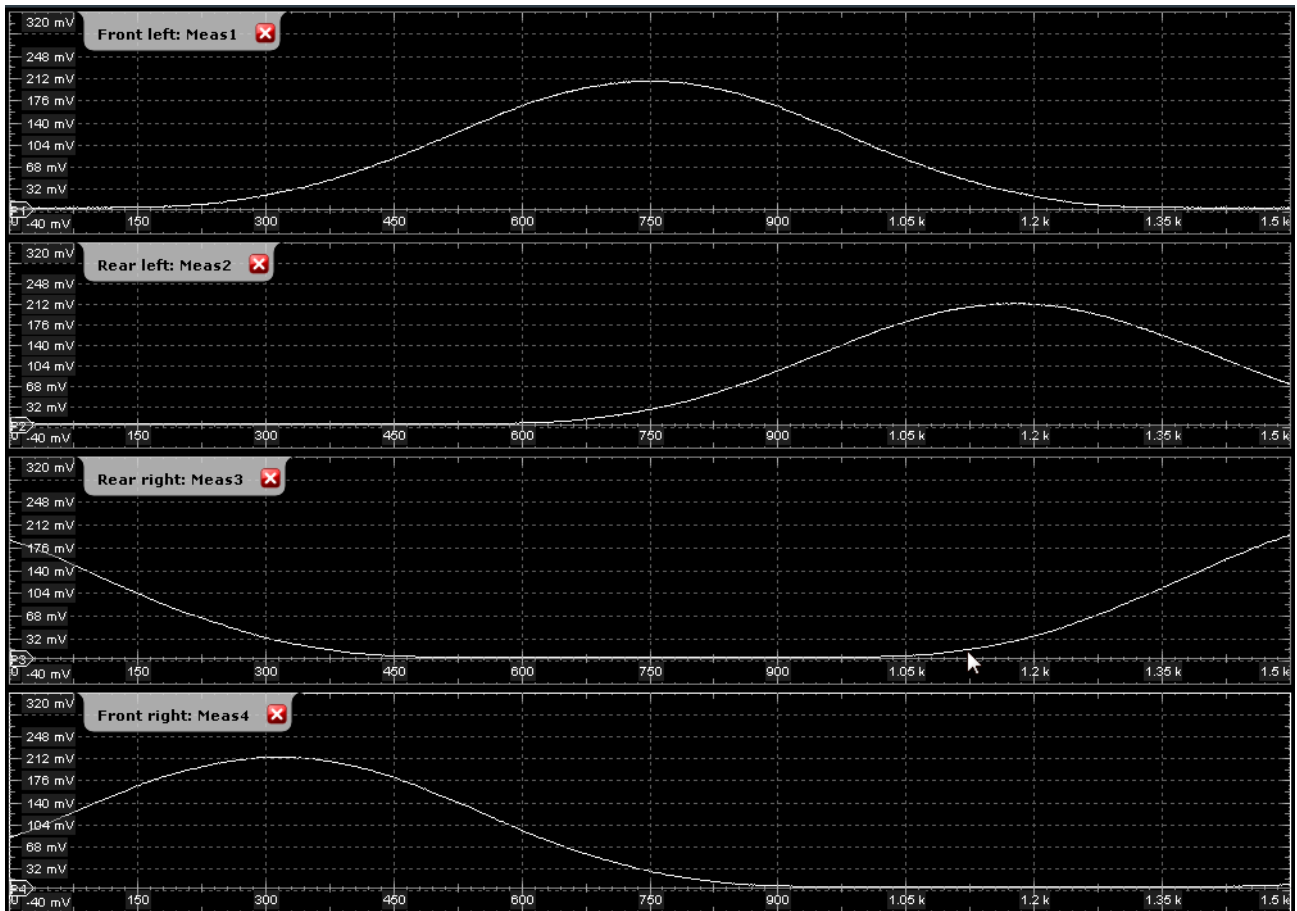


Figure 37: Amplitudes (linear scale) of pulses over time as an emitter moves around the receiver, shown for the front left, rear left, rear right and front right antenna

These signals can now be used to test the behavior of the receiver in the scenario that you created in the Pulse Sequencer RF software.

8.2 Using R&S RFPAL

In case you have done the alignment using R&S RF Ports Alignment (see section 7.3), launch Pulse Sequencer RF, open the desired repository, and go to Configure -> Signal Generators (Figure 38).

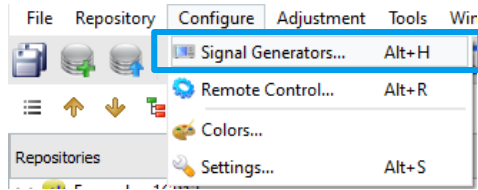


Figure 38: Where to configure the signal generators

Click on the menu icon (Figure 39)

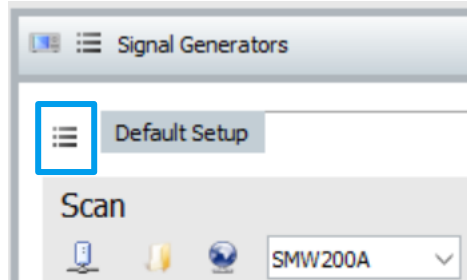


Figure 39: Click on the menu icon to open the import dialog

and choose "Import RF Ports Alignment" (Figure 40).

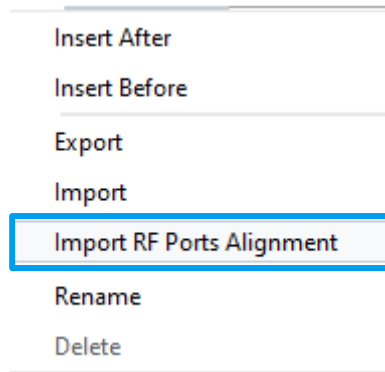


Figure 40: Click here to import an RF Ports Alignment setup

Enter the resource string of the primary SMW (Figure 41). You can find it in the GUI of the primary SMW under System Config -> Remote Access... -> Visa Resource Strings.

Enter the path to the RFPAL setup file (*.rfsa) on the primary SMW and click on "Import".

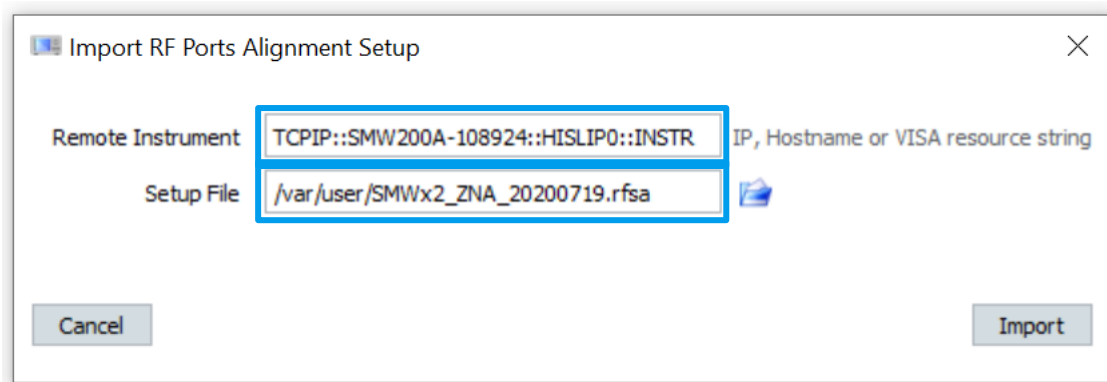


Figure 41: Enter a Visa resource string of the primary SMW and the path to the RFPAL setup file on the primary SMW's file system

Go to the desired scenario. In the Signal Generation block, click on the menu icon next to “Config” and make sure Target -> Generator is chosen (Figure 42).

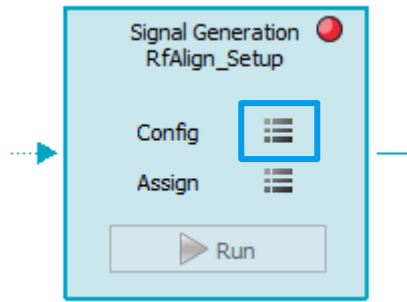


Figure 42: Click here and make sure Target -> Generator is chosen

Next, make sure that the recently imported RF Ports Alignment Setup (default name: “RfAlign_Setup”) is chosen.

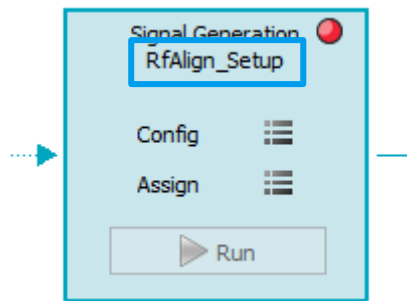


Figure 43: Make sure the desired signal generator setup is displayed here (s. blue frame)

If this is not the case, click on the menu icon next to “Config”, choose “Signal Generators...” (or use the way shown in Figure 38), select the desired setup by clicking on its name (Figure 44) and close the Signal Generators window.

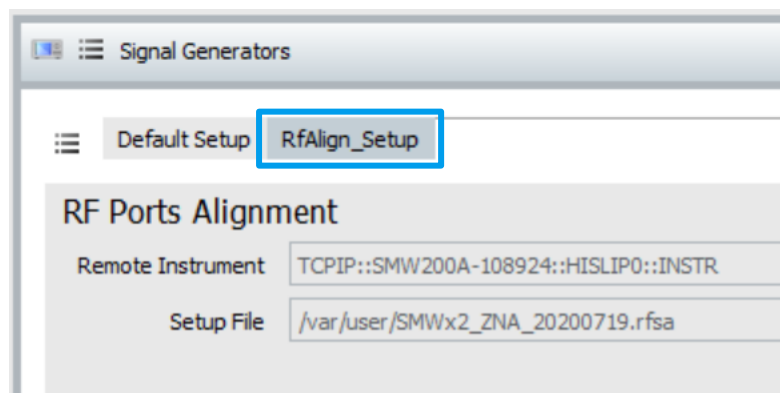


Figure 44: Select the desired setup by clicking on the name

Now, the Signal Generation block should show the correct setup name (compare Figure 43).

Click on the menu icon next to “Assign” (Figure 45)

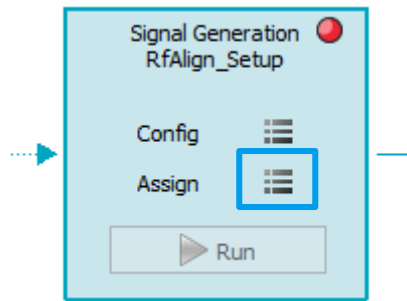


Figure 45: [Click here to assign signals to RF outputs](#)

and assign the receiver signals to the desired signal generators and RF paths by dragging the receiver signals from the left part of the window and dropping them on the respective RF path on the right part of the window (Figure 46).

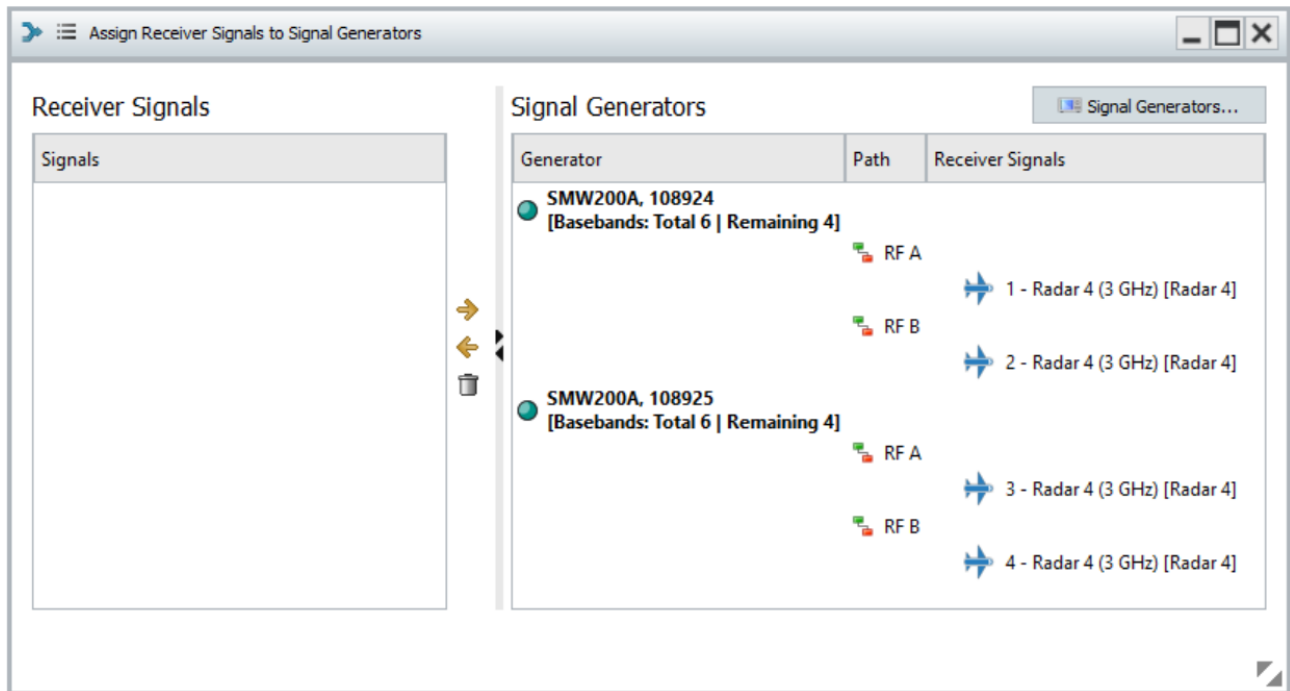


Figure 46: [Assigning signals to signal generators and RF paths](#)

If the signals are not yet calculated, press “Calculate” in the “Signal Calculation” block.

When the calculation is finished, you can start signal generation on the SMW200As by clicking on “Run” in the “Signal Generation” block.

If you want to watch the emitters moving on the map while the signals are generated, enable “Start preview after trigger” (Figure 47).

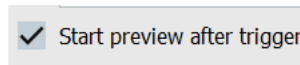


Figure 47: When “Start preview after trigger” is enabled, the movement of the emitters will be displayed while the signals are generated

In the example scenario 4 (see section 5.4), an emitter (Radar 4) moves around the receiver, which has a uniform linear antenna array attached.

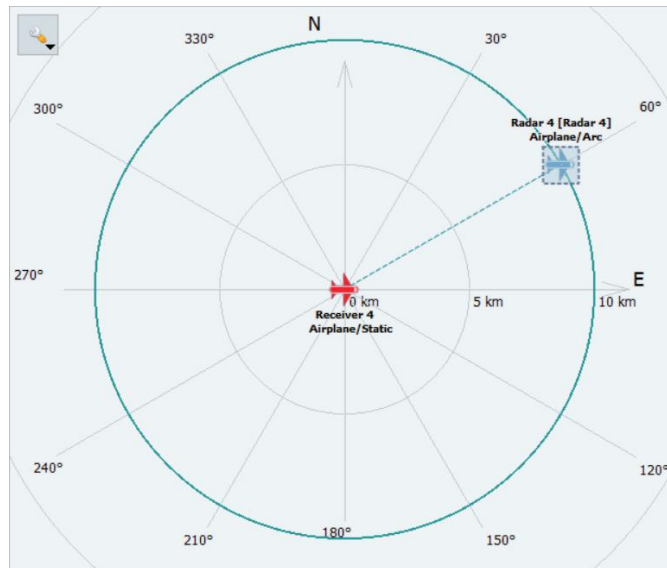


Figure 48: Example scenario 4 (compare

Figure 49 shows the resulting phase differences between any two consecutive antennas of the receiver (antenna 2 / antenna 1, antenna 3 / antenna 2, antenna 4 / antenna 3) as the emitter moves around the receiver in a constant distance. This results in phase differences that are sinusoidal. Since the antennas are spaced by half a wavelength, the minimum and maximum values are -180° and 180° , respectively (see equations in 7.4.3).

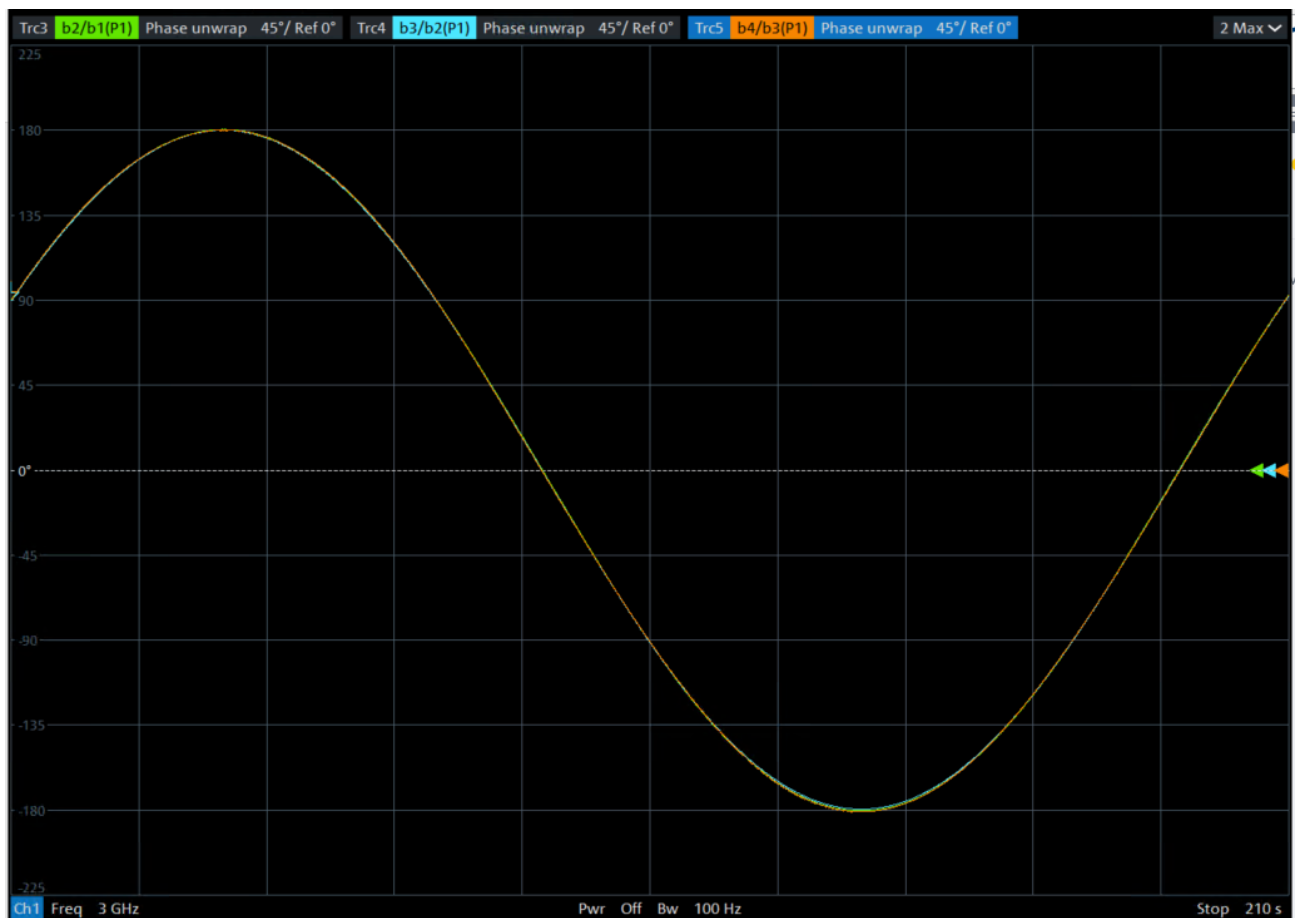


Figure 49: Phase differences over time between pairs of adjacent antennas (antenna 2 / antenna 1, antenna 3 / antenna 2, antenna 4 / antenna 3) as the emitter moves around the receiver at a constant distance. The graph shows 3 coincident traces, since the phase differences between any two consecutive antennas are identical.

Please note that the graph shows 3 coincident traces, since the phase differences between any two consecutive antennas are identical – in theory as well as measured.² The time covered by the plot is 210 seconds which corresponds to the time it takes the emitter to finish one complete circle around the receiver. The fact that the traces are coincident shows the perfect alignment of the signals, which can therefore be used to test the behavior of the DUT in the scenario that you created in the Pulse Sequencer RF software.

9 Literature

- [1] "Generation of Radar Signals in a Hardware in the Loop (HIL) Environment," Munich, Rohde & Schwarz, 2021.
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- [8] S. E. Lipsky, Microwave Passive Direction Finding, Raleigh: SciTech Publishing Inc., 2004.

² Please note the following when trying to reproduce this measurement using a vector network analyzer: The spectrum of the periodic RF pulses consists of multiple spectral lines. The actual frequencies and amplitudes of these lines depend on the signal's carrier frequency, the pulse shape and the PRI. Depending on these parameters and the bandwidth and the intermediate frequency of the vector network analyzer, image frequencies might fall into the measurement bandwidth and contribute to the measurement result. Thus, the displayed phase difference might differ from the true phase difference between the signals. Make sure that only desired spectral components are within the measurement bandwidth.

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