Products: R&S®SMATE200A, R&S®SMU200A, R&S®SMJ100A, R&S®SMBV100A

Phase Adjustment of Two MIMO Signal Sources with Option B90 (Phase Coherence)

Application Note

For beamforming and other measurement setups that require more than one RF output (such as measurements on phased antenna arrays or differential RF), phase coherence is vital. To achieve this with the R&S®SMATE200A, R&S®SMU200A, R&S®SMJ100A or R&S®SMBV100A, the B90 option is available. To set the phase between the RF outputs to a dedicated value, an additional adjustment is needed.

This Application Note shows how to adjust phases using a spectrum analyzer.
Overview

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1 Overview

This Application Note is intended for anyone who needs to adjust RF phases of two or more signal generator outputs. Specifically, it explains how to achieve optimal results using the PhaseTracker PC software (which can be downloaded from the same website) for controlling R&S®SMATE200A, R&S®SMU200A, R&S®SMJ100A and R&S®SMBV100A fitted with option B90 and a spectrum analyzer from Rohde & Schwarz.

Chapter 2 explains how the generation chain of an RF signal generator is built up and how the phase is influenced. Some characteristics are shown.

Chapter 3 describes four possible test setups to measure the phase between two RF signals.

Chapter 4 deals with the theoretical background of the combiner&spectrum analyzer method.

Chapter 5 explains the test setup and how to manually adjust phases.

Chapter 6 describes the use of the PhaseTracker software, which supports simple phase measurement and recording of characteristics (phase versus temperature, level, frequency and time).

Chapter 7 shows how to adjust the phase during operation.

Chapter 8 gives a summary of phase adjustment and some tips on how to easily obtain optimal results.

Note

The following abbreviations are used throughout this Application Note:

- FSL for the R&S®FSL spectrum analyzer
- FSU for the R&S®FSU spectrum analyzer
- SMATE for the R&S®SMATE100A vector signal generator
- SMBV for the R&S®SMBV100A vector signal generator
- SMJ for the R&S®SMJ200A vector signal generator
- SMU for the R&S®SMU200A vector signal generator
- ZVM for the R&S®ZVM vector network analyzer

This Application Note covers the use of dual-port signal generators (such as SMATE with two RF paths) as well as single-port signal generators (SMATEs/SMUs with only one RF path or SMJs/SMBVs). Test setup descriptions always refer to a dual-port SMATE and can easily be applied to all other setups mentioned above.
2 How the Phase between Two RF Connectors Is Influenced

What Is Phase Coherence?

Phase coherence of two RF signals means that there is a defined and stable phase relationship between two RF carriers, i.e. there is a fixed delta phase $\Delta\phi$ between the carriers. Strictly speaking, phase coherence is only defined for CW carriers with the same frequency (or for CW carriers at frequencies that are multiples of each other).

![Diagram of phase coherence between two RF signals](image)

The Generation Chain

The following figure shows a block diagram of a vector signal generator with all relevant parts regarding the phase:

![Block diagram of a vector signal generator](image)

Fig. 2.1: The generation chain of a signal generator

The modulation coder generates a digital baseband signal which can be subjected to a phase offset (a frequency offset can also be applied, but this is less important for phase coherence).

The two DACs deliver the analog I/Q signal to the I/Q modulator, which mixes the complex input signal to the RF domain using the local oscillator.
How the Phase between Two RF Connectors Is Influenced

(=LO) signal from the synthesizer. The phase of the LO signal can also be adjusted.

The I/Q modulator’s output has already got the correct RF frequency but must be levelled to the desired value. This is done in two steps: amplification and electronic step gain attenuation. This resulting output signal, which may be in the range between ~130 dBm to 30 dBm (depending on instrument, frequency and installed options) is then fed to the RF output connector.

The synthesizer has its own built-in reference oscillator but can alternatively use the reference frequency signal from an external source. In both modes, the resulting LO signal is generated in several steps from the 10 MHz signal using PLLs.

If two signal generators are coupled via their 10 MHz reference, they generate exactly the same frequency, but only from the long-term perspective. A closer look at the instantaneous differential phase (“delta phase” or simply “phase”) of these two RF signals reveals that this phase is quite instable. This is due to the following factors:

1. Phase noise of the two synthesizers.
2. “Weak” coupling at 10 MHz needs a long synthesis chain up to the RF domain. If, for instance, the phase drifts 0.1° in the 10 MHz reference loop (due to effects such as offset drifts of the phase detector), the RF phase at 1 GHz will drift 10°.
3. Other drifts in the DACs, the I/Q modulator, the power amplifier and the electronic attenuator.
4. Temperature differences leading to thermal expansion of conducting paths or cables, which changes the electrical length of the signal path. At a frequency of 6 GHz, wavelength \( \lambda \) is 3.3 cm. So an additional length of 1 mm means a phase shift of about 11° (calculated for coaxial cables where the velocity of propagation is approximately two-thirds that of free space. Consequently, the wavelength will be approximately two-thirds that in free space, and the electrical length approximately 1.5 times the physical length).
   Copper has a coefficient for thermal expansion of \( 16.4 \times 10^{-6} \text{ K}^{-1} \). So using a copper cable of 1 m and changing the temperature by 10K will lead to a change in length of 164 µm, which means approx. 2° phase drift.

Because factor 2 is very dominant (>95 %), there is only one way to effectively stabilize the phase between two signal generators: to use a common synthesizer / LO source. This is supported by the SMATE-B90, SMU-B90, SMJ-B90 or SMBV-B90 option.

An installed B90 option is a prerequisite for all test setups in this Application Note. If not stated otherwise, a common LO is used (“coupled”).

Using a common synthesizer also eliminates the first problem. The two remaining factors 3 and 4 can be minimized by means of internal adjustment and thermostatization where necessary.

Influence of RF Frequency

When the RF frequency of both signal generators is changed, the phase is normally changed dramatically, depending on the used frequency. While a common LO source is vital for phase stability, the phase itself is primarily determined by the different electrical lengths \( \Delta x \) of both RF paths.
How the Phase between Two RF Connectors Is Influenced

Let's have a look at the following figure, which shows a simple model of wave propagation in two RF paths of different lengths:

![Wave propagation in two RF paths](image)

**Fig. 2.2: Wave propagation in two RF paths**

The phase depends on the $\Delta x$ and $\lambda$ (frequency) and propagation speed $v$:

$$\varphi = \frac{\Delta x}{\lambda} \mod 2\pi = \frac{\Delta x \cdot f}{v} \mod 2\pi$$

Here is a plot measured with PhaseTracker software:

![Phase as a function of frequency](image)

**Fig. 2.3: Phase as a function of frequency**

From the period of the characteristic (roughly 800 MHz), $\Delta x$ can be estimated to be around 25 cm (assuming $v = 2 \times 10^8$ m/s).
How the Phase between Two RF Connectors Is Influenced

Generally the used frequency is the most important parameter for phase measurement, also with regard to phase stability.

Influence of RF Level Variation

The RF level of a signal generator is set by the driving of the power amplifier and the switching in the electronic step gain attenuator. Both components have an impact on the phase:

- The amplifier changes the phase depending on the driving. A typical value is 1°/dB but depends on the instrument used (please refer to the data sheets).
- The electronic step gain attenuator switches several paths which may differ several centimeters in length. It is obvious that this will cause very big changes of the phase.

If a level has to be set, the strategy of the SMATE, SMU, SMJ and SMBV vector signal generators is to achieve the optimal RF performance with regard to noise and harmonics. Therefore the amplifier is always operated within its sweet spot and the attenuator is switched quite often. To avoid these phase leaps, set the attenuator mode to “Fixed”:

![Fig. 2.4: How to set attenuator mode to “Fixed”](image)

Looking at the differential phase of two signal generators, the situation is generally less critical. Ideally both instruments would use the same working points and the same attenuator switching. In this case, there would be only very little impact from level changes on the phase due to individual characteristics of the components.

In the real world, the frequency response must be calibrated in the factory, and driving and switching points are individual for each instrument. In addition, driving will change over time when automatic level control (ALC) is used.

Here is a characteristic measured with the SMBV:
How the Phase between Two RF Connectors Is Influenced

Fig. 2.5: Phase as a function of level

In this case, the phase is changed by 3° when changing the level by 20 dB.

Influence of Temperature Drift

If the temperature of the signal generator is changed, the phases will change due to drifts in electronic components and changes of the electrical length (thermal expansion) of cables and conductor paths. These effects are rather small, typically better than 0.1°/K. However, it is advisable to let the instrument warm up for at least 30 minutes after switching it on.

The following plot shows the results of a SMATE subjected to a temperature profile starting from 15 °C up to 25 °C in steps of 2.5 °C. The internal temperature is shown by the pink curve. The blue curve refers to the measured phases. Due to noise in the instrument's readings, a trend line (yellow curve) has been added. From this chart, we can see that the phase is changed by 0.05° when changing the temperature by 2 °C / 2K.
How the Phase between Two RF Connectors Is Influenced

Influence of Time

The influence of time is also very small. The reasons are drifts and aging processes in the instrument, which can be reduced by internal adjustment. Therefore this is typically not an issue at all.

Influence of Synthesizer Delta Phase

The phase of the synthesizer can be set in the RF frequency dialog:

As a common synthesizer/LO is used for all RF paths, this phase has no impact on the differential phase of either of them.

Baseband Phase Offset: The Ideal Way

All vector signal generators from Rohde & Schwarz are able to change the phase of the signal in the digital baseband domain.

Fig. 2.6: Phase as a function of temperature and time

Fig. 2.7: Changing the phase in the digital baseband domain
Because the I/Q modulation is a complex multiplication, the resulting phase of the RF signal is changed by the same amount the basesband phase offset is changed.

This phase offset is very precise and not affected by temperature, time or level. The only constraint is that the baseband section has to be used also when generating CW signals.

This (pseudo-)CW signal can be generated by using DC signals for I and Q; the simplest way is to select Custom Digital Modulation and use the following settings: Data Source = All 0; Modulation Type = BPSK. Alternatively (for instance if no realtime option is available), use the ARB and generate the DC-Waveform by using WinIQSIM.

### 3 Methods of Phase Measurements

Phase adjustment always means that the phase between two RF paths has to be measured and that this value has to be taken into account for later testing. Therefore we are going to have a closer look at several different methods of phase measurement.

#### Using an Oscilloscope

**Test setup:**

Connect both RF outputs of the SMATE200A to the two input ports of an oscilloscope. Show both signals vs. time. Adjust the size of both traces to the same value. Use the baseband phase offset to fit both traces.

**Pros and cons:**

+ oscilloscopes are very common
+ test setup is very simple
- bad time / phase resolution. To get an uncertainty of below one degree, a oversampling of 10 is required. For a 5 GHz signal, an instrument of the 70 GHz scope class is recommended.
- not suitable for levels below −30 dBm

#### Using a Network Analyzer

**Test setup (e.g. the ZVM):**

Open reference port 1 and connect RF A of the signal generator with reference port 1 IN of the ZVM.

Connect RF B with port 2.

Start S21 measurement (sweeping vs. time) and measure the phase.

**Pros and cons:**

+ fast
- relatively expensive and less common in the lab
- not suitable for levels below −50 dBm

#### Using a Mixer and a Voltmeter

**Test setup (using two instruments):**
The IF_out signal is given by

\[ IF_{out} = RF_{in} \cdot LO_{in} \]

where

\[ RF_{in} = A \sin(\omega t) \text{ and } LO_{in} = B \sin(\omega t + \varphi) \]

\[ IF_{out} = A \sin(\omega t) \cdot B \sin(\omega t + \varphi) \]

\[ = \frac{AB}{2}(\cos(\omega t - \omega t - \varphi) - \cos(\omega t + \omega t + \varphi)) \]

\[ = \frac{AB}{2}(\cos(-\varphi) - \cos(2\omega t + \varphi)) \]

The DC voltmeter only measures the DC component, and the voltage is linear with \( \cos(\varphi) \). To measure the phase, first adjust the system by searching for maximum, minimum and zero voltage. Afterwards the phase can be calculated by applying the \( \cos \) function to the measured voltage.

**Pros and cons:**

+ quite inexpensive setup
- high mixer level necessary (not suitable for levels below +10 dBm)
- only the absolute value of the phase can be measured, but not the sign (due to the characteristic of the \( \cos \) function)

**Using a Combiner and a Spectrum Analyzer**

**Test setup (using two instruments):**
The Combiner&Spectrum Analyzer Method in Detail, Some Theory

Two unmodulated RF signals (also known as “continuous wave” or “CW” signals) with levels A and B and a relative phase of \( \phi \) are added. The resulting signal \( RF_{AB} \) is then

\[
RF_{AB} = A \sin(\omega t) + B \sin(\omega t + \phi)
\]

Assuming both levels A and B are equal (A=B=L), this expression turns into

\[
RF_{AB} = L \sin(\omega t) + \sin(\omega t + \phi)
\]

Using now the addition theorem

\[
\sin(x + y) = \sin(x)\cos(y) + \cos(x)\sin(y)
\]

the resulting RF signal can be written as

\[
RF_{AB} = L (\sin(\omega t) + \sin(\omega t)\cos(\phi) + \cos(\omega t)\sin(\phi))
\]

\[
= L (\sin(\omega t)(1 + \cos(\phi)) + \cos(\omega t)\sin(\phi))
\]
This can be seen as the sum of two orthogonally rotating vectors, one with length $1 + \cos(\varphi)$ and the second with length $\sin(\varphi)$.

\[ \text{The resulting magnitude of this vector is} \]
\[ \text{Mag} = \sqrt{(1 + \cos(\varphi))^2 + \sin(\varphi)^2}; \]

the level of the RF signal $\text{Level}(\text{RF}_{\text{AB}})$ is given by

\[ \text{Level}(\text{RF}_{\text{AB}}) = L \times \text{Mag}, \] so the magnitude can also be denoted as the gain of the addition.

For $\varphi=0^\circ$, the gain equals 2, which can be expected when we are superposing two identical signals.

It is also obvious that for $\varphi=180^\circ$, the gain equals 0, because both signals are in the phase constellation of destructive interference.

The following plot shows the logarithmic gain vs. the phase:
Gain = $f(\text{Phase})$

Fig 4.2: Gain as a function of phase

Obviously the curve is symmetric to 180°. The following table shows the gain/dB depending on the phase distance to 180°. Because the dedicated phase of the RF outputs of the signal generator can be set digitally without any additional uncertainty, this table also shows the phase uncertainty of the phase setting as a function of gain (equivalent to the measured carrier suppression).

<table>
<thead>
<tr>
<th>Phase distance to 180°</th>
<th>Gain/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>-15.17</td>
</tr>
<tr>
<td>5°</td>
<td>-21.19</td>
</tr>
<tr>
<td>2°</td>
<td>-29.14</td>
</tr>
<tr>
<td>1°</td>
<td>-35.16</td>
</tr>
<tr>
<td>0.5°</td>
<td>-41.18</td>
</tr>
<tr>
<td>0.2°</td>
<td>-49.14</td>
</tr>
<tr>
<td>0.1°</td>
<td>-55.16</td>
</tr>
<tr>
<td>0.01°</td>
<td>-75.16</td>
</tr>
<tr>
<td>0.001°</td>
<td>-95.16</td>
</tr>
<tr>
<td>0.0001°</td>
<td>-115.16</td>
</tr>
</tbody>
</table>

Table 4.3: Gain as a function of phase
So, as a rule of thumb, we need about 40 dB of carrier suppression (including some dB of the combiner and relative to the used signal generator output level) to have a phase adjustment of 1°.

To improve the adjustment by the factor of 10, we have to suppress the signal by an additional 20 dB.

This dependency is easy to understand if we look at the Taylor approximation close to $\phi=180^\circ$ of

$$RF_{AB} = L(\sin(\omega t)(1 + \cos(\phi)) + \cos(\omega t)\sin(\phi))$$

$$\sin(\phi) \approx -\phi$$

$$\cos(\phi) \approx -1$$

$$RF_{AB} \approx -\phi \cos(\omega t))$$

But what happens if the phase is adjusted perfectly but the levels of both signal generators are not equal to each other?

The difference of both amplitudes still remains and can be seen as a residual signal. To calculate its amount, we first have to convert the logarithmic levels to voltages, calculate the difference and convert this back to the logarithmic domain.

Example:

Both signal generators are set to $-30$ dBm. Due to uncertainties (according to the data sheet, below 0.5 dB), the real levels are

Signal generator A: $-30.3$ dBm

Signal generator B: $-29.8$ dBm

As dBm refers to 1 mW, the linear powers are

Signal generator A: $10^{-30.3/10}$ mW = 0.933 μW

Signal generator B: $10^{-29.8/10}$ mW = 1.047 μW

Next, we calculate the amplitudes $P = U^2 / R$, with $R = 50$ Ω

Signal generator A: 6.83 mV

Signal generator B: 7.24 mV

So the residual amplitude is 0.41 mV, which is 3.36 nW or $-54.7$ dBm.

To obtain a general formula, it is easier to calculate directly with voltages and set the resistance $R = 1$.

$$residual / dBm = 20 \times \log(abs(10^{A / dBm/20} - 10^{B / dBm/20}))$$

where A and B are the output levels of both signal generators in dBm.
Assuming an average value of $L$ for both sources and a difference of $\Delta>0$, then we get

\[
\text{residual } / \text{dBm} = 20 \cdot \log(10^{(L+\Delta/2)/20} - 10^{(L-\Delta/2)/20}) \\
= 20 \cdot \log(10^{L/20} \cdot 10^{\Delta/10} - 10^{L/20} \cdot 10^{-\Delta/10}) \\
= 20 \cdot \log(10^{L/20} \cdot (10^{\Delta/10} - 10^{-\Delta/10})) \\
= L + 20 \cdot \log(10^{\Delta/10} - 10^{-\Delta/10})
\]

So the gain is only a function of the level difference of both RF signals:

![Gain = f(level difference)](image)

Fig. 4.4: Gain as a function of level mismatch

Here are some characteristic values:

<table>
<thead>
<tr>
<th>Level difference/dB</th>
<th>Gain/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>-12.74</td>
</tr>
<tr>
<td>0.5</td>
<td>-18.77</td>
</tr>
<tr>
<td>0.2</td>
<td>-26.73</td>
</tr>
<tr>
<td>0.1</td>
<td>-32.76</td>
</tr>
<tr>
<td>0.01</td>
<td>-52.75</td>
</tr>
<tr>
<td>0.001</td>
<td>-72.76</td>
</tr>
<tr>
<td>0.0001</td>
<td>-92.76</td>
</tr>
</tbody>
</table>

Table 4.5: Gain as a function of level mismatch
So level adjustment is a must for precise phase adjustment. The residual carrier consists of two contributions, one from the phase mismatch and one from the level mismatch. If both have the same value, the total gain is 3 dB more than the value specified in the tables/characteristics. Having two signal generators with equal level setting and external cabling, the level difference is typically below 0.2 dB. The gain caused by this level mismatch is roughly \(-30\) dB, which corresponds to 2° in the phase domain. So, as a rule of thumb, level adjustment is required if phase uncertainty should be 1° or less.

5 Manual Phase Adjustment

So, after all this theory, let’s start a measurement session. In addition to the two RF sources and the spectrum analyzer, we need some cables, connectors and, of course, the combiner.

Setup for Adjustment and Testing

The following figure shows a setup with the following instruments:

- SMATE200A
- FSU
- Weinschel Resistive Power Divider/Combiner Model 1506A

![Test setup for phase adjustment](image)

During phase adjustment, the gray cables are used. After adjustment, the same two cables between RF outputs and combiner (now shown as dotted blue lines) are used to connect the DUT, which may be a MIMO receiver, two antennas or any other two-port DUT.

The adjustment plane is the input of the power combiner. Consequently:

- The cables need not be of equal length, but the same cables must be used during adjustment and testing. They should have good phase stability against temperature and flexing.
- The connectors of the combiner should be the same type as used at the DUT. Otherwise use very compact adapters of high quality.
Selecting the Combiner

Also the selection of a combiner is important for the attainable phase uncertainty. Strictly speaking, we need to use a resistive power divider with excellent characteristics in terms of temperature stability and phase tracking. This type of instrument has the following structure:

---

![Resistive Power Splitter Diagram](from the Weinschel Model 1506A data sheet)

Due to its symmetric design, it can be used in both directions, for dividing the electrical power and for adding it.

A non-resistive power splitter (often used as a synonym for a power divider) is not suitable for our application because it can only be used in one direction, to split the power.

The First Adjustment

- Connect the instruments as shown in Fig. 5.1
- Connect an external display to the SMATE or connect it via LAN/remote desktop
- Press <Preset> on both instruments
- SMATE:
  - Open RF Frequency dialog and set
  - External Reference Frequency Source = External
  - LO Coupling Mode = Coupled A->B
**Manual Phase Adjustment**

- Select Custom Digital Modulation for both basebands and use the following settings
  - State = On
  - Data Source = All 0
  - Modulation Type = BPSK

(or use ARB and generate DC-Waveform externally using WinIQSIM or PhaseTracker/"Setup SMx")

- Activate I/Q Modulation and RF for both paths, and set levels to
**Manual Phase Adjustment**

Fig 5.5: Settings in the block diagram

- **FSU:**
  - Center Frequency = 1 GHz
  - Span = 100 Hz
  - Reference Level = 0 dBm

- Change the phase of baseband 1 until RF level is minimal (typically around −40 dBm)

Fig 5.6: Setting the baseband phase

- Then vary the level of path A or B (in steps of 0.01 dB) and try to suppress the carrier down to −60 dBm

- In the last step, make the fine adjustment of the phase (in steps of 0.01 deg); the carrier should go down to −80 dBm

- The current phase leads to a 180° phase relation at the combiner input. If the phase offset is, for example, 64.38°, set the phase to 244.38° to have a zero phase at combiner input. Alternatively keep the phase of baseband A and set the phase offset of baseband B to 180°.
Adapting the Spectrum Analyzer to Signal Level and Phase Uncertainty

The spectrum analyzer must be adapted to the signal regarding the following parameters:

- The reference level should always be set to the signal level of the signal generator.
- The range should be fixed to 80 dB.
- The span should be fixed to 100 Hz, sweep time and video bandwidth to “Auto”.
- The resolution bandwidth must be selected according to the expected analyzer level, which depends on the signal generator level and allowed phase uncertainty. The following list shows some suggested settings. Please be aware, that not all Rohde & Schwarz spectrum analyzers support all resolution bandwidths:

<table>
<thead>
<tr>
<th>Signal generator level</th>
<th>Suggested spectrum analyzer resolution bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;-40 dBm</td>
<td>1 kHz</td>
</tr>
<tr>
<td>-40 dBm to -60 dBm</td>
<td>100 Hz</td>
</tr>
<tr>
<td>&lt;-60 dBm</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

Table 5.7: Suggested resolution bandwidths

Of course, measuring at very low levels is always a trade-off between speed and accuracy. In order to reduce sweep time, also wider resolution filters can be attractive.

Limits and How to Push Them

If we want to adjust at very low levels and/or with very small uncertainties, we are forced to apply some tricks.

Level Adjustment

To adjust phases down to tenths of degrees, the levels should be adjusted by varying the 0.001 dB digit. This can't be done so easily because the user interface limits the input to 0.01 dB. One workaround is to switch to μV, which allows smaller increments (at ~80 dBm, .01 μV corresponds to .003 dBm). The second workaround is to use remote control, where the setting precision is nearly unlimited.

Analyzer Noise Level

The most important limiting factor is the noise level of the spectrum analyzer, strictly speaking the displayed average noise level (DANL). This figure denotes the measured signal level with open RF input. It depends on the used spectrum analyzer. For the FSL, it is ~117 dBm at 300 Hz; for the FSU, ~158 dBm at 1 Hz – where the given bandwidths are the smallest available resolution bandwidths of the instruments.
If we assume that the uncertainty of the level measurement should not exceed 1 dB, we need approximately a level of 30 dB above the noise level. Using the FSL, the combiner output should be at least −90 dBm, which corresponds to the minimum generator signal level of −60 dBm assuming a gain of −30 dB (which means a phase uncertainty of about 1 to 2 degrees).

By replacing the FSL with the FSU, we can profit from the better noise figure. A reduced DANL of 30 dB means that signals can be measured which are 30 dB weaker. So, the combiner input should be at least −120 dBm, the signal generator level −90 dBm.

Of course, these measurements can be improved by using averaging in cases where averaging the phases is more effective than averaging the traces.

Because phase measurement is a stochastic process, uncertainty/accuracy is described by standard deviation. This figure depends on the spectrum analyzer used and its settings, the signal generator level and averaging. Here are some representative results:

<table>
<thead>
<tr>
<th>Level dBm</th>
<th>Standard deviation FSL w/o averaging</th>
<th>Standard deviation FSL with averaging 10</th>
<th>Standard deviation FSU w/o averaging</th>
<th>Standard deviation FSU with averaging 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>&lt;0.01°</td>
<td>&lt;0.01°</td>
<td>&lt;0.01°</td>
<td>&lt;0.01°</td>
</tr>
<tr>
<td>−40</td>
<td>0.04°</td>
<td>0.02°</td>
<td>0.03°</td>
<td>0.01°</td>
</tr>
<tr>
<td>−60</td>
<td>0.13°</td>
<td>0.05°</td>
<td>0.05°</td>
<td>0.02°</td>
</tr>
<tr>
<td>−80</td>
<td>1.2°</td>
<td>0.4°</td>
<td>0.2°</td>
<td>0.03°</td>
</tr>
<tr>
<td>−90</td>
<td>5.2°</td>
<td>1.6°</td>
<td>0.46°</td>
<td>0.12°</td>
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<tr>
<td>−100</td>
<td>12.5°</td>
<td>4.7°</td>
<td>1.5°</td>
<td>0.53°</td>
</tr>
<tr>
<td>−110</td>
<td>~50°</td>
<td>~20°</td>
<td>5.7°</td>
<td>3.1°</td>
</tr>
</tbody>
</table>

Table 5.8: Accuracy of phase adjustment

In addition to averaging and using the best analyzer available with the smallest resolution bandwidth, there are other ways to extend the dynamic range of the test setup – for example, by using low noise pre-amplifiers or modifying the adjustment algorithm.

**A Modified Algorithm for Very Low levels**

Up to now, we have always tried to find the minimum level and use the current phase as the measurement result. Another way is feasible, if we look at the characteristic of the level vs. phase:
Fig. 5.9: A modified algorithm for finding the minimum level

The idea behind this method is as follows:

1. Search roughly for a minimum (designated as "minimum phase")
2. Decrease the phase until the level is, for instance, 20 dB above the spectrum analyzer's DANL, where we can measure with high accuracy
3. Go back to the minimum phase and increase the phase until the level has the same value as that obtained in step 2
4. Use the average value of both phases as minimum phase
6 Using the PhaseTracker Software

Phase adjustment takes some time and needs to be repeated after changes in the following:

- Test setup, e.g. cabling
- Frequency and level
- Ambient temperature

In order to ease the required measurements, a program called “PhaseTracker” is supplied with this Application Note.

![PhaseTracker Software Screenshot](image)

**Fig. 6.1: Screenshot of PhaseTracker software for phase adjustment**

**Installation and Start**

A VISA installation is required.

Execute PhaseTracker V1.4.exe to install the software. Afterwards it can be launched from the start menu or the desktop.

**Connection Setup**

After starting PhaseTracker, you are prompted to enter the remote addresses of the instrument used:
Using the PhaseTracker Software

Fig. 6.2: Screenshot of PhaseTracker software (instrument selection)

Besides the typical VISA notation ending with "::INSTR", also some shortcuts are supported (see above). If both signal sources come from a single two-path unit, enable the "Use RF B of Generator 1" checkbox. Otherwise the address of the second signal generator has to be entered.

Press OK to proceed to the main dialog.

General Operation

Fig. 6.3: Screenshot of PhaseTracker software for phase adjustment

(1) Connection Info
Using the PhaseTracker Software

On the left-hand side, some general information regarding cabling is shown. On the right-hand side, the current connections are listed.

(2) Phase Display
The big reading shows the phase, which is updated after Single, Continuous or Sweep measurements and after Adjustment. To be precise, the displayed phase has different meanings:
During measurement: The applied baseband phase offset of generator 1 to achieve the 180° phase constellation.

During adjustment: The phase that is used as phase offset of generator 1 to achieve a 0° constellation.

Next to the big display is some statistical information that is only relevant for continuous measurements. The standard deviation is also shown graphically below the digital display.

(3) Control
This area is used to set up new connections, setup SMx to prepare for standard measurements, to start and control measurements and to finally adjust the phase to 0°.

(4) Sweep
In order to record characteristics of the phase depending on frequency and level, the limits and the step size of the sweep can be set. Sweep progress is shown below.

(5) Status
This field is used to display status information especially about writing log files.

Setup SMx

The button is used to set the signal generators to a standard configuration which enables the phase measurement and adjustment. Nevertheless pressing this button is optional, baseband setup can also be done manually. The following settings are made:

- *RST
- Activate LO-Coupling
- Transfer a waveform file dc.wv to instruments and start ARB generation
- Activate I/Q-modulator
- Activate RF output @ 0dBm

Single-Phase Measurement

Press first or set the signal generator according to the manual measurement explained in chapter 5 Manual Phase Adjustment.
**Using the PhaseTracker Software**

Within the single-phase measurement, only the following parameters are controlled from PhaseTracker:

- RF frequency of the second signal generator, if used
- Baseband phase of the first signal generator
- Level of the first signal generator

The spectrum analyzer is completely remote-controlled, so no manual settings have to be made.

Press the GetPhaseSingle button and wait a few seconds. The baseband phase of signal generator 1 is modified until the minimum level is found with the spectrum analyzer. Typically the minimum level is about 40 dB below the signal generator level.

### Level Adjustment

The measured level depends on the phase constellation of both RF carriers as well as on the level mismatch.

Press the Adjust Levels button and wait a few seconds. The RF level of signal generator 1 is modified until the minimum level is found with the spectrum analyzer. Typically the minimum level is about 10 dB below the level without phase adjustment. The effect of level adjustment is determined by the distance to the DANL of the spectrum analyzer. In other words: the higher the signal generator levels, the more effective the level adjustment.

### Continuous Measurements

It is often interesting to measure the phase continuously without changing frequency, level or other parameters – e.g. for the following purposes:

- Measuring the influence of ambient temperature and/or time
- Gathering statistical information such as average value and standard deviation
- Observing other effects such as modifying cables, adapters, etc.

First configure the period of measurements. A value of 30 means that every 30 seconds a new measurement is triggered. This helps to reduce data in the case of long-term measurements.

Press the GetPhaseCont button to start the measurement. After the second phase measurement has been performed, the current phase is displayed together with some statistical information.

The measurement is stopped (may take some seconds) after has been pressed.

Afterwards, all readings can be found in the PhaseLogCont.csv file in the current working directory. This file can easily be edited and post-processed using a spreadsheet program. It looks like this:
Using the PhaseTracker Software

Table:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<tbody>
<tr>
<td>1</td>
<td>DeltaPhase Measurement Logfile versus Time</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2</td>
<td>Frequency/Hz = 10000000000 Level/dBm = 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td>DATE</td>
<td>TIME</td>
<td>TEMP Gen1</td>
<td>TEMP Gen2</td>
<td>PHASE</td>
</tr>
<tr>
<td>4</td>
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<td>15:53:48</td>
<td>40.674</td>
<td>42.485</td>
<td>208.026</td>
</tr>
<tr>
<td>5</td>
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<td>15:53:53</td>
<td>40.67</td>
<td>42.486</td>
<td>208.711</td>
</tr>
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<td>6</td>
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<td>208.77</td>
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<td>42.486</td>
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<td>42.485</td>
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</tr>
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<td>11</td>
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<td>15:54:31</td>
<td>40.668</td>
<td>42.486</td>
<td>208.227</td>
</tr>
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</table>

Fig. 6.4: Spreadsheet view of the adjustment results (continuous mode)

Column A: date in notation mm/dd/yy
Column B: time in notation hh:mm:ss
Column C: internal temperature of signal generator 1 / degrees centigrade
Column D: internal temperature of signal generator 2 / degrees centigrade
Column E: relative phase in degrees

Sweep Measurements

This mode allows you to record characteristics of the phase depending on frequency and/or phase, also two-dimensionally.

Set the limits and the steps of the sweeps. To perform one-dimensional sweeps, select the same values for the upper and lower limits of the parameter not to be varied.

Example: How to make a level sweep in "Fixed" attenuator mode:

1. Select Attenuator Mode = Fixed in the RF level menu of the signal generator(s).
2. Set Start Frequency and Stop Frequency to the same value you want to measure.
3. Set Start Level and Stop Level to the desired values which should be in the fixed range displayed in the signal generator dialog.
4. Set the Step to 1 dB.
5. Press StartSweep to start the measurement. The progress is shown below.

After the sweep has finished, all readings can be found in the PhaseLogSweep.csv file in the current working directory. It can easily be edited and post-processed using a spreadsheet program. It may look like this:
Using Averaging and Phase Rotation

Averaging is a way to reduce any kind of noise influencing the phase measurement. This reduces the uncertainties but extends the adjustment time.

One main cause of phase drifts over time are drifts of the I/Q signals of the DACs. If phase rotation is active, these drifts are compensated by varying the phase of the CW constellation point when using averaging.

7 From Phase Measurement to Phase Adjustment

We already know how to measure phases. This is the first and most demanding step. This chapter explains how to use these measurement results to adjust the phases between two RF ports (strictly speaking at the combiner input measurement plane, which should be equal to the DUT input plane) to the desired value.

The phase depends on RF frequency, RF level, temperature and time:

<table>
<thead>
<tr>
<th>Influence factor</th>
<th>Impact if not taken into account</th>
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</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Very high, up to 360°</td>
</tr>
<tr>
<td>Level</td>
<td>High, up to 30° (depending on instrument)</td>
</tr>
<tr>
<td>Temperature</td>
<td>Moderate, &lt;2° typically</td>
</tr>
<tr>
<td>Time</td>
<td>Minor</td>
</tr>
</tbody>
</table>

The time effect is rather small and can be eliminated by means of internal adjustment. Since this will take some time, it is advisable to adjust only the
From Phase Measurement to Phase Adjustment

level, which covers the adjustment of all relevant parts that are responsible for phase drifts.

Fig. 7.1: Using internal adjustment to eliminate phase drifts

The three dominant effects – frequency, level and temperature – are repeatable and therefore can be compensated by means of a phase adjustment. This can be performed in the following ways:

- Manually
- With assistance from PhaseTracker V1.4
- By using any customized system control software

But what kind of adjustment is needed? Of course, this strongly depends on the following:

- The used frequency range
- The used level range
- The possibility to keep the (ambient) temperature constant
- The requirements for phase accuracy

**Manual Phase Adjustment**

The phase measured and displayed by PhaseTracker V1.4 “\(\varphi_m\)” is the phase to be set for generator 1 to achieve 180° phase relation between the two ports while the phase of generator 2 was fixed to 0°.

To set an arbitrary phase \(\varphi\) between generator 2 and 1:

- Set the phase offset \(\varphi_{o1}\) of generator 1 to \(\varphi_m + 180°\)
- Set the phase offset \(\varphi_{o2}\) of generator 2 to \(\varphi\)

This manual method is, of course, only practicable if the frequency and level of the signal generators are changed very rarely or not at all.

**Phase Adjustment Using PhaseTracker V1.4**

PhaseTracker V1.4 is able to adjust the phase to 0° using characteristics recorded in former sweeps, strictly speaking PhaseLogSweep.csv in the current working directory.

Press \[\text{Adjust to } 0°\] to perform two-dimensional interpolation based on the characteristics, which determines the best phase at the given frequency and level. This phase is set for the first signal generator and displayed in
the phase display of PhaseTracker. The phase of the second signal generator remains unchanged and can be used to set the nominal phase that will be effective between the two RF outputs.

**Phase Adjustment Using Customized System Software**

In the following cases, PhaseTracker V1.4 is not the right choice for phase adjustment:

- If the signal generators are not operated manually but are remote-controlled, this software should be extended with phase adjustment possibilities
- If the temperature effect must be compensated
- If the setup consists of more than two signal generators

For MIMO or phased antenna array setups, several signal generators are used with very similar settings. Therefore remote operation is highly recommended in order set all instrument used to the same frequency or level or to apply changes in the baseband section.

Here is an example of how to adjust phases in a setup with four single-path signal generators such as SMBVs:

**Fig. 7.2: Phase adjustment of four SMBVs**

First measure the phase $\phi_{m1}$ between LO master and slave 1. This phase can either be a single dedicated value (measured with $\text{GetPhaseSingle}$) or the result of the interpolation over a characteristic recorded with $\text{GetPhaseCont}$ (showing the dependency on temperature) or
a characteristic recorded with StartSweep (showing the dependency on frequency and level).

These interpolations have to be done on the system controller side. Therefore store the recorded files and rename them to e.g. PhaseLogSweep1.csv and PhaseLogCont1.csv.

Then repeat the same measurements, but use LO slave signal generator 2 instead of LO slave signal generator 1. Please be aware that the LO cabling must remain the same for all measurements. Only the LO slave signal generator 2 must be selected in the connect dialog, and the second combiner input must be switched.

Store the recorded files and rename them to e.g. PhaseLogSweep2.csv and PhaseLogCont2.csv.

Repeat this for LO slave signal generator 3.

After measuring all phases, remove the combiner and connect the DUTs instead, e.g. RX input connectors or antennas.

For initialization and after all relevant changes of the frequency, level or temperature, the system software should set the phase offsets ϕ₀ in the baseband section of the signal generator:

1. Read the characteristics from DeltaPhase.csv and find the phase for the current frequency and level by means of interpolation.

2. If necessary, apply a correction value for the temperature:
   - Determine the effect of temperature difference of the two signal generators from the DeltaPhaseLog.csv
   - Multiply this value by the ratio between the current frequency and the frequency at which DeltaPhaseLog.csv has been recorded
   - This yields ϕₘ at the current working point

3. Set the baseband phase offsets ϕₑₑ, ϕₒ₁, ϕₒ₂, ϕₒ₂ according to the formulas given in the shaded boxes in Fig. 7.2.

8 Summary

Equipped with the B90 phase coherence option, the SMATE200A, SMU200A, SMJ100A and SMBV100A signal generators from Rohde & Schwarz offer excellent phase stability versus time, level and temperature. However, working with coherent RF signals always means spending some effort on adjustment. Where levels above −50 dBm are used, network analyzers are a good choice due to their speed. For levels below −50 dBm, the combiner&spectr um analyzer method is highly recommended due to its sensitivity and simplicity.

The PhaseTracker software enables precise measuring of phases and makes it possible to save characteristics to a file format that is easy to process for adjustment.

9 Additional Information

This application note is updated from time to time. Please visit the website http://www.rohde-schwarz.com/appnotes/1GP67 in order to download the newest version.
# 10 Ordering Information

## Signal generators

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<thead>
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<th>Model</th>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
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<td>Vector Signal Generator</td>
<td>1400.7005.02</td>
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<td>RF path A 100 kHz to 3 GHz</td>
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<td>R&amp;S®SMATE-B106</td>
<td>RF path A 100 kHz to 6 GHz</td>
<td>1401.1200.02</td>
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<tr>
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<td>1401.1400.02</td>
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<td>RF path B 100 kHz to 6 GHz</td>
<td>1401.1600.02</td>
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<tr>
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<td>1404.7500.02</td>
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<td>Phase Coherence</td>
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<td>Vector Signal Generator</td>
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<td>1161.0766.02</td>
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<td>1403.8702.02</td>
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</tr>
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## Spectrum analyzers

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