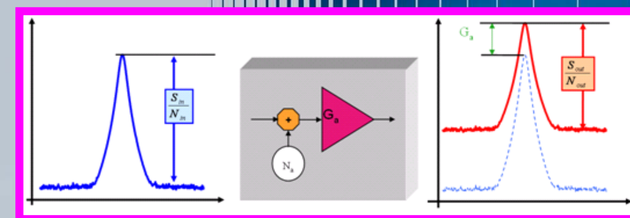
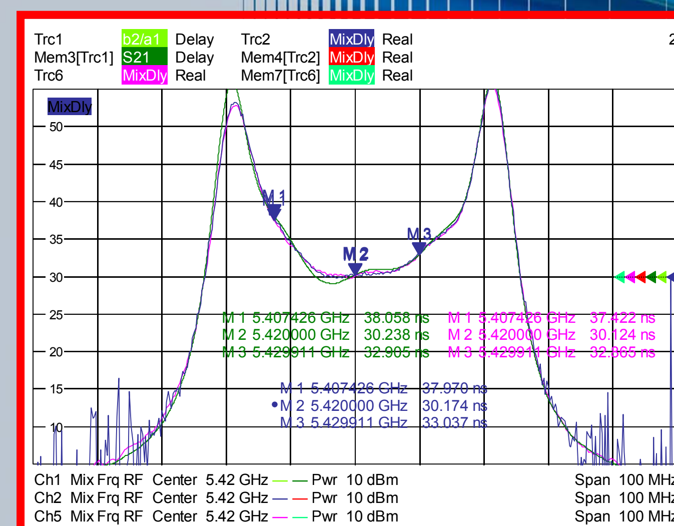
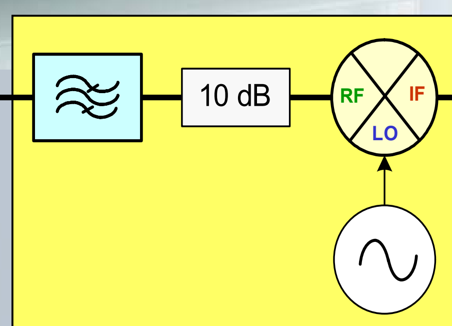
Novel Approaches for Measuring Frequency Converted Group Delay







75 Years of Driving Innovation

ROHDE&SCHWARZ

ABSTRACT Frequency Spectrum is a limited resource. There is continual pressure to utilize this resource more efficiently. The end result is that transmitters and receivers must accommodate higher order digital modulation techniques, such as CDMA and OFDMA, to accommodate higher data rates in limited bandwidths. This leads to more effective sharing of the frequency spectrum, and also higher data rates and quality of service options for the end customer.

This places stringent demands on the design of the transmitter and receiver. In particular, linear distortion performance such as frequency amplitude response and group delay variation become more important. These parameters have a direct impact on the error vector magnitude (EVM) performance of the system, which ultimately determines the amount of data or information that can be transmitted across the channel.

In this presentation we will review the concepts of group delay, frequency dispersion, and deviation from linear phase. We will show the EVM performance of a channel with different amounts of group delay variation to directly see the impact of group delay variation. We will also review a variety of techniques for making group delay measurements, including envelope delay, phase measurement on a multi-carrier signal, S parameter techniques, reference-mixer techniques, a new VNA technique without LO access, and finally a vector corrected S parameter measurement on a mixer or receiver with LO access. The second part of this presentation will explore existing NF measurement techniques, and introduce a new VNA-based technique.

Each measurement has its place, trading off parameters such as complexity, accuracy, measurement speed, and cost. By reviewing the available techniques, the engineer will be better prepared to select the best approach for a particular application.

Outline (slide 1 of 2)

- **What is Linear Distortion?**
  - Frequency Response
  - Phase ripple
    - Deviation From Linear Phase
    - Group Delay
    - Dispersion
  - Impact on EVM

Outline (slide 2 of 2)

- **Methods of Measuring Group Delay and Phase Response**
  - Time-based
    - Gaussian Pulse
    - FM modulation & Envelope delay
  - Multi-Carrier signal and delta phase
  - Network Analyzer, 2 port S-parameters
  - Network Analyzer plus *frequency translation*, now what?
    - Relative measurements with reference mixer
    - LO recovery technique for embedded LO
    - 2 tone Network Analyzer approach for embedded LO
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Interesting Questions…

- What is group delay?
- Can we have a negative group delay?
- Does group delay = signal delay through a device?
- Does a CW signal "experience" group delay?
- If I know the group delay of a device, do I know it's insertion phase?
- What is phase delay?
- Is group delay a "linear" or "non-linear" distortion?
- Can group delay be compensated? Perfectly?
- Is group delay required to measure deviation from linear phase?
- What is the "correct" way to measure deviation from linear phase?

Sinusoids

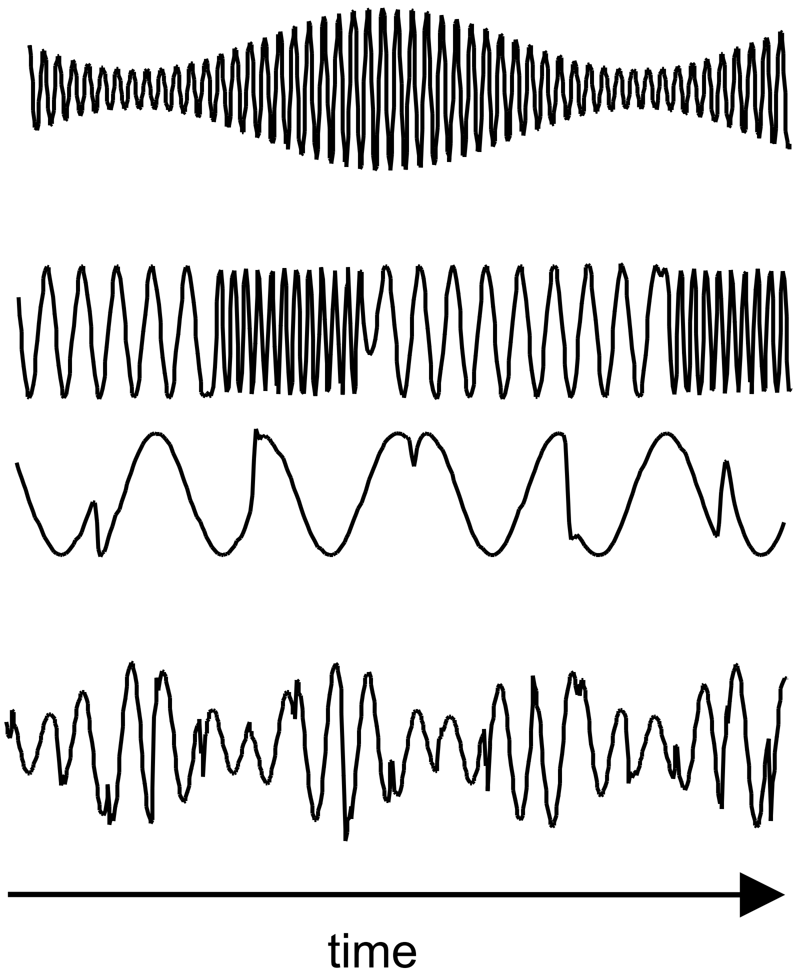
- **Sinusoids are defined by three parameters**
  - Frequency
  - Amplitude
  - Phase

Sinusoids – parameters we can modify

Amplitude

Frequency
or
Phase

Amplitude
and Phase



Modulation Methods

- **We vary the amplitude and phase to transmit information**
  - Analog modulation: AM, FM, PM
  - ***Digital modulation:*** FSK, BPSK, QPSK, 16 QAM, and more…

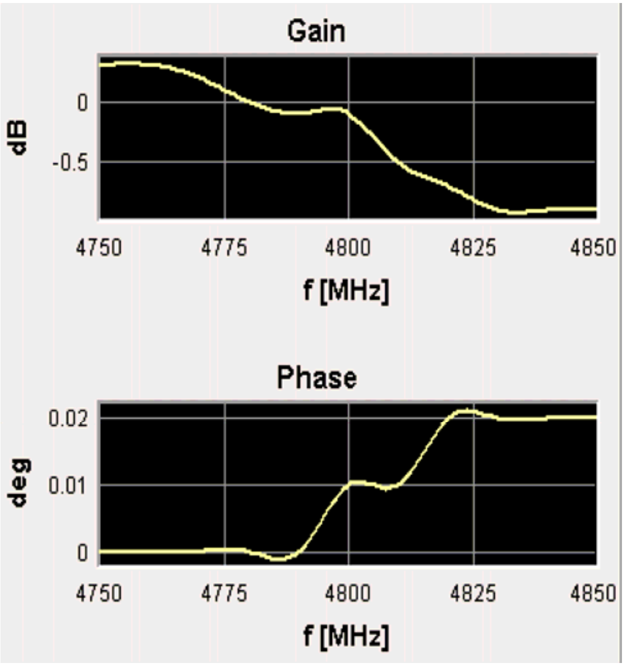
- **We use different techniques to share the channel**
  - FDMA, TDMA, CDMA, ***OFDMA***, MIMO and others….

Sinusoids and Distortion

- **Amplitude response variation (or ripple) vs. frequency results in linear distortion of the input signal's amplitude.**

- **Phase response variation (or ripple) vs. frequency results in linear distortion of the input signal's phase.**

- **Linear Distortion is distortion of the signal that is *independent* of the signal's envelope level.**

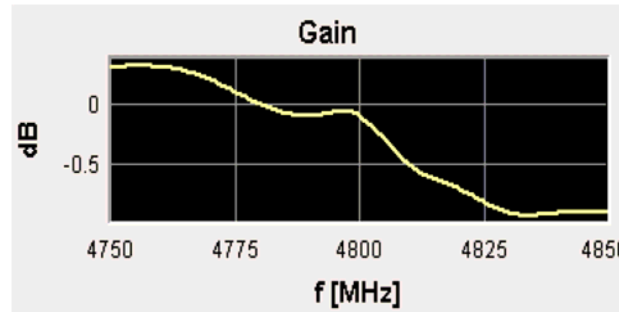


- **This is in contrast to NON-Linear Distortion, which *is* related to the signal's envelope level. For example, compression, AM-PM distortion, 2nd order and 3rd order non-linearities are examples of NON-Linear Distortion.**

Amplitude Distortion

- **Easy to comprehend**

- **Some frequencies are transmitted well, others are attenuated.**
  - Example
    - Listen to a recording of a band or a CD.
      - Missing the highs and lows
      - Doesn't sound "live"

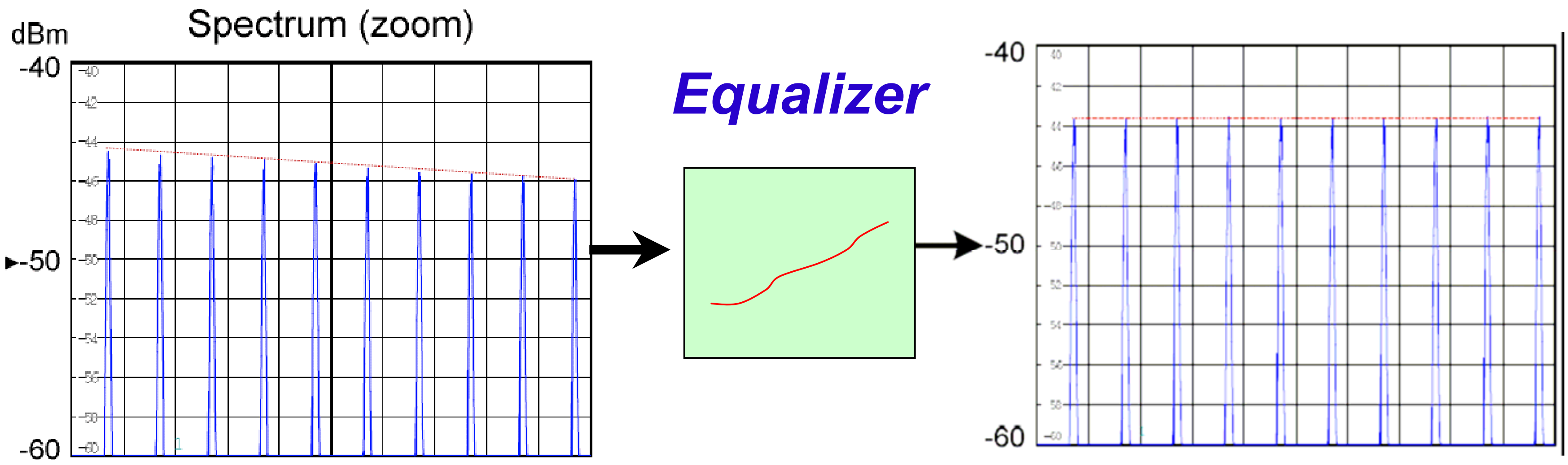


  - Playback with an equalizer
    - Restore the correct amplitudes by adjusting gain at different frequencies
    - Goal is to restore the original amplitude levels

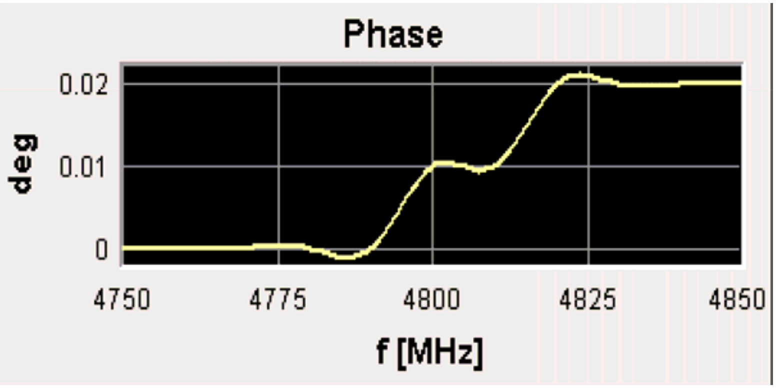
- **This is "linear" compensation. It doesn't matter what we play back, the equalizer, once adjusted, can compensate any "sound."**
    - As long as it isn't attenuated to the level where the S/N ratio is no longer satisfactory

Amplitude Distortion

- **Example of Amplitude Compensation:**



Phase Distortion



- **Not as intuitive, needs more study**
- **So we end up with**
  - Deviation from Linear Phase
  - Group Delay
  - Dispersion

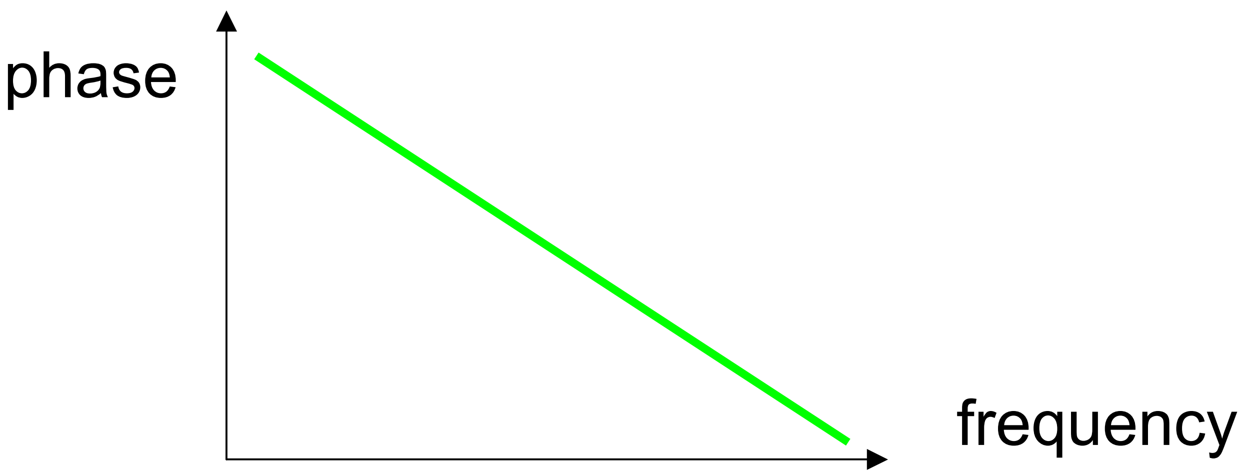
Additional terms to help us explain phase distortion.

- **Like amplitude distortion, phase distortion is different amounts of phase shift at different frequencies.**
- **A phase equalizer would is just as effective as an amplitude equalizer.**

Phase Distortion & Deviation from Linear Phase

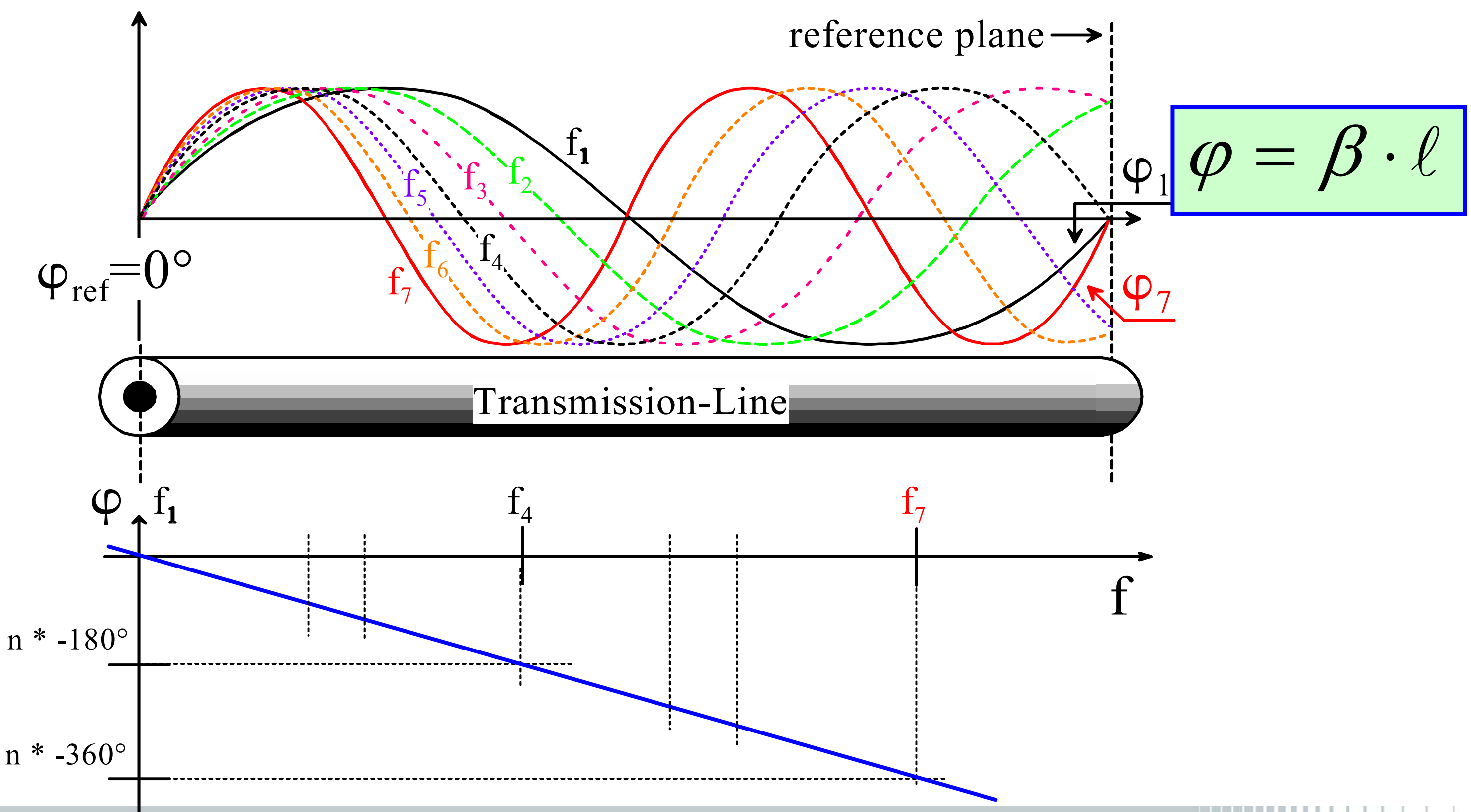
- **What makes this confusing?**
  - A linear phase response results in a ***sloping line.***
  - The amount of slope depends on the DUT's insertion delay
  - ***Any*** slope is ok, as long as it is a "straight" line
  - So to measure phase distortion, we need to know how straight the line really is

- **So we measure the "deviation" from straight line, or deviation from linear phase in order to measure phase distortion.**



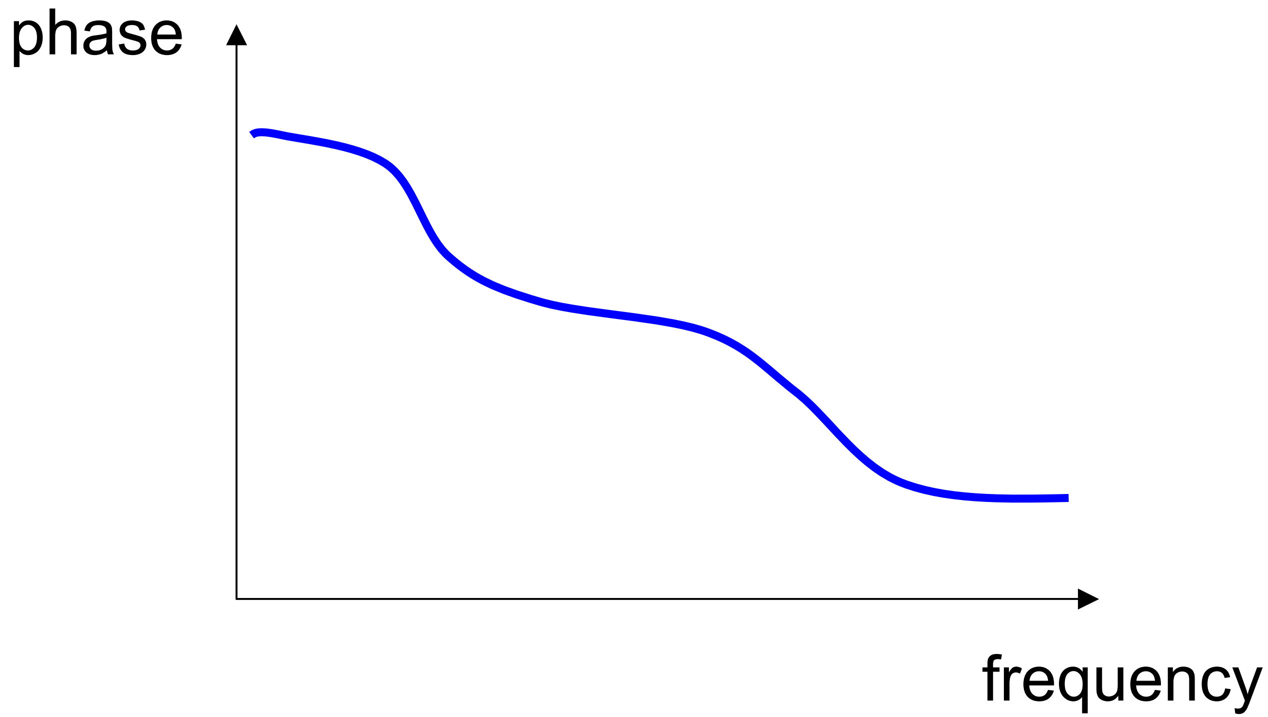
Phase Distortion & Deviation from Linear Phase

- **Why does a phase response have a sloping line?**
  - Each frequency passed through a transmission line will have a different amount of phase shift due to its wavelength.



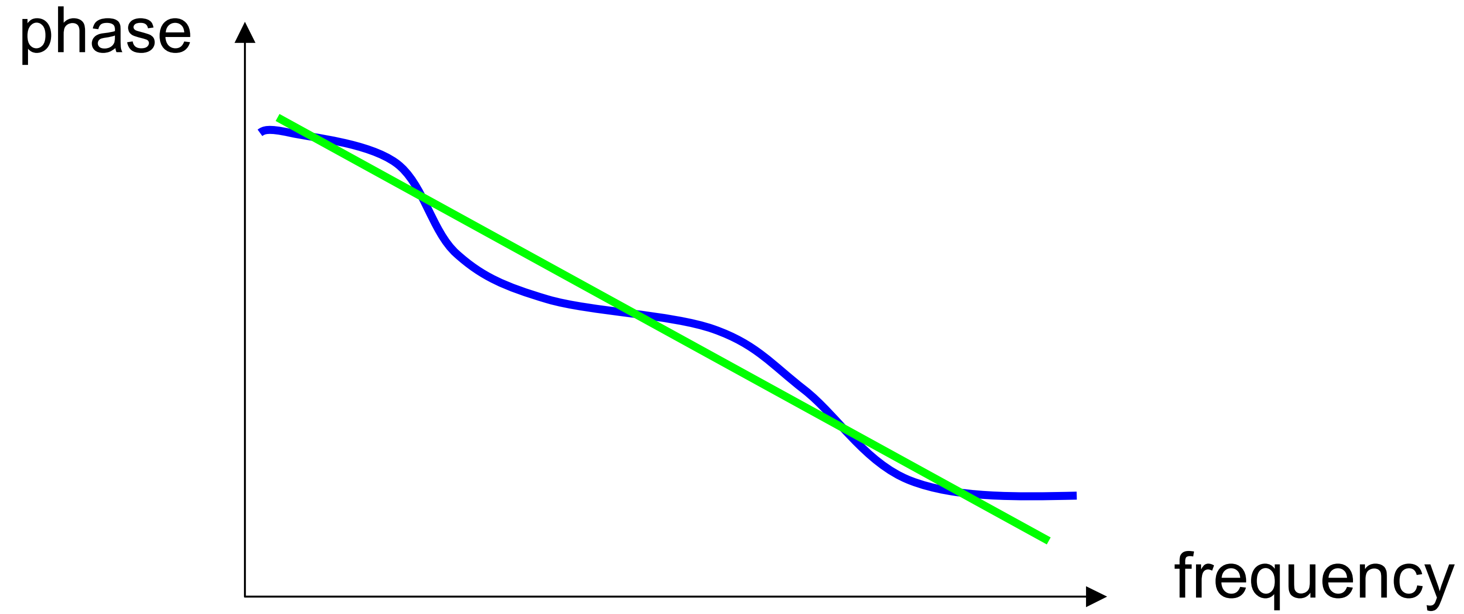
Phase Distortion & Deviation from Linear Phase

- **Consider this phase response vs. frequency**



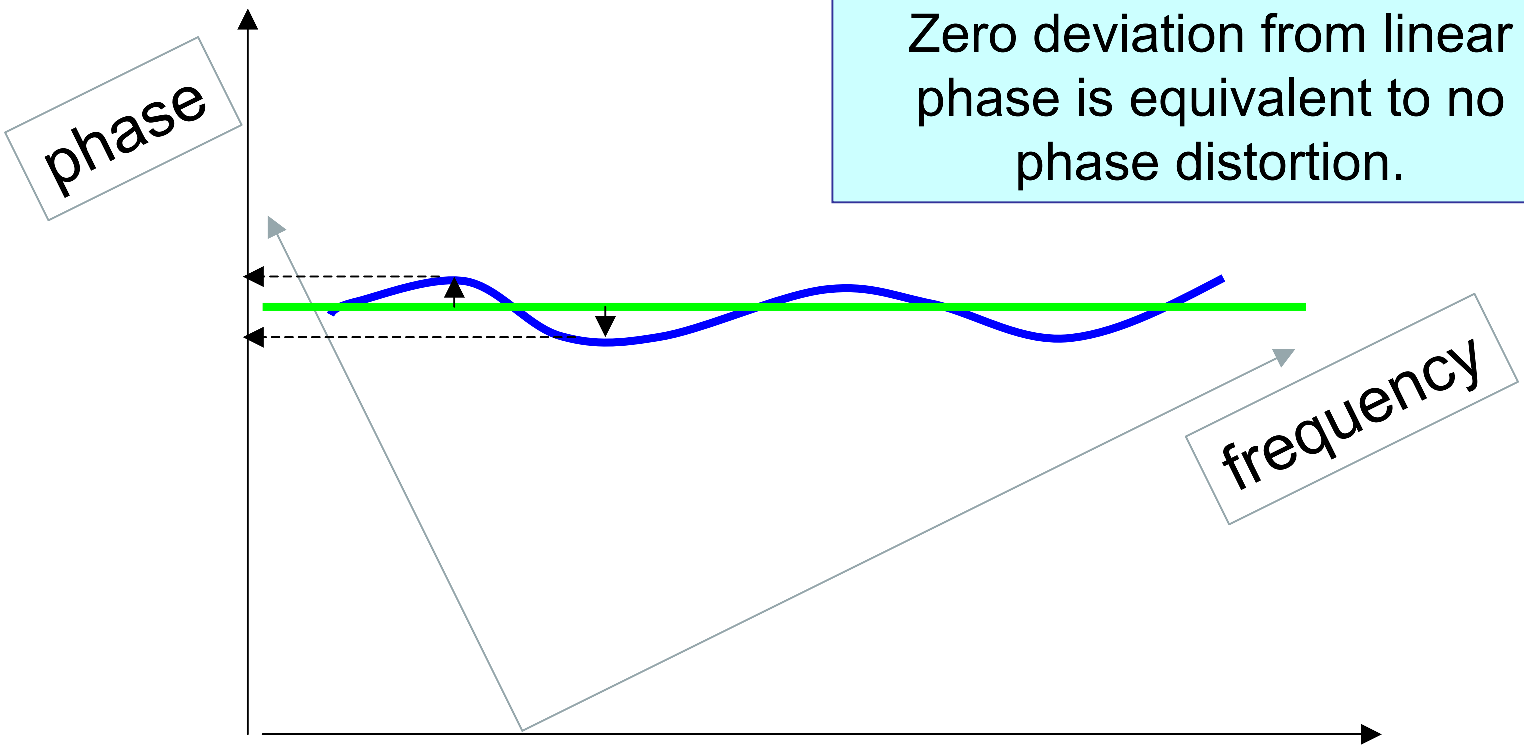
Phase Distortion & Deviation from Linear Phase

- **Draw a straight line that represents <u>no</u> phase distortion.**



Phase Distortion & Deviation from Linear Phase

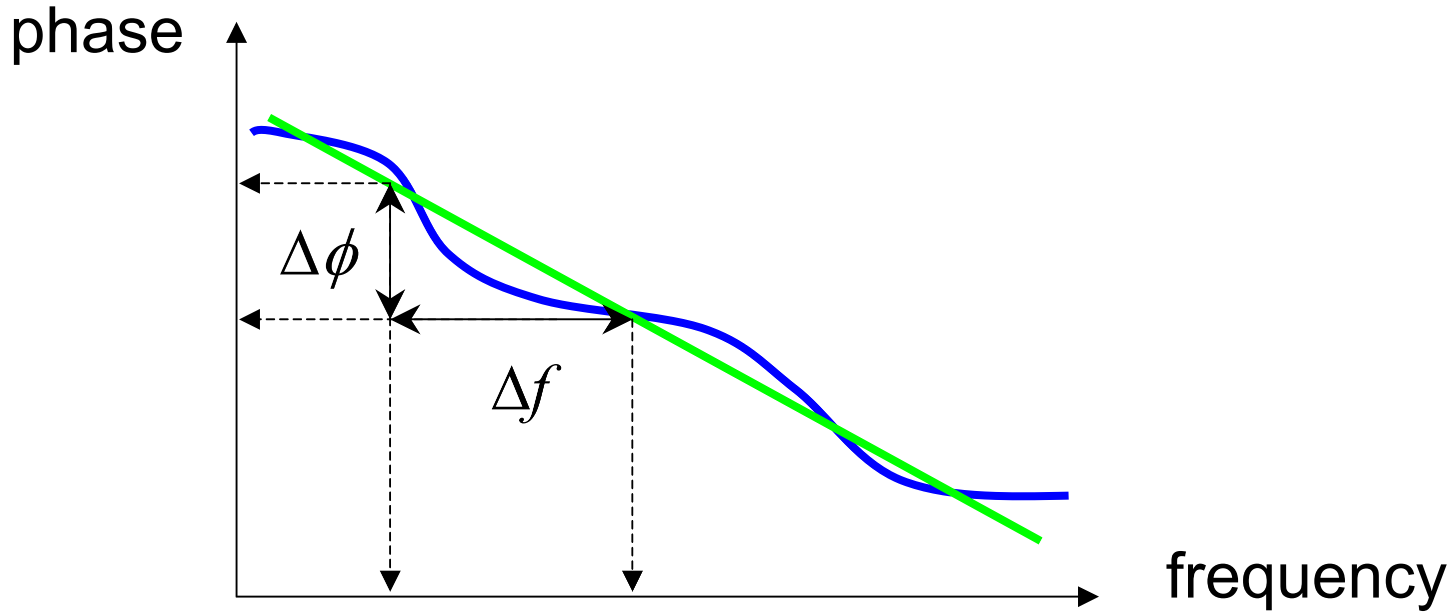
- **To measure deviation from linear phase, we first "tilt" the response until it most closely fits a horizontal line.**
- **Then we consider how much it deviates from this horizontal line at each frequency.**



Zero deviation from linear phase is equivalent to no phase distortion.

Phase Distortion & Group Delay

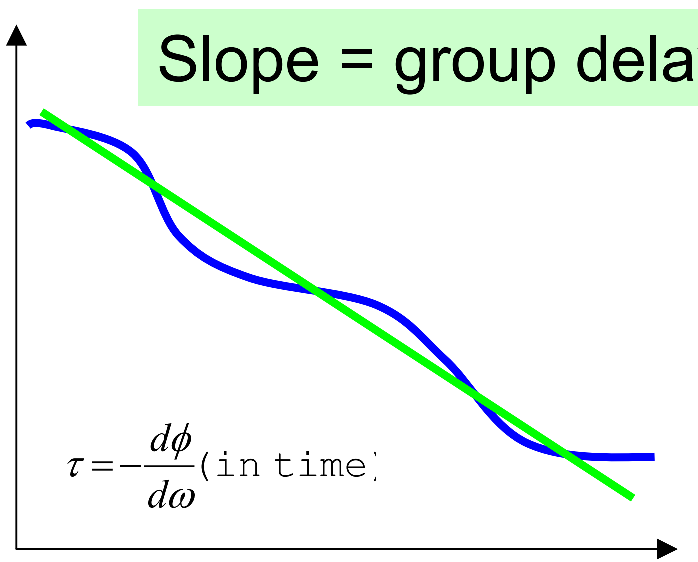
- **Group Delay is defined as:** $\tau = -\dfrac{d\phi}{d\omega}$ (in time)

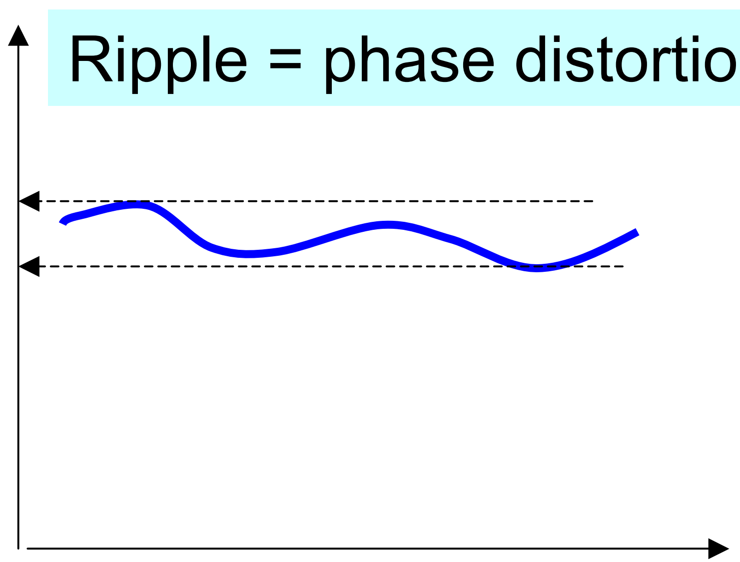


Phase Distortion & Deviation from Linear Phase

- **Slope of the green “curve fitted” line represents nominal group delay over frequency range.**

- **The deviation from linear phase is our phase distortion.**





Phase Distortion and Group Delay

- **Group delay is also a measure of how long it takes for a signal's information to propagate through a channel or device under test.**

- **So there are times when we also care about group delay even when we do not care about phase distortion…**

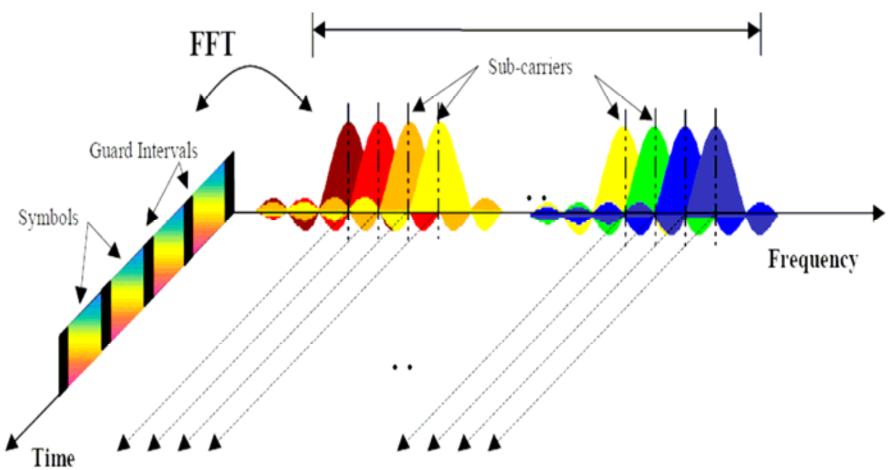
- **Example:** ***Gaming on a cell phone…***

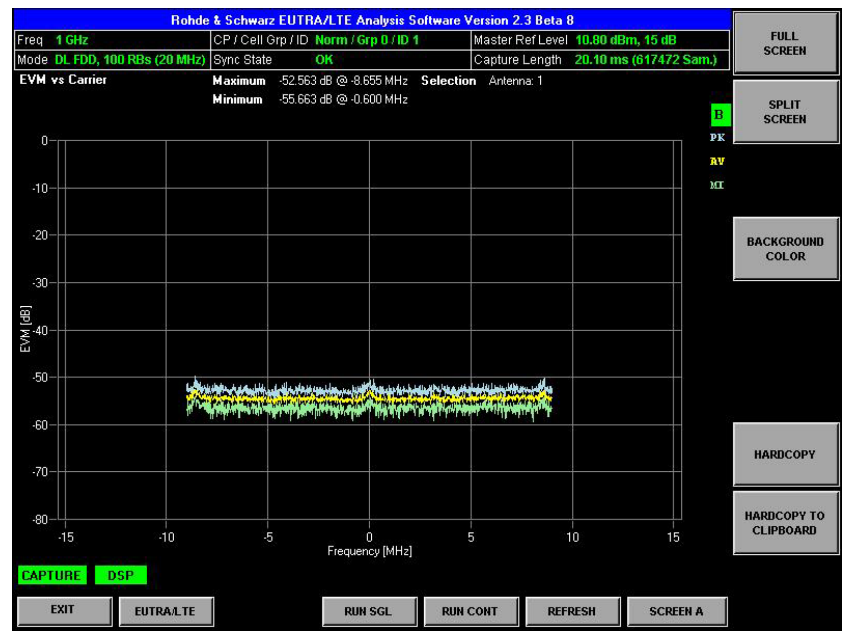
Phase Distortion and Dispersion

- **Now that we opened the door on derivatives, we can also consider the derivative of group delay with respect to frequency.**
- **This is a measure of the signal's frequency dispersion.**
- **Dispersion is another way of describing linear distortion.**

Real world example: OFDMA and EVM

- **Consider an OFDMA signal that is 20 MHz wide, 1201 sub-carriers**
- **With "nearly flat" amplitude and phase response…**
  - **EVM is ~ -55 dB; a fairly low value.**





Real world example: OFDMA and EVM

- **Introduce "linear" amplitude and phase distortion via a channel filter, which primarily impacts the band edges…**
  - **Approximately 0.5 dB of amplitude response**
  - **Approximately 2.5 nS of group delay response**
- EVM is now -35 dB at the band edges

Methods of Measuring Group Delay

- **Timing-based methods**
  - **Gaussian Pulse**
  - FM modulation & Envelope delay
- **Multi-Carrier signal and delta phase**
- **Network Analyzer, 2 port S-parameters**
- **Network Analyzer plus frequency translation, now what?**
  - Relative measurement with reference mixer
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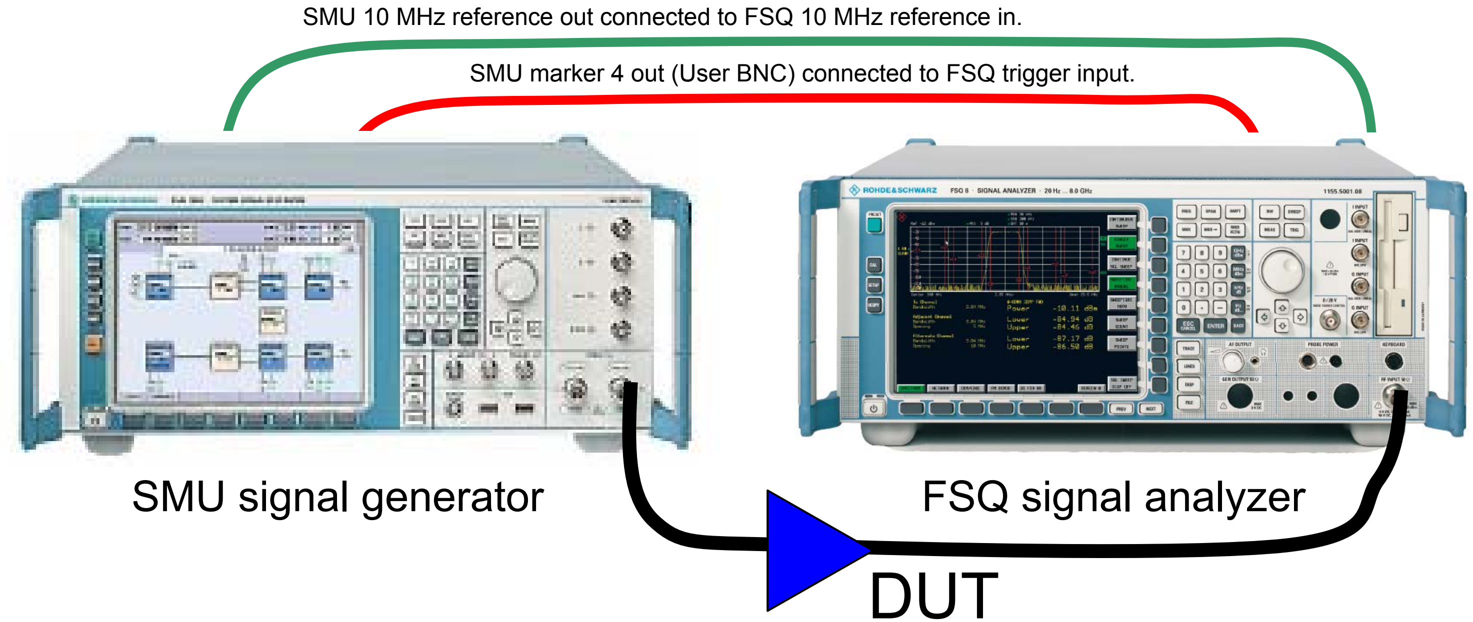
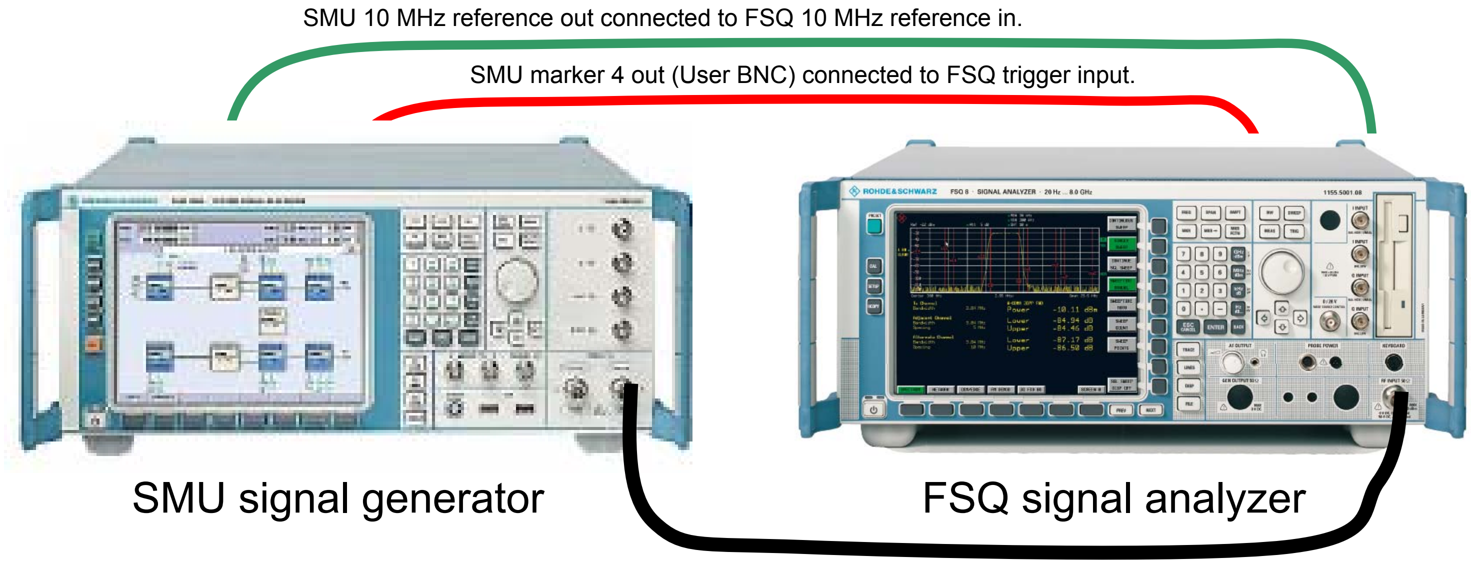
Timing method of measuring group delay

- **Use a VSG and a VSA**
- **Send a “pulse” through the DUT.**
- **Send a marker to the VSA telling it when to start timing**
- **Measure the arrival of the pulse relative to the marker**
  - Simple subtraction tells us the transit time of the pulse



Timing method of measuring group delay

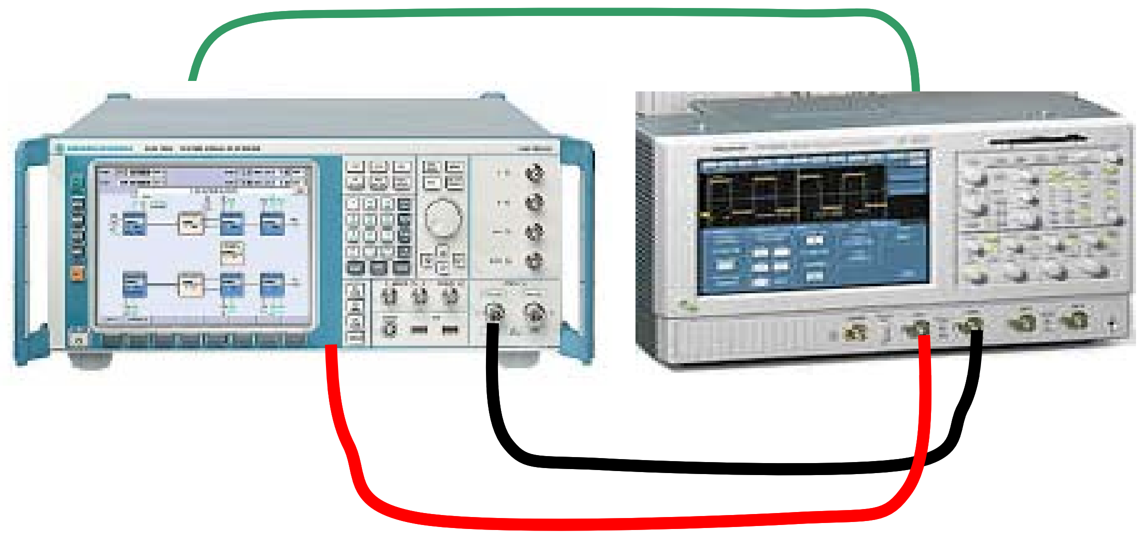
- **Cautions:**
  - This measures the delay through the test equipment ***and*** DUT
  - Normalization can be utilized to address this
    - Remove the DUT, measure the starting time delta



Timing method of measuring group delay

- **Example: Measure internal delay between marker and RF pulse on a Rohde and Schwarz SMU Vector Signal Generator**

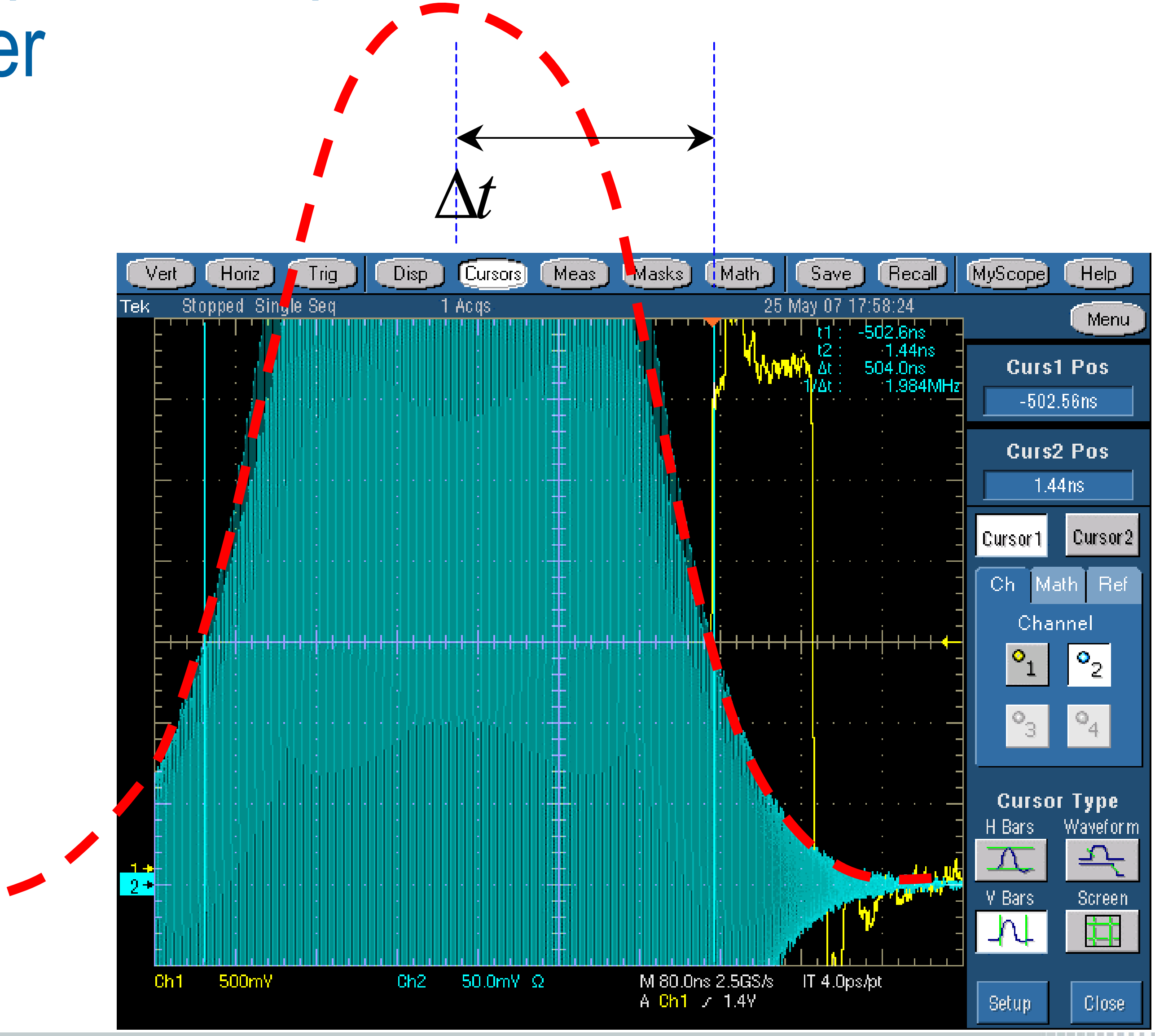
SMU 10 MHz reference out connected to oscilloscope 10 MHz reference



SMU marker 4 out (User BNC) connected to FSQ trigger input.

SMU signal generator   Tektronix TDS 5104B

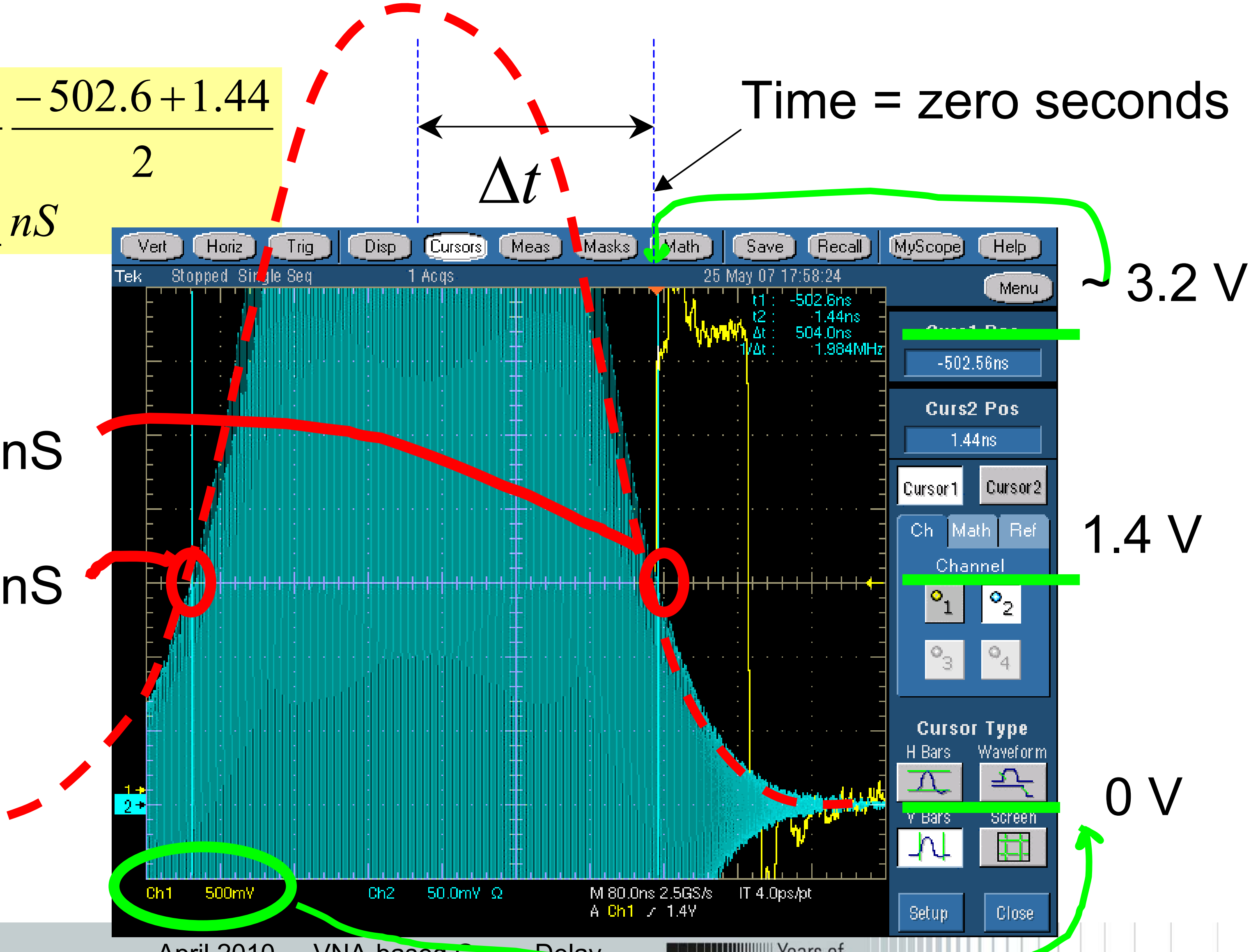
Example: Compare Arrival of Pulse and Marker



Example: Compare Arrival of Pulse and Marker

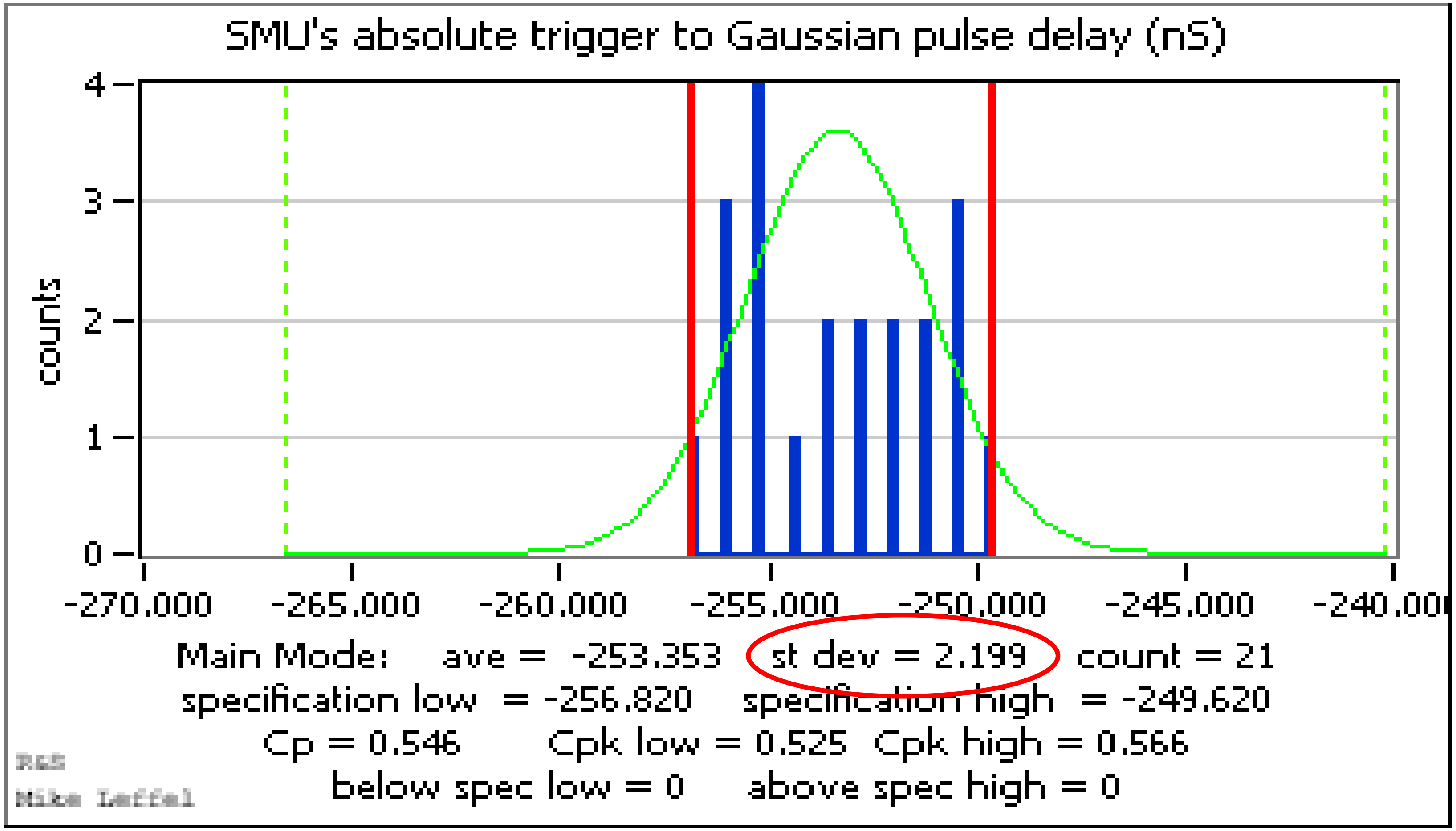
$$\Delta t = -502.6 + \frac{-502.6 + 1.44}{2}$$

$$\Delta t = -250.6\_nS$$



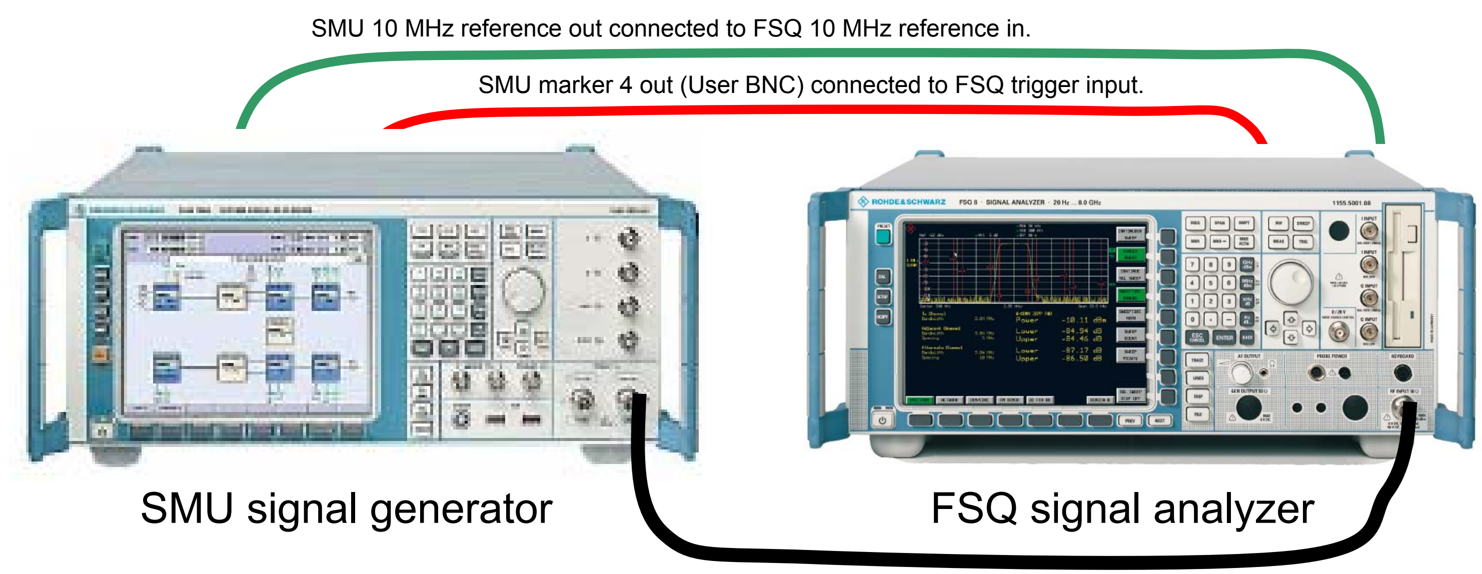
Example: Compare Arrival of Pulse and Marker

- **Results of 21 manual measurements using Tek Scope:**



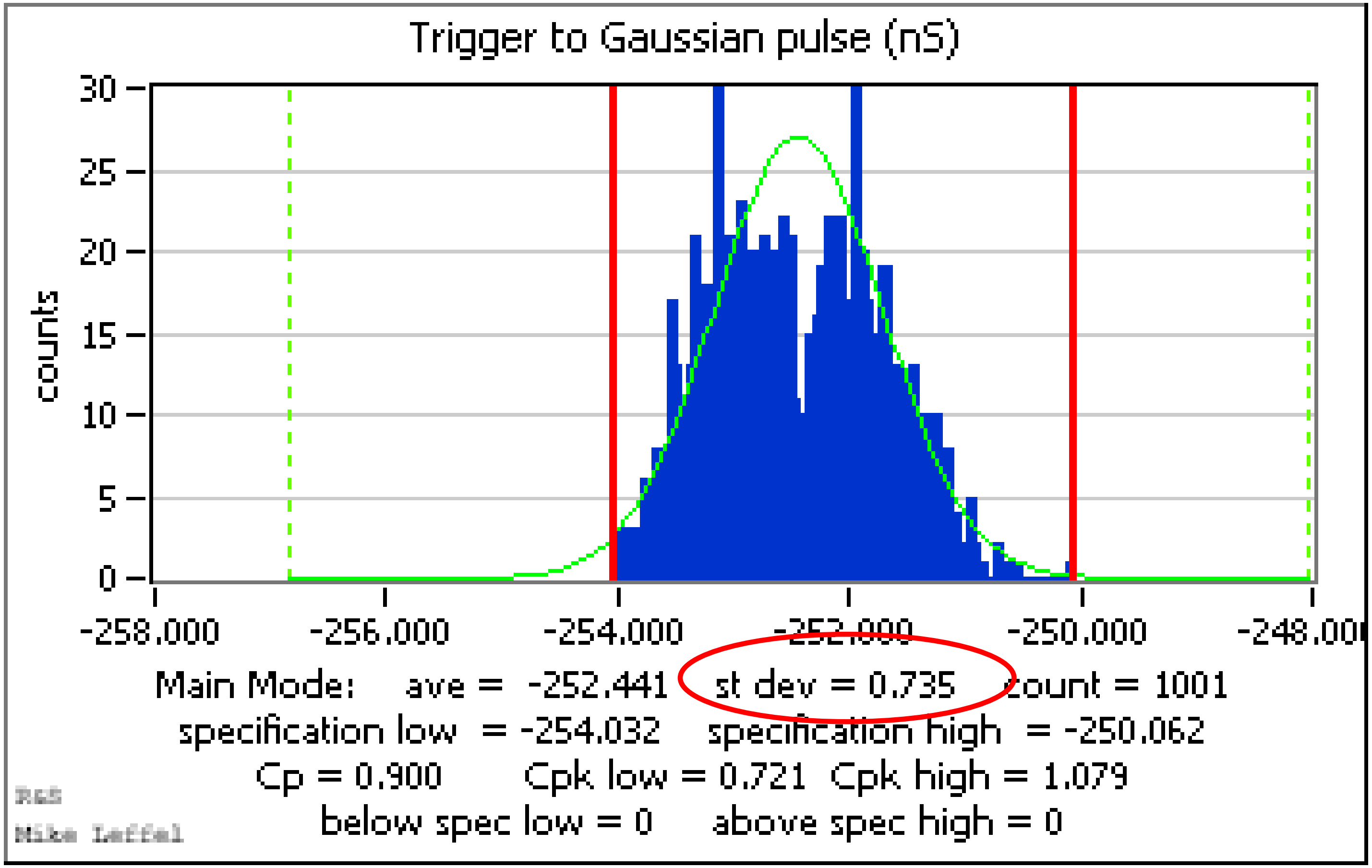
Example: Compare Arrival of Pulse and Marker

- **Now repeat the measurement using a Rohde and Schwarz FSQ.**
  - Automate it this time, manual measurements take too long.



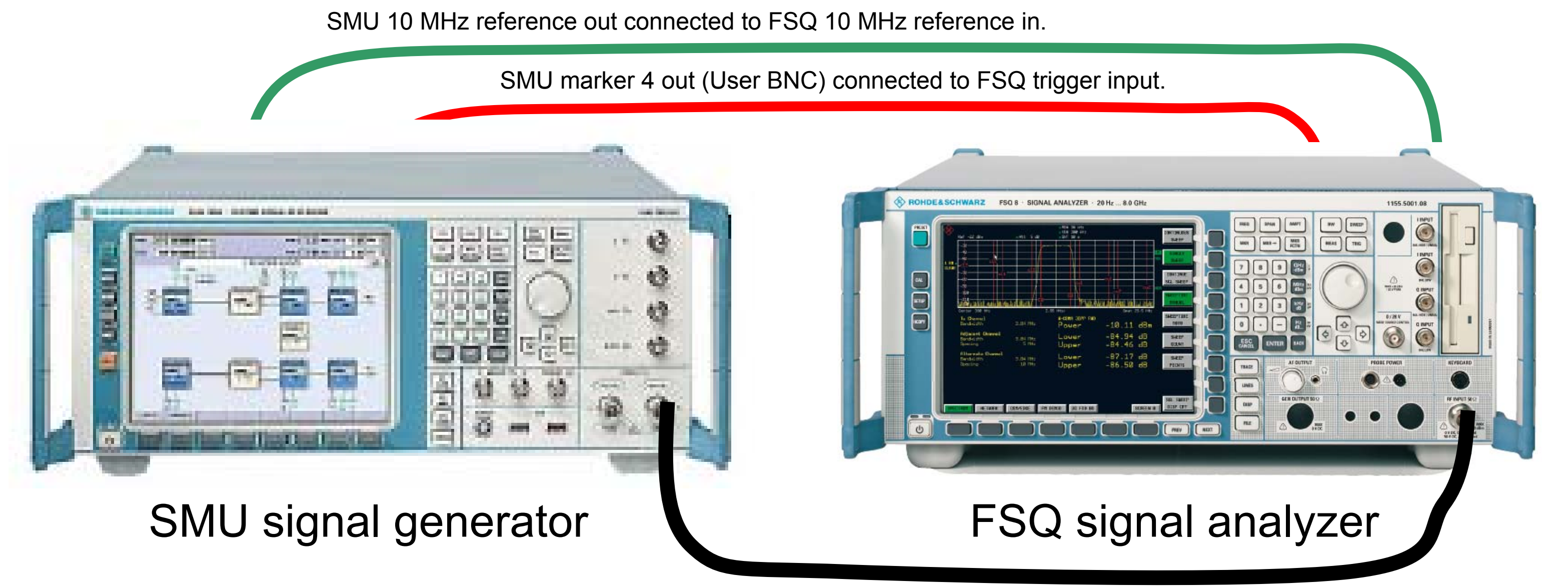
Example: Compare Arrival of Pulse and Marker

- **Results of 1001 “automated” measurements, SMU to FSQ**



Example: Compare Arrival of Pulse and Marker

- **This technique allows us to measure group delay with a standard deviation that is < 1 nS.**
- **Works well for devices that have >> 1 nS of group delay.**
- **Also works with frequency translating devices…**



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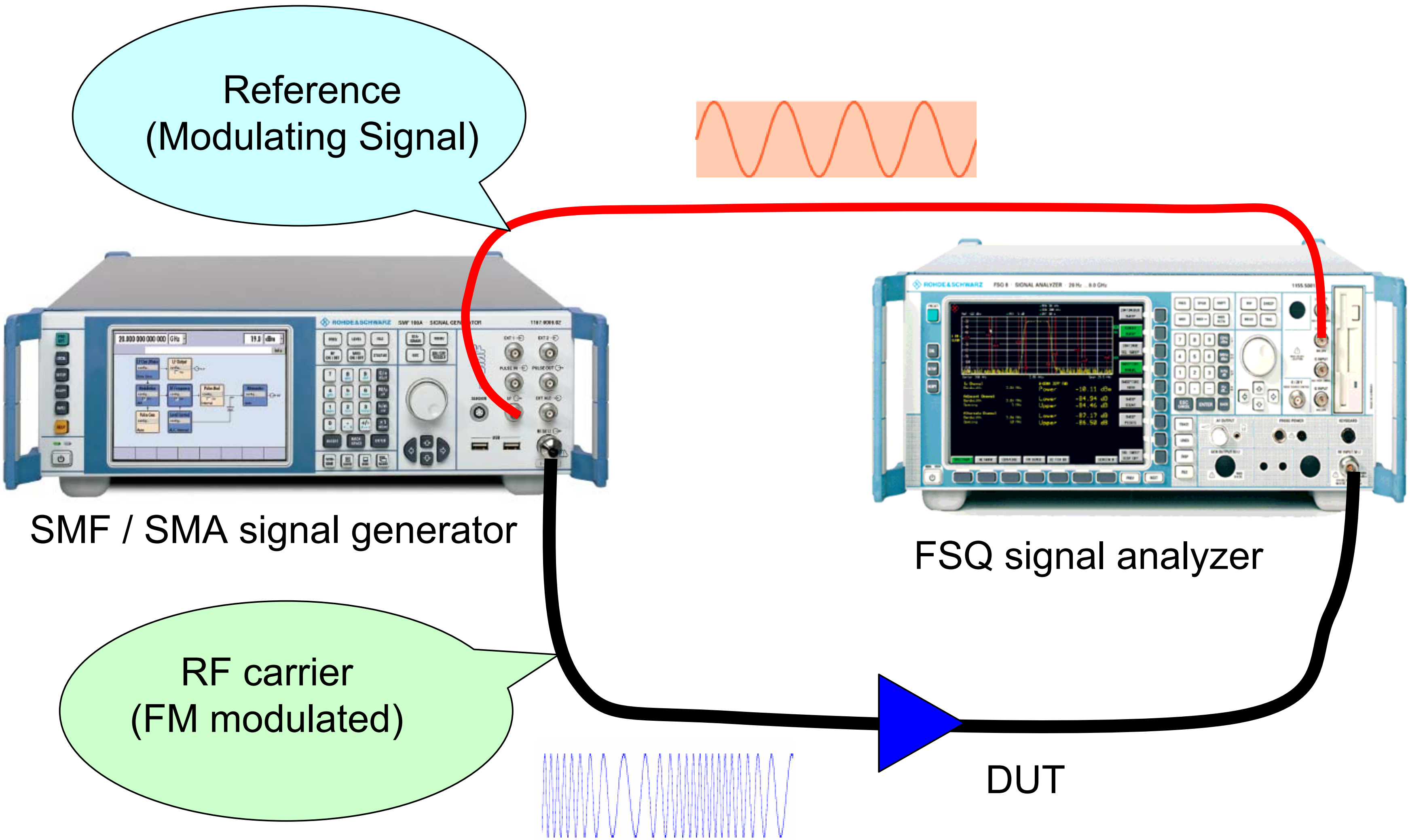
FM Modulation (envelop delay) Method



Measurement Details (envelope delay)

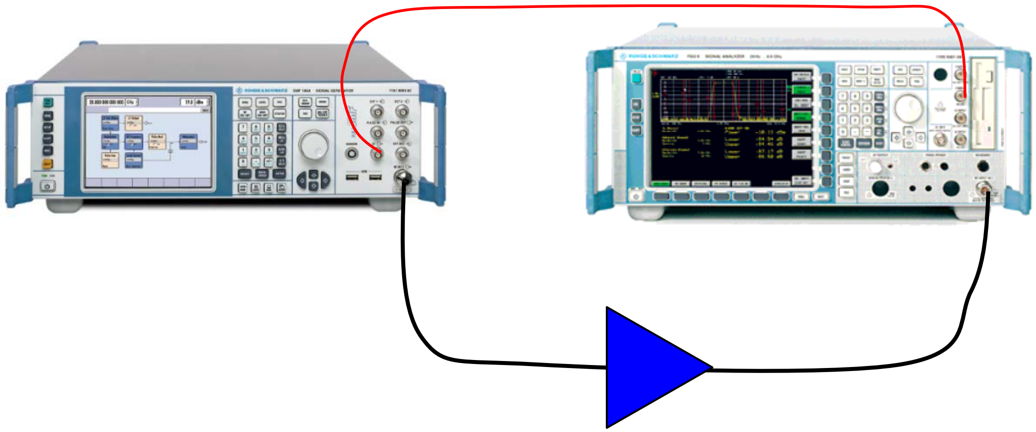
- **FSQ can capture the FM modulated carrier within its digital IF.**
  - Utilize one of the two A/D convertors

- **Simultaneously, the FSQ can capture the low frequency reference path signal, which is the modulating tone for the RF carrier.**
  - Utilize the second A/D convertor

- **These signals are captured and stored simultaneously with the same capture clock.**

- **So we can compare the arrival time of the two signals.**

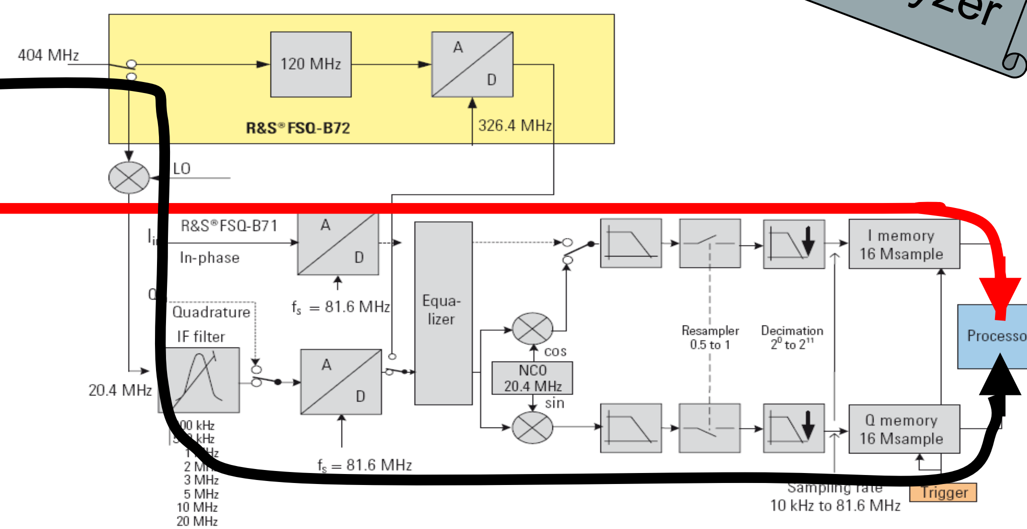
Measurement Setup



Block Diagram of the FSQ signal analyzer

RF carrier
(FM modulated)

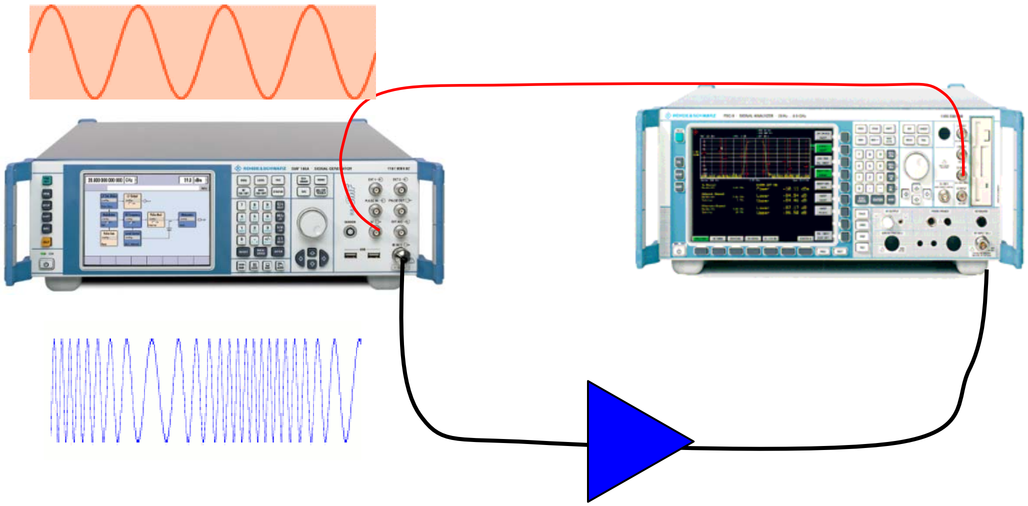
Reference
(Modulating Signal)



Block diagram of vector signal analysis section in the R&S® FSQ.

Measurement Setup

- **This is a technique that is similar to the Gaussian Pulse.**
- **We still have the ability to test frequency converting devices.**



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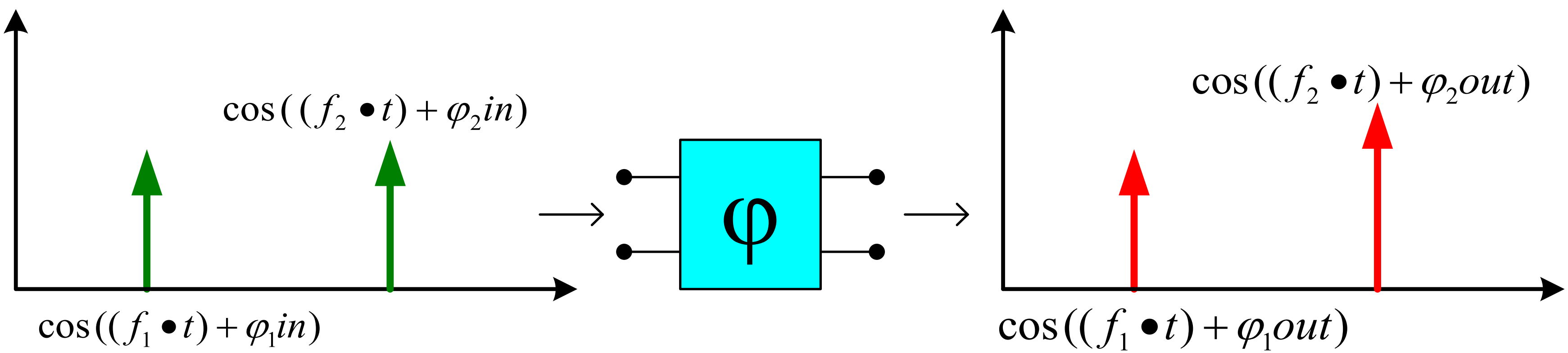
Multi-carrier technique

- **Up to now we have been “timing” the arrival of the signals as a method of measuring the “group delay” directly.**

- **An alternate approach exists if we look at the phase shift of multiple carriers across frequency instead of directly at the timing of the signals.**

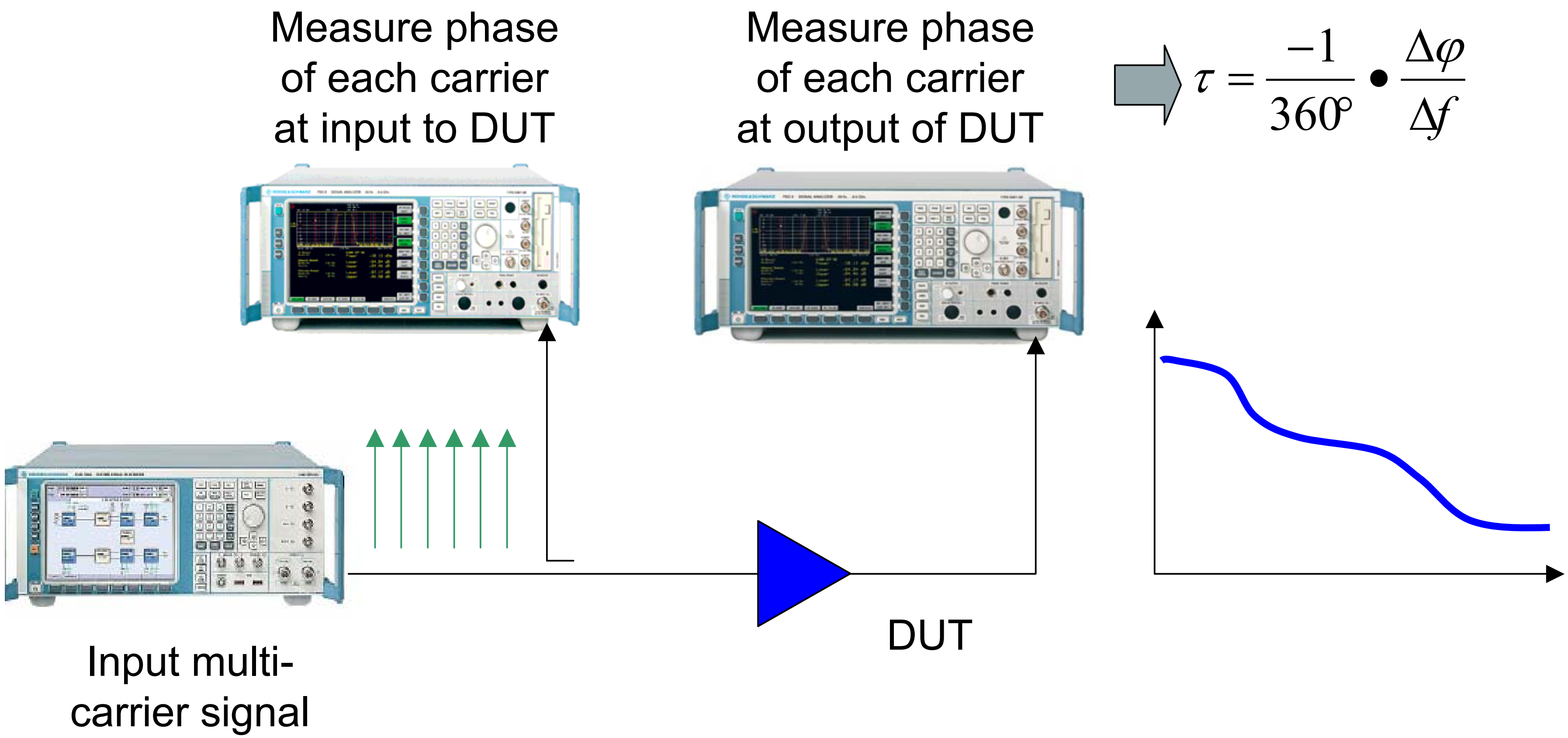


$\Delta f = f1 - f2$ $\quad$ $\Delta\varphi = (\varphi 2out - \varphi 1out) - (\varphi 2in - \varphi 1in)$

$$\tau = \frac{-1}{360°} \bullet \frac{\Delta\varphi}{\Delta f}$$

Multi-carrier technique

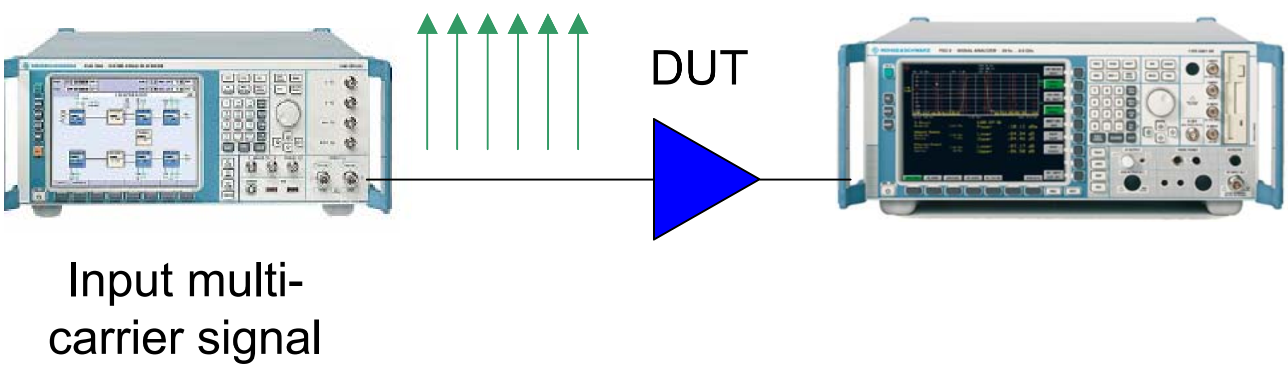
- **And we can inject more than two tones. We can use as many as we like to make a very quick wideband measurement.**



Multi-carrier technique

- **We are measuring phase shifts across frequency instead of "timing"**
- **We do not really have to measure the phase of the carriers at the input to the DUT. We can normalize the results instead**
- **Frequency converting devices are still an option**

- **But notice, no reference path or connection is needed between the input and the output of the DUT.** ***This is new. Note this, we will use it again…***



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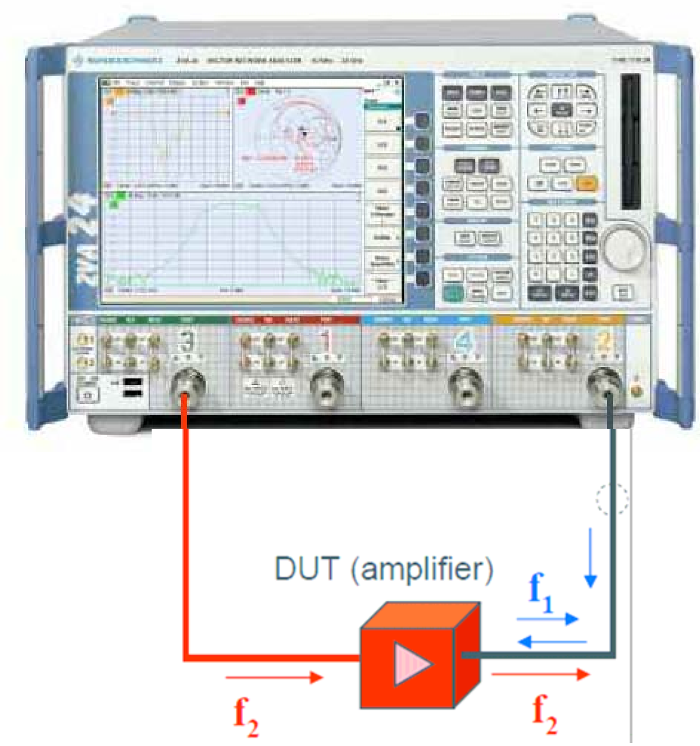
Vector Network Analyzer

- **Traditionally:**
  - A Vector Network Analyzer is an ideal instrument for making magnitude and *phase* measurements.
  - It can easily make group delay measurements.
  - It is optimized for speed.
  - Offers full error correction.

This is the instrument we have been looking for…



Vector Network Analyzer

- **So what is the drawback?**
  - Input and output frequency to the DUT have to be the same.
  - Doesn't work with mixers, amplifier harmonics, doublers, prescalers…
- **So far every other method we discussed was able to handle frequency translation…**
  - But they did not offer full error correction.

  - Of course we want to combine frequency conversion with full error correction. So let's move in that direction.

Methods of Measuring Group Delay

- **Timing**
  - Gaussian Pulse
  - FM modulation & Envelope delay

- **Multi-Carrier signal and delta phase**

- **Network Analyzer, 2 port S-parameters**

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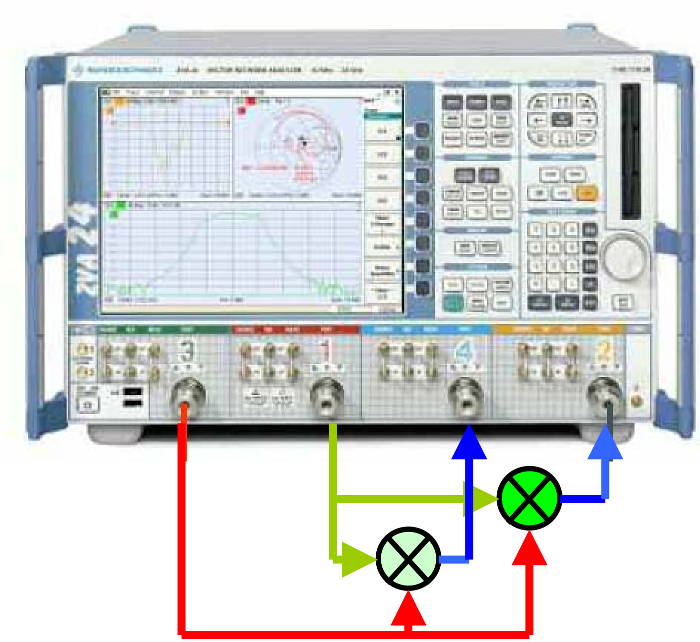
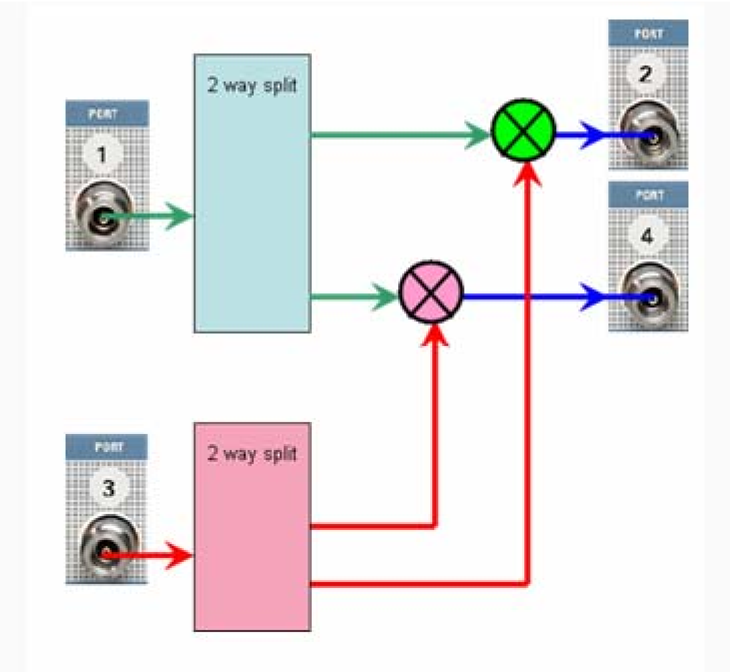
VNA plus frequency translation

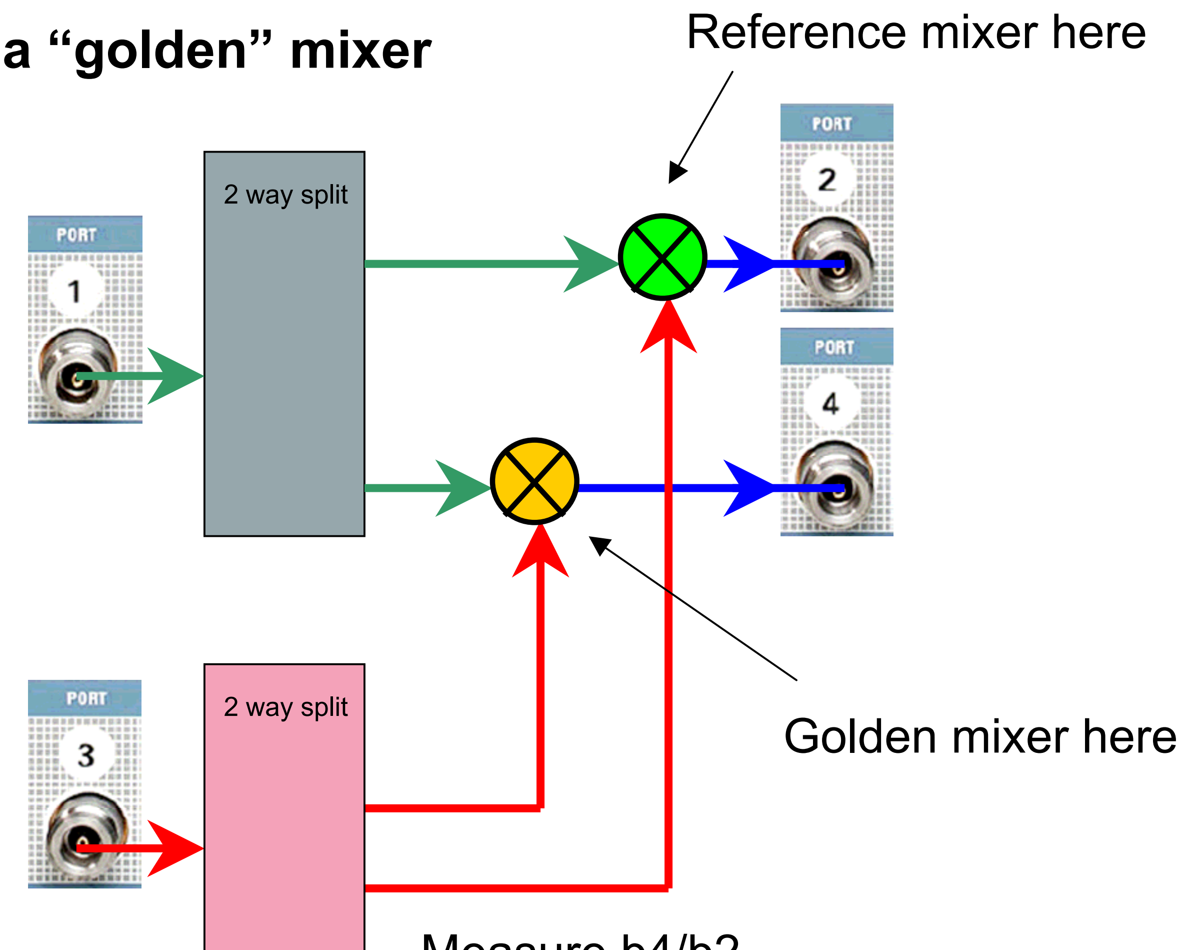
- **Add a reference (mixer) path**
  - Reference mixer provides a “phase reference” at the IF frequency.
    - As a reference path, it needs to have linear phase & flat group delay response
  - Now we can make measurements looking at phase shifts through the DUT
  - And we can calculate the group delay “relative” to the reference path.





VNA plus frequency translation

- **Calibrate with a "golden" mixer**

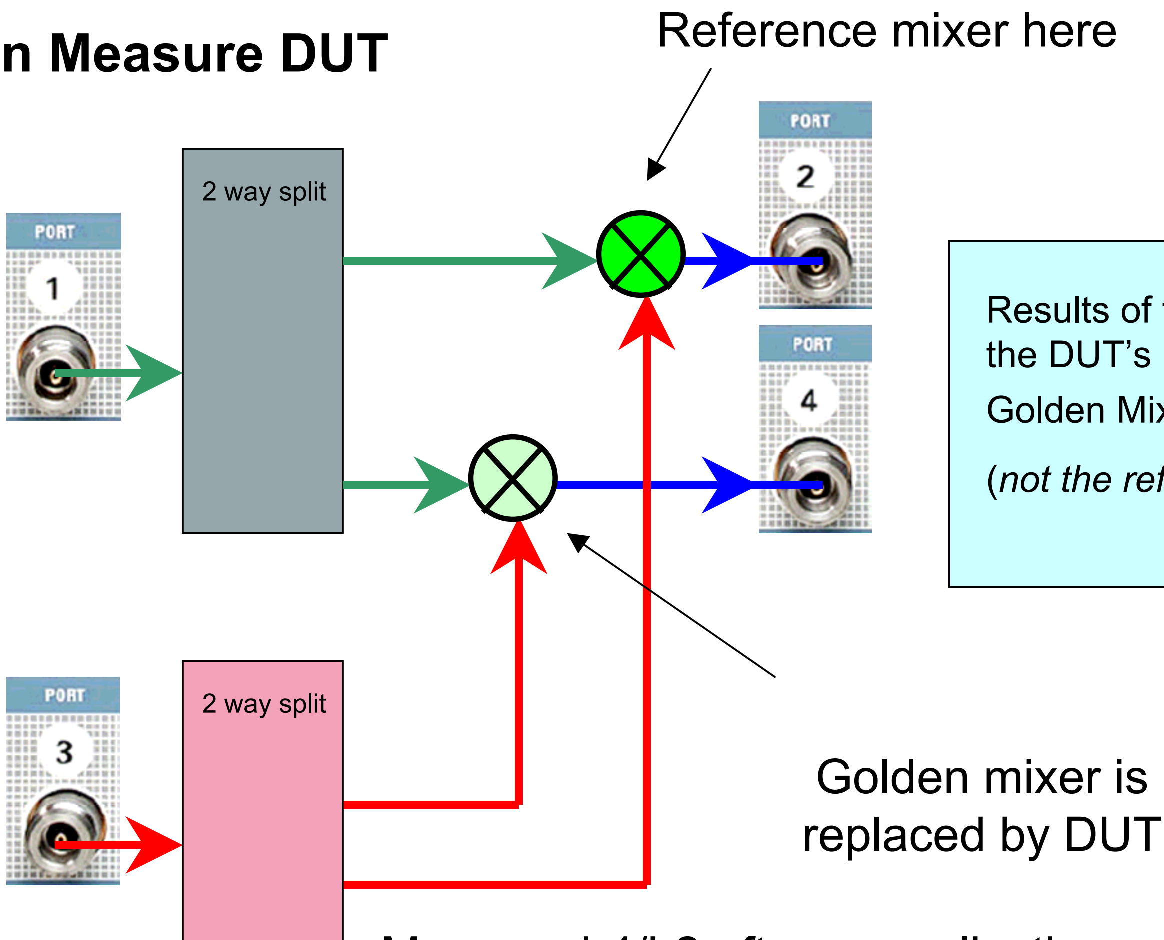


Measure b4/b2

Save the results (data -> memory)

VNA plus frequency translation

- **Then Measure DUT**



Results of the b4/b2 measurement is the DUT's performance relative to the Golden Mixer's performance.

(*not the reference mixer*…)

Measure b4/b2 after normalization

(data = data / memory)

VNA plus frequency translation

- **Drawbacks of reference mixer approach**
  - Normalized measurement, can't achieve full error correction
  - Need access to the LO of the DUT for the reference path
- **But, this is perfect for making deviation from linear phase measurements.**
  - Easy to setup, especially on a four port network analyzer.
  - Easy to normalize. Wizard available from R&S.

Methods of Measuring Group Delay

- **Timing**
  - Gaussian Pulse
  - FM modulation & Envelope delay

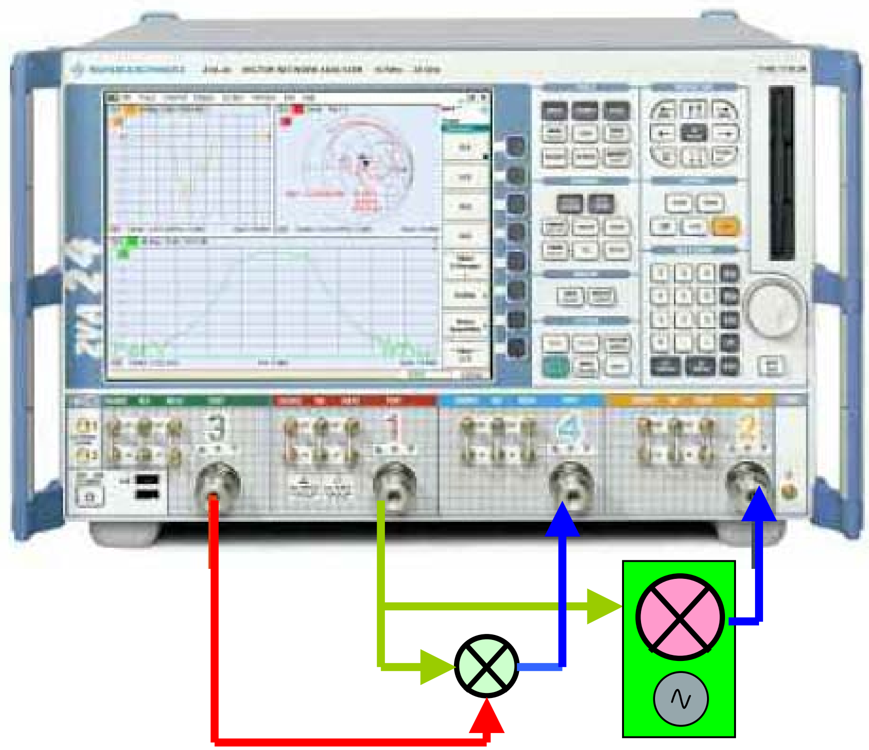
- **Multi-Carrier signal and delta phase**

- **Network Analyzer, 2 port S-parameters**

- **Network Analyzer plus frequency translation, now what?**
  - Relative measurement with reference mixer
  - **LO recovery technique for embedded LO**
  - 2 tone Network Analyzer approach for embedded LO
  - Full error correction via adaptor removal technique with a mixer
  - Full error correction via unknown through technique with a mixer

VNA plus embedded LO: LO recovery

- **Without access to the LO, one option is to create an external LO signal, and adjust its frequency until it matches the embedded LO's frequency.**
- **This can work if the embedded LO is very stable.**



VNA plus embedded LO: LO recovery

- **Drawbacks of LO recovery**
  - Normalized measurement, can’t achieve full error correction
  - LO needs to be very stable.
    - Preferably it will share a 10 MHz reference with the VNA.
  - More effort to “find” and adjust to the LO frequency.

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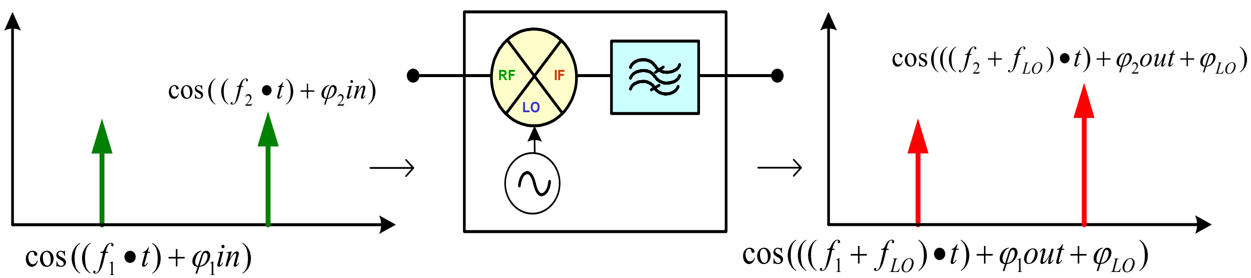
VNA plus embedded LO: two tone approach

- **Without access to the LO, a second option is to use two tones to make the measurement.**

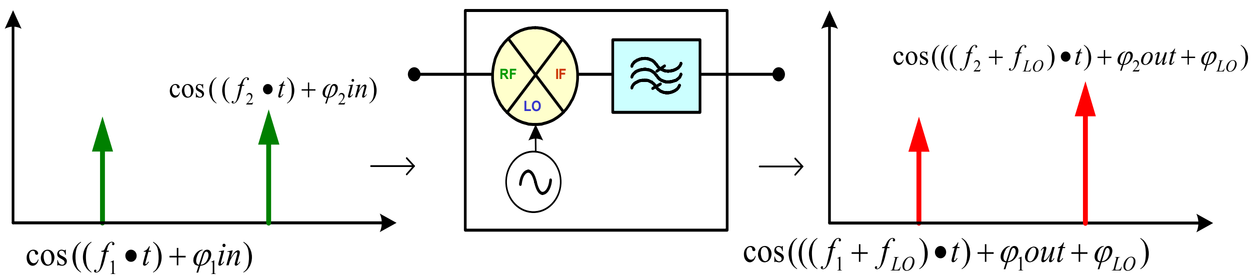


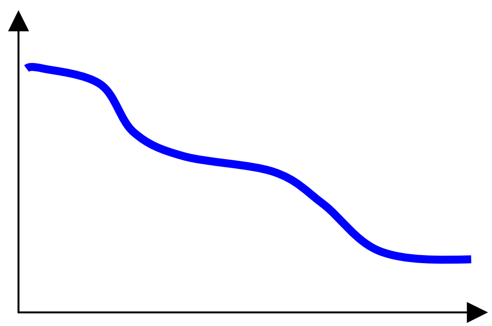
- **As before, we compare the phase of the two tones before and after the DUT. The shifts tell us the insertion phase of the DUT**

$$\Delta\varphi = (\varphi 1out + \varphi LO - \varphi 2out - \varphi LO) - (\varphi 1in - \varphi 2in)$$

VNA plus embedded LO: two tone approach

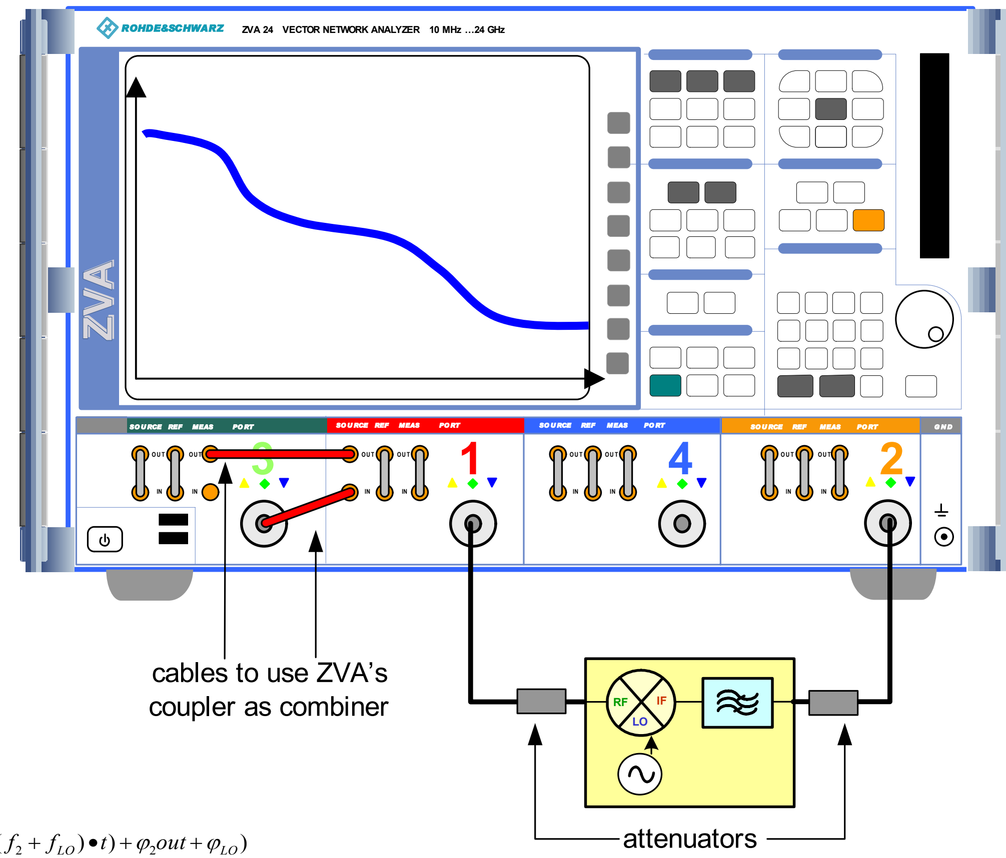
- **Technique is similar to the previously described approach using a signal generator and a spectrum analyzer.**
- **When adapted to a dual source VNA, however, it is much more compelling as a single box approach, completely automated.**

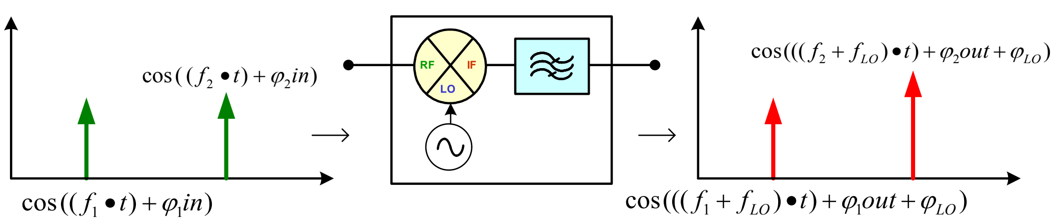




VNA plus embedded LO: two tone approach

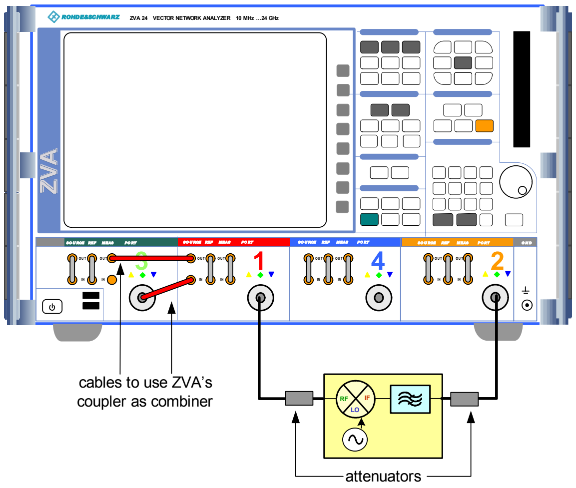
- **This approach can tolerate a large amount of LO drift.**
- **Also works very well with multiple conversion stages in the DUT.**





VNA plus embedded LO: two tone approach

- **Advantages of the two tone approach**
  - Much more tolerant of a drifting LO
  - No need to “find” and estimate LO frequency to a high degree of accuracy
  - Simple to setup and start a measurement
  - There is no “reference” path
  - Ability to measure absolute delay by using a calibration mixer



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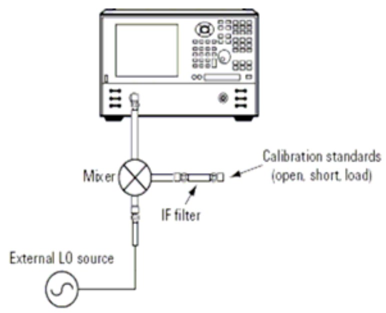
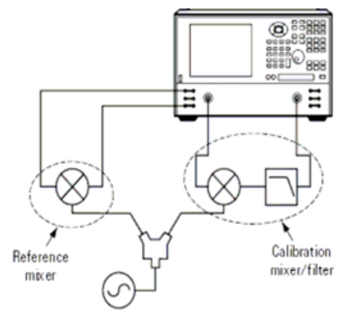
VNA plus full error correction

- **This approach uses the “adaptor removal” technique of calibration.**
- **Calibrate port 1 twice, once without the calibration mixer, a second time with it.**
  - Requires a “reciprocal” mixer
- **This provides the VNA with knowledge about the mixer so it can be “subtracted” from the calibration.**
- **One reference mixer is utilized to provide the IF with a phase reference.**



Setup to characterize the mixer



Setup to calibrate the analyzer

Methods of Measuring Group Delay

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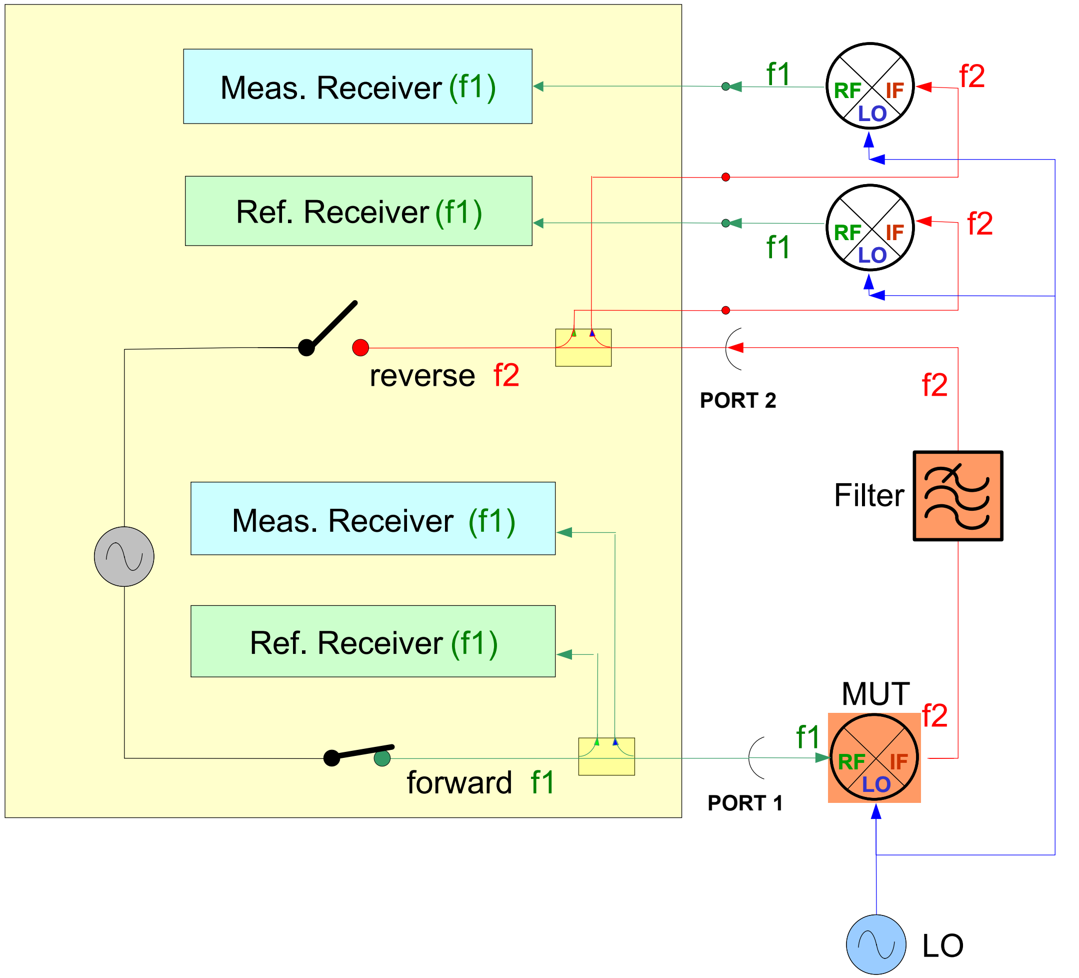
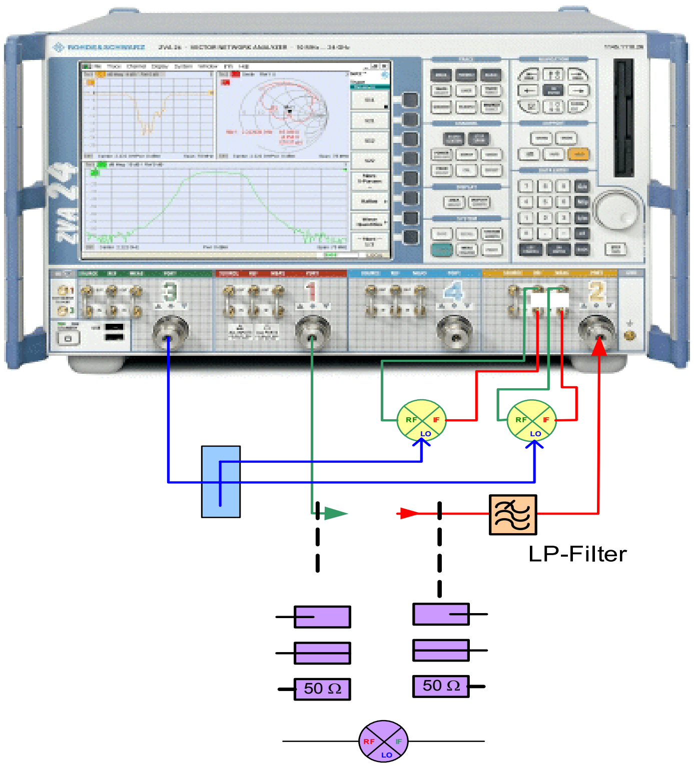
The New R&S Solution – Test Setup

- Re-conversion of IF frequency at Port 2 back to RF frequency
- Use of same LO for reconversion and for mixer under test (MUT) (eliminates LO phase and frequency shift)
- Filter to select desired IF-band

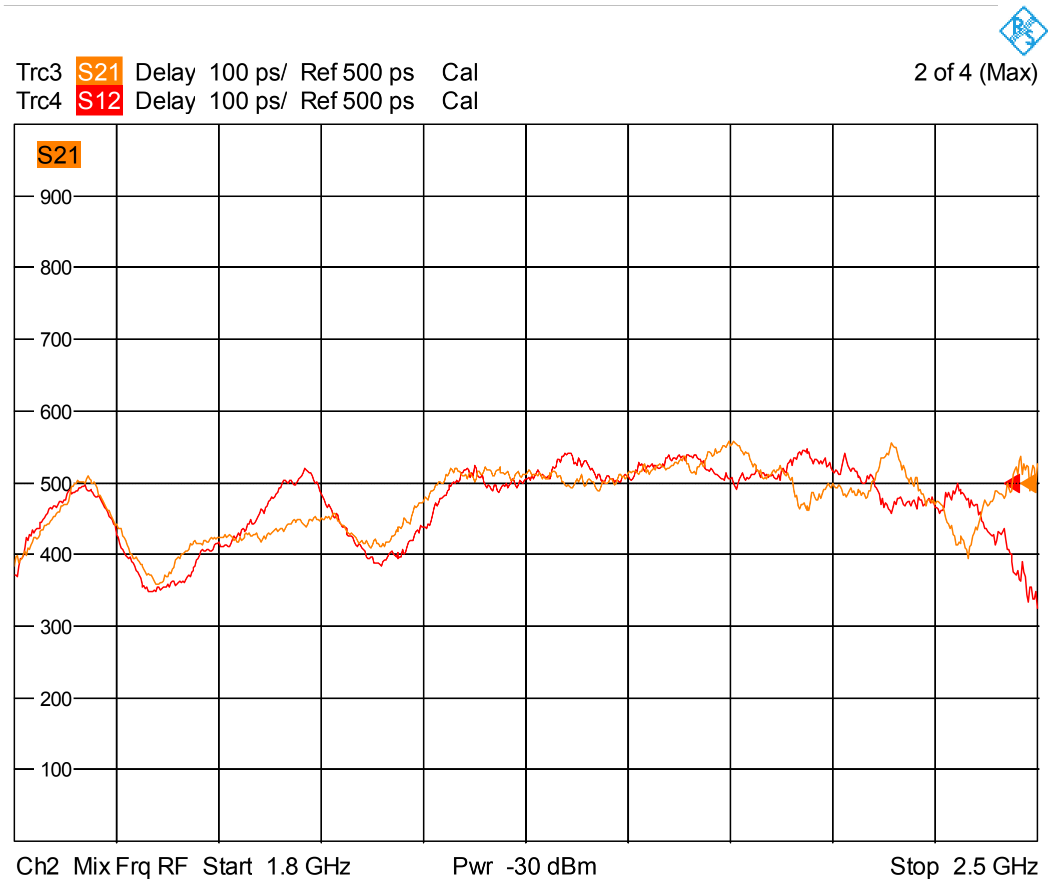


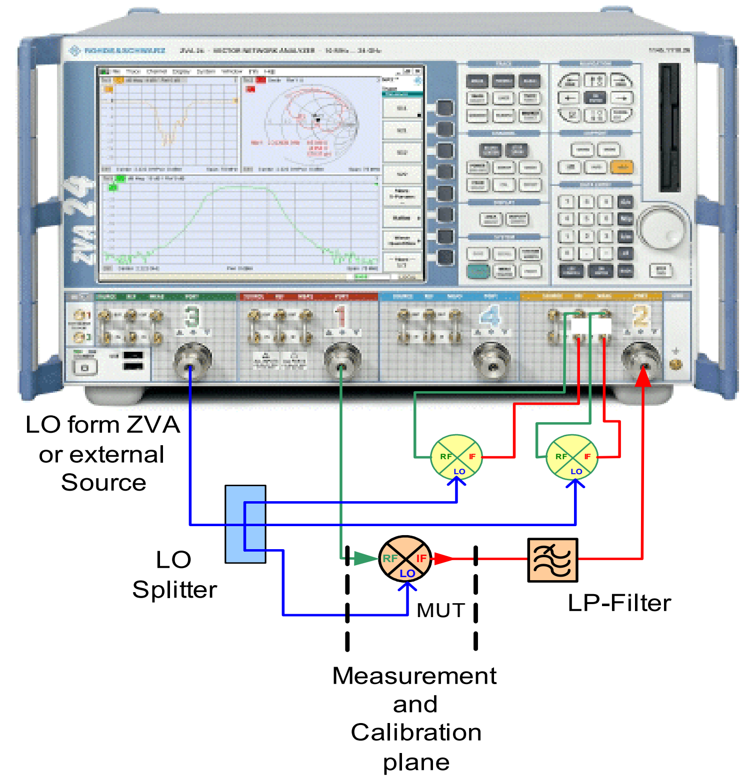
VNA plus full error correction

- **This approach uses the "unknown through" calibration technique.**
- **A pair of auxiliary mixers provide the IF receiver with a phase reference.**
- **Unknown through requires a reciprocal mixer during the "through" calibration.**



VNA plus full error correction





Methods of Measuring Group Delay

• Review of the methods

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  - Gaussian Pulse
  - FM modulation & Envelope delay
- **Multi-Carrier signal and delta phase**
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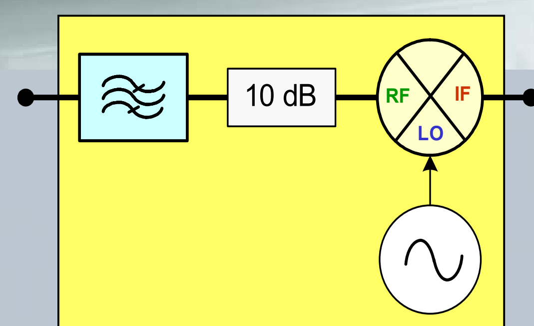
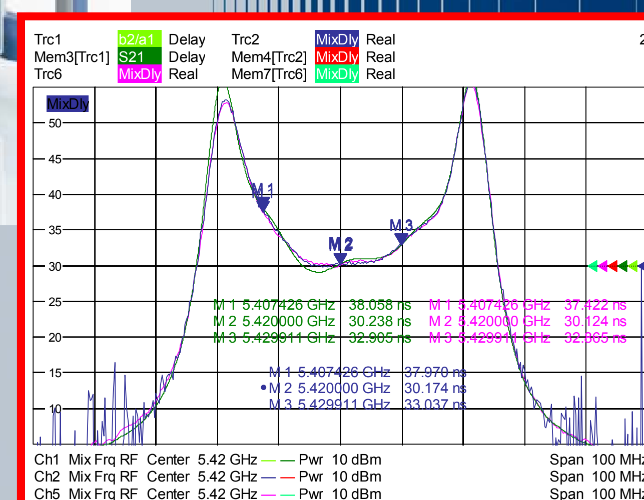
ZVA-K9: Mixer Group Delay Measurement without LO Access

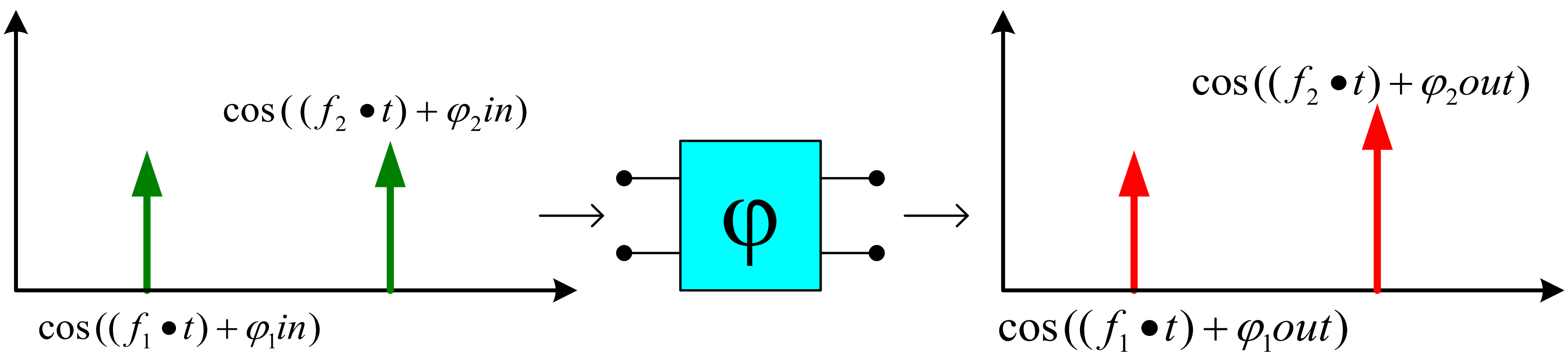




75 Years of Driving Innovation

ROHDE&SCHWARZ

Group Delay – Two Tone Method (Patent Pending)



- **Two signals at frequencies f1 and f2 injected into the DUT**
- **Phase shifts at the output due to the phase response of the DUT**

Δf = f1- f2 $\Delta\varphi = \varphi 2 - \varphi 1$

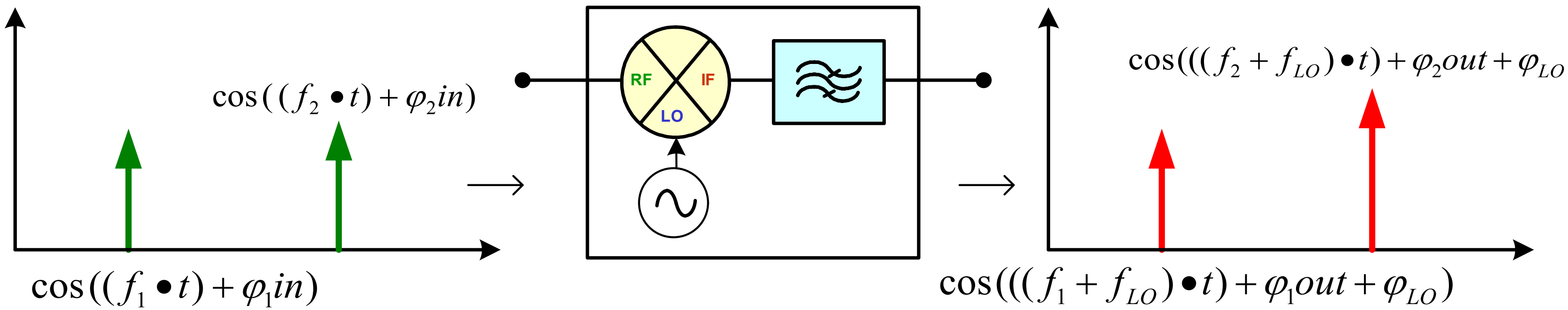
$$\tau = \frac{-1}{360°} \bullet \frac{\Delta\varphi}{\Delta f}$$

The Measurement (Patent Pending)

- **Stimulation with a two carriers f1 and f2 (=f1+Δf)**
- **Measurement of phase difference of the input signals**
  (φ1in - φ2in)
- **Phase shift of φ1out and φ2out due to the phase response of the DUT**
- **Measurement of phase difference of the output signals**
  (φ1out - φ2out)

➢ $\Delta\varphi$ = **(φ1out - φ2out) - (φ1in - φ2in)**

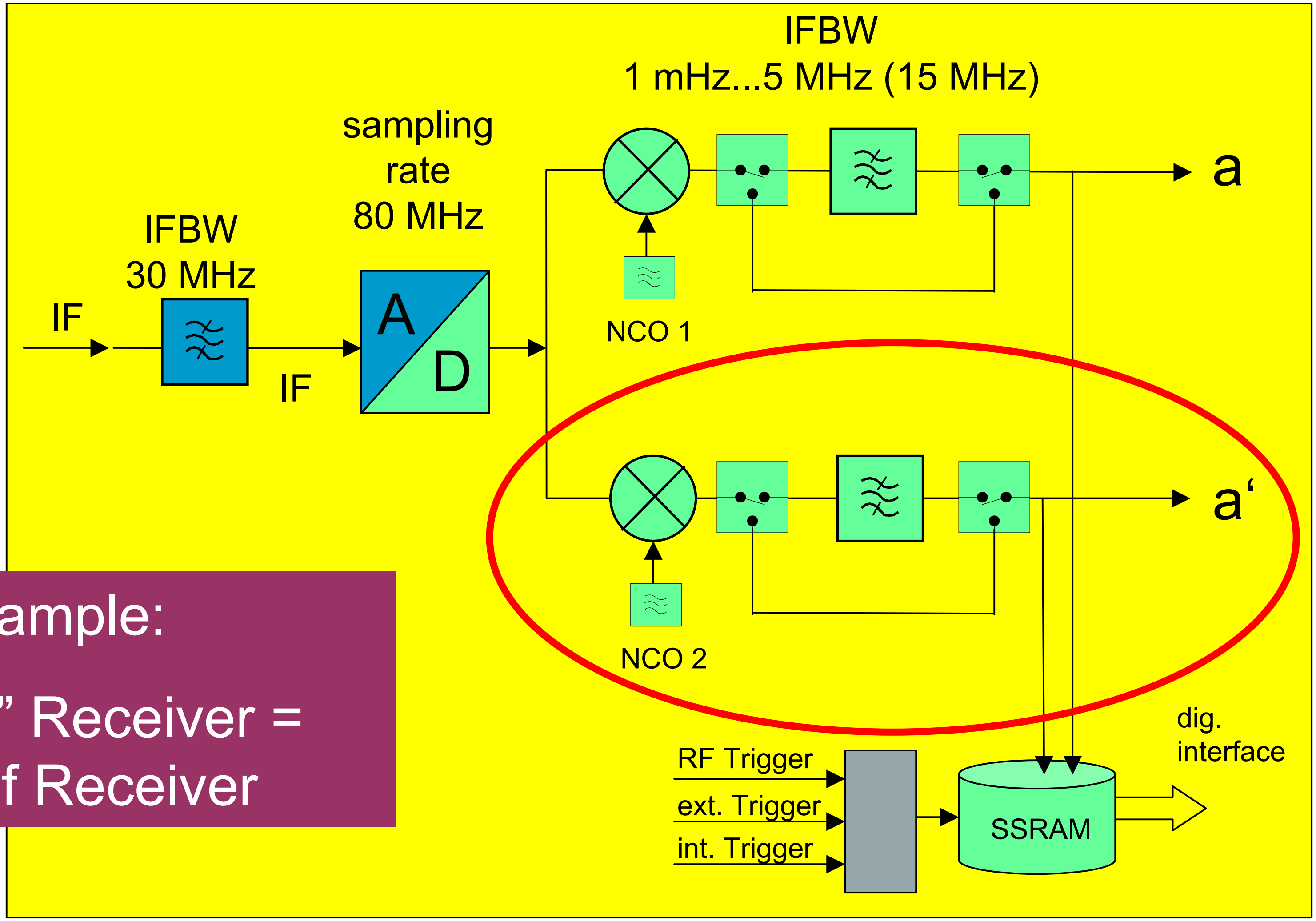
The Measurement of a Converter



- ***Any*** **LO phase is added to φ1out and φ2out by** ***same amount***
- **The** ***difference*** **of φ1out and φ2out is** ***independent*** **of the LO phase**

➢ **Δφ = (φ1out +φLO- φ2out-φLO) - (φ1in - φ2in)**

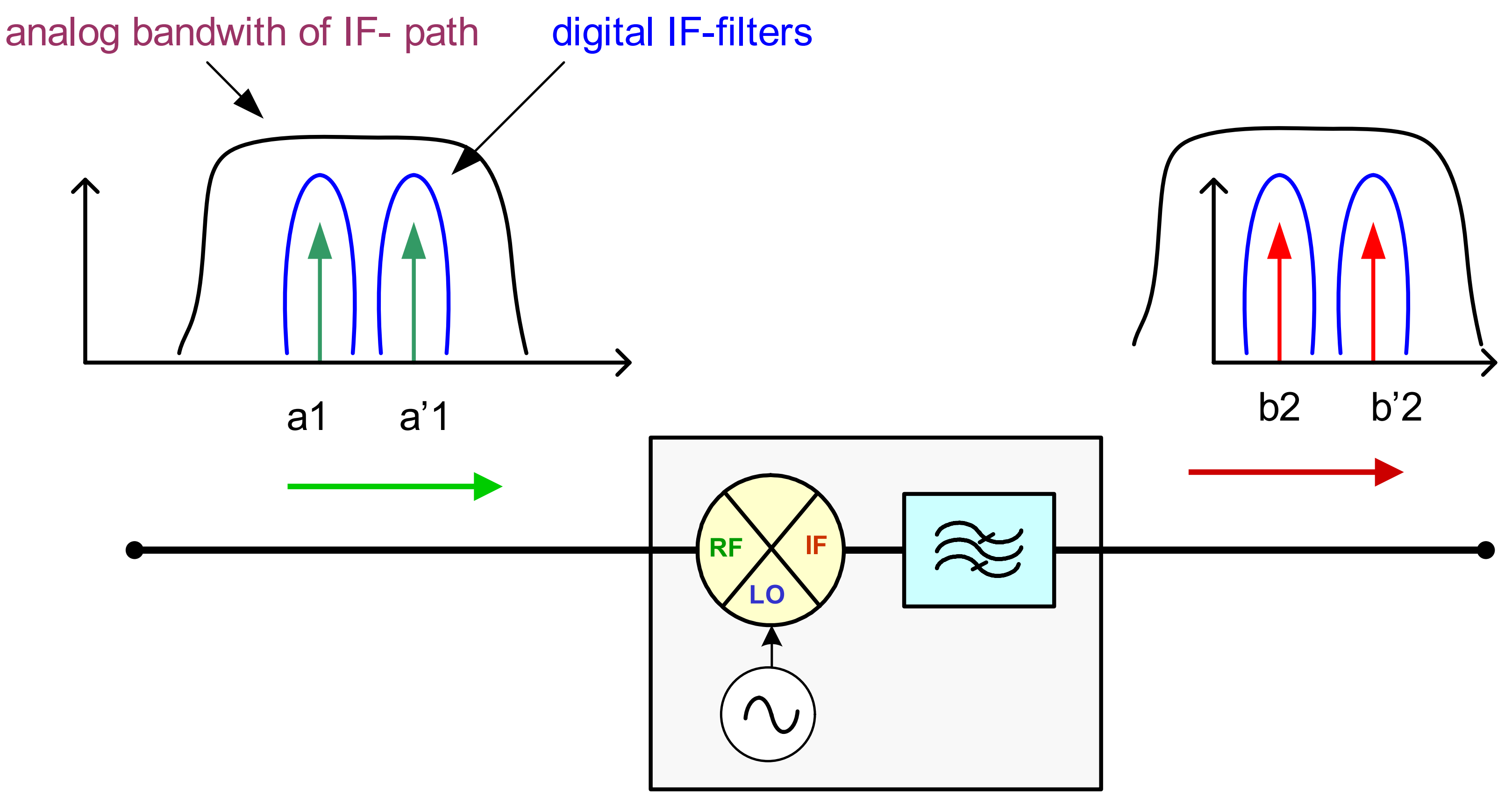
Digital *Dual* Receiver Frontend of ZVA



Example:

“a” Receiver =
Ref Receiver

Using ‘ Wave Quantities

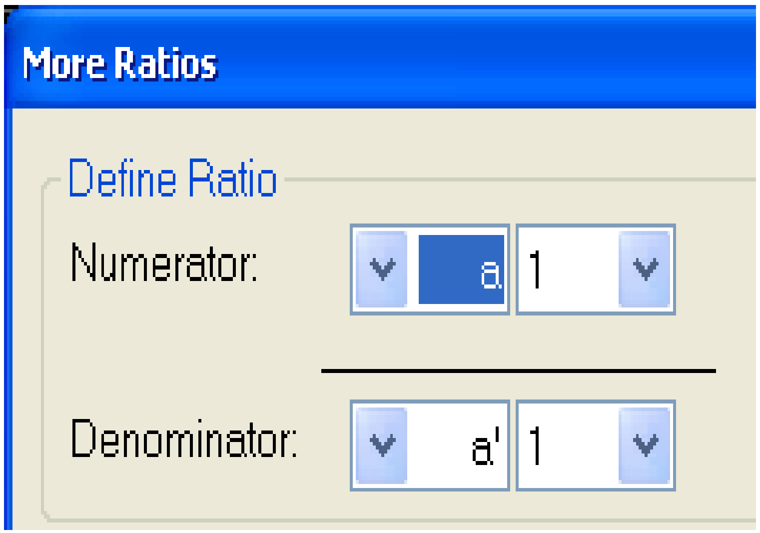


The Measurement

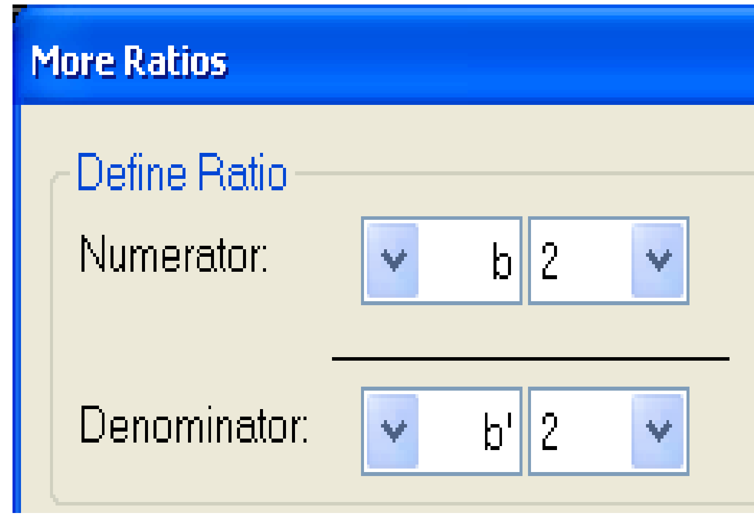
- **Measurement of phase difference (φ1in - φ2in) of both input signals with dual receiver frontend of Port 1**
  - Analog down conversion to IF (20 MHz) with LO2 (=LO1-LO) (to measure f1 and f1+df)
  - Digital down conversion to IF (0 Hz) with 2 numeric controlled oscillators (NCO), frequency offset = df

- **Measurement of phase difference (φ2out- φ2out) of both input signals with dual receiver frontend of Port 2**

Accessing ‘ Wave Quantities for Measurement

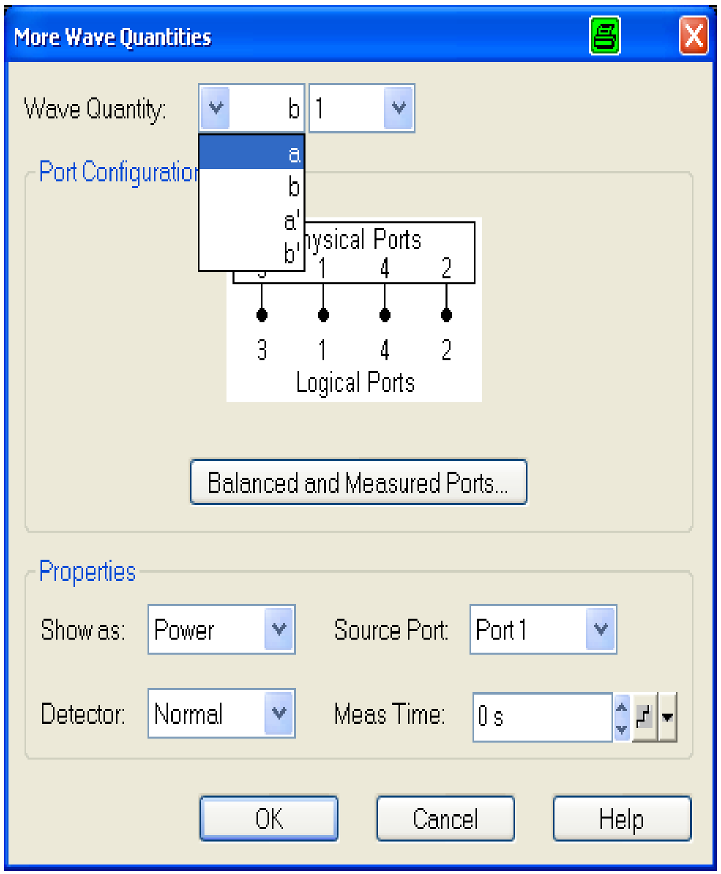


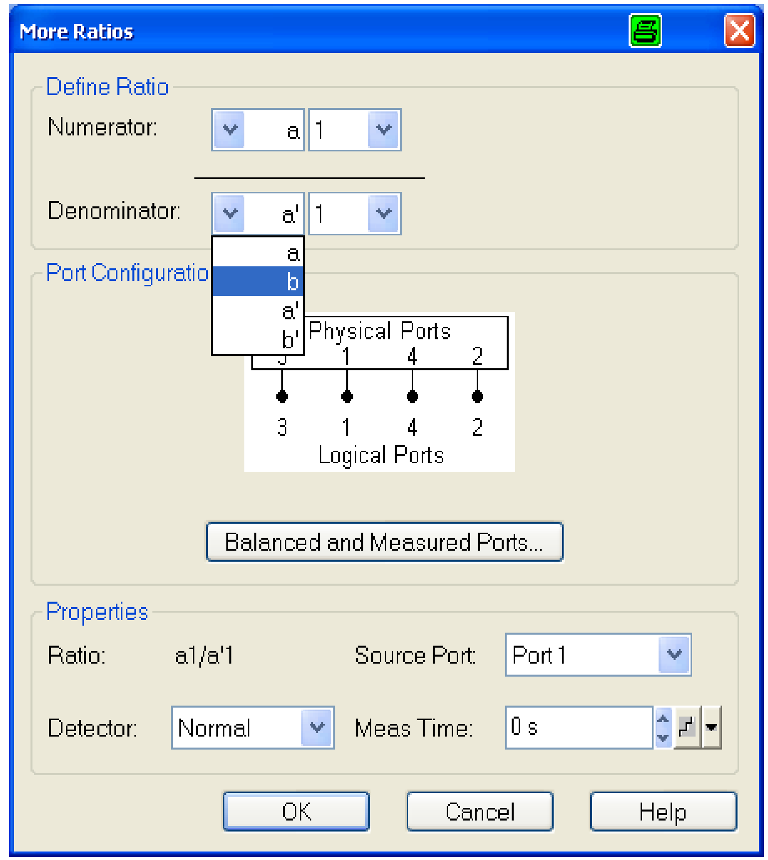
(φ1in - φ2in)



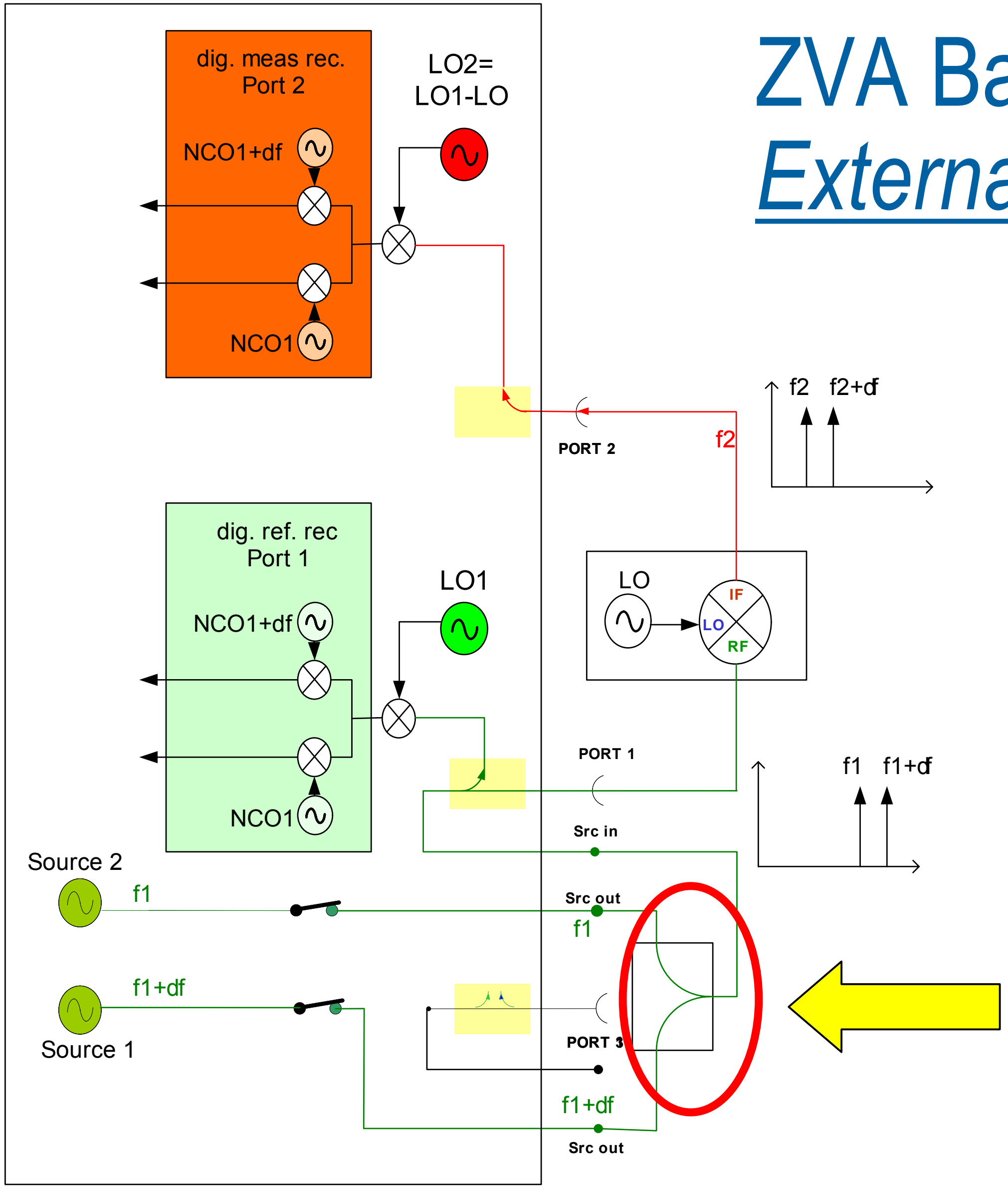
(φ1out - φ2out)

Wave Quantities and Ratios

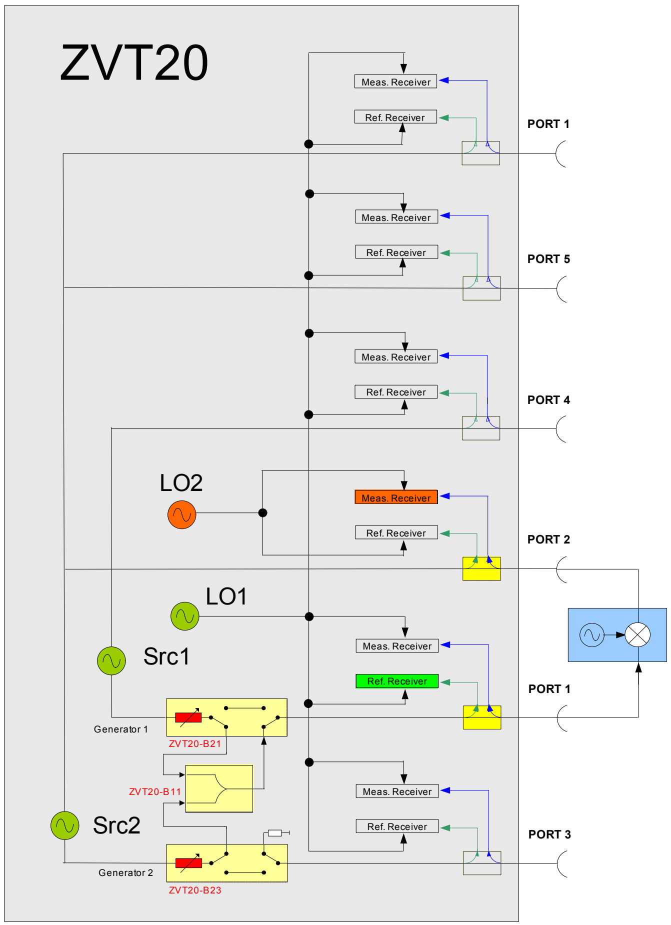




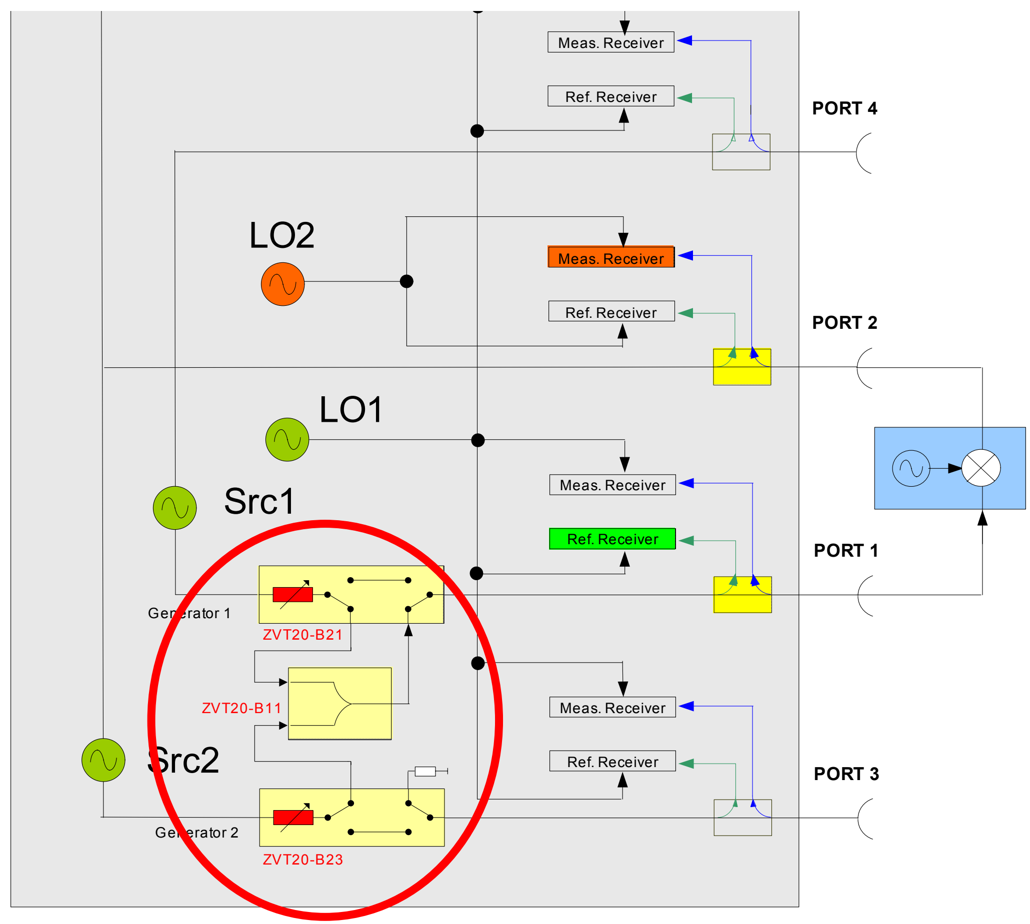
ZVA Basic Test Setup: *External* Power Combiner



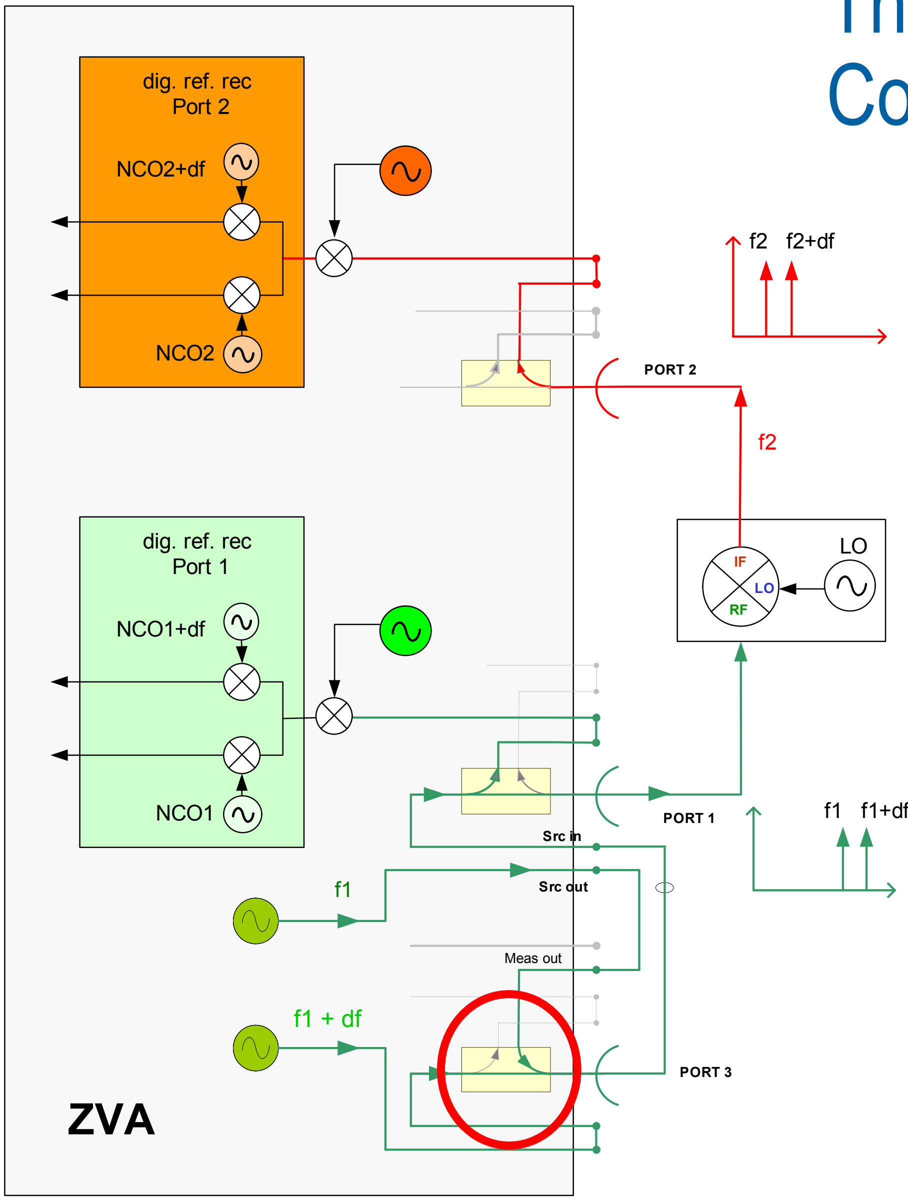
The ZVT20 Setup (with Internal Combiner)



Close-up View:



The ZVA Setup with Internal Coupler (as Combiner)

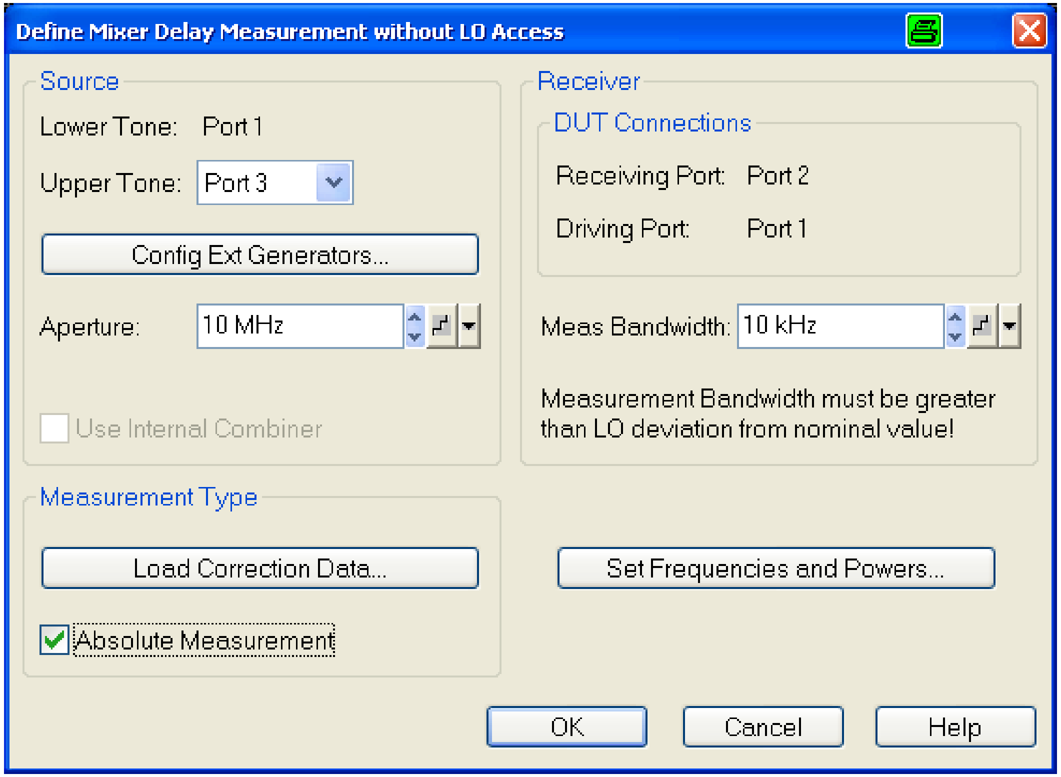


Note: This Setup *NOT* recommended for low-freq IF upconverters (70, 140 MHz) due to Coupler Loss

Calibration

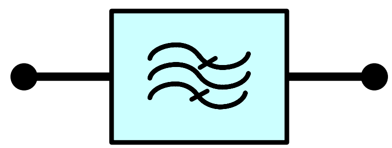
- **Calibration with known Cal Mixer**
- **Calibration with ideally assumed Cal Mixer e.g. ZX05-153 (400 ps delay)**
- **Normalization at RF frequency**

The User Interface



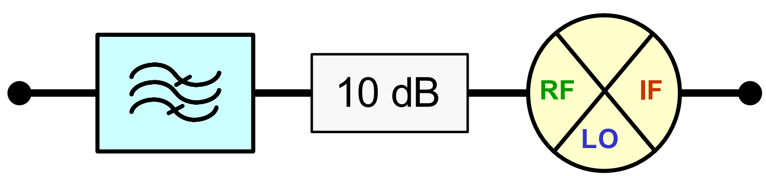
Verification

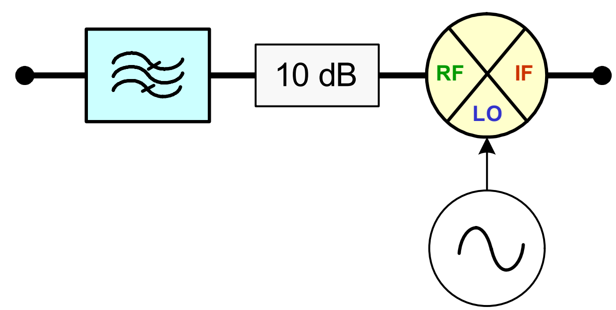
1. Measurement of group delay of the filter without mixer using full two port calibration



2. Measurement of converter (mixer + attenuator + filter)

- Attenuator to avoid that mismatch influences the transmission behavior due to mixer mismatch
- Attenuator has about 40 ps of group delay





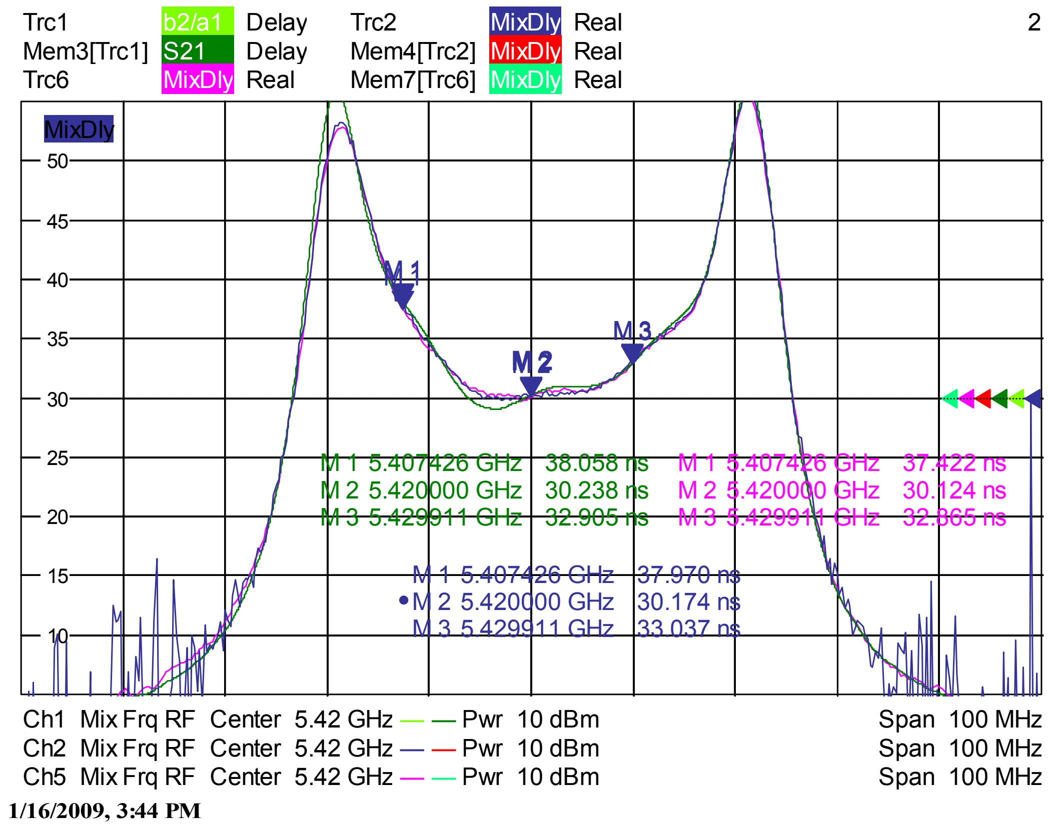
Measurement Result

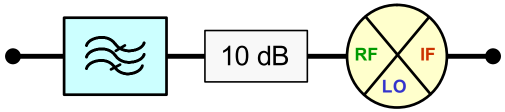
Green:

Filter without mixer (2-port cal)

Blue:

Converter with calibration with linear mixer





Advantages

- **Independent of drift of internal LO**
  - LO has only to be within the IF bandwidth of the ZVA
- **Independent of LO phase noise**
  - Cancelled out because it acts on both carriers the same way
- **Ideal for converters with multiple mixer stages**
- **Independent of thermal drift of test equipment**
  - Only relative measurements
  - Interesting for measurements in thermal chambers
- **No additional external components necessary**
  - Instead of using an external combiner, the internal coupler can be used as well.

Non-Linear VNA measurements

- **The VNA can now do it all**
  - Harmonics of a signal
  - Compression: AM/AM, AM/PM and AM/DM distortions
  - Two tone intercept points, 3rd and 5th order distortion
  - S-functions: Generalized non-linear S parameters
  - Dynamic Range: Measure Noise Figure and TOI

- **No limitations to the type of DUT**
  - Measure amplifiers
  - Mixers
  - Doublers
  - Triplers

Required ZVA Configuration:

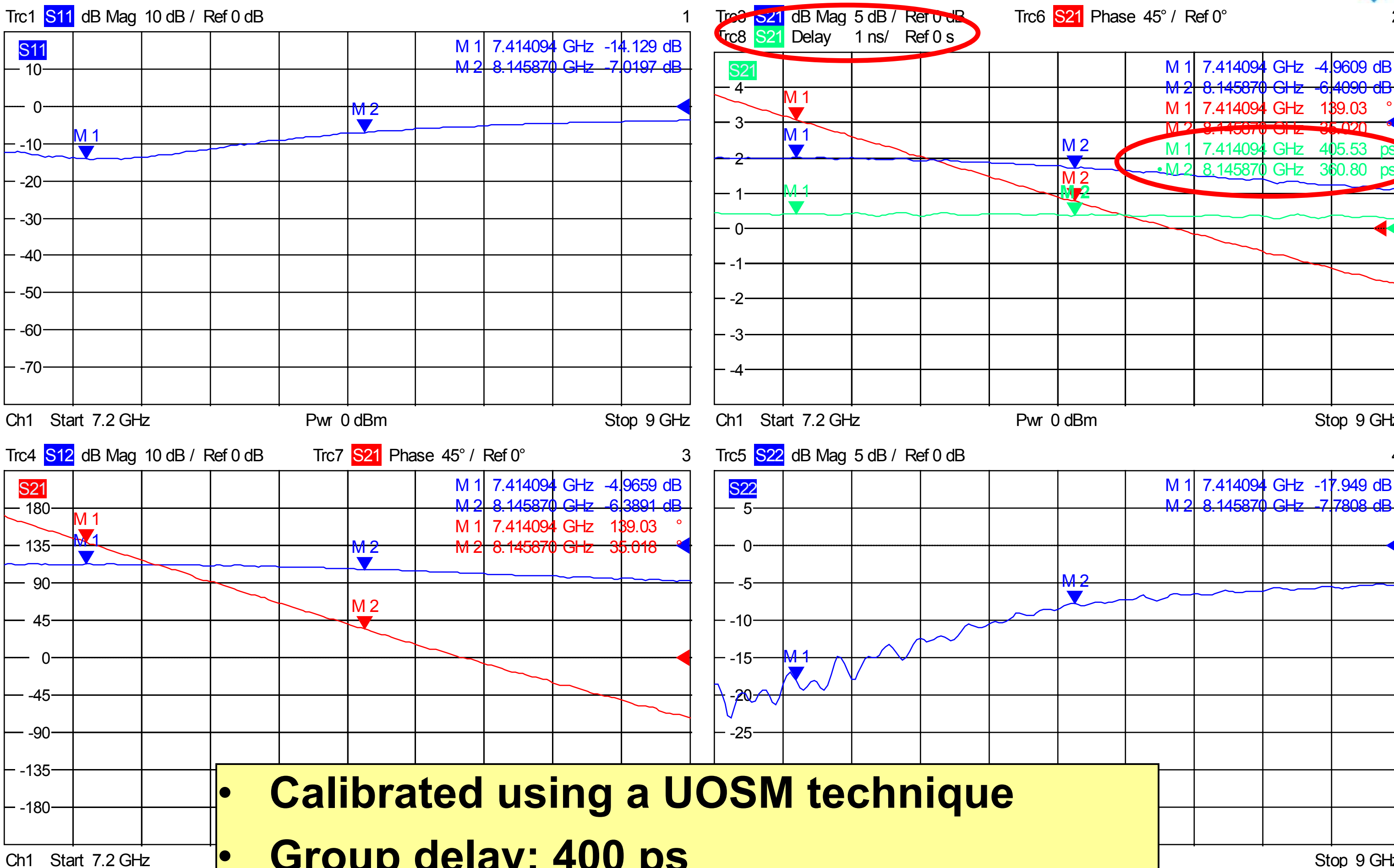
• **R&S network analyzer with 4 ports**	**ZVA or ZVT**
• **Direct generator receiver access**	**ZVA-B16**
• **Frequency conversion**	**ZVA-K4**
• **Mixer group delay without LO access**	**ZVA-K9**

Conclusions

- **A number of different techniques have been employed for making group delay measurements**

- **The new VNA method derives from established techniques, but makes the measurement task much easier, particularly for frequency-converting devices without LO access**

Calibration Mixer



- **Calibrated using a UOSM technique**
- **Group delay: 400 ps**
- **GDL Ripple: 180 ps (Pk-Pk)**