UNCERTAINTY IN AOA CALIBRATION AND SIMULATION

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ROHDE&SCHWARZ

Make ideas real

AGENDA

- RWR Antennas
- Interferometry
- Measuring & Correcting Errors
- Source of Errors
- Using a ‘scope to Calibrate Errors
- Using a VNA to Calibrate Errors
- Scaling to Higher Channel Counts
- Summary

TYPICAL RWR ANTENNA INSTALLATION, AS SHOWN ON THE U-2R AIRCRAFT

RWR Antennas

Note:
4 Wing-tip antennas
Mounted at look angles of:
45°, 135°, 225°, and 315°

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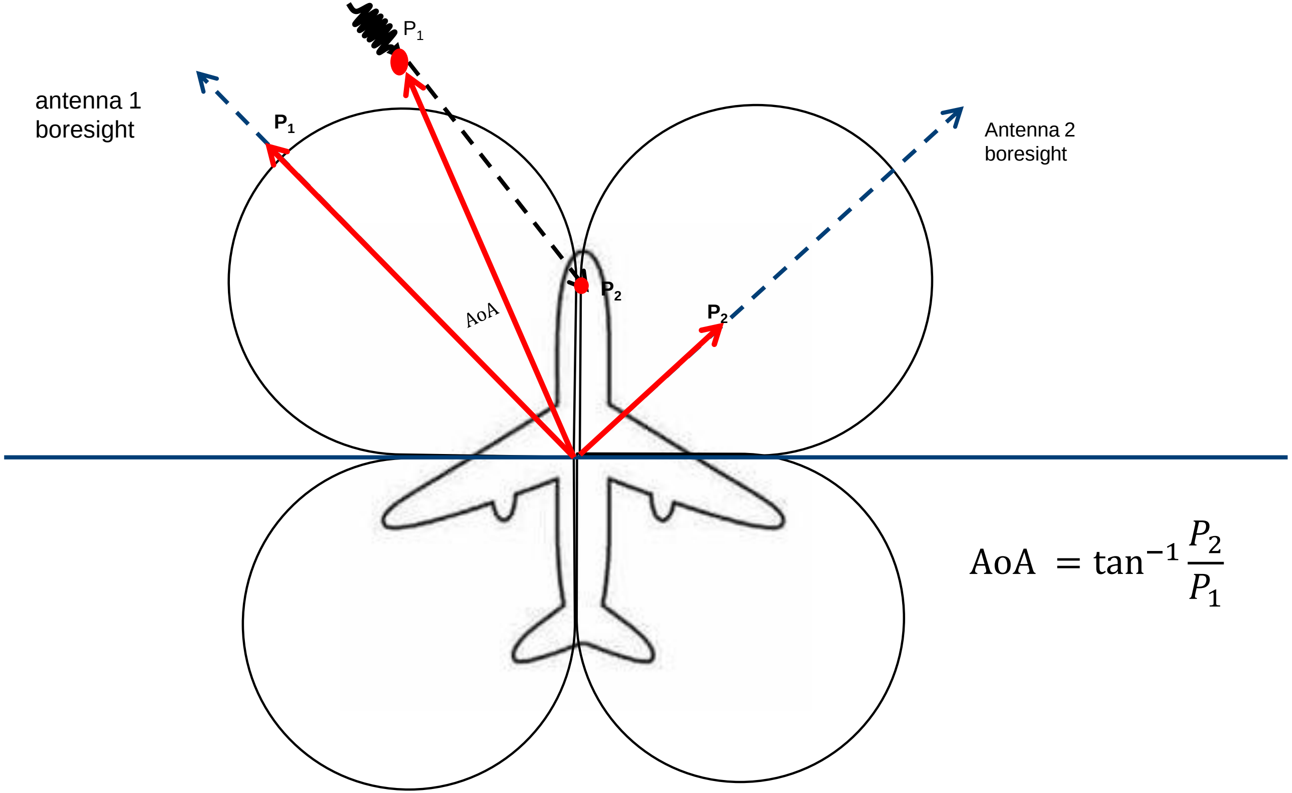
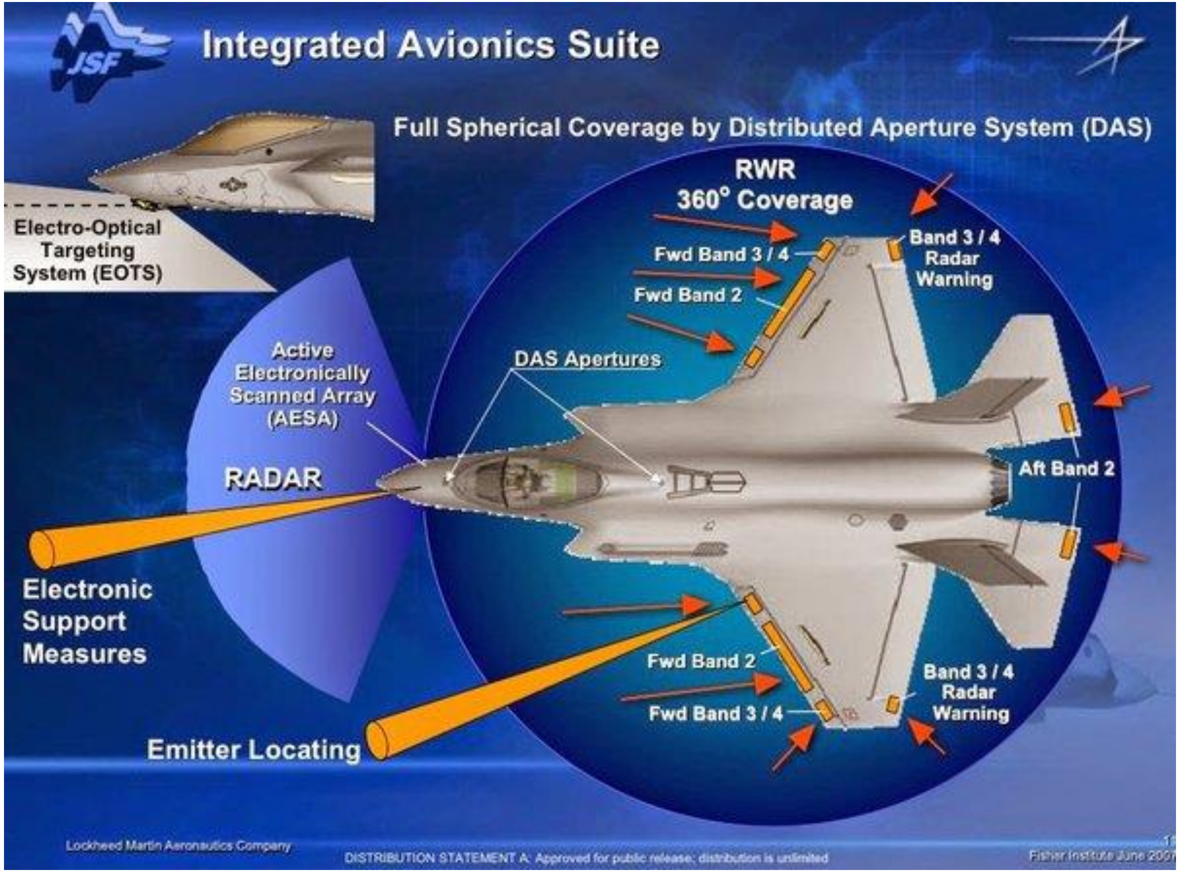
AMPLITUDE COMPARISON - MONOPULSE



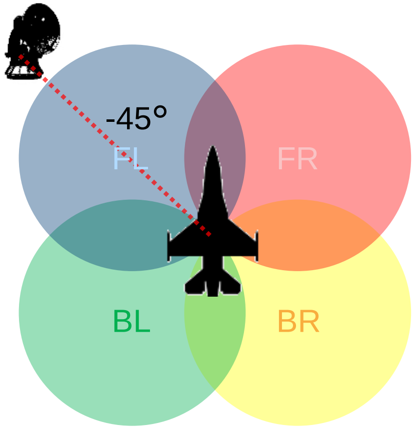
$$\text{AoA} = \tan^{-1}\frac{P_2}{P_1}$$

RWR APERTURES ON THE F-35



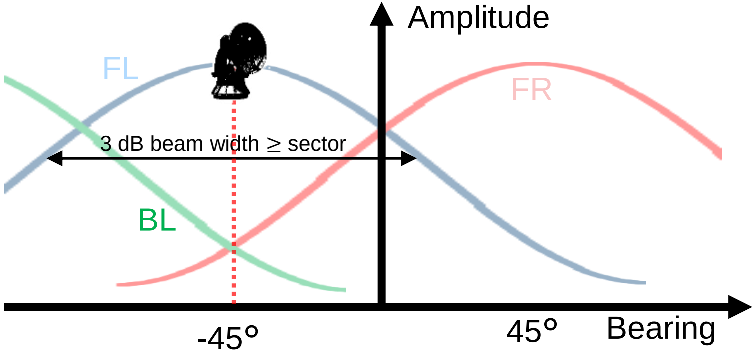
Source – Lockheed Martin

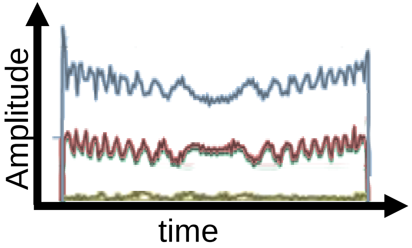
BASICS OF DIRECTION FINDING
AMPLITUDE MONOPULSE ANGLE OF ARRIVAL (AOA)



- Amplitude Monopulse DF requires 2 or more spatially separated receiver channels
- Overlapping directional antenna diagrams with gain, based on the bearing of an emitter
- From sum and difference signals of the normalized amplitudes, the bearing can be calculated

RWR Antenna Diagrams

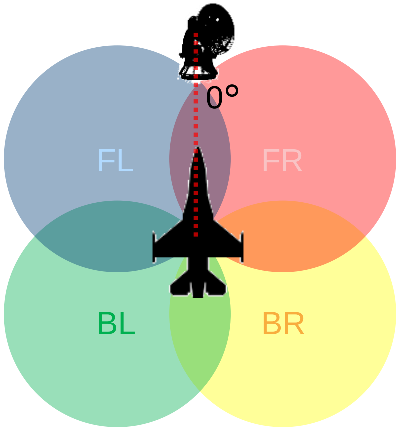




→ Σ and Δ channels
AoA relative to antenna 1 boresight

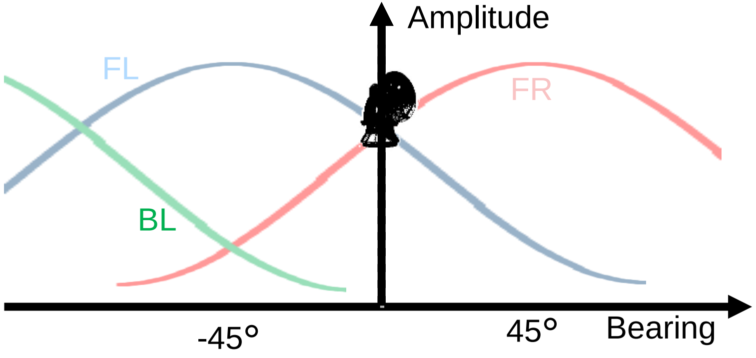
BASICS OF DIRECTION FINDING
AMPLITUDE MONOPULSE ANGLE OF ARRIVAL (AOA)

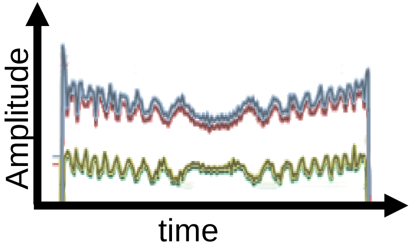
Amplitude Monopulse Angle of Arrival (AoA) – Part II



- Amplitude Monopulse DF requires 2 or more spatially separated receiver channels
- Overlapping directional antenna diagrams with gain, based on the bearing of an emitter
- From sum and difference signals of the normalized amplitudes the bearing can be calculated
- Techniques is often used in RWR due to its fast & easy implementation in DSP, but the downside is a somewhat inaccurate measurements

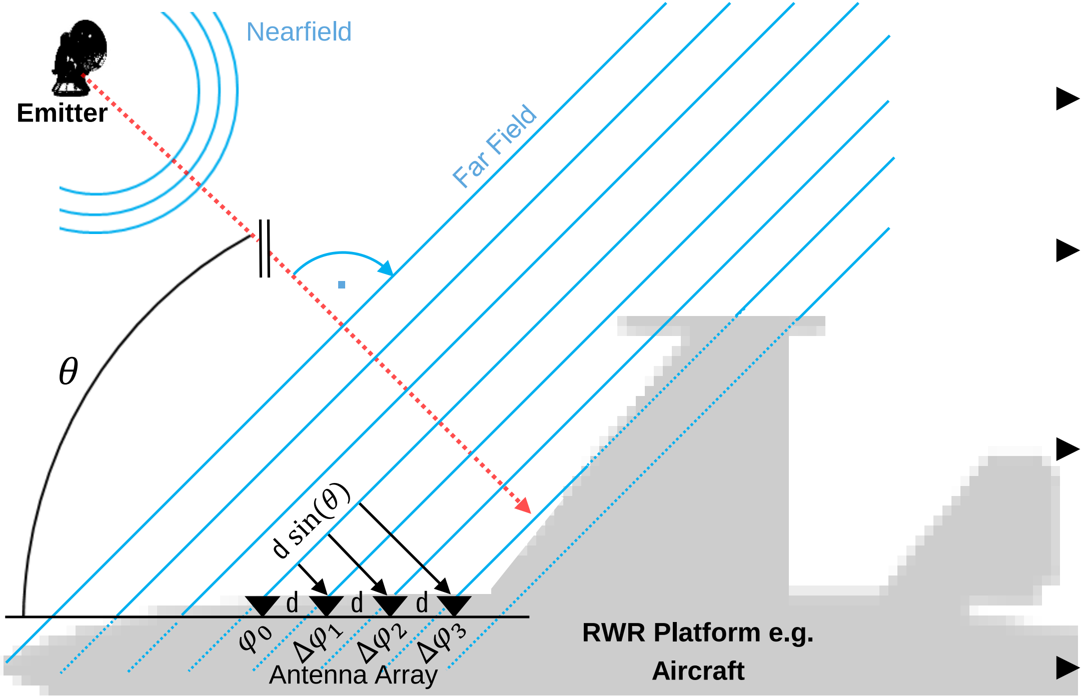
RWR Antenna Diagrams





→ Σ and Δ channels
AoA relative to
antenna 1 boresight

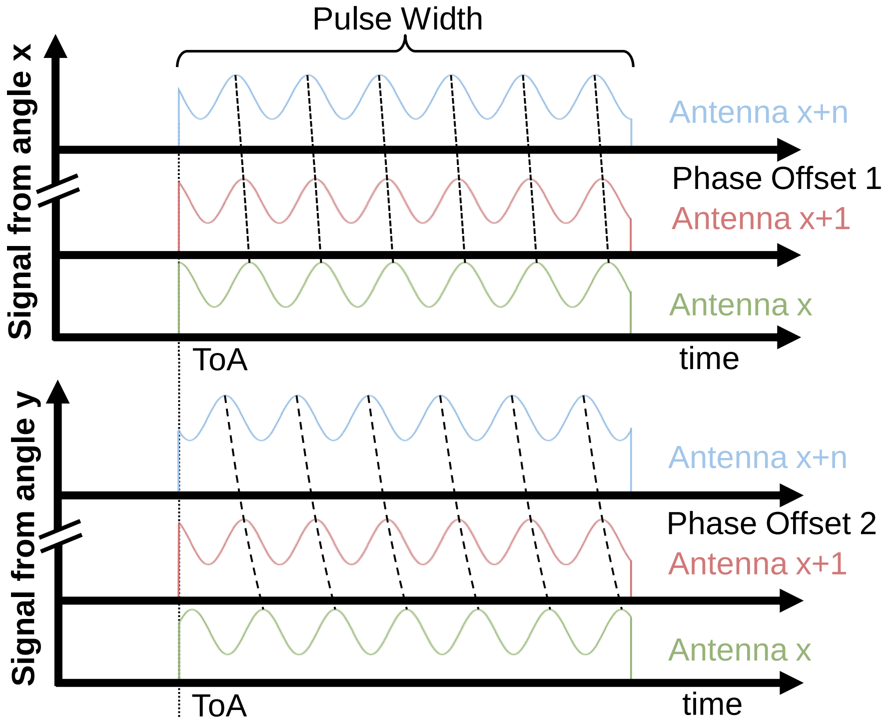
BASICS OF DIRECTION FINDING
PHASE MONOPULSE ANGLE OF ARRIVAL



- A signal from an emitter with an angle θ compared to the RWR receiver antenna's spatial plane as the reference is shown
- The incident isophase surfaces are considered to be parallel due to far field conditions
- The elements of the antenna array are separated by a distance d, therefore the received signal has to travel an additional distance of $\mathrm{d} \cdot \sin(\theta)$
- This corresponds to a frequency dependent phase difference of $\Delta\varphi_n = \frac{2\pi}{\lambda} d \sin\theta$ between a reference and other antenna elements
- Therefore, the angle of arrival θ can be calculated using a measured phase

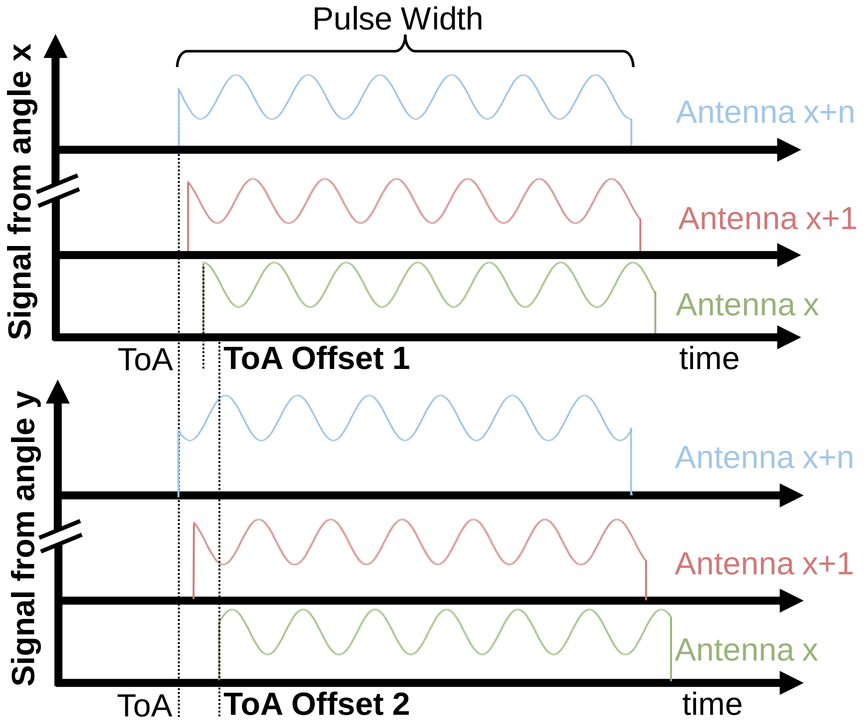
BASICS OF DIRECTION FINDING
PHASE MONOPULSE ANGLE OF ARRIVAL

- The array architecture (number of elements) is dependent on the requirements of angular resolution and the “focus” threat RF, as antennas can be somewhat wideband, but their spacing is fixed (grating lobes)
- Depending on the angle the incident wave front hits the array, different phase offset between the elements can be measured



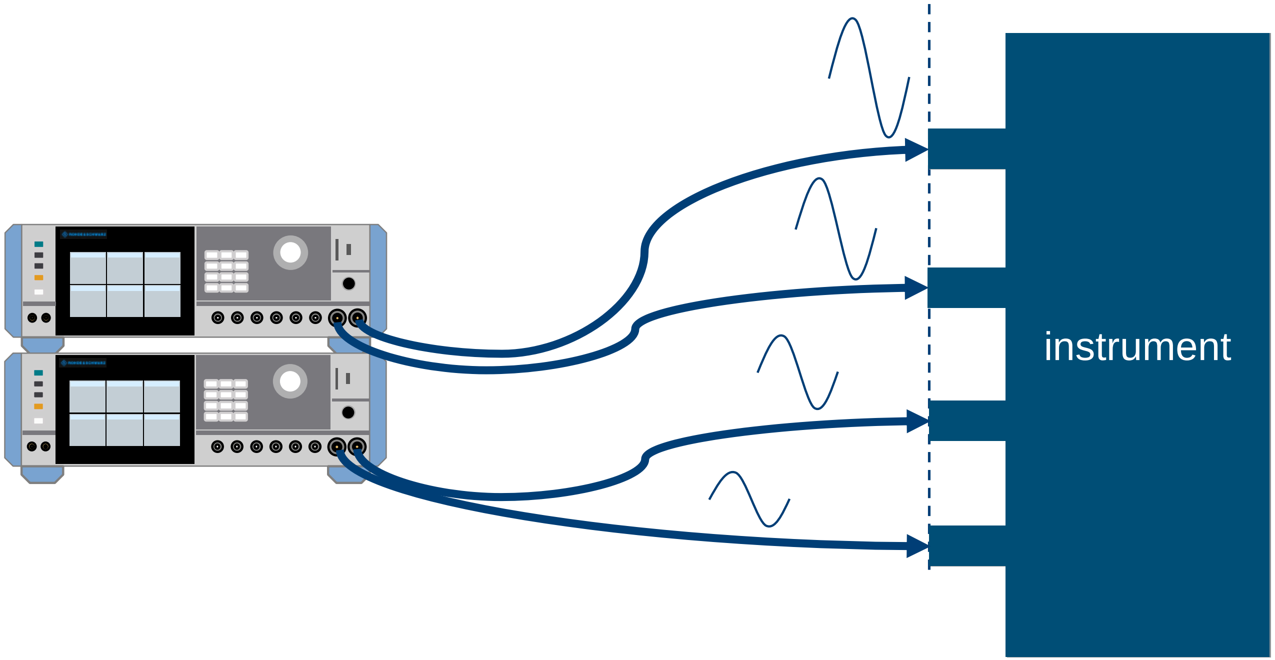
BASICS OF DIRECTION FINDING
PHASE MONOPULSE ANGLE OF ARRIVAL

- The array architecture (number of elements) is dependent on the requirements of angular resolution and the “focus” threat RF, as antennas can be somewhat wideband, but their distance is fixed (grating lobes)
- Here it can be seen, that dependent on the angle the incident wave front hits the array, different phase offset between the elements can be measured
- The offset in the time of arrival can be measured but it is dependent on element spacing. Those offsets are in the magnitude ~1ns though



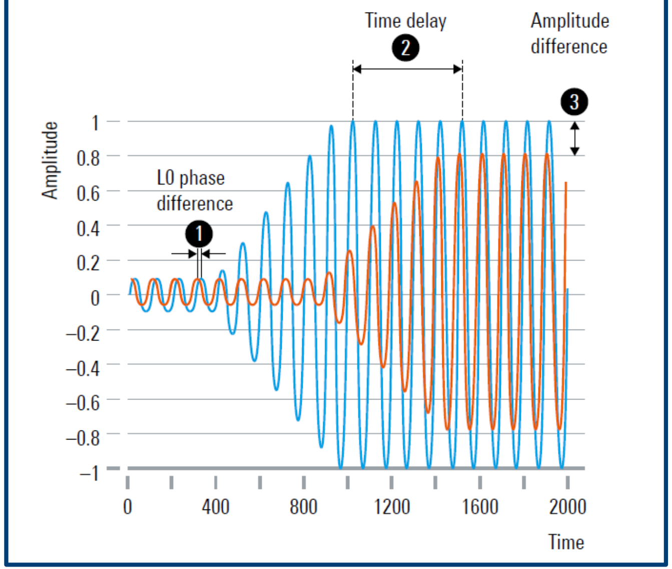
MEASURING AND CORRECTING AOA ON SIGNAL GENERATORS

Reference plane: We need to know the simulated phase/amplitude/time difference here.



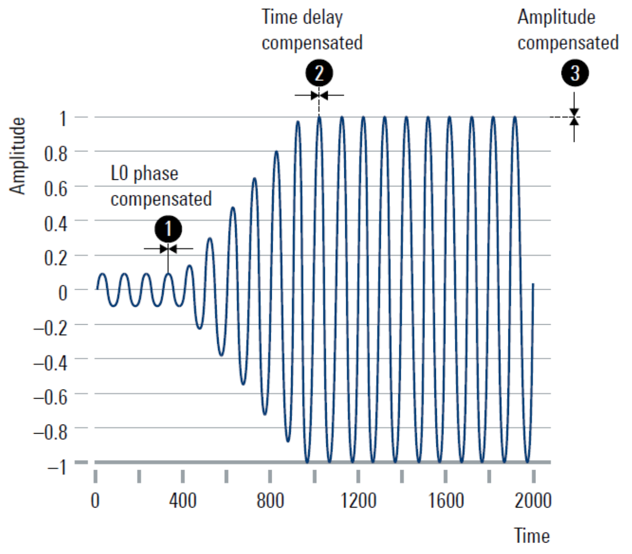
CALIBRATION

Before Alignment



Amplitude, Delay and Phase alignment

After Alignment



The RF Port Alignments software together with an R&S vector network analyzer provides a standard and tailored solution for calibrating **amplitude**, **time** and **phase** between channels

WAYS TO CALIBRATE AOA: POWER SENSORS

Pros

- Simple
- Cheap
- Small
- Scalable
- Broadband – CFs provide match vs frequency
- Some power sensors have high dynamic range

Cons

- **Absolute amplitude only** – no phase or time

RANDOM ERRORS DUE TO NOISE

- You’re always measuring S+N.
  - In peak-detected spur measurements the goal is to minimize noise to be <1% of the measurement which requires an SNR of >20 dB.
- Noise power/sensitivity = kTB + NF of the instrument:
  - NF is an instrument specification
  - kTB
    - k = Boltzmann’s constant (1.38×10^{-23} joule/°K)
    - T = temperature in degrees Kelvin
    - B = bandwidth of noise, in Hertz
- Reducing B reduces noise power and increases sensitivity. Trade-off is slower measurement since measurement time in filtered measurements $\propto 1/B$

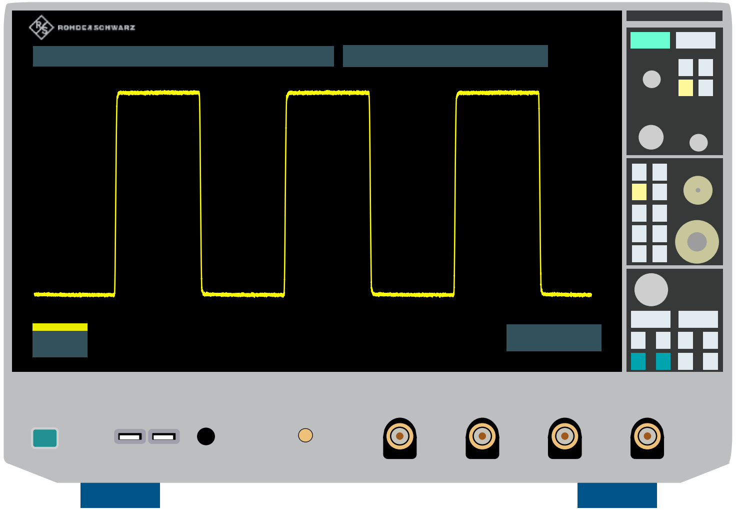
MEASUREMENT NOISE EXAMPLE

- For example, the sensitivity of a 16 GHz scope with a 11 dB noise figure at room temperature is
  - 10log(kT) = -174 dBm
  - 10 log (16 x 10^9) = 102 dB
  - NF = 11
  - -174 dBm + 102 dB + 11 dB = - 61 dBm.
- At first, this may seem adequate, but as you approach this noise floor your measurement noise increases.
- The minimum signal power for accurate measurements is 20 dB above this (1% of measurement), or -41 dBm.

WAYS TO CALIBRATE AOA: ‘SCOPE

Pros

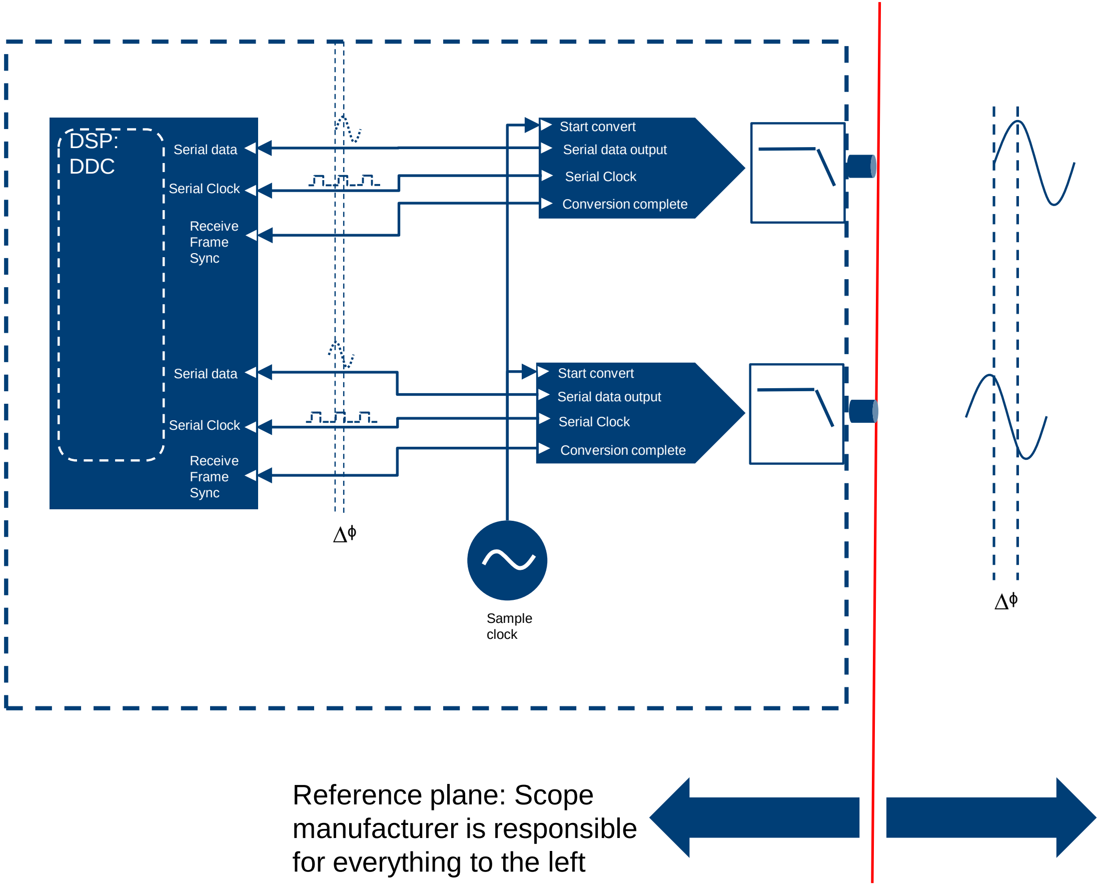
- Simple
- Broadband
- Measure amplitude and phase and time



Cons

- Low dynamic range (no RBW/IBW filters), but better than the power sensor due to ADC dyn range (we have DDC)
- Higher cost for 16 GHz scopes, instruments using downconversion are lower cost, at higher frequencies
- Must de-embed everything past the instrument ports
- Not great for amplitude measurements as ’scopes operate on a linear scale.
- Not great for phase at higher frequencies due to sample rate of ADC, LPF filter roll-off noise bandwidth

‘SCOPE PHASE MEASUREMENT – BASIC CONCEPT



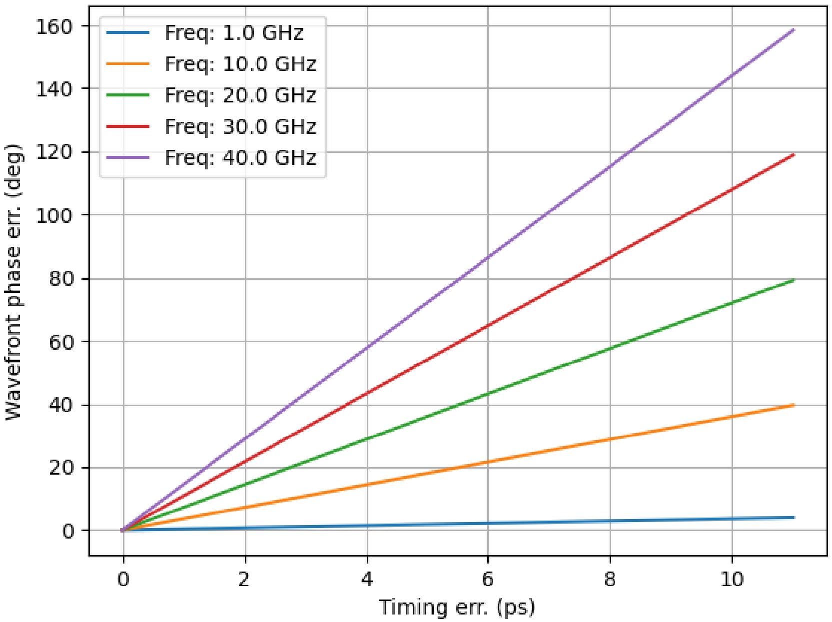
Reference plane: Scope manufacturer is responsible for everything to the left

Measurement plane: The customer must measure and de-embed everything to the right, such as cables or OTA chamber, switches, etc.

‘SCOPES ARE THE GOLD STANDARD FOR TIME-DOMAIN MEASUREMENTS

Instrument time skew vs simulated wavefront error

$$AoA = \phi = \sin^{-1}\frac{\Delta t * c}{L}$$



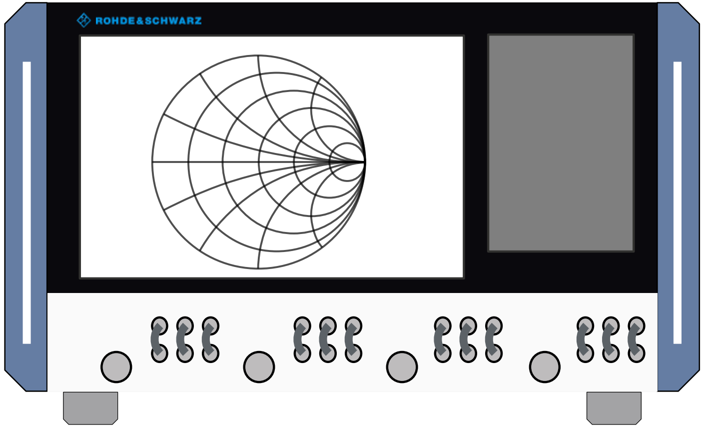
USING VECTOR NETWORK ANALYZER TO CALIBRATE AOA

Pros

- Wide frequency range
- Measure amplitude, phase and time w/group delay
- High dynamic range allows phase calibration at lower power levels
- Flexible calibration plane

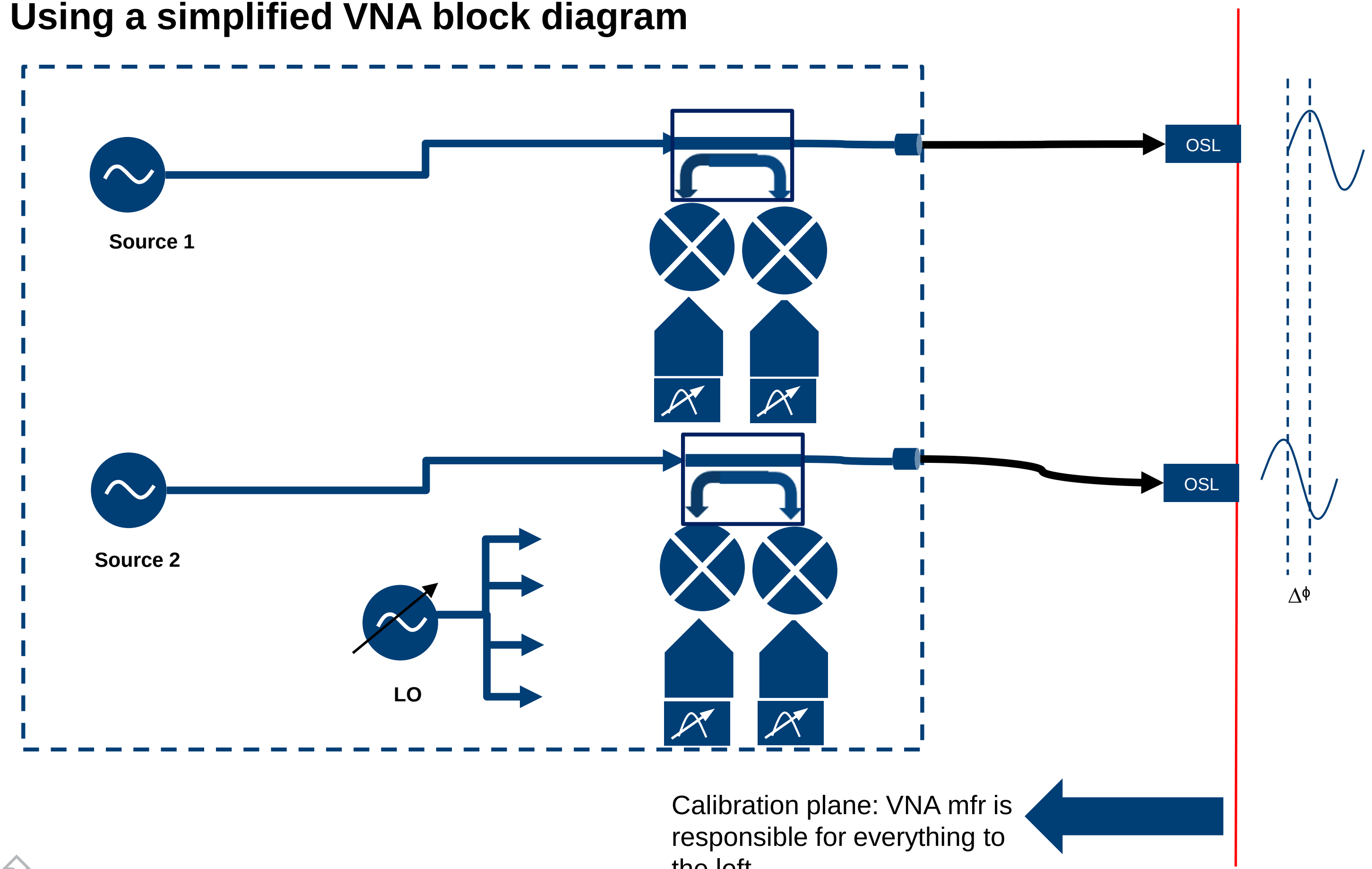
Cons

- Requires vector error correction – an added step but has many benefits



PHASE MEASUREMENTS USING VNA

Using a simplified VNA block diagram



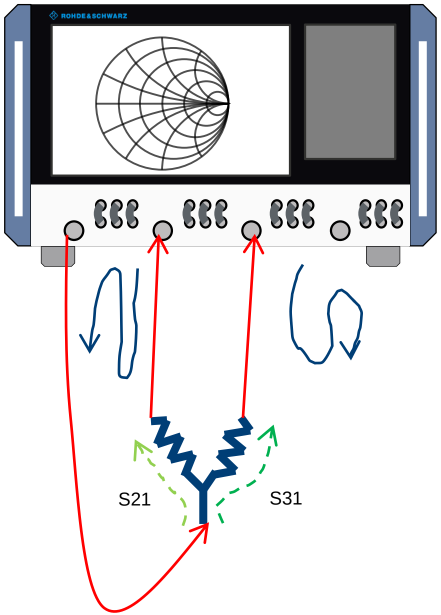
Calibration plane: VNA mfr is responsible for everything to the left

UNCERTAINTY IN PHASE MEASUREMENT ON THE VNA

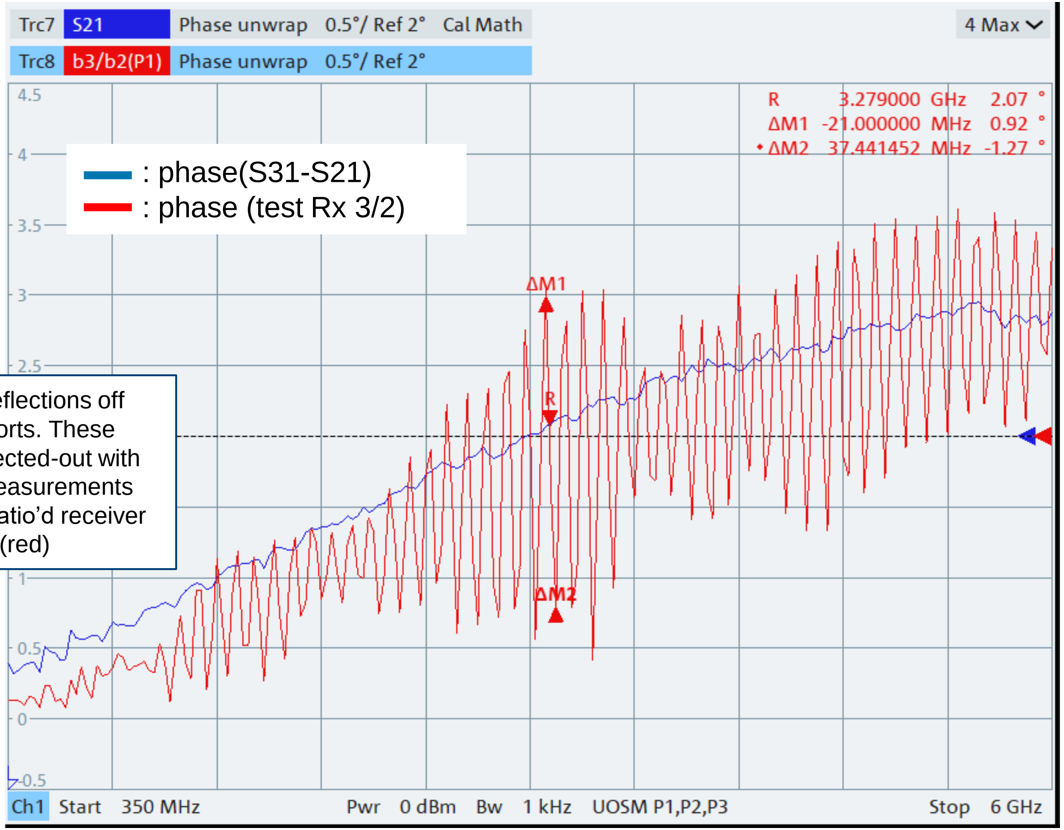
- Three types of measurement uncertainty:
  - **Systemic**
  - **Random**
  - **Drift**
- Each of these will be discussed in more detail in the following slides
- It’s important to understand the relative magnitude of each error to determine the effect of each and thus what to correct

PHASE MEASUREMENT UNCERTAINTY: SYSTEMIC ERROR

Reflections between the source and SUT ports are the biggest source of systemic error*



Ripple due to reflections off SUT (splitter) ports. These waves are corrected-out with S-parameter measurements (blue), but not ratio'd receiver measurements (red)



Trc7 S21 Phase unwrap 0.5°/ Ref 2° Cal Math

Trc8 b3/b2(P1) Phase unwrap 0.5°/ Ref 2°

4 Max

R 3.279000 GHz 2.07 °

ΔM1 -21.000000 MHz 0.92 °

• ΔM2 37.441452 MHz -1.27 °

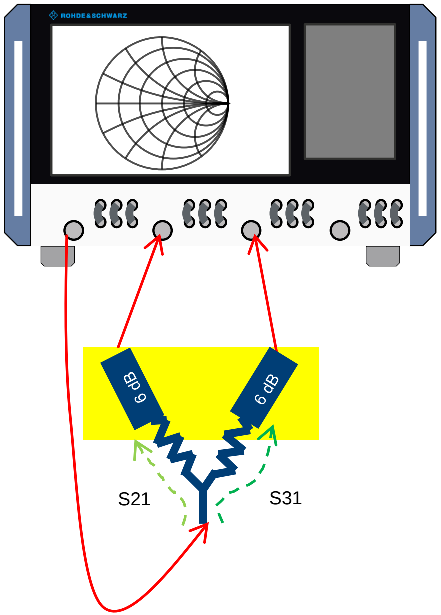
🟦 : phase(S31-S21)

🟥 : phase (test Rx 3/2)

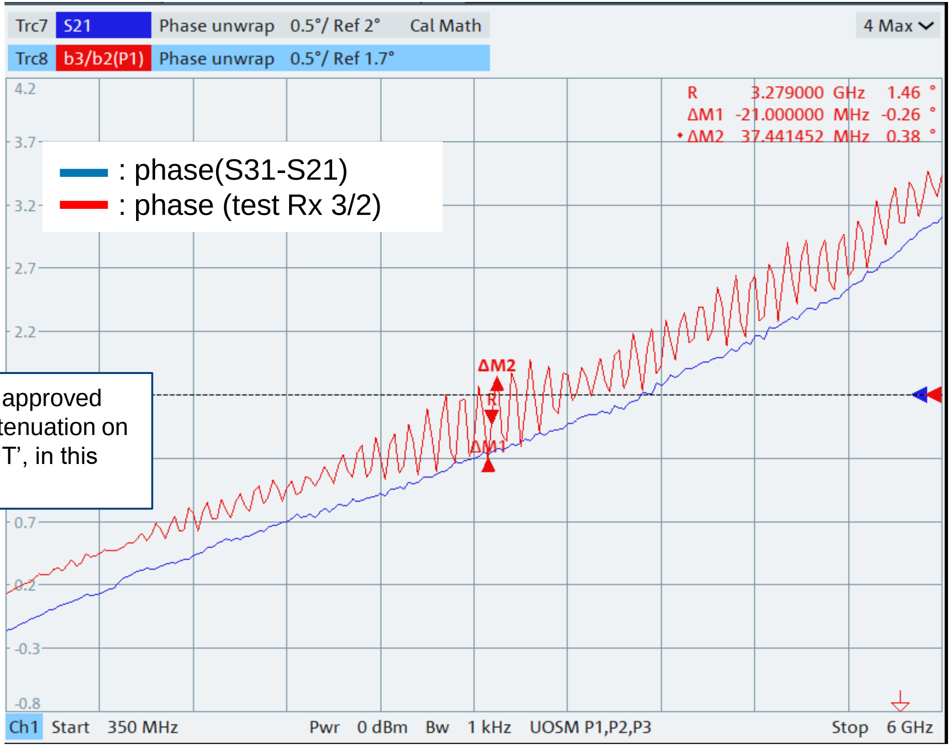
Ch1 Start 350 MHz Pwr 0 dBm Bw 1 kHz UOSM P1,P2,P3 Stop 6 GHz

PHASE MEASUREMENT UNCERTAINTY: SYSTEMIC ERROR

Improving match with attenuators on the output of the SUT



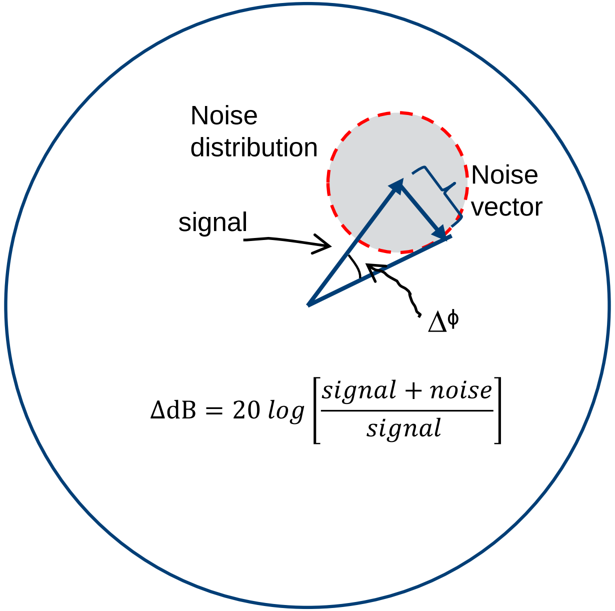
The ripple can be approved by adding 6 dB attenuation on the end of the ‘SUT’, in this case, our splitter.



RANDOM ERROR: NOISE AFFECTING PHASE UNCERTAINTY

In this application, we mean, “noise”

- This can be solved by increasing signal power or reducing instrument noise.
- In a VNA, measurement noise shows up as trace noise and can be reduced by reducing IFBW.
- As this pertains to phase – the **magnitude** and **phase** of the noise contributes to the phase error as shown to the right.
- Mathematically, $\Delta\phi = 6.6 \cdot \Delta dB$

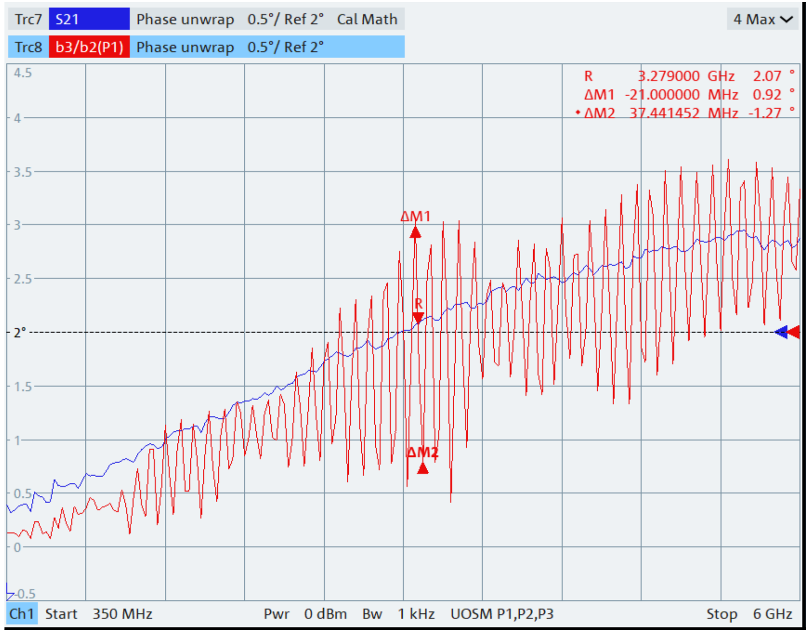


$$\Delta\text{dB} = 20\,log\left[\frac{signal + noise}{signal}\right]$$

Increasing the IFBW by a factor of 1000

PHASE MEASUREMENT UNCERTAINTY: RANDOM ERROR

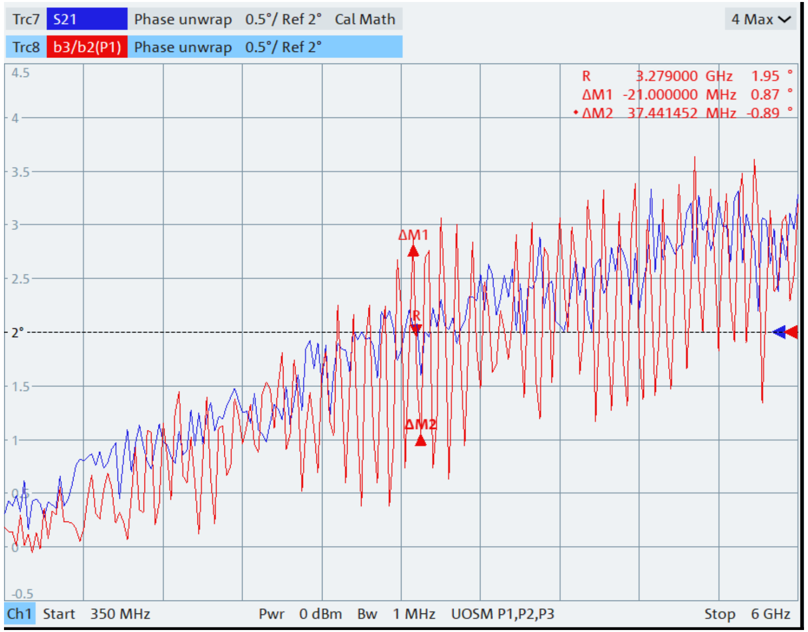
IFBW = 1 kHz / src power -10 dBm


Trc7 S21 Phase unwrap 0.5°/ Ref 2° Cal Math
Trc8 b3/b2(P1) Phase unwrap 0.5°/ Ref 2°
4 Max

R 3.279000 GHz 2.07 °
ΔM1 -21.000000 MHz 0.92 °
• ΔM2 37.441452 MHz -1.27 °

Ch1 Start 350 MHz Pwr 0 dBm Bw 1 kHz UOSM P1,P2,P3 Stop 6 GHz

IFBW = 1 MHz


Trc7 S21 Phase unwrap 0.5°/ Ref 2° Cal Math
Trc8 b3/b2(P1) Phase unwrap 0.5°/ Ref 2°
4 Max

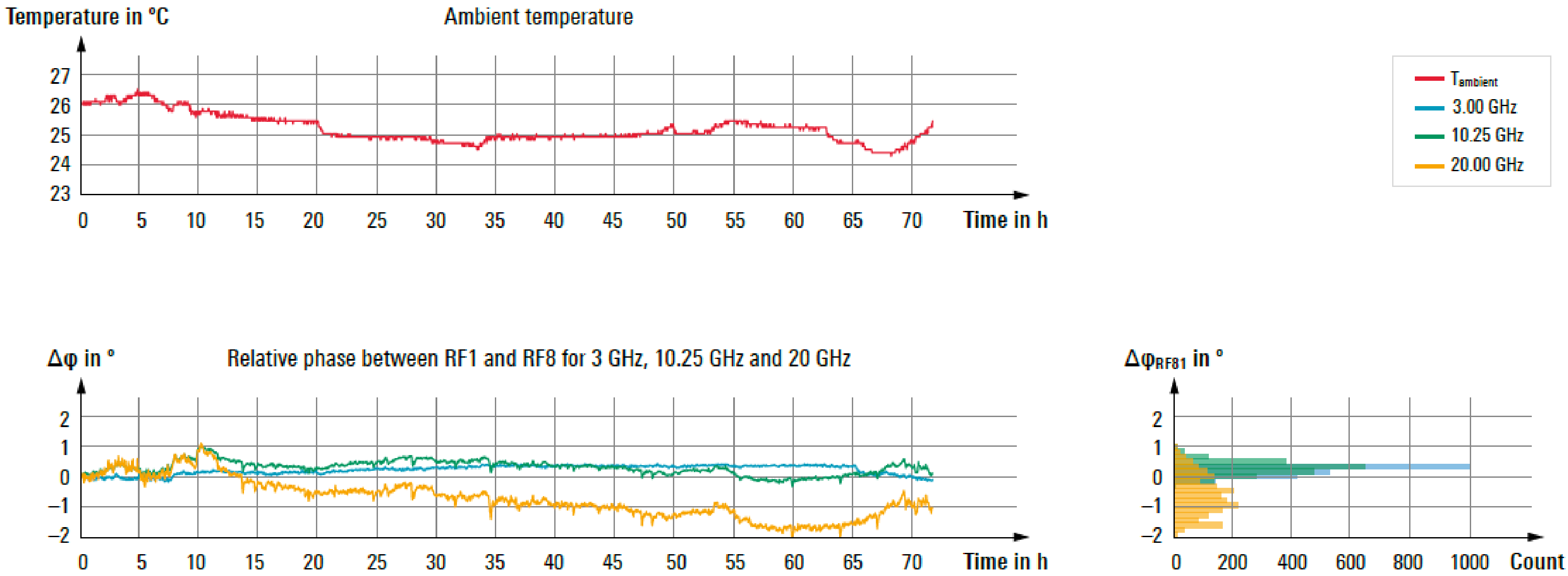
R 3.279000 GHz 1.95 °
ΔM1 -21.000000 MHz 0.87 °
• ΔM2 37.441452 MHz -0.89 °

Ch1 Start 350 MHz Pwr 0 dBm Bw 1 MHz UOSM P1,P2,P3 Stop 6 GHz

PHASE MEASUREMENT UNCERTAINTY: DRIFT

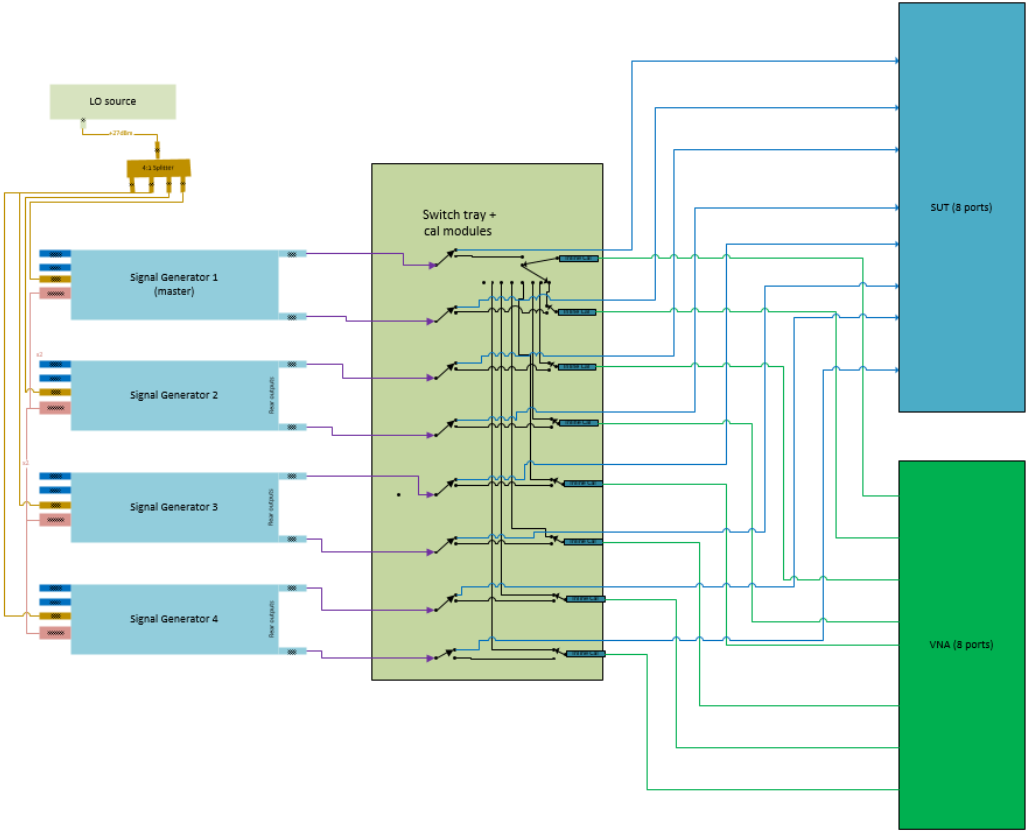
vs. time/temperature

Phase repeatability and stability of switching frequencies for a setup with eight RF ports



PORT COUNT SCALING

- As port counts grow, AoA calibration becomes more difficult and time-consuming
- Switches and in-line calibration modules can be used to automate and update calibration
- Replicate this and de-embed combiners and cables into the SUT as needed.



SUMMARY

- You always measure signal + noise.
- Amplitude and phase AoA calibration is best accomplished with a VNA because:
  - The VNA provides vector-error corrected measurements as close to the DUT plane as you want.
  - The VNA reduces measurement noise with filtering
  - The VNA has a wide frequency range and is cost-effective
- There is an uncertainty in every measurement
  - In the VNA, it can be traced through the S-parameter standards (to a first order).