Welcome to “Advances in Converter Test”.

Frequency translating devices such as mixers and converters are at the core of all of today's high-frequency radar and communication systems. These devices present unique measurement challenges since input and output frequencies differ, requiring different measurement and calibration techniques than those used for linear devices such as filters and amplifiers. This paper explores how modern vector network analyzers employ advanced vector-error-correction techniques to make highly accurate magnitude, phase, and group delay measurements of frequency-translating devices. Other practical techniques for improving measurement accuracy will also be covered.

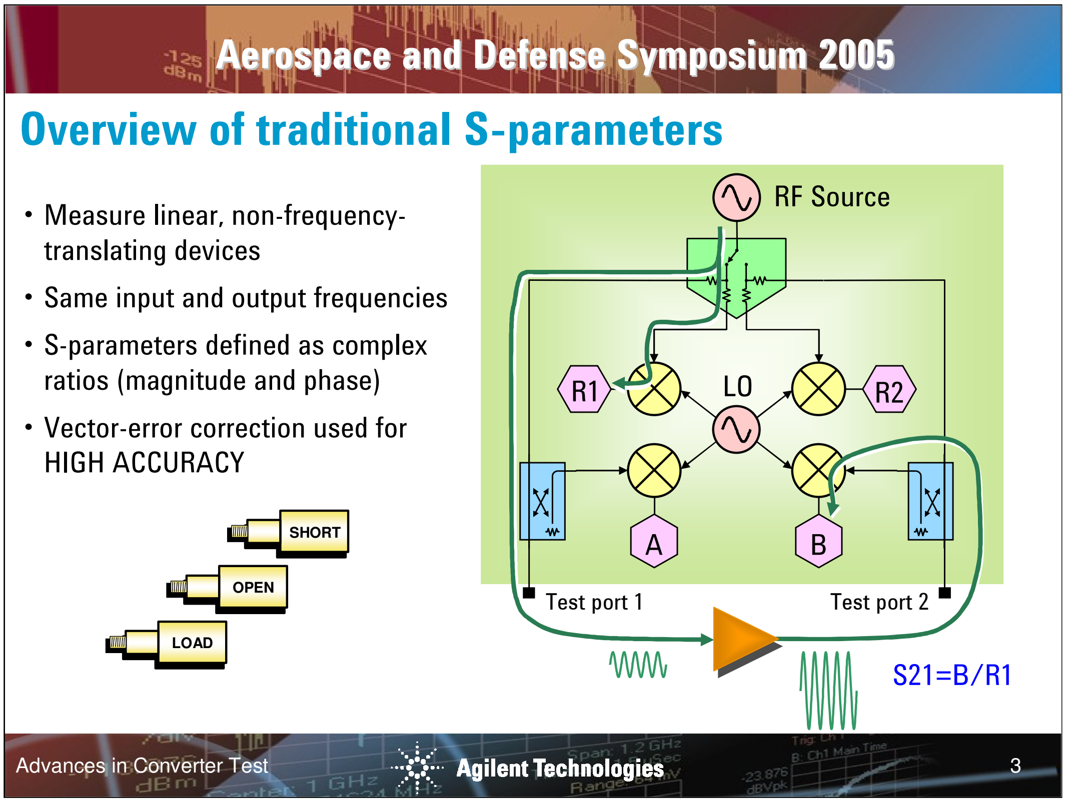
Agenda

- **Review of mixer/converter measurements**
- Traditional versus modern VNA-based solutions
- New mixer calibration techniques

  SMC: Scalar Mixer Cal

  VMC: Vector Mixer Cal
- Measuring delay of multistage converters
- Tips and techniques for successful measurements

We will start out with an overview of the types of measurements that are typically made on frequency-translating devices such as mixers and converters. Next, we'll examine both the traditional and modern approach to solving these measurement needs. In particular, we will discuss new calibration techniques that bring unprecedented accuracy to converter measurements. Next, we will explain how one of the new calibration techniques can be applied to measuring the delay of multistage converters, which up to now, has been exceedingly difficult. Finally, we will provide some practical tips and techniques to help make you more successful when measuring converters.



Before we talk about measuring frequency-translating devices like mixers and converters, it is helpful to review conventional S-parameter measurements. The underlying assumption for these measurements is that the stimulus and response (input and output) frequencies are the same. This allows us to make ratioed measurements between two receivers (reference receivers R1, R2, and test receivers A, B), giving complex data having a magnitude and phase portion. Each S-parameter is a unique ratio:

S11 = A/R1 (source from port 1)

S21 = B/R1 (source from port 1)

S12 = A/R2 (source from port 2)

S22 = B/R2 (source from port 2)

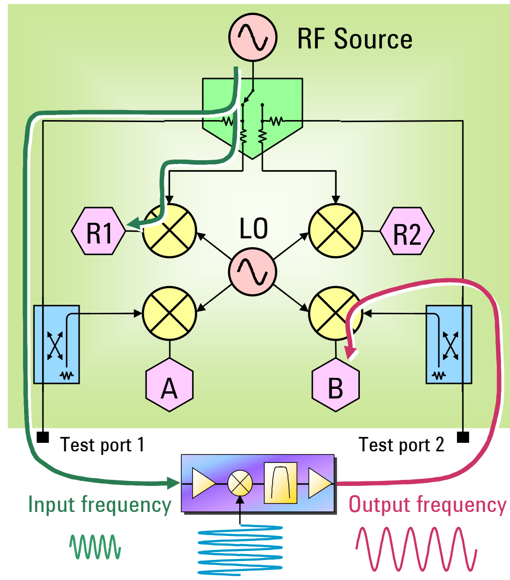
To improve measurement accuracy, we measure complex data from calibration standards such as opens, shorts and loads, calculate systematic error terms, and use the error terms to correct the raw S-parameter measurements of the DUT. This process gives very high accuracy, which is one of the key reasons that people use vector network analyzers (VNA).

Why mixers/converters are hard to measure

- Can't measure complex ratios when $F_B \neq F_{R1}$

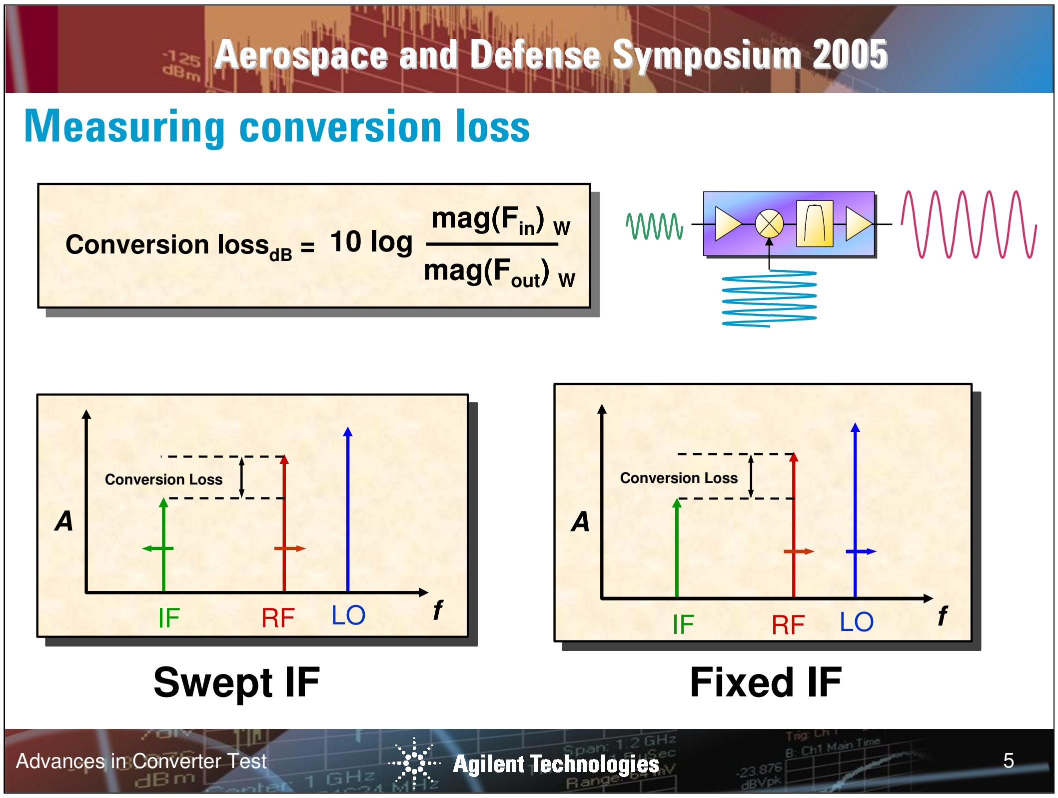
  ~~S21 = B/R1~~

- For transmission magnitude, must measure absolute power in receivers
- What about transmission phase?
- Source phase-lock requirements further complicate measurements



When measuring frequency-translating devices like converters, the assumption that the input and output frequencies are the same is no longer valid. The VNA can no longer measure complex ratios as described before. For transmission measurements, we must now measure the absolute powers in the reference and test receivers. What about phase measurements? These will require external hardware in the form of reference mixers.

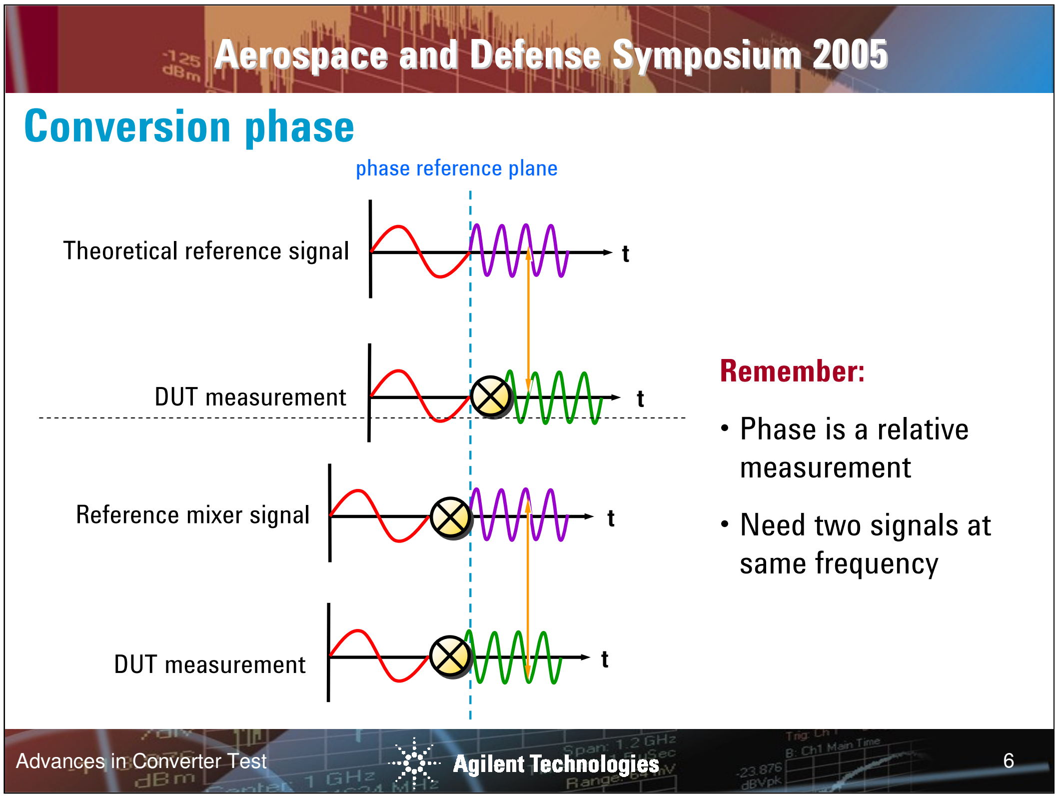
To further complicate matters, it can be difficult to maintain the conditions required to phase-lock the source over a range of frequencies when frequency-offset between source and receivers is desired.



Lets look at the most common measurements made on mixers and converters. The first measurement we will cover is conversion loss, or as often is the case with converters, conversion gain. Conversion loss/gain is defined as the ratio of CW output power to the CW input power, expressed in dB, for a given amount of applied local oscillator (LO) power. It is usually measured versus frequency. While conversion loss of a mixer is usually relatively flat within the frequency span of its intended operation, the average loss will depend on the power level of the LO.

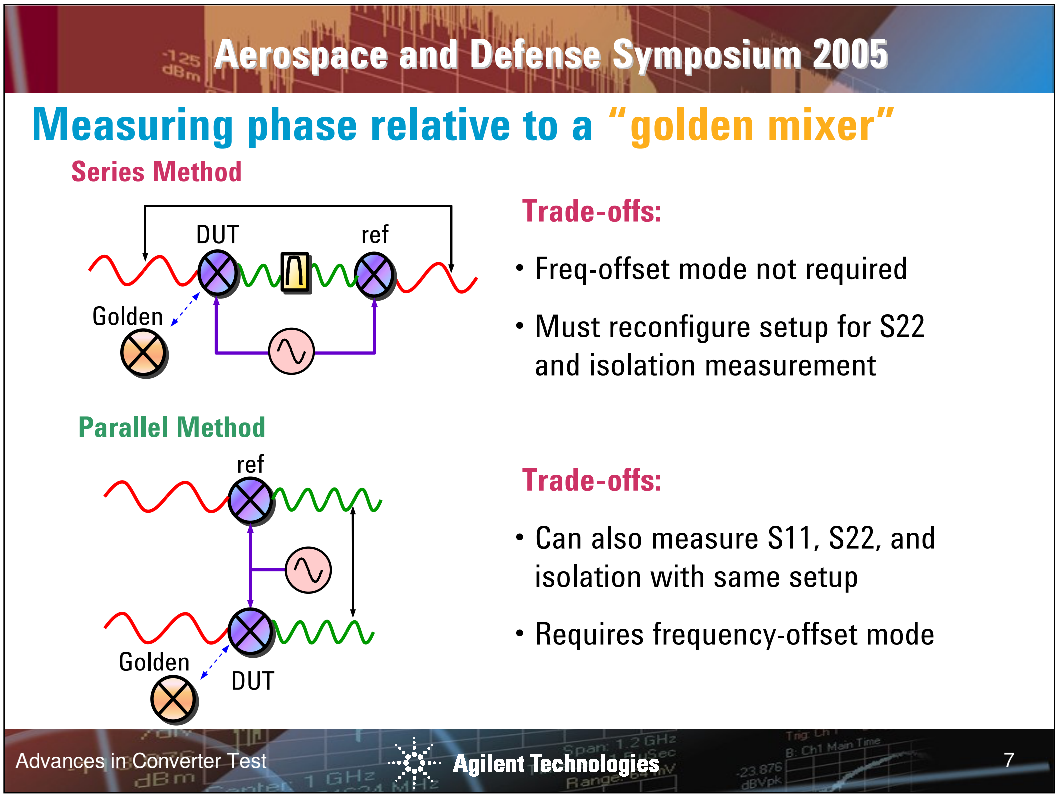
The easiest way to measure conversion loss or gain flatness is to sweep the RF input and keep the LO frequency constant. This is called a swept-IF or swept-output measurement. This type of measurement is often done on converters to measure the frequency response of the converter, for a given center frequency. It will show the effective frequency response of the various components inside the converter, which is usually dominated by a narrowband output filter. Notice when the LO is above the RF, known as high-side mixing, the IF will sweep in the opposite direction from the RF.

To easily measure a broad range of input frequencies, it is common to keep the output of the converter fixed to a frequency within its passband, while the input is swept. This requires the RF and LO signals to track one another, at an offset determined by the output frequency. This measurement mode is called fixed-IF, fixed-output, or swept-LO sweep. In many cases, this measurement more closely matches the operation of the DUT in its actual application.



Many applications require characterization of the phase-versus-frequency response of the mixer or converter. Since the input and output frequencies are not the same, the definition of conversion phase can be confusing. We define the conversion phase as the phase shift of the output compared to a reference of some kind, at the same frequency. The top half of the slide shows a theoretical reference signal that has instantaneously undergone a frequency shift to produce a signal at the same frequency as that coming out of the DUT. With two signals at the same frequency, we can compare their phase at any arbitrary reference time. The phase shift between the two signals is the same, no matter at which point in time we make the measurement. What is mostly of interest is how the phase varies as a function of input frequency. In the real world, the reference signal is typically created by a reference mixer, which we will examine on the next slide.

Just as conversion loss/gain is a function of LO power, the phase of the output signal is a function of the input phase and the LO phase. Therefore, the reference signal should be converted in frequency with the same LO as the signal it will be compared to. This is referred to as synchronous conversion. The lack of a synchronous LO causes phase noise and drift when measuring converters with internal LOs without access to the LO signal itself or a common time base. We will discuss phase measurements on embedded-LO converters with time-base access in the latter part of this presentation.



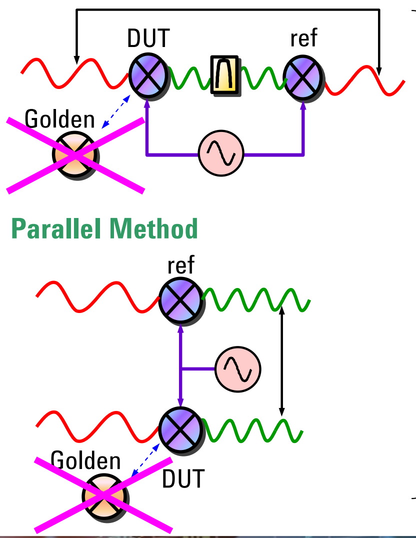
There are two basic ways to use a reference mixer to create a reference signal that can be used as a phase reference. The top example shows the series method. In this case, the reference mixer is used to re-convert the output signal of the DUT to the same frequency as that at the DUT's input. In this way, the VNA measures signals that are the same. A filter is required between the mixers to select the desired mixing product. The filter prevents the unwanted mixing products from distorting the response of the desired signal. The filter's frequency response must be removed from the pair's response with normalization or de-embedding, and the mismatch between the filter and the mixers often causes additional measurement uncertainty. The series method supports both up/down and down/up conversion, which is determined by the LO and filter frequencies. This configuration makes life easy for the VNA (it doesn't need a frequency-offset mode), but there are several important measurements that are not easily made when the reference mixer is in series (notably S22 and input-to-output isolation).

The bottom example shows the parallel method. In this case, the input signal is split into two signals, one going to the DUT and the other going to the reference mixer. The two mixers again share a common LO, so their outputs are at the same frequency. This configuration requires the VNA to have a frequency-offset mode, but has the advantage that the VNA can switch between normal S-parameter measurements to measure input and output match and isolation, as well as offset measurement to measure relative phase.

Both methods are often used with a "golden mixer", which is a device used for normalization. The golden mixer's response is considered good enough for whatever system it goes into, and DUTs are measured to ensure that their performance does not deviate too far from that of the golden mixer. The golden mixer is measured first, and then subsequent data is compared to this data (using the data-divided-by-memory feature). This normalization process removes the frequency response errors of the test system, and means that all test data is relative to the golden device. By using a golden mixer, the frequency response of the reference mixer is removed from the measurements. Note that if a golden mixer is not used, then the DUTs performance is relative to the reference mixer.

Measuring absolute phase

Series Method



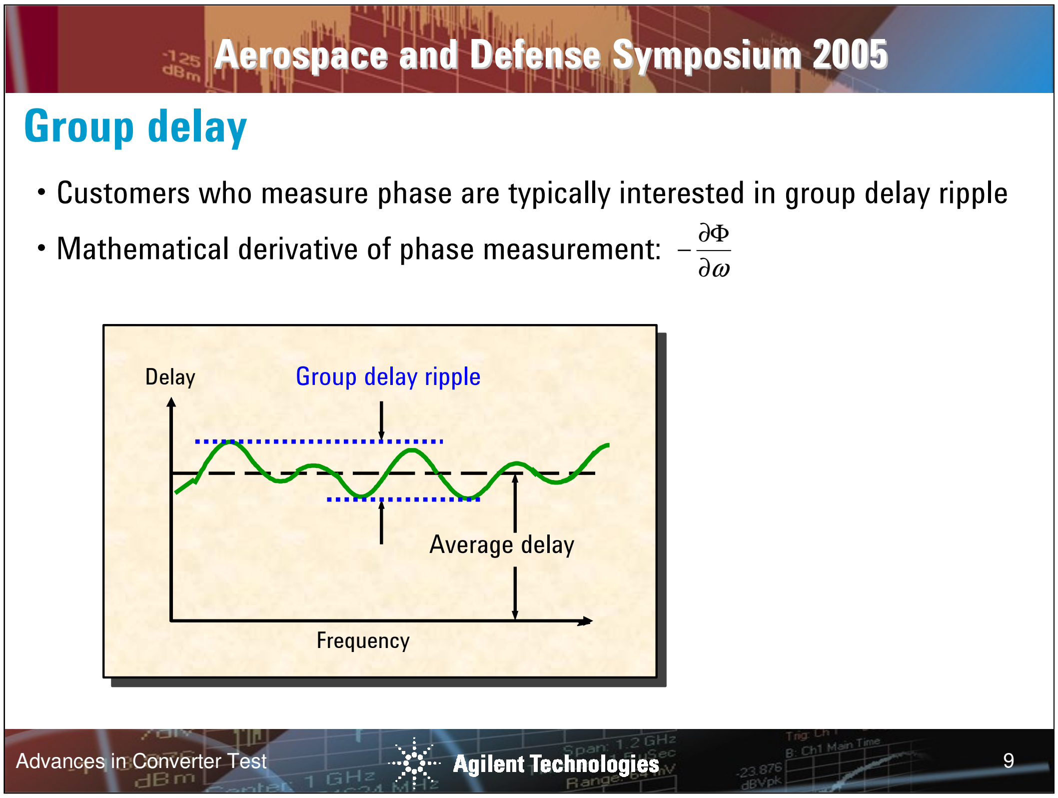
Why?

- Obtain actual performance of DUT
- No need for golden mixer

How?

- New, advanced calibration techniques are needed!!

Many engineers are interested in obtaining the absolute phase or absolute group delay of their DUT. This allows matching of devices with similar performance and aids in accurate system simulations, which require magnitude and phase responses to calculate mismatch errors. In order to obtain the absolute response of a DUT, all of the systematic errors due to cables, filters, and the reference mixer must be characterized and removed from the measurement. Various calibration (or characterization) techniques have been developed in order to remove the systematic errors and display the absolute phase or delay of the DUT. When these techniques are employed, there is no need for a “golden” mixer. Later, we will examine in more detail a novel calibration technique invented at Agilent that yields measurements of absolute phase and group delay.



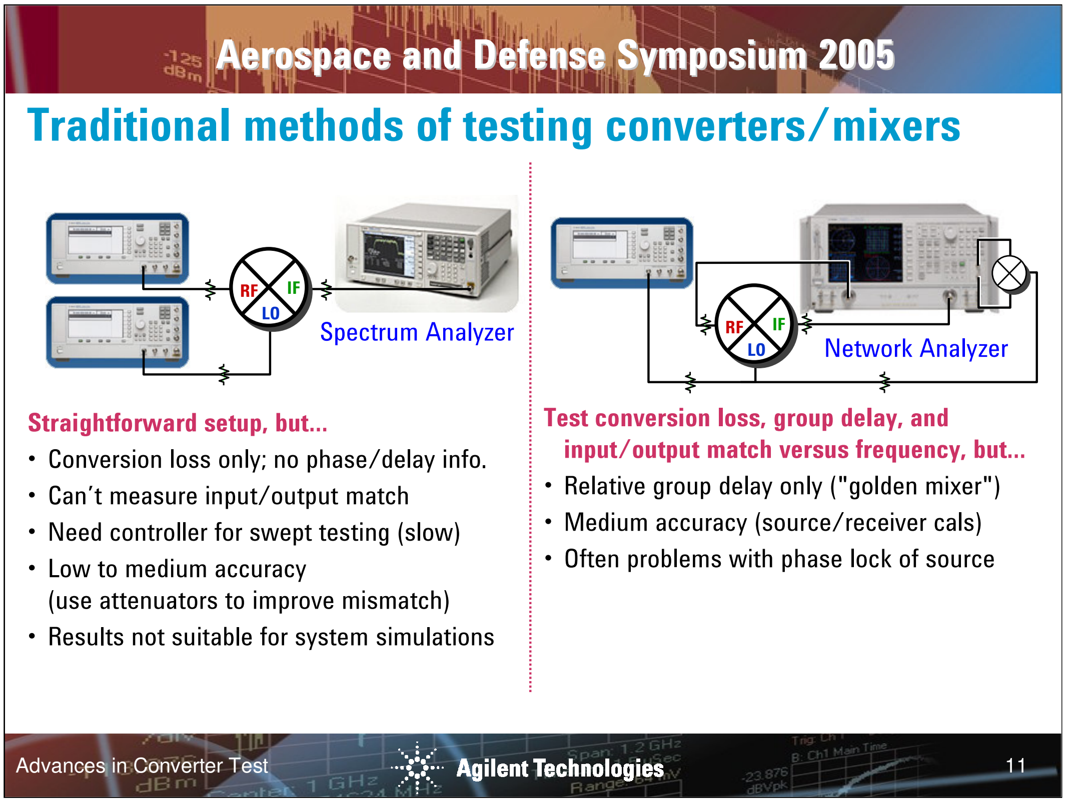
Generally when people talk about measuring absolute phase, they really want to see phase variation versus frequency to see how linear the phase shift is. Just as magnitude nonlinearity can distort waveforms, so can phase distortion. Phase linearity is especially important in digital communications because slight changes in the phase relationship of the frequency components of any modulated signal can drastically alter its waveform and the system bit-error rate. Satellite-transponder manufacturers are especially concerned with group delay because their devices must receive and transmit a wide variety of digital signals over a very broad frequency range. Mixers often have baluns that affect their phase response near the limits of their operating frequency ranges.

One common way to look at phase variation is by measuring group delay. Group delay is calculated by differentiating the insertion-phase response of the mixer or converter under test versus frequency. Another way to say this is that group delay is a measure of the slope of the transmission-phase response. The linear portion of the phase response is converted to a constant value (representing the average signal-transit time) and deviations from linear phase are transformed into deviations from constant group delay. Variations in group delay cause signal distortion, just as deviations from linear phase cause distortion. Group delay is just another way to look at phase distortion.

Agenda

- Review of mixer/converter measurements
- **Traditional versus modern VNA-based solutions**
- New mixer calibration techniques
  - SMC: Scalar Mixer Cal
  - VMC: Vector Mixer Cal
- Measuring delay of multistage converters
- Tips and techniques for successful measurements

In this next section, we will discuss traditional methods for measuring mixers and converters, and what modern VNAs offer.

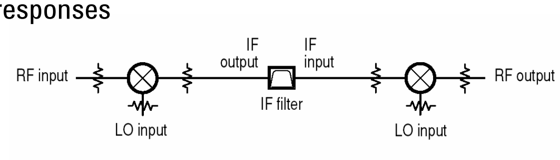


One very common way to measure mixers and converters is to use external signal generators (SGs) for the stimulus and LO signals, and a spectrum analyzer (SA) to analyze the response signal. This is a well-understood, straightforward technique, but one with several serious drawbacks. First of all, this solution can only measure transmission magnitude. Transmission phase and delay, and input/output matches must be done with other equipment. For swept measurements, it requires a controller of some kind, and the sweeps are slow compared to those using a VNA. The lack of vector-error correction limits the accuracy of the results, which when combined with the lack of phase information, means the results are not suitable for system simulations.

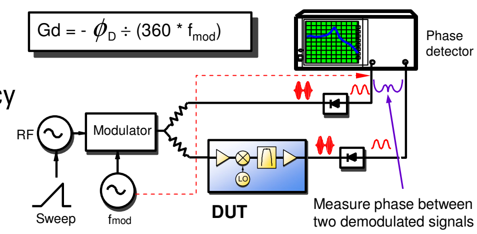
For these reasons, many people use VNAs to test mixers and converters. The VNA can sweep very quickly, and older VNAs offered at least some error-correction techniques (such as source and receiver calibrations) to improve measurement accuracy. Phase and group delay measurements are possible, but with older VNAs, they were always relative to some golden device. One annoying problem that affected many older VNA's was loss of source phase-lock during frequency-offset sweeps. This was usually due to interactions between an external reference mixer and the VNA's internal samplers. We'll show later how modern VNA's overcome the phase-lock problem, as well as provide more sophisticated error-correction techniques to give high accuracy and absolute delay measurements.

Traditional methods for absolute group delay

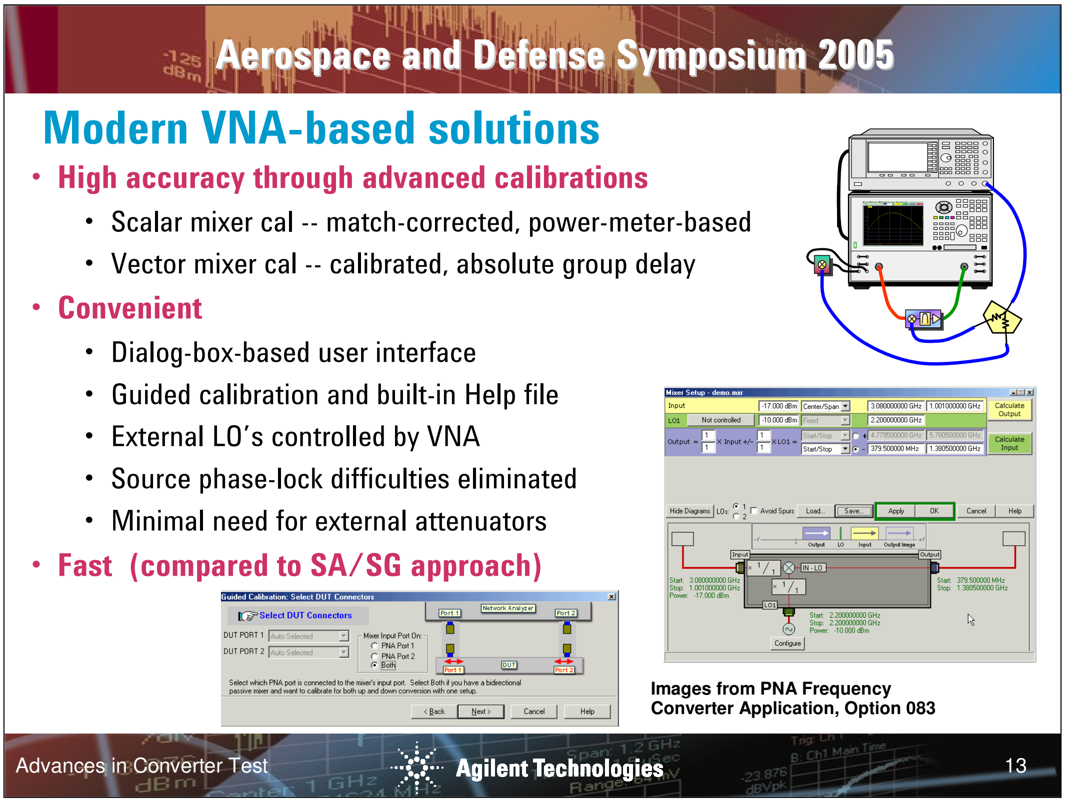
- **Up/down conversion with equal mixers (uses VNA)**
  - Assumes mixers have identical responses
  - Mixers must be reciprocal
  - Must remove IF filter effects
  - Susceptible to mismatch errors



- **Modulation method**
  - Sweep carrier with AM or FM
  - Noisy: typically limited to 5-10 ns accuracy
  - Especially good for fully embedded LOs

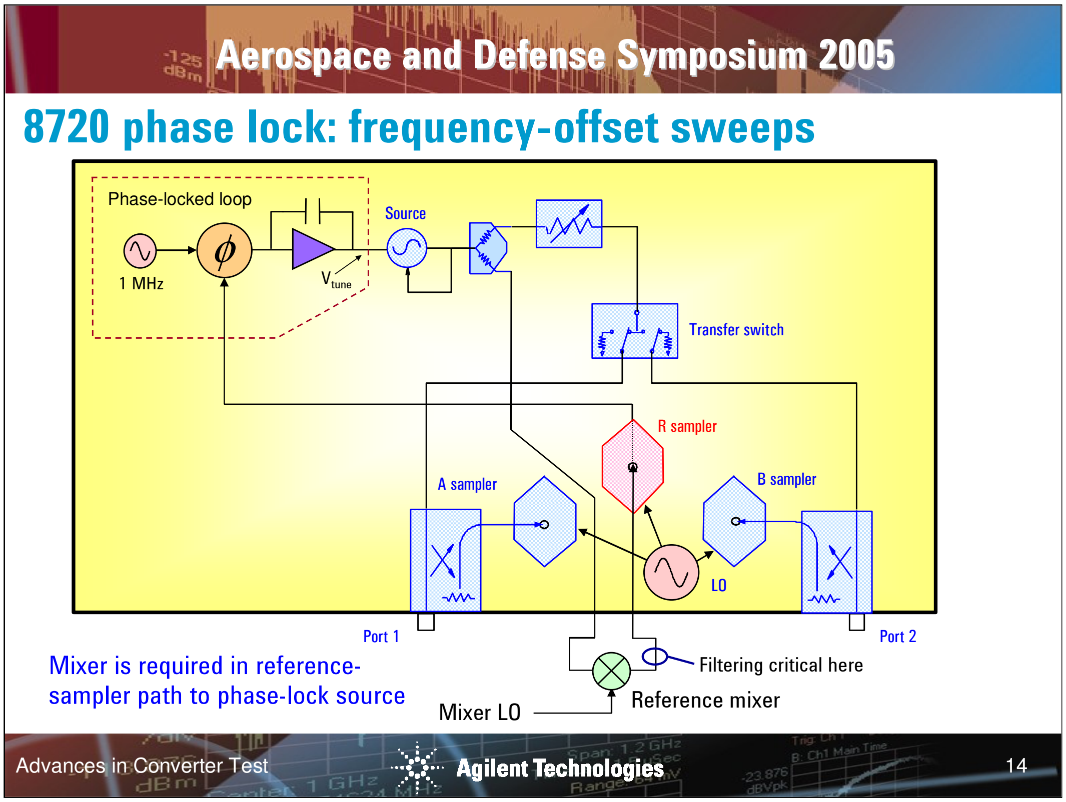


For absolute group delay measurements of mixers and converters, more complicated techniques exist. The up/down method is limited to identical mixers, and is often plagued by mismatch errors. Another well-known method is to measure the envelope delay of the DUT using a swept, modulated RF carrier. In this case, group delay and envelope delay are equivalent. This is accomplished by modulating an RF signal (usually with AM or FM) and stepping the carrier in frequency across the frequency range of interest. At each frequency point, the output of the DUT is demodulated, and the phase of the demodulated signal is compared to either the original modulation signal, or a demodulated signal obtained by splitting the input signal. Group delay is easily calculated from the phase shift and the modulation frequency. The aperture of the measurement is determined by the modulation frequency. This technique is noisy compared to using a VNA, but it is the only method that works on devices with fully embedded LOs, such as satellite transponders.



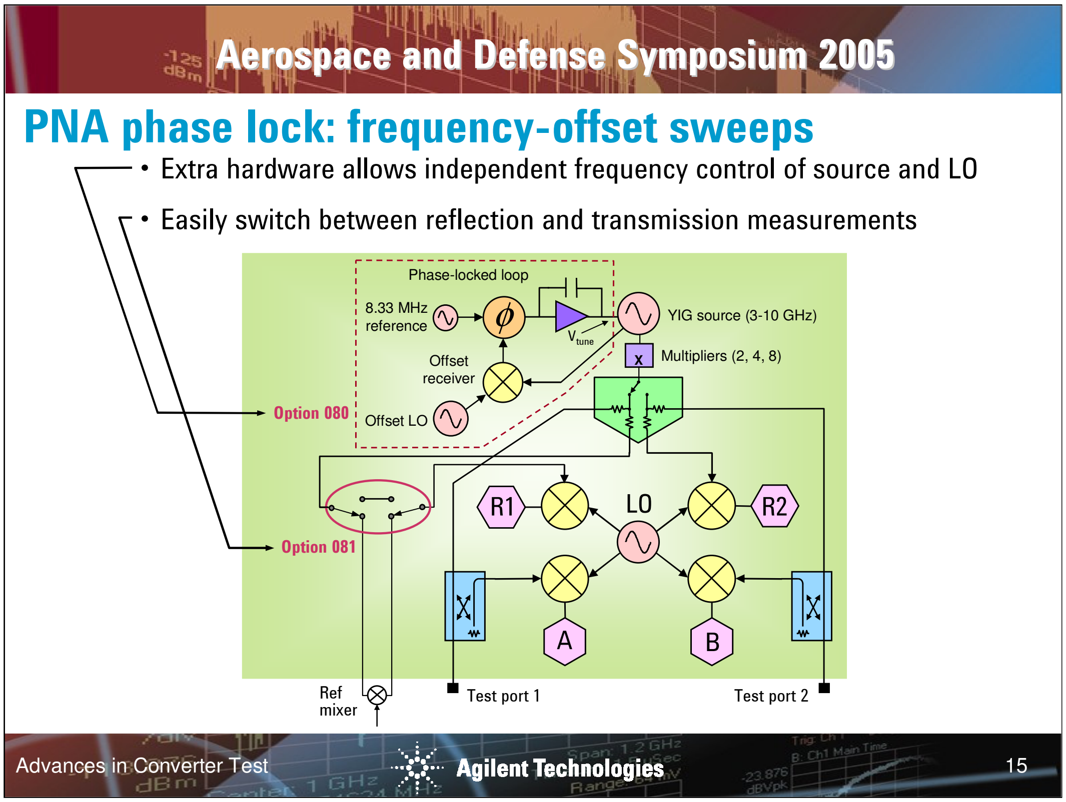
Modern VNAs provide two key areas of improvement compared to older models. The first is with respect to calibration. For example, Agilent has developed two new calibration techniques especially for measuring mixers and converters. These techniques provide the highest accuracy compared to any other solution. The scalar mixer calibration (SMC) combines vector-error and power-meter correction to give accurate conversion gain/loss measurements. The vector-mixer calibration (VMC), which we will describe shortly, provides calibrated measurements of absolute group delay.

The other major contribution of modern VNAs is in the area of convenience. This is manifested in several ways. Dialog-box-based user interfaces are intuitive and easy-to-use. Guided calibrations greatly simplify the calibration process. Built-in "help" files provide a wealth of measurement expertise. Advanced hardware architectures eliminate source phase-lock difficulties. The advanced error correction eliminates or minimizes the need for external attenuators, used in the past to minimize mismatch errors. And finally, external signal generators used for LO signals can be set up and swept by the VNA, using the VNA's user interface.



Let's look at the issue of phase-locking the source with a frequency offset for testing mixers and converters. The 8720 family of VNAs required placing an external mixer in the phase-lock path. The output of the reference mixer was connected to a sampler-based receiver, which opened the possibility of many undesirable interactions. It was extremely critical to filter away unwanted mixer signals to make sure the phase-lock loop did not unlock or lock at the wrong offset frequency.

This block diagram shows how the 8720 source was phase locked for offset-frequency sweeps. The external reference mixer was placed in between the source signal and the reference receiver, to provide an arbitrary frequency offset within the phase-locked loop. Besides providing an arbitrary offset to the source, the reference mixer was also used for relative phase measurements.



The PNA series of VNAs has eliminated the source phase-lock problems inherent to the 8720 family by using internal hardware alone for phase locking the source, both for normal and frequency-offset sweeps. For normal sweeps, the reference receivers provide the signal for the source's phase-locked loop. For offset sweeps, a 5th receiver (provided by Option 080) is used to phase lock the source. This provides independent frequency control of the source and the LO used to drive the mixers in the reference and test receivers. An external reference mixer is required only for phase measurements, but not for achieving phase lock of the source.

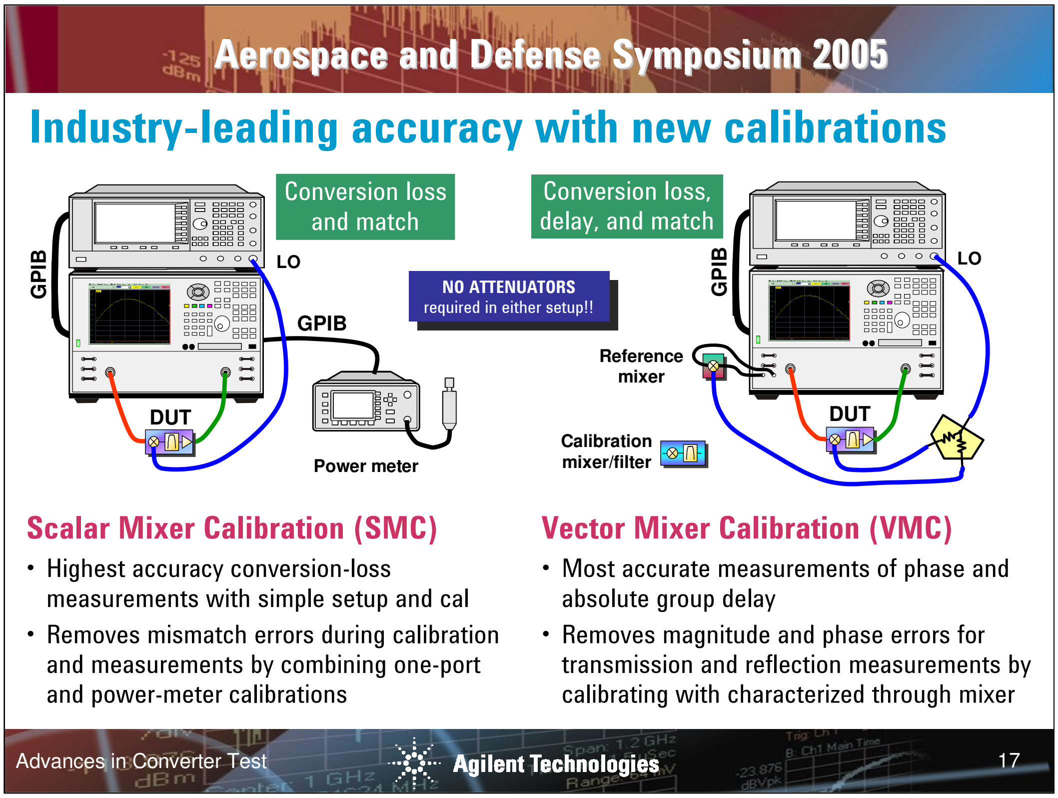
The block diagram on the slide shows the extra receiver that provides an IF signal to the phase-lock loop. The offset LO (using the same architecture as the main LO) is used to tune the source to any arbitrary frequency. The source is now locked to the offset LO instead of the main LO. For frequency sweeps, both the main and offset LOs are swept.

Option 081 provides an R1 reference switch that can bypass the front-panel reference loop. This means that the reference mixer can be switched out for measurements of S11 (where the source and receivers are tuned to the same frequency) and switched in for phase measurements of the mixer or converter under test. This switch is also key for the vector-mixer-calibration technique, which we will describe later.

Agenda

- Review of mixer/converter measurements
- Traditional versus modern VNA-based solutions
- **New mixer calibration techniques**
  SMC: Scalar Mixer Cal
  VMC: Vector Mixer Cal
- Measuring delay of multistage converters
- Tips and techniques for successful measurements

In this next section, we will discuss modern calibration techniques used for measuring mixers and converters.



Here is a summary of the two new calibration techniques available with the PNA. Scalar mixer calibration (SMC) provides the highest accuracy conversion-loss measurements. It is simple to set up and calibrate. It requires the use of a power meter during calibration, along with the usual open, short, and load standards. SMC corrects for DUT mismatch during transmission measurements by taking advantage of the VNA's ability to measure its source and load match (during calibration), and the DUT's input and output match.

Vector mixer calibration (VMC) provides the most accurate measurements of phase and absolute group delay. It uses a characterized mixer as a calibration through standard, along with the usual open, short and load standards. VMC removes magnitude and phase errors for both transmission and reflection measurements. It also requires an external reference mixer.

Because both calibration techniques perform corrections for mismatches, the use of external attenuators is eliminated or greatly reduced. In the following slides, we will explore these two techniques in a little more detail.

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Traditional power-meter calibration versus SMC

Both techniques

- Level source power at input frequency
- Correct receiver response at output frequency

Traditional Power-Meter Calibration

- No vector error correction applied during calibration or measurement
- Only optimized for DUT with same input impedance as power sensor

SMC

- Corrects for mismatch during calibration
- Applies vector error correction for DUT input and output mismatches
- Requires three sweeps during measurement

Result: much less mismatch ripple, higher accuracy

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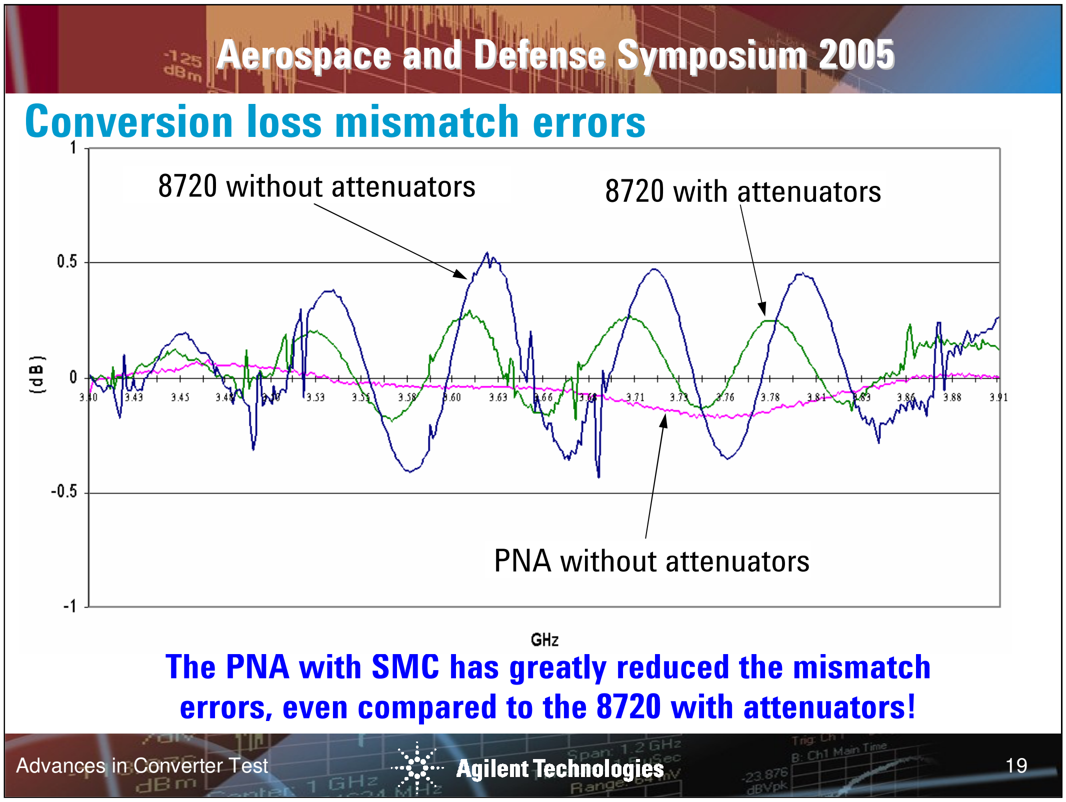
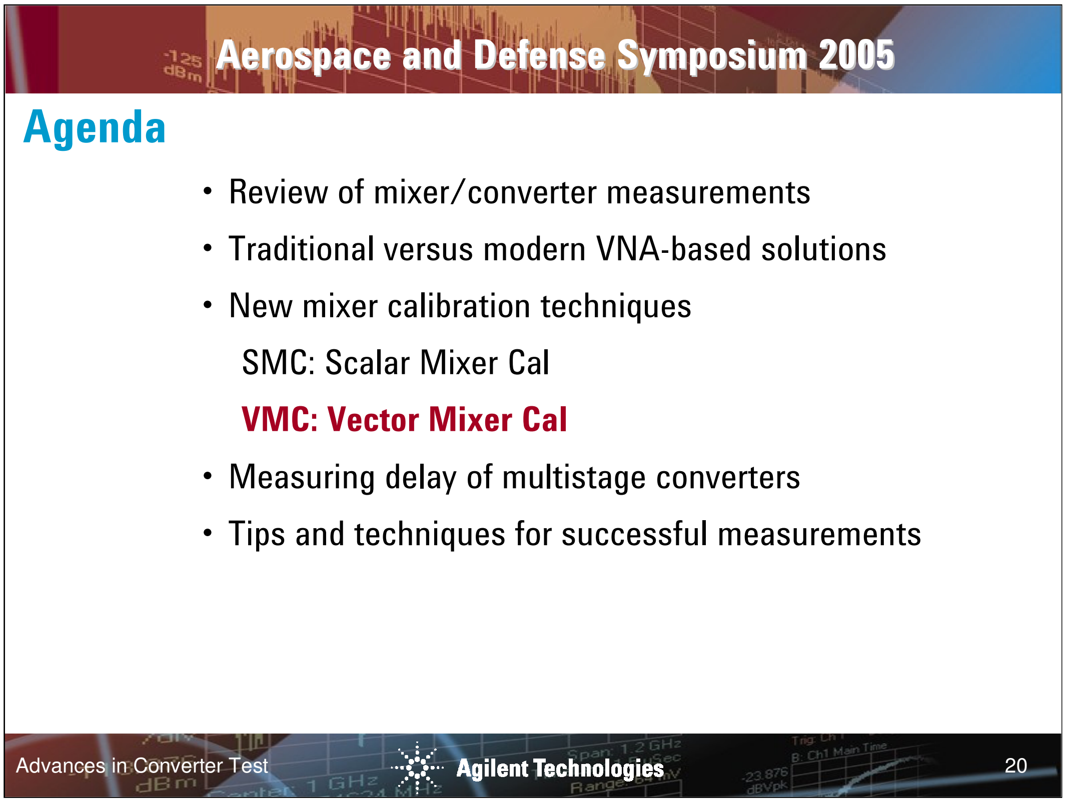
Since two-port error correction is not available when making frequency offset measurements on a network analyzer, often a source and receiver power calibration have been the best method of calibration available.

In a traditional power-meter calibration, the analyzer's source power is calibrated and leveled over the input frequency range, and the receiver's response is calibrated (in absolute magnitude) over the output frequency range. Since the analyzer is calibrated in the presence of the power sensor's input impedance, and because no mismatch corrections are applied during the measurement, any deviation between the match of the sensor and DUT input or output match will translate into measurement error.

SMC also levels the source and calibrates the receiver over the appropriate frequency ranges. In addition, it extends the calibration methodology by adding one-port calibrations at the end of the test cables, yielding the source and load match terms of the VNA. With this information, the input match of the power sensor can be measured versus frequency, and the power readings can be corrected for mismatch error. During the measurement of the DUT, vector error correction is applied to remove the effects of input and output mismatch error. With SMC, three sweeps are required to make a transmission measurement. The result is considerably less ripple in the transmission measurement as compared to the traditional power-meter-based calibration.



Here are some example conversion-loss measurements taken on Agilent 8720 and PNA network analyzers. A traditional source and receiver calibration was used on the 8720, while SMC was used on the PNA. The 8720 measurement was done with and without external attenuators. Adding external attenuators reduces, but does not eliminate, mismatch error, which is not corrected for on the 8720. In both cases, the 8720 mismatch ripple was much worse than the PNA, which did not use any attenuators. You can see that the PNA, even without attenuators, shows very little mismatch errors, due to the use of SMC.



In the following section, we will discuss VMC in more detail. We will start off by describing another technique to yield measurements of absolute delay of a mixer or converter.

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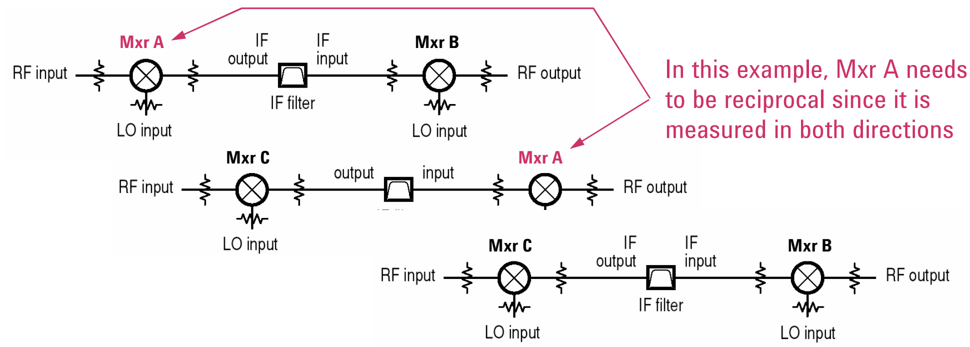
Three-mixer technique

- Requires 3 mixers, one of which MUST be reciprocal (others can be converters)
- Requires filtering of images
- Does not correct for mismatch between mixers
- IF filter effects must be removed with de-embedding



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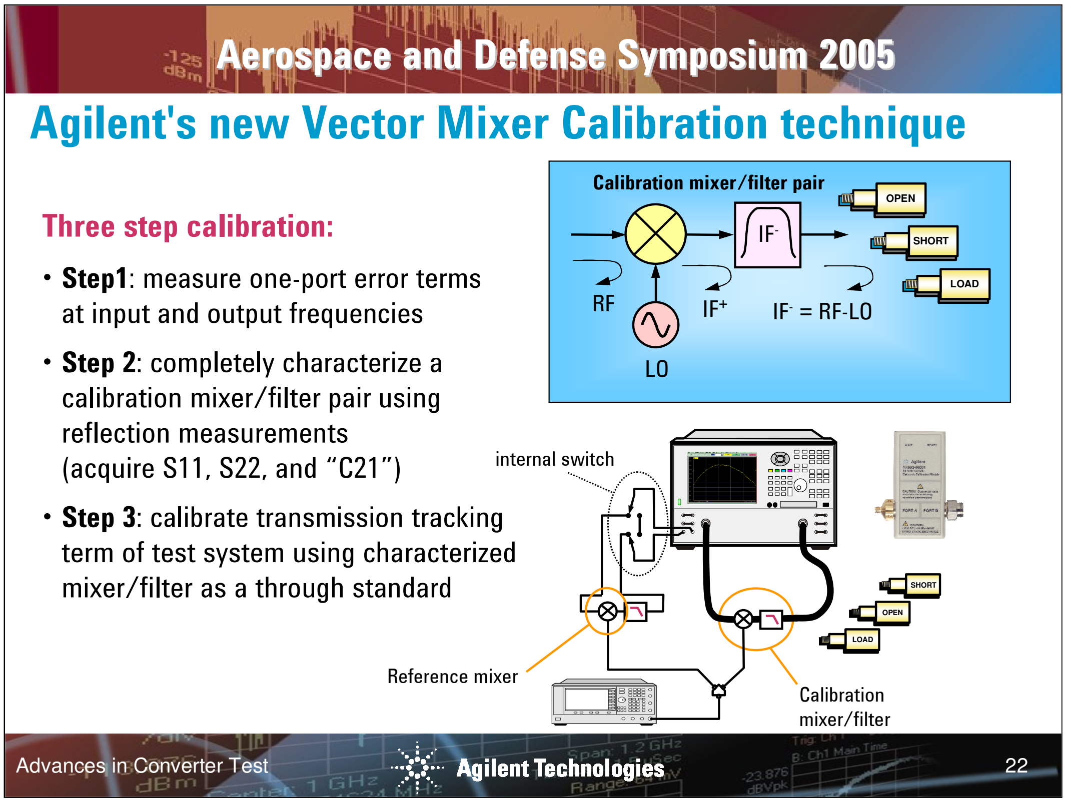
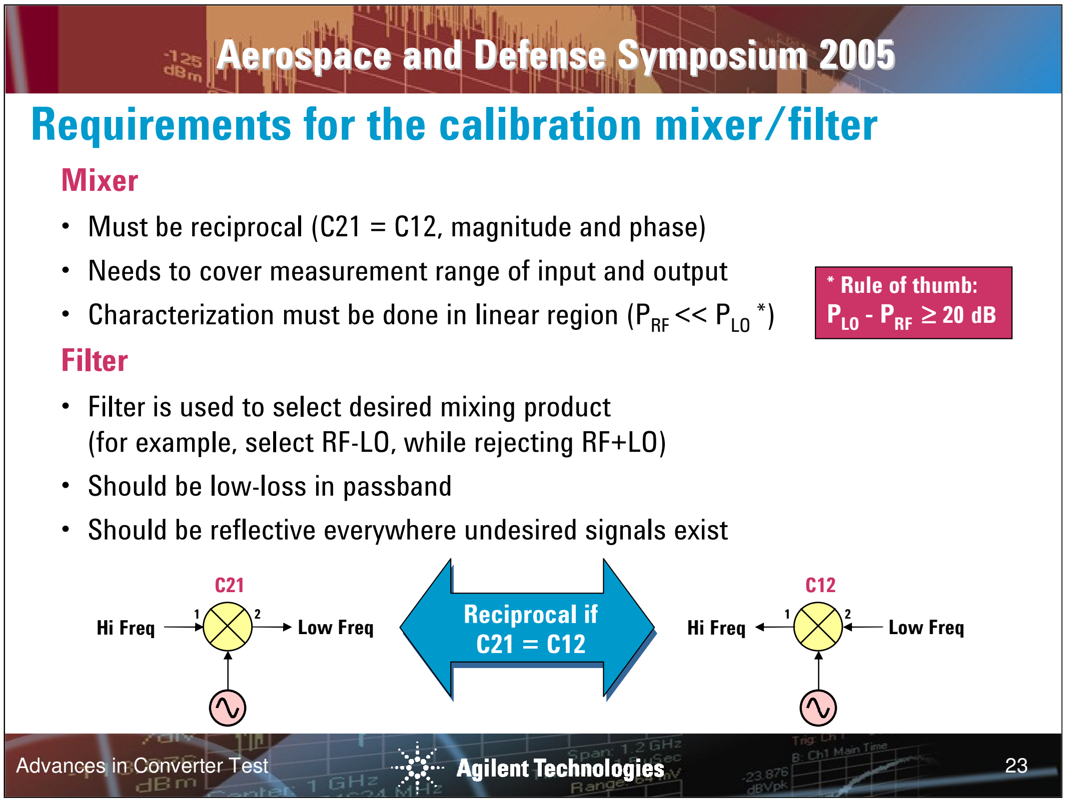
One technique used in certain VNAs that measures the absolute magnitude and delay of a mixer (or converter) requires three mixers or two mixers and a converter. These devices are measured in pairs in a series up/down or down/up configuration. With this method, one need not assume that the mixers have identical behavior, as is assumed in the two-mixer up/down technique. The idea with this technique is that three unique series measurements are made with different combinations of mixers. Since there are three measurements and three mixers, one can solve for the response of each mixer by itself. This method requires that one of the mixers must be reciprocal (more on this later), and that a filter be placed between the mixers to remove the unwanted mixing products.

While this technique, at least in theory, yields absolute measurements, it has some serious limitations in practice, most notably related to mismatch errors, which are difficult to remove. It is also a more lengthy and complicated process than using Agilent's VMC. Later, we will show a measurement comparison between this technique and VMC.

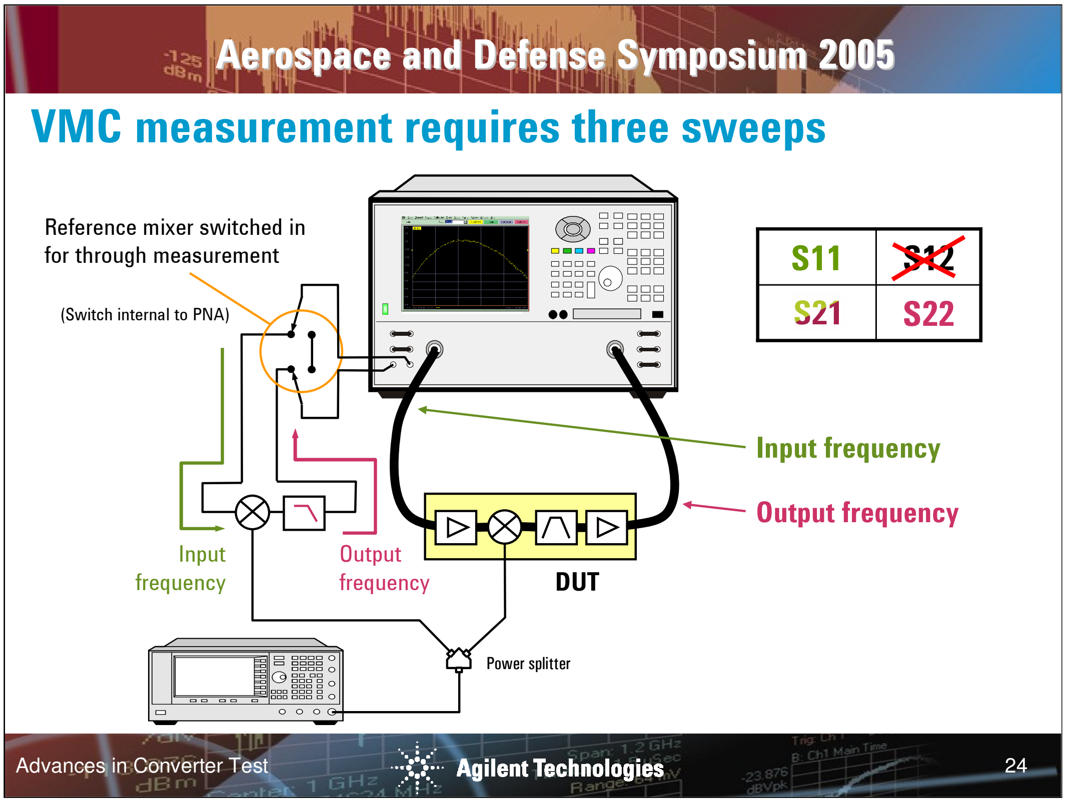


A new method developed by Agilent eliminates most of the sources of errors of previous methods. It is a three-step process. In step one, we measure short, open and load standards to build a one-port error model for each test port at the appropriate input or output frequency. Next, we characterize a mixer/filter combination (again, using an open, short and load), which becomes the "calibration mixer". Finally, we use the calibration mixer/filter pair to calibrate the entire VNA-based test system, which includes test cables, adapters, etc. In the last step, we use the external reference mixer in order to make phase measurements, but its effect on the measured DUT data will be removed as part of the correction process. In this way, we measure the absolute performance of our DUT.

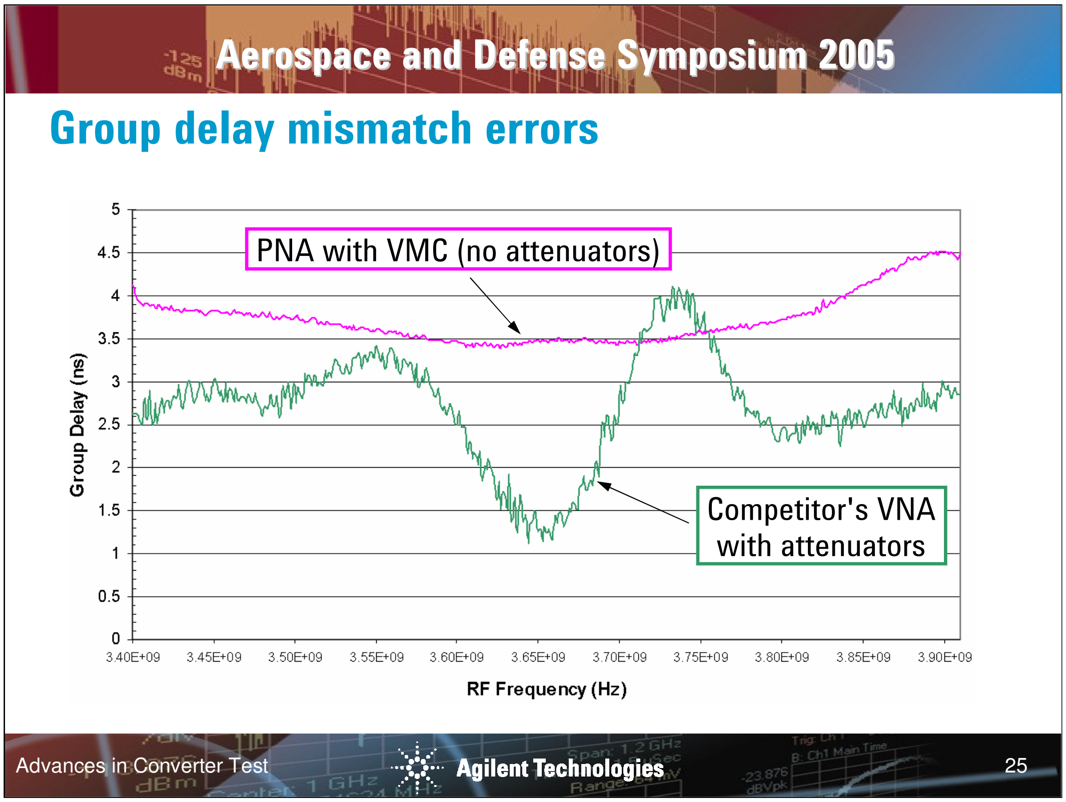
The VMC calibration process can be greatly simplified by using Agilent's ECal electronic calibration modules.



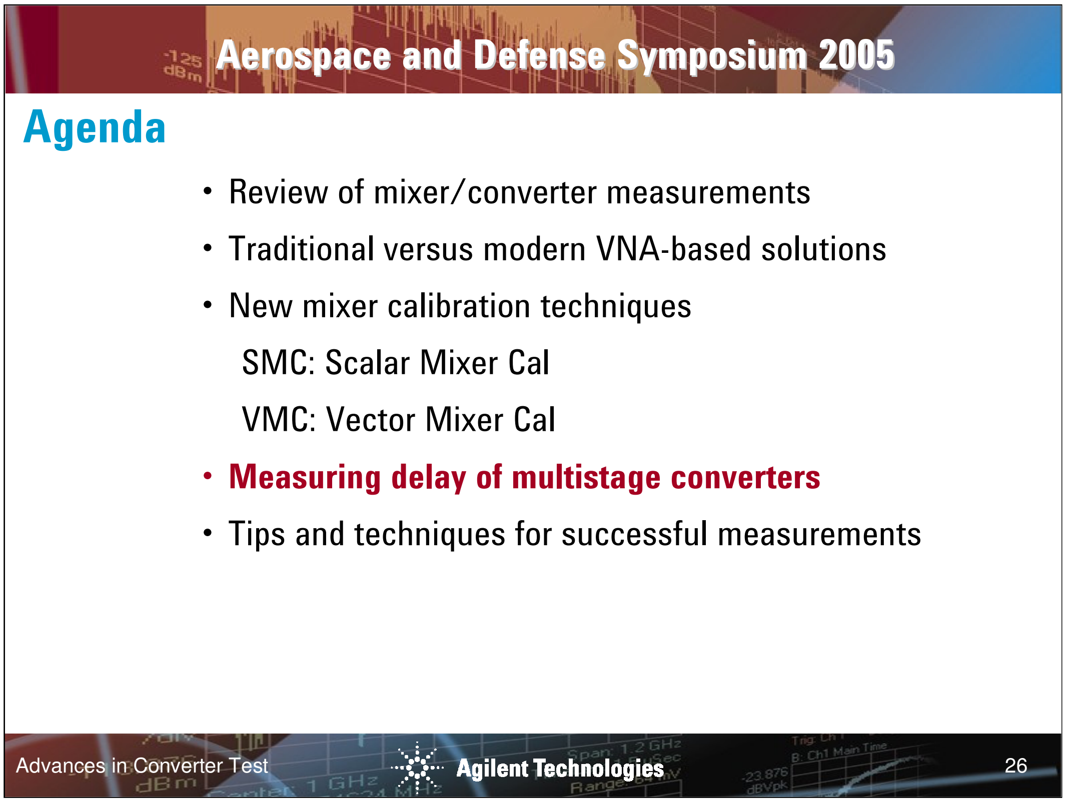
This new method developed by Agilent maintains only two basic restrictions. The first restriction is that the undesired mixing product coming out of the mixer must be filtered out (for example, the RF+LO product). The second restriction is that the mixer be reciprocal in response. A reciprocal mixer is one that has the same conversion response when it is used as either an up-converter or down-converter, as shown on the slide. These are two of the restrictions of the previous methods, but this method inherently removes the effects of the filter and reduces the number of connects (and their attendant sources of error), thereby greatly reducing mismatch errors and increasing accuracy. The slide covers some of the finer points regarding selection of the mixer and filter.



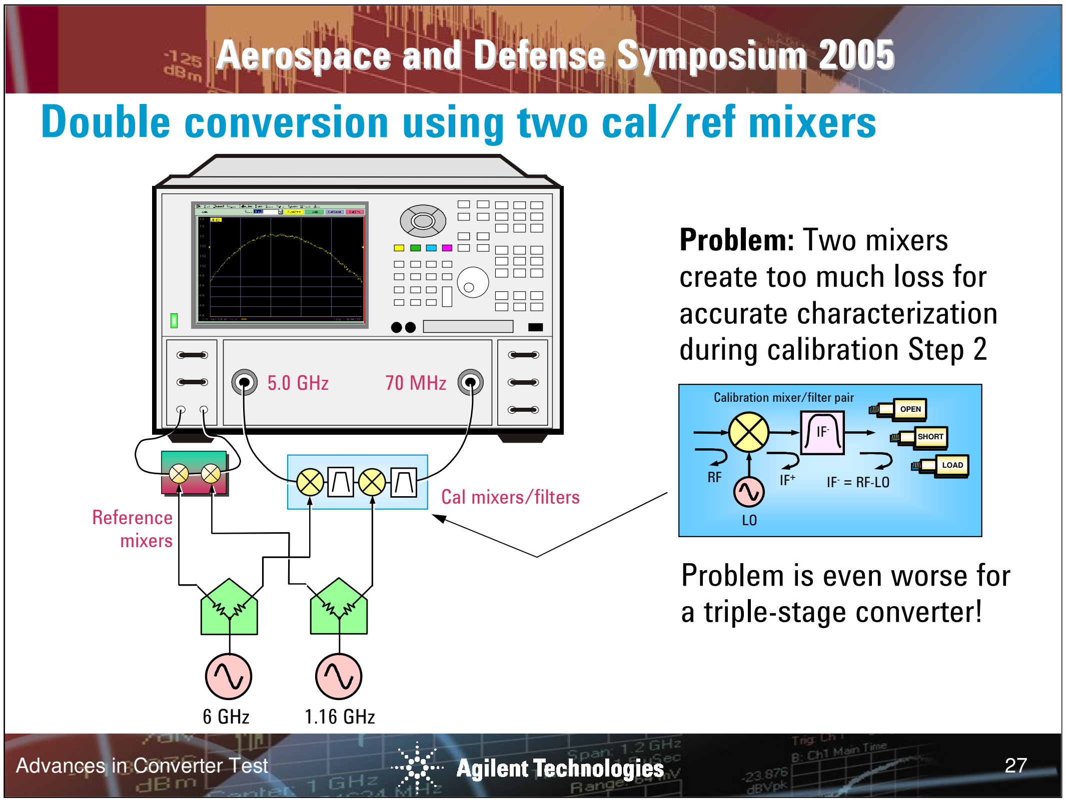
For the actual measurement of the DUT, the PNA makes three sweeps. Two of the sweeps are reflection measurements of the DUT's input and output match, at the input and output frequencies, respectively. These sweeps do not require a frequency-offset sweep or the reference mixer, so the reference switch is set to bypass the reference mixer. For the third sweep, the PNA makes a transmission measurement, with the reference switch set to include the reference mixer, so that both magnitude and phase data can be acquired. This data, along with the data acquired during the calibration, provides absolute magnitude and phase data of the DUT that is corrected for input and output mismatch error.



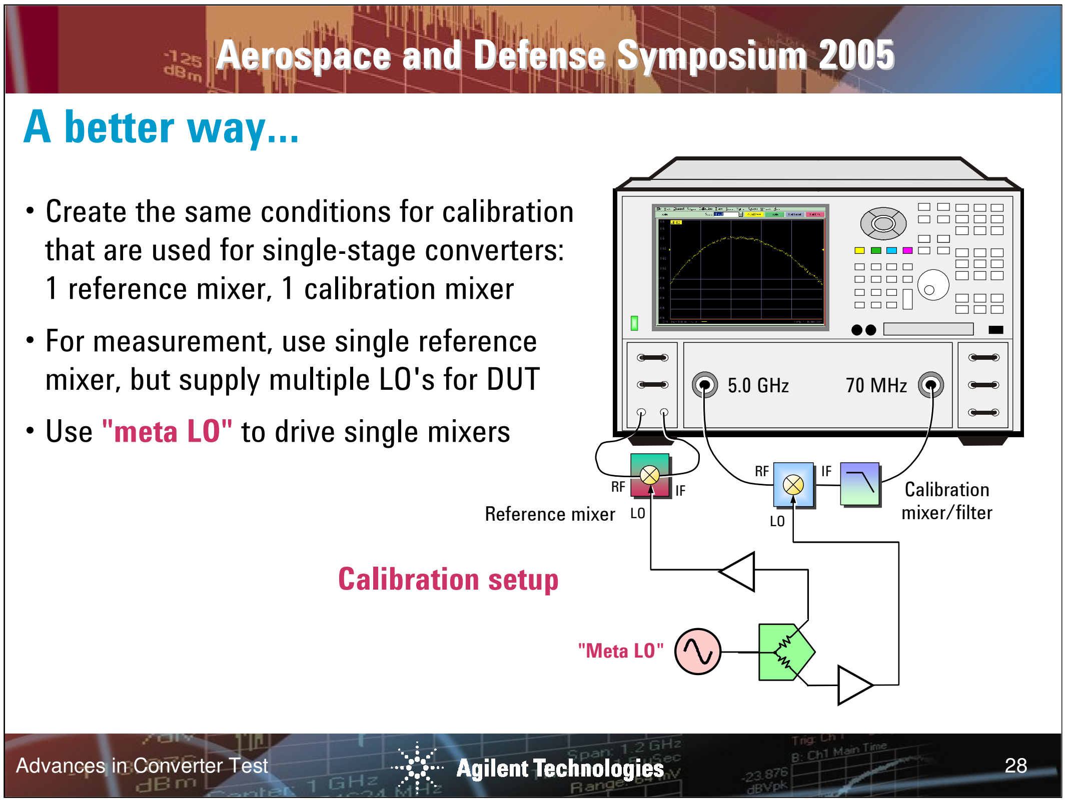
In this example, we compare measurements of the same DUT done on a PNA using VMC (with no attenuators), and on a competitor's VNA using the three-mixer technique and 3 dB pads on the test ports to minimize mismatch ripple. As can be clearly seen, VMC provides significantly reduced mismatch errors, as well as a less-noisy trace.



In this next section, we will show how VMC can be applied to converters with more than one down-conversion stage.



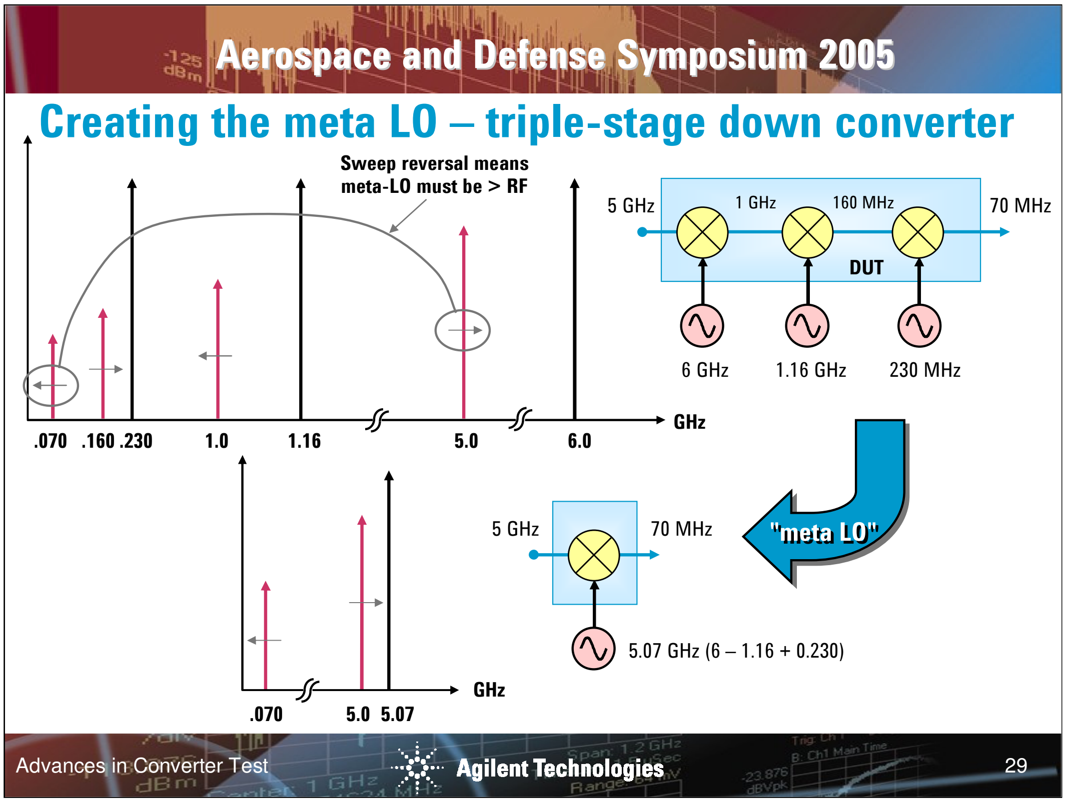
The straight-forward way to perform VMC for a device with two stages of conversion is to use two reference mixers and two calibration mixer/filter pairs. Having two reference mixers is fine, but two calibration mixers presents problems, because two mixers in series create too much loss for accurate characterization during step 2 of VMC (the "characterize the mixer/filter pair with reflection measurements" portion). With the loss of two mixers, it is hard to tell the difference between measuring the highly reflective standards (short or open), and the low-reflection load standard. The problem of too much loss would be even worse for a triple-stage converter, if we tried to use three mixers in series as a calibrated through.



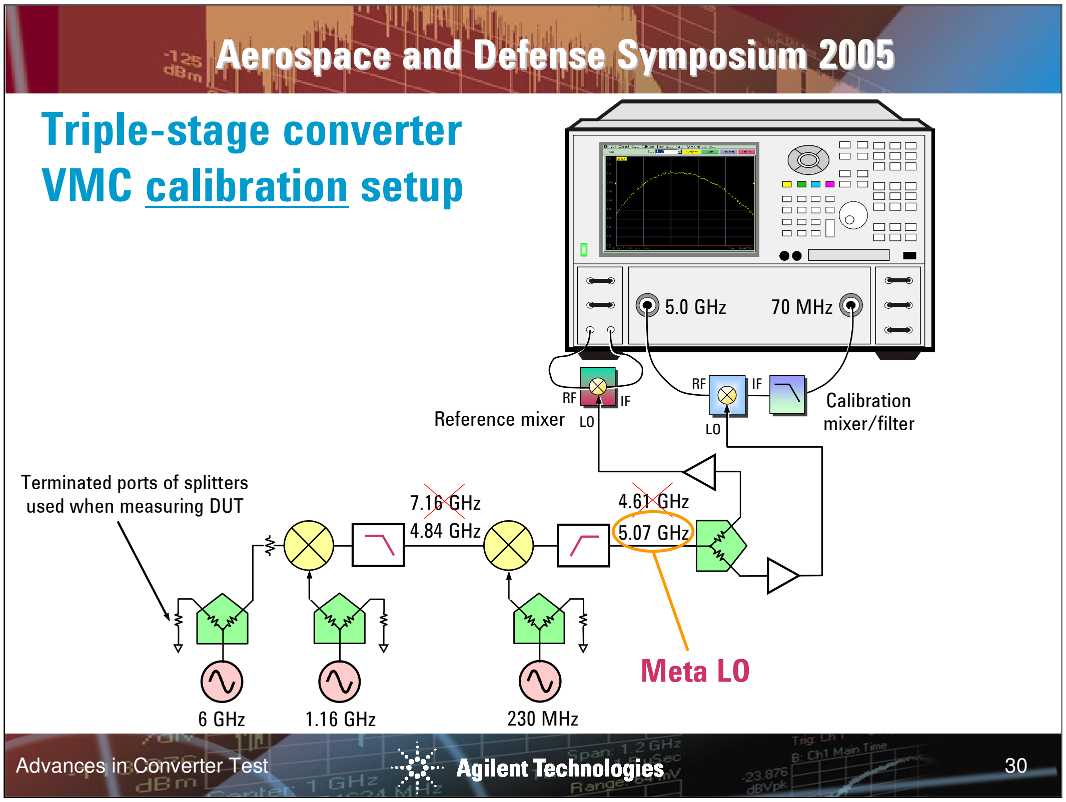
A better way to measure multistage converters is to configure a test setup where we use one reference mixer and one calibration mixer during the calibration process, and for the measurement of the DUT, we continue to use one reference mixer, but supply multiple LOs to the DUT. For this to work, we have to generate a "meta-LO" to drive the reference and calibration mixers.

The meta-LO is a single LO that mimics the combined conversion process of the multiple LOs in the DUT. In the general case, it is derived from the LO's used for the DUT (we will discuss a special case later, where the meta-LO comes from a single external signal generator). External mixer(s), amplifiers, and filters are used to combine the multiple LOs used for the double or triple converter. For the most accurate measurements, it is best to use external signal generators for the DUT LOs where possible. If the DUT has embedded LOs with access to each LO output, then these LOs can be used to generate the meta-LO, but isolation between LOs becomes crucial. The special case mentioned above is when the DUT has embedded-LO's with access only to a common timebase, rather than LO outputs themselves. This case results in noisier measurements, as we will see later.

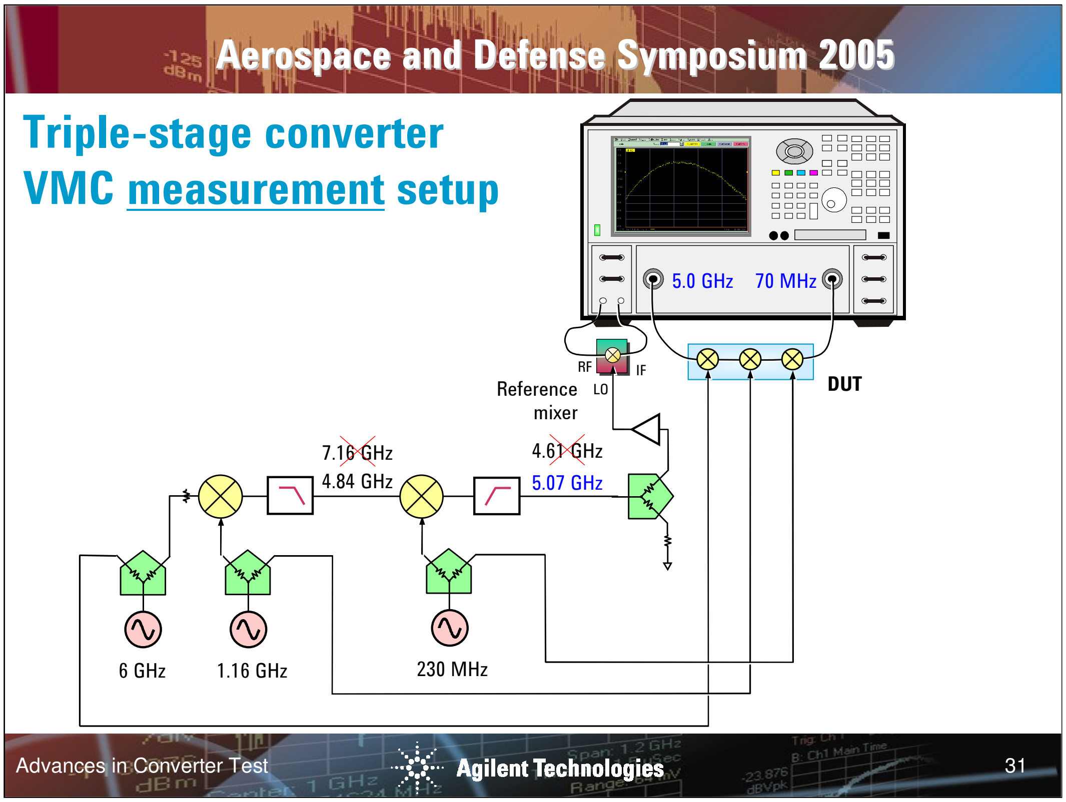
The use of a single reference and calibration mixer, both driven from the meta-LO, eliminates the problem of too much loss of the calibration mixer.



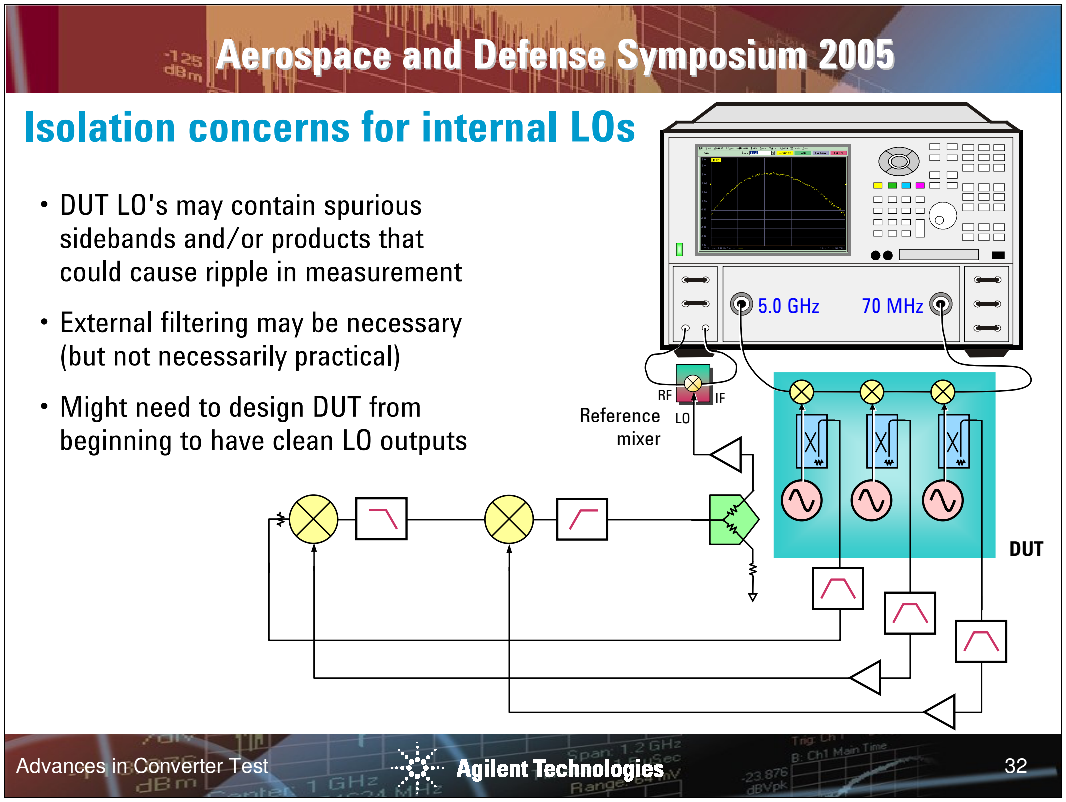
Here is an example of calculating the meta-LO frequency for a triple-stage down-converter. Notice that there is a sweep inversion between the input and output of the DUT (the IF output sweeps down when the RF input sweeps up). This means the meta-LO must be above the RF input signal, as shown on the slide. The single mixer stage with a 5.07 GHz LO provides the same output frequencies as the DUT (over a prescribed range of input frequencies).



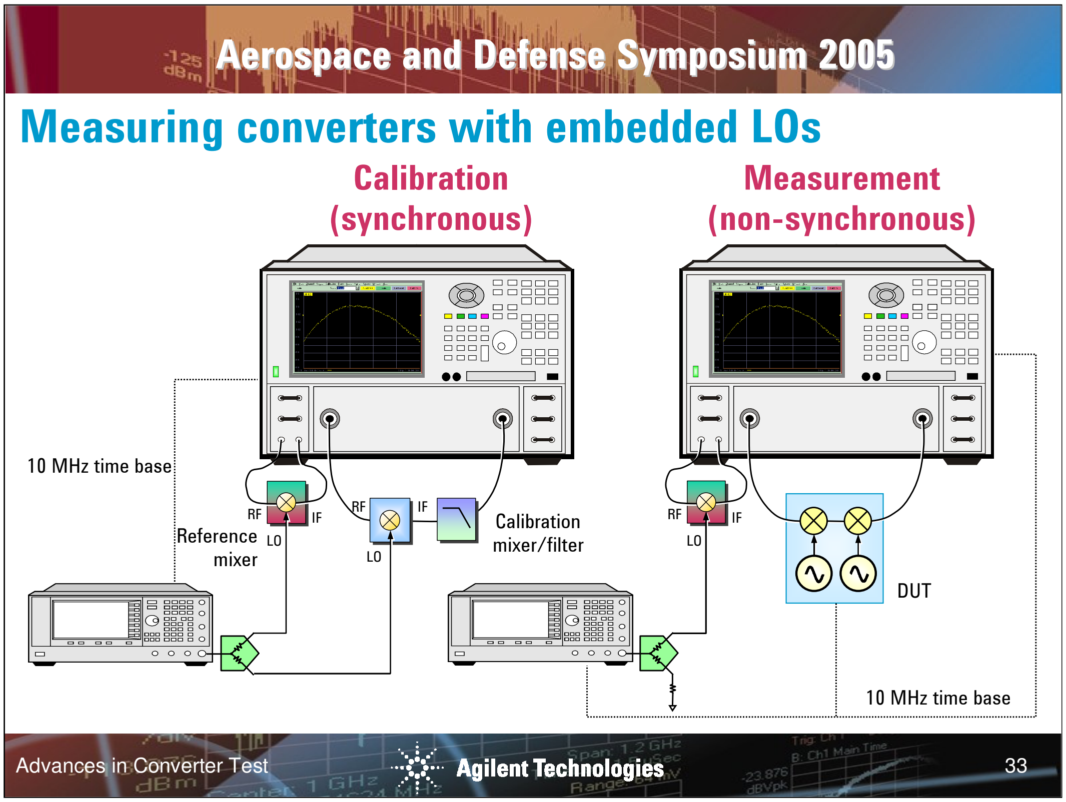
This slide shows the hardware setup during calibration to create the meta-LO of 5.07 GHz. The proper filtering after each mixer (to select the desired plus or minus mixing product) is crucial. The LOs in this example come from external signal generators. The amplifiers are used to boost the meta-LO to a power level sufficient to drive the reference and calibration mixers, and provide isolation between the two mixers. Good isolation helps minimize ripple during the measurement.



This slide shows the setup for measuring the DUT. Now, each individual LO is used for the down-conversion in the DUT, as well as for creating the meta-LO which drives the reference mixer as was done in the calibration process.

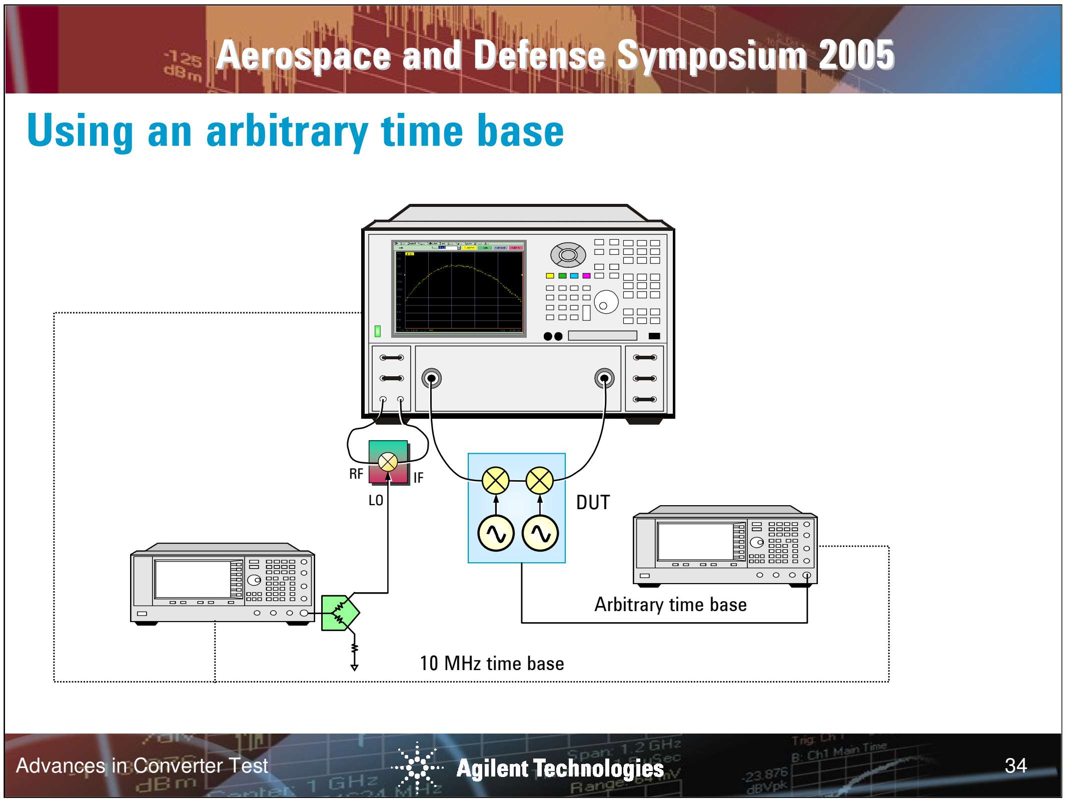


When using internal LOs, some caution is needed. The DUTs LOs may contain spurious sidebands and/or spurious products that, when combined to make the meta-LO, can cause ripple in the measurement. External filtering may be necessary to clean up the signals, but the bandwidths required of the filters may not be practical to implement in the real world. It may be necessary to design the DUT from the beginning to have clean LO outputs. This can be accomplished with internal amplifiers, filters, attenuators, isolators, etc.

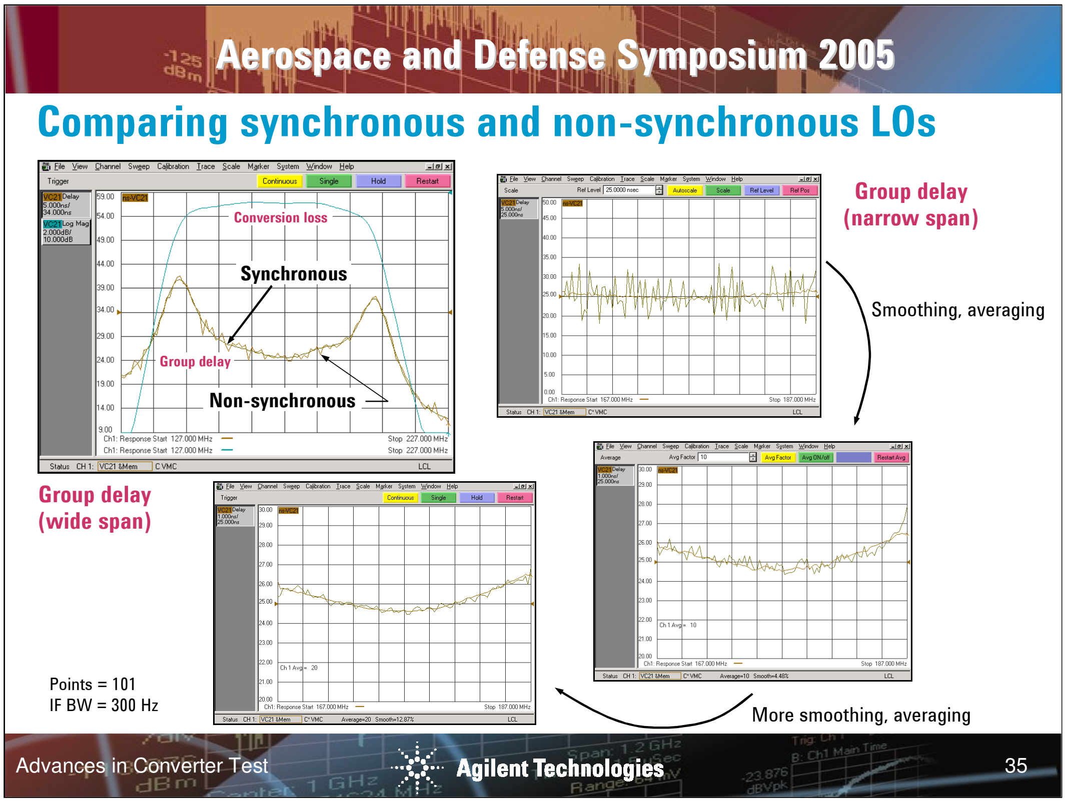


This setup covers the special case where the DUTs LOs are embedded, with no direct access to the LO frequencies themselves. If there is access to a common time base, then an external signal generator and the PNA can be frequency locked to the DUT's LOs to ensure that the signals coming from the DUT are exactly where the PNA is tuned. In this example, everything is locked to a common 10 MHz time base (choose the cleanest 10 MHz source if possible). During calibration, the external signal generator drives both the reference and calibration mixer. During measurement of the DUT, the external signal generator only drives the reference mixer.

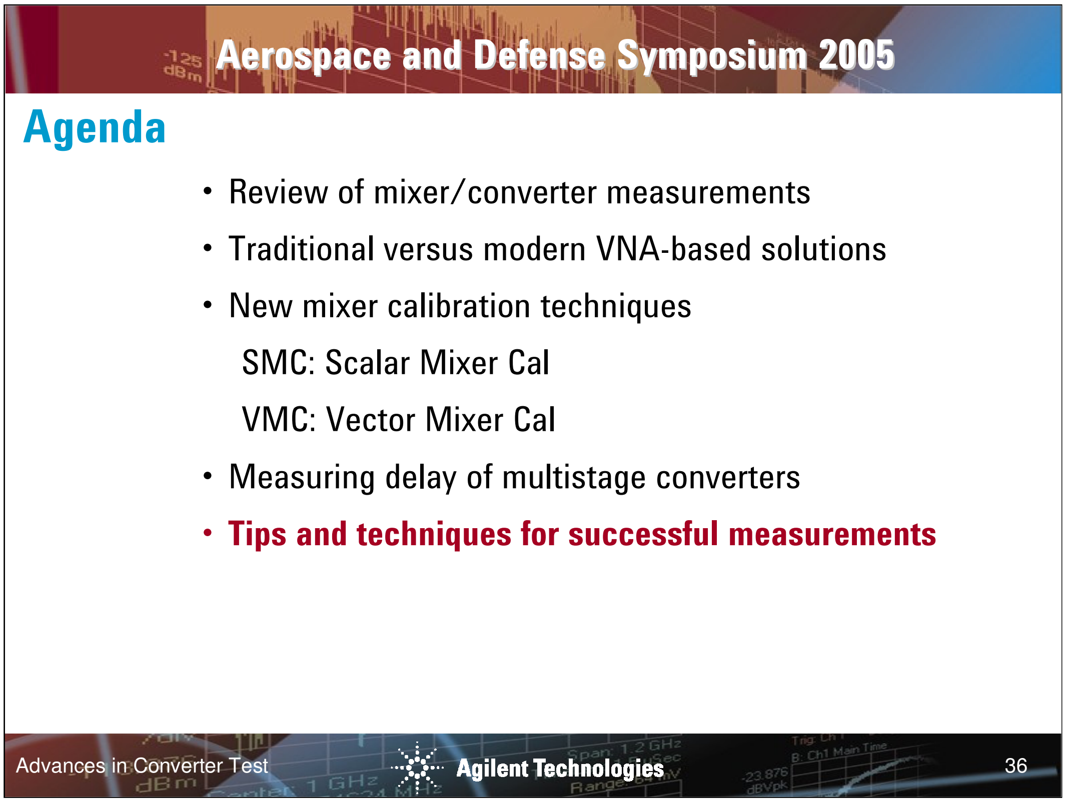
This configuration generates more trace noise when measuring phase or delay than the case where the meta-LO is derived directly from the DUT's LOs. In the latter configuration, any phase noise present on the LOs gets ratioed out of the measurement. With this setup, the phase noise of the external signal generator and the DUT's LOs are not synchronous, so no phase-noise improvements due to ratioing are possible.



In this example, an extra signal generator is used to create an arbitrary time base. This is necessary if the DUT does not use 10 MHz to lock its internal LOs.



Here are some real measurement examples using VMC, comparing the fully synchronous meta-LO case to the non-synchronous case where an external signal generator is used for the reference mixer, but not for the DUT. As is readily apparent, the trace from the synchronous meta-LO case is much less noisier than the trace resulting from the non-synchronous case. As the measurement span is narrowed, the effective group delay aperture is decreased, which gives even more noise. With aggressive smoothing and averaging, the non-synchronous method can produce results that, while still not as good as the synchronous VMC case, are far superior to other measurement techniques, and good enough for most real-world DUTs. Note that the scale for the lower left plot is 1 ns/division.

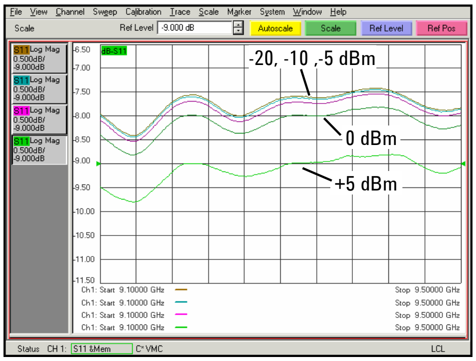


In this last section, we will cover some practical tips and techniques to help you achieve successful measurements of your mixers and converters.

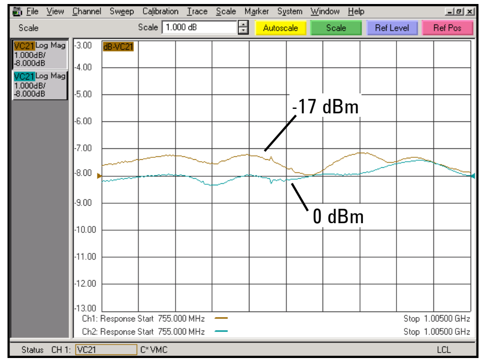
Power level for VMC cal-mixer characterization

Make sure cal mixer is characterized in linear region

(RF input power should be 20 to 30 dB lower than LO power)

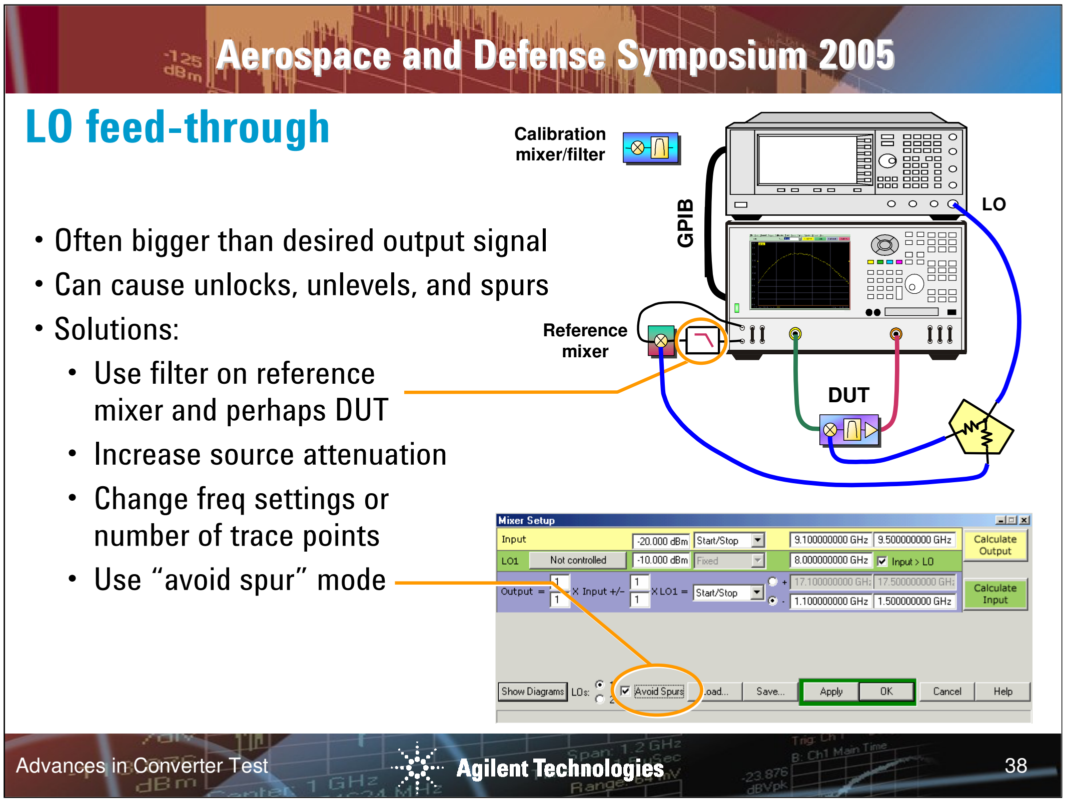


Return loss of the calibration mixer versus power



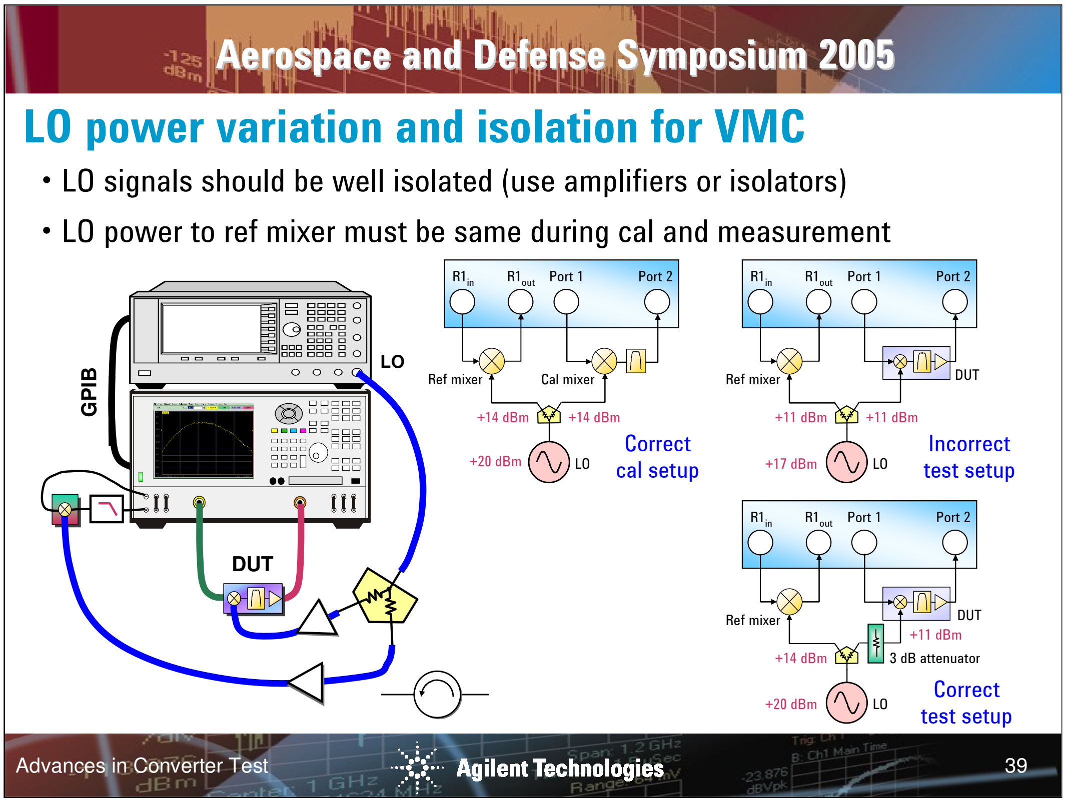
Mixer measurement using VMC with different power levels during cal

When performing VMC, it is critical that you don't drive the calibration mixer too hard (too much input power). The cal mixer must be characterized in a region where it behaves linearly. In a linear region, S11 is independent of input power. The left plot shows that when the power is varied between –20 and –5 dBm, a small amount of deviation in S11 occurs. As the power is further increased to 0 and then +5 dBm, S11 changes by a much larger amount. This is due to compression in the calibration mixer, which must be avoided for a good calibration. A good guideline to follow is to make the RF input power 20 to 30 dB lower than the LO power. The right plot compares traces when the RF input was –17 dBm (in the linear region) and when the RF input was 0 dBm (in the compression region). The 0 dBm case caused nearly 1 dB of additional measurement error.



For many reference mixers, the LO feed-through present at the output of the mixer is often considerably larger than the desired mixing product. This large LO feed-through signal, if fed directly into the reference-receiver input on the PNA, sometimes causes the PNA's source to become unleveled, or in extreme cases, unlocked. It can also mix inside the PNA's receivers to create spurs on the traces. Several solutions can be used to minimize or eliminate this problem.

The simplest is to add a filter at the reference mixer output that attenuates the LO feed-through. Another good technique is to manually increase the source attenuator setting by 10 dB. The increased attenuation provides more isolation between the mixer output and the PNA's source, which often cures unleveled errors. It is not always practical to manually override the auto-attenuation setting, as sometimes this act will cause the source to become unleveled because the PNA's automatic-level-control (ALC) range is exceeded. Another technique is to step around the spurs that the LO feed-through produces. This can be done by changing the frequency settings or the number of trace points of the sweep, or by using the analyzer's "avoid spur" mode. Note that use of the "avoid spur" mode must be consistent between calibration and measurement of the DUT.



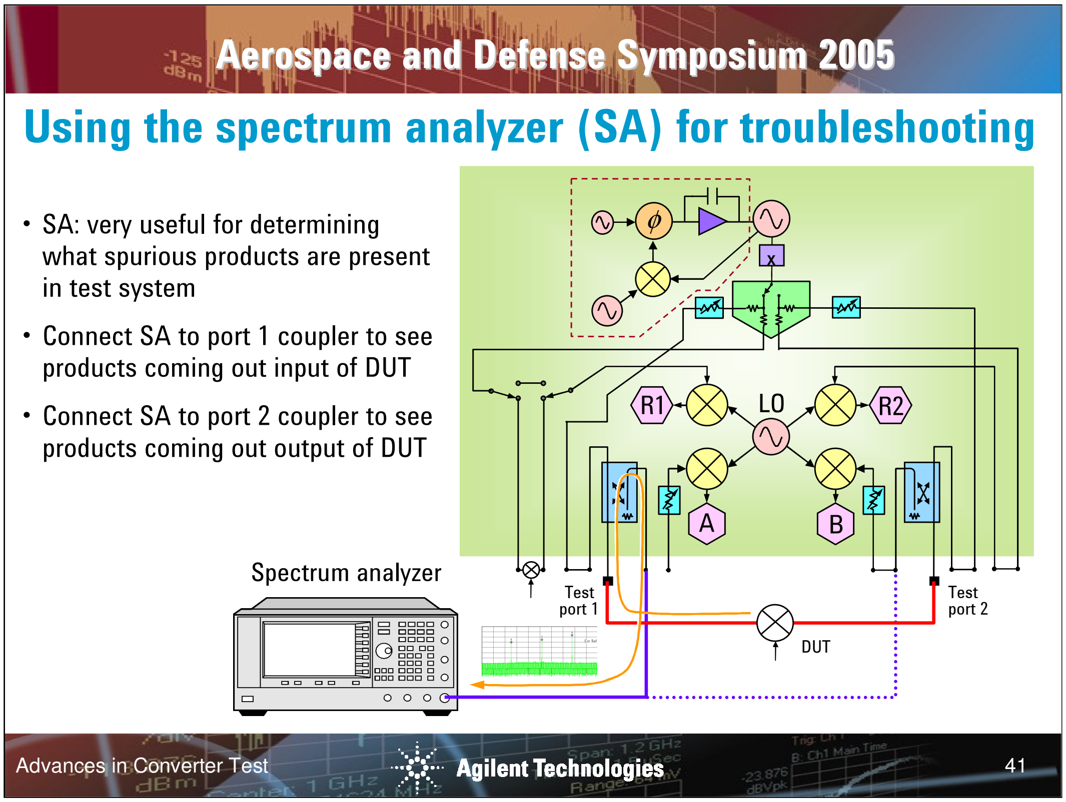
There are two considerations related to the LOs used in VMC-based measurements. The first consideration is that of LO isolation. Without proper LO isolation, spurious mixing products from the reference mixer can contaminate the calibration-mixer response or the measurement of the DUT via the common LO path, and vice versa (spurious signals can enter the reference mixer via the common LO path). A separate amplifier or isolator in each LO path greatly diminishes this problem.

The second consideration is that of the LO power levels during calibration and measurement of the DUT. If the DUT LO requires a different power level than that required for the calibration mixer, then care must be taken to keep the LO power to the reference mixer constant between the calibration process and the measurement of the DUT. This can occur when using mixers with different LO requirements (such as a level 7 calibration mixer and a level 13 DUT), or when measuring a converter with specific LO power requirements that are different than the calibration mixer. In the example shown on the slide, the calibration is done with two +14 dBm LO signals, one for the reference mixer, and one for the calibration mixer. The DUT requires a +11 dBm signal. A bad measurement would result if we simply lowered the source power by 3 dB, because the reference mixer's LO power would also drop, which would result in a different frequency response compared to that obtained during the calibration. The correct way to measure the DUT would be to add a 3 dB attenuator to the DUT LO path only, keeping the power to the reference mixer constant.

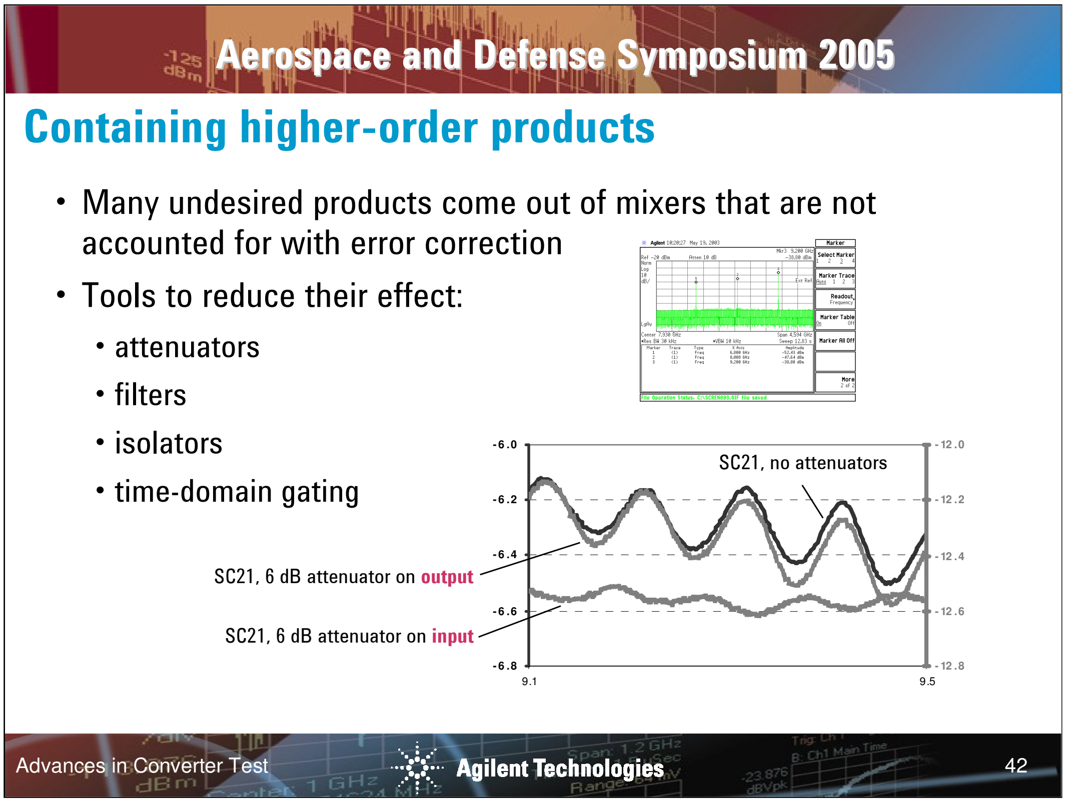
Using FOM to view receivers separately

- When troubleshooting traces that don't make sense, it is very helpful to view reference and measurement receivers separately
- Use separate measurement channel with frequency offset mode (FOM) and non-ratioed traces

When trying to track down the source of spurs in a VMC measurement, it is very helpful to observe the responses in the reference and test receivers separately, rather than as a ratio. For example, if we saw a spur in a VC21 trace, which is the ratio of the "B" test receiver to the "R1" reference receiver (equivalent to S21), we would not know if the spur was present in the R1 receiver, or the B receiver, or both. To see the unratioed responses of the receivers, we have to create a separate measurement channel on the PNA, and then use the frequency-offset mode (not the Frequency Converter Application) to set the proper stimulus and response values. The example on the slide shows that the spur is present only in the B receiver, which means it is not due to spurious products coming from the reference mixer.



When confronted with a spurious response on a measurement of a mixer or converter, it is often very difficult to figure out where a particular spur is coming from only using the VNA. A spectrum analyzer (SA) is a very useful tool for determining what spurious products are present in a test system. The SA, combined with the directional couplers of the VNA, can be used to measure the signals coming out of both the input and the output of the mixer. Once the spurious inputs and outputs are identified in the frequency domain, one can begin to understand how they might interact with the VNA to create a measurement spur.



Here is an example of using a spectrum analyzer to help understand why the measurement had excessive ripple. The SA showed that the largest products were coming out of the input side of the DUT, which, in this case, was a mixer. The particular frequencies are outlined below.

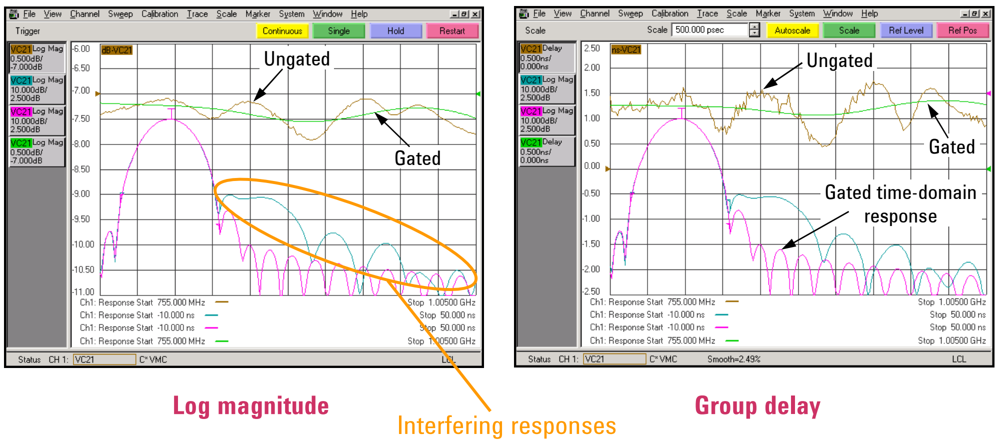
Conditions:

- Input = 9.2 GHz, LO = 8 GHz, Output = 1.2 GHz
- Spectrum analyzer connected on input side of DUT
- Marker 1: 6.8 GHz (output reflects off port 2, mixes with LO, reflects off port 1, produces 1.2 GHz delayed response)
- Marker 2: 8.0 GHz (LO leakage reflects off port 1, remixes with RF input, produces 1.2 GHz delayed response)
- Marker 3: 9.2 GHz (RF reflection; corrected with SMC)

Of the three signals identified with the markers, only one is corrected for with SMC marker 3. The other two signals, which are at the same frequency as the output, but delayed in time, will cause constructive and destructive interference versus frequency (ripple). Adding an attenuator at the output of the DUT did not help much because the delayed signals were created on the input side. Adding an attenuator at the input to the DUT made a significant improvement, since the interfering signals passed through the attenuator twice, and the RF input passed through only once, giving a net increase to the signal-to-interference ratio equal to the value of the attenuator.

Other components that can reduce measurement ripple are filters and isolators. Time-domain gating is another tool we can use to remove time-delayed responses. We will examine this technique on the next slide.

Time-domain gating



Whenever time-delayed responses interfere with the main response from a DUT, causing measurement ripple versus frequency, time-domain gating is a good candidate to help eliminate the effect of the interfering signal. In the example above, we see a measurement of a DUT that has ripple in the conversion measurement, looking at both log magnitude and group delay. If we perform a time-domain transform of this measurement, we see there are significant responses delayed in time from the main response. The time-domain gating feature can be used to keep the response of interest while suppressing the undesired responses. When we transform back to the frequency domain with the gating applied, we see the conversion measurement is much smoother now, with less noise and spurs.

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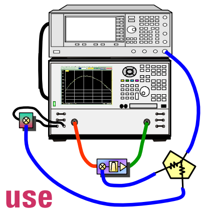
Additional resources

- **AN 1408-1** "Mixer Transmission Measurements Using the Frequency Converter Application (5988-8624EN)
- **AN 1408-3** "Improving the Accuracy of Frequency Converter Application Calibrations and Measurements (5988-9642EN)
- White paper "Novel Method for Vector Mixer Characterization and Mixer Test System Vector Error Correction" (5988-7826EN)
- White paper "Comparison of Mixer Characterization Using New Vector Characterization Technique" (5988-7827EN)
- White paper "Measuring Absolute Group Delay of Multistage Converters"(5989-0219EN)

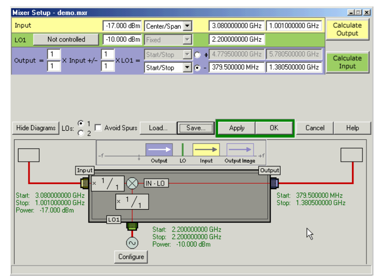
Advances in Converter Test   Agilent Technologies   44

The slide shows additional resources that should be helpful for developing a deeper understanding of the topics raised in this paper.

VNAs: Best Tool For Testing Mixers/Converters



- **Advanced calibration techniques provide high accuracy**
  - Scalar mixer cal → match-corrected, power-meter-based
  - Vector mixer cal → calibrated, absolute group delay
- **Many improvements make measurements easier to set up and use**
  - Dialog-box-based user interface
  - Guided calibration and built-in Help file
  - External LO's controlled by VNA
  - Source phase-lock difficulties eliminated
  - Minimal need for external attenuators
- **Sweep speeds are very fast compared to using spectrum analyzers and signal generators**



As we have seen in this paper, VNAs are the best tool for measuring mixers and converters. Advanced calibration techniques such as scalar-mixer and vector-mixer calibration provide high accuracy for conversion loss and absolute group delay measurements. Modern VNAs also have many improvements to make measurements easier to set up and use. Some examples are dialog-box-based user interfaces, built-in help systems, control of external LO's by the VNA, minimal need for external attenuators due to the advanced calibration techniques, and elimination of source phase-lock difficulties. The VNA provides sweep speeds that are very fast compared to using spectrum analyzers and signal generators.

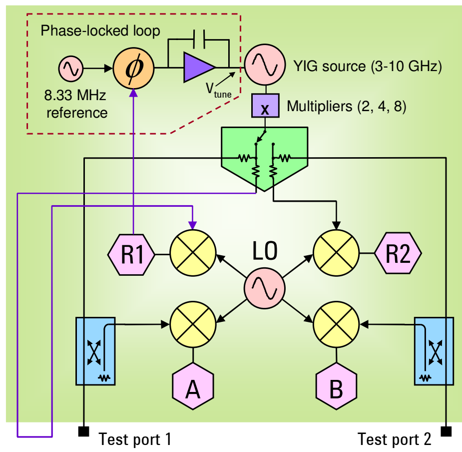
Appendix

Additional material that could not be covered in the amount of time available for the live presentation of this paper is available in this section.

PNA phase lock: normal sweeps

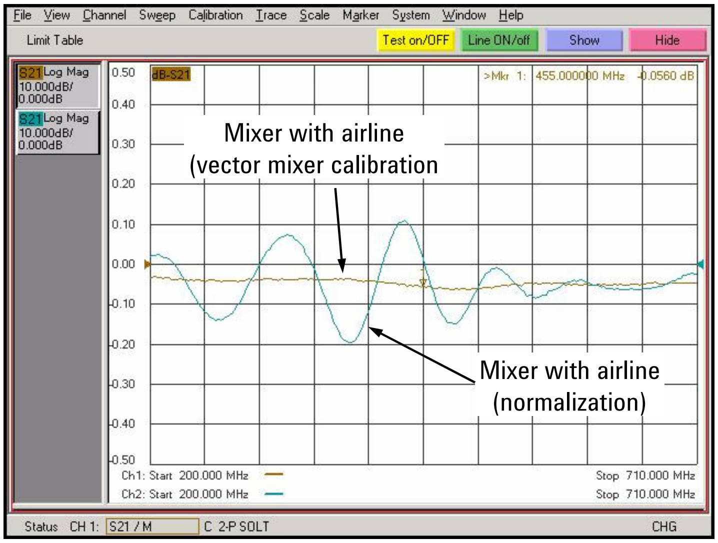
- Source is phase-locked to the LO using the reference-receiver IF signals
- Results in fast sweep speeds and low trace noise

Forward sweep case shown here

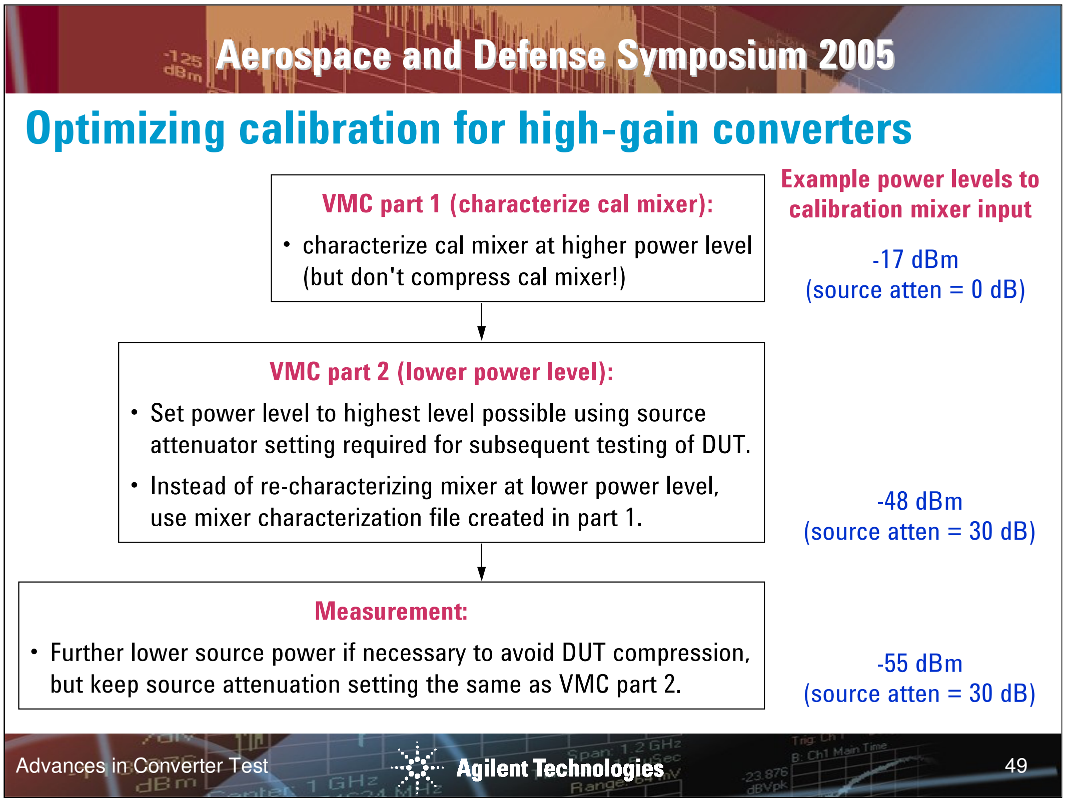


For normal sweeps, the PNA uses the reference receiver to provide a signal to the phase-locked loop. The source is locked to the LO, but with an offset equal to the 1st IF, which is 8.33 MHz. When the fractional-N-based LO is swept, the source is swept along with it. This architecture yields fast sweep speeds and low trace noise.

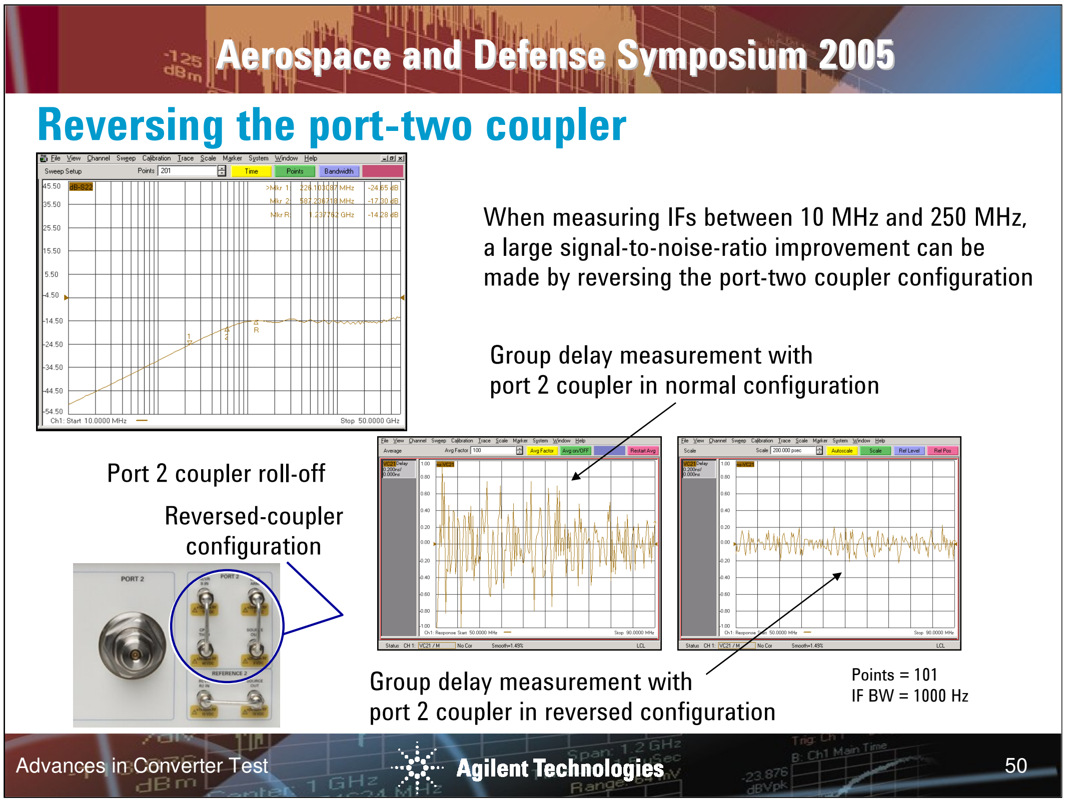
Effect of 15 cm airline at input (normalized)



This simple test shows that the input mismatch of the DUT is being correctly accounted for when using VMC. First we measure a mixer with two different traces. With one trace, we use VMC, and with the other, we don't do any error correction. After the measurement, we normalize the data to itself (data to memory; data divided by memory), which yields a flat line. The second part of the measurement involves adding a length of transmission line in between the test port and the DUT. In this example, we use a 15 cm coaxial airline, which has negligible mismatch itself. The airline adds very little loss to the measurement, but it does add significant phase rotation of the VNA's source match term. This is manifested in the uncorrected trace by the addition of mismatch ripple, shown on the slide as about 0.2 dB worst case. The trace that has VMC applied, shows the loss of the airline (about 0.03 dB) with virtually no increased ripple. This means that the proper vector input mismatch correction is being applied.



This slide shows how we can optimize VMC when measuring high-gain converters. Two tricks are used. First, we characterize the calibration mixer with a high input power level, followed by saving the data to a file. This characterization file will be used later for the through portion of the cal. The second trick is to use the highest power possible for a given attenuator setting during the through calibration, and then lowering the power to the right level for measuring the DUT, without changing the source-attenuator setting. The source attenuator must remain the same between calibration and measurement of the DUT -- if it is changed, significant measurement error can be introduced.



When measuring down-converters with IF outputs between 10 MHz and about 250 MHz, sometimes there is not enough output signal available to overcome the roll-off of the PNA's internal couplers, which behave like high-pass filters with a corner frequency of around 587 MHz. In this case, an improved signal-to-noise ratio can be achieved by reversing the configuration of the port-two coupler (swapping the coupled arm for the main arm). This gives about 15 dB less loss for S21, at the expense of 15 dB less available port power for S12. For forward group delay measurements of converters, this is usually an advantageous trade-off. The lower plots show the improvement in group delay trace noise when the coupler is in the reversed configuration

Acronyms

AM	Amplitude Modulation
BW	Bandwidth
C12	Reverse transmission response of a mixer or converter
C21	Forward transmission response of a mixer or converter
DUT	Device under Test
F	Frequency
FM	Frequency Modulation
FOM	Frequency Offset Mode
FTD	Frequency Translating Device
GD	Group Delay
GPIB	General Purpose Interface Bus
IF	Intermediate Frequency
LO	Local Oscillator
Mod	Modulation
MXR	Mixer
P	Power
PNA	Performance Network Analyzer
REF	Reference
RF	Radio Frequency
SA	Spectrum Analyzer
SG	Signal Generator
SMC	Scalar Mixer Calibration
VMC	Vector Mixer Calibration
VNA	Vector Network Analyzer
YIG	Yttrium-Iron Garnet