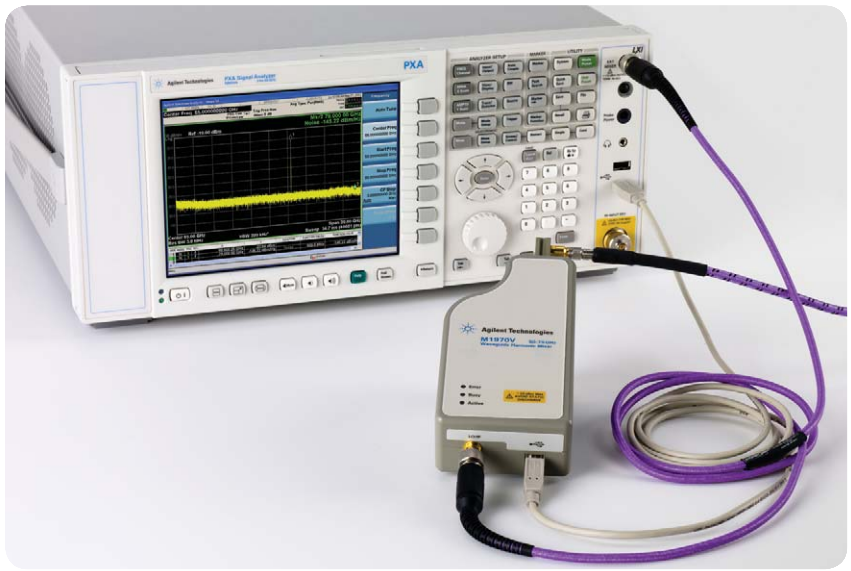
# Microwave and Millimeter Signal Measurements: Tools and Best Practices

Application Note




Accurate microwave and millimeter frequency signal measurements are important in many applications. This note will help you make the right choices and take the right steps to get accurate, reliable and cost-effective measurements.

Agilent Technologies

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# Introduction

Making good spectrum and vector signal measurements such as demodulation gets tougher as frequencies get higher, and there are special challenges at millimeter frequencies and beyond. This application note will discuss the choice of measurement tools and will describe techniques to help you make accurate and cost-effective measurements in different application environments.

**Microwave?**
**Millimeter frequencies?**
**Terahertz?**

Definitions vary but most consider microwave frequencies to cover 3 to 30 GHz while "millimeter frequencies" or extremely-high frequencies (EHF) refers to 30 to 300 GHz. Frequencies above 300 GHz are often called terahertz radiation.

## Choosing the Location of the First Mixer

In signal analyzers, one of the first elements in the signal path is a mixer used as a frequency-translating device. For microwave and millimeter analysis this mixer is the first step in several stages of converting the signal to a range where it can be measured, typically the final intermediate frequency (IF) stage. This mixer is very close to the input connector because signal-path loss increases rapidly with frequency, and sensitivity is optimized when the signal is downconverted as early as possible. This "first mixer" need not be inside the signal analyzer in all cases. To optimize measurement performance, solution cost, and operational convenience, one can consider alternatives in light of recent developments in analyzers, mixers and ultra-wide bandwidth signal-sampling technology.

### The fundamental mixer choice

Most choices related to signal connection and mixing can be boiled down to three categories: internal mixing, external mixing and "no mixer." Each of these is worth a closer look.

**Internal mixing**
This is the default choice, especially for microwave (as opposed to millimeter) measurements. The first mixer is inside, and very near the input connector of the analyzer, often preceded by an attenuator and sometimes a preamplifier. This is a single-box, single-connection approach that typically uses a coaxial connection. The analyzer handles all operations including downconversion, digitizing, analysis and display. For microwave and millimeter measurements, some form of harmonic mixing is used inside the analyzer, and in many analyzers a bandpass "preselector" filter (inside the analyzer) is tuned to the frequency of the signal/ system under test (SUT) to avoid the production or display of unintended mixing products.

**External mixing**
This method typically takes one of two forms, either standalone external mixers or separate downconversion assemblies. As the name implies, the first mixer is external to the analyzer and typically does not include an attenuator, preamplifier or preselector (some preselected external mixers are available). Instead, the analyzer supplies a microwave local oscillator (LO) signal to the external mixer and receives an intermediate frequency (IF) signal from the mixer. This IF signal is the result of mixing the SUT with harmonics of the analyzer-supplied LO signal. The external mixer is often attached directly to the SUT using a waveguide or coaxial connection. The analyzer further processes the IF signal with filtering, digitizing, analysis and display operations similar to those for internally-mixed signals.

**No mixer**
The advent of oscilloscopes with analog bandwidths that extend to microwave and millimeter frequencies has widened the solution landscape. When paired with signal-analysis software (typically vector signal analysis or VSA software) oscilloscopes can handle traditional signal-analysis tasks such as spectrum analysis, temporal analysis and demodulation or modulation-quality analysis. With a microwave or millimeter oscilloscope the SUT is digitized directly and the sampled signal represents the entire frequency range rather than a narrower band of frequencies in the vicinity of the signal of interest. Though this may be characterized as a "no mixer" approach, many signal measurements still involve band-selective analysis, with the VSA software performing the downconversion (mixing), filtering and data-reduction operations that would otherwise be handled by analog hardware.

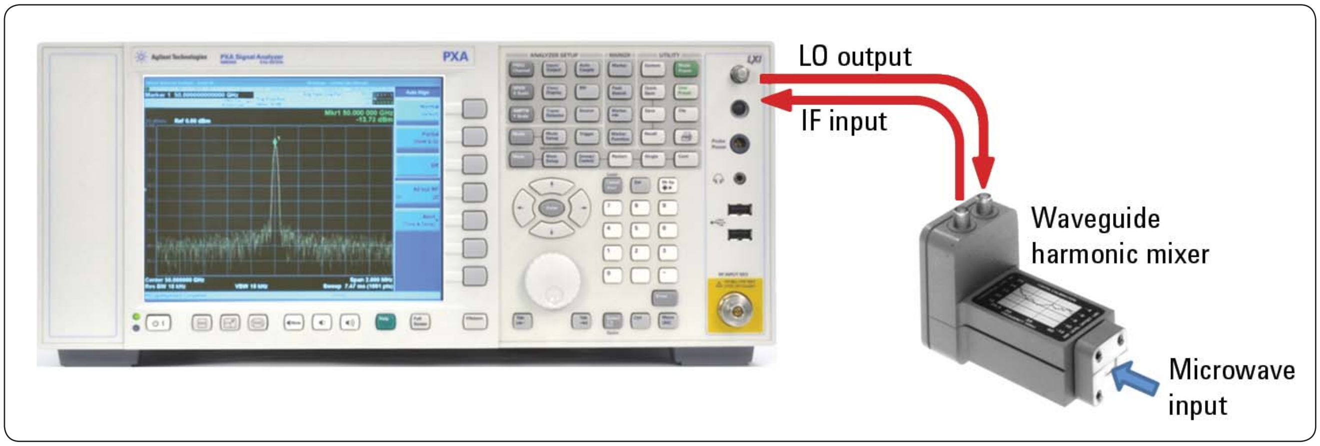



*Figure 1. External mixing, shown here with the Agilent PXA signal analyzer, moves the first mixing (downconversion) stage outside of the analyzer by sending an external mixer a tuned LO signal and bringing an IF signal back in. Further signal processing is similar to internally-mixed measurements.*

**Benefits of external mixing**

- Cost
- Convenience
- Sensitivity
- Frequency coverage
- Performance

## Potential benefits of external mixing

**Cost**
Analyzer price generally increases with frequency range, and microwave or millimeter frequency coverage may only be needed only for a specific band or bands. External mixing can allow an analyzer otherwise limited to RF or low microwave coverage to analyze signals at any frequency, using the appropriate external mixer.

**Convenience and sensitivity**
Some signals are provided through waveguide, which has comparatively low transmission loss but with connections that are typically inflexible and expensive. External mixing can allow the first mixer to be bolted directly to waveguide supplying the SUT, with the analyzer connections then accomplished by flexible, inexpensive, (comparatively) low-frequency, low-loss cabling.

**Frequency coverage**
Some frequency ranges are only covered by externally mixed solutions. Some signals cannot be readily connected to single-box solutions because of a combination of distance, physical configuration and loss in transmission.

**Performance**
Direct connection of the mixer to the SUT can improve the noise figure of the measurement system, improving both signal-to-noise-ratio (SNR) and accuracy. Phase noise performance may also be improved, due to higher LO output frequencies from modern analyzers and the resulting lower harmonic numbers used by the external mixers. In some cases, externally-mixed measurements can have significantly lower phase noise than one-box solutions.

## Smarter mixers function as a "remote test head"

External mixer connections are relatively simple, requiring just one or two relatively low-frequency (≤ 10 GHz) cables for the interface with a spectrum or signal analyzer. Accurate measurements require the analyzer to be configured for the correct output frequency (mixer harmonic number) and associated mixer conversion loss. Mixer conversion loss is accounted for through frequency response curves supplied by the mixer manufacturer and entered as amplitude correction factors in the analyzer. These amplitude correction factors can be entered manually or uploaded from a disk or USB device.

Configuring the analyzer for a specific mixer introduces opportunities for error: in the entry of conversion loss numbers, the association of those numbers with a specific mixer, and in connection problems such as inadequate or unflat LO drive levels.

A simple digital interface between the host analyzer and an enhanced or "smarter" mixer can solve all these problems at once. For example Agilent's new M1970V/W waveguide harmonic mixers (Figure 2) store factory-measured conversion-loss parameters internally, along with model and serial number.

These mixers also contain an LO power measurement/monitor circuit to help optimize LO drive level across their frequency range and detect any connection problems. Instruments such as the Agilent N9030A PXA signal analyzer can then automatically detect these mixers through a simple USB cable, then download conversion loss information, configure themselves correctly for the specific mixer, and perform an LO drive-level alignment for optimum accuracy.

The result is enhanced performance and measurement convenience, reduced chance of errors, and the implementation of a simple "remote measurement head" that can be placed in the optimum configuration to the SUT.

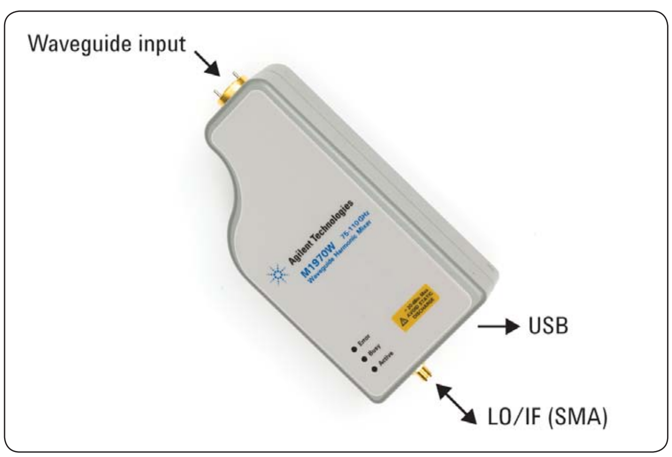



*Figure 2. A "smart" external mixer simplifies connection and setup, requiring only a single multiplexed signal connection (LO input and IF output) and a USB connection to detect the mixer, automatically download conversion loss information, monitor drive levels and other factors.*

## Comparing first-mixer approaches

*Table 1. Comparing first mixer approaches*

| Application factors | Internal mixing | External mixing | Direct sampling |
|---|---|---|---|
| Frequency coverage | Limited to a maximum of 50 to 70 GHz | Microwave to 1 THz or more | 32/33 GHz with single frequency range sampling |
| Setup convenience | Simple one box, one connection | Mixer connection and conversion-loss download required; automatic with "smart" mixers | One-box solution; signal analysis typically uses VSA software |
| Connection flexibility: coax | Simple, but coax loss may impose distance limits | Mixers typically waveguide, may require coax-waveguide adapter | Simple, but coax loss may impose distance limits |
| Connection flexibility: waveguide | May be cumbersome, depending on config. of SUT | Direct, flexible connection to SUT | May be cumbersome, depending on config. of SUT |
| Accuracy, ease of calibration | One-box solution, fully specified, typically most accurate | Specs depend on analyzer plus external mixer parameters; can be similar to internal mixing | One-box solution, though specs may be indirect with VSA software. Accuracy depends on digitizer. |
| Signal identification (identifying image signals produced in the downconversion process) | No separate process required due to preselection | Wideband meas (≥ 600 MHz or 2x IF) may require manual or automated process | No separate process required due to input BW limits and VSA digital filtering |
| Sensitivity | Highest, with preamplifier, low noise path, noise floor extension | No preamplifier, but short/ direct connection to SUT may improve sensitivity | Moderate due to wide bandwidth and limited sampling depth |
| Cost | Moderate to expensive | Moderate | Most expensive |
| Instantaneous analysis bandwidth | 160 MHz with internal digitizer, 900 MHz with external sampling of IF output | 120 MHz or more with internal digitizer, 700 MHz or more with external sampling of IF output | 32 GHz with single frequency range sampling |

# Choosing Solutions for Wideband Analysis

Traditional spectrum measurements require a maximum analyzer IF bandwidth similar to or wider than the widest resolution bandwidth to be used. Other measurement types such as pulse analysis and demodulation may require considerably wider IF bandwidths and compatible signal sampling capability.

## One-box signal analyzer solutions

Spectrum and signal analyzer IF and sampling bandwidths have been increasing along with the signals they are used to measure. 25 MHz and 40 MHz bandwidths are readily available, and the widest bandwidths are now 160 MHz or higher in analyzers such as the Agilent PXA. IF digitizers in modern signal analyzers are combined with all-digital IF processing to provide a complete range of spectrum and other signal measurements for in-band and out-of-band measurements.

Many integrated one-box solutions such as the Agilent X-Series analyzers also support a range of measurement applications such as phase noise and channel power, along with applications tailored to modern communications standards. The X-Series analyzers can also host the Agilent 89600 vector signal analysis (VSA) software for a wide range of vector and demodulation measurements including the newest ones available to support emerging communications standards.

Preselectors in microwave and millimeter signal analyzers are wider than the widest resolution bandwidths and are configured to track the analyzer center frequency for traditional spectrum measurements. However, for analysis of wideband signals it may be important to remove preselector filtering from the signal path. This is accomplished through a "preselector bypass" capability (often optional) that is activated from the front panel or remotely.

With their combination of convenience, available software solutions, and high resolution, wide-bandwidth digitizers today's signal analyzers are often the best choice for all kinds of analysis of wideband signals. Alternative choices (such as those described below) are most often considered when signal analyzer bandwidth is insufficient.

## Signal analyzers as wideband downconverters

Some spectrum and signal analyzers such as the Agilent PXA can also be used as tunable downconverters and/or detectors at microwave and millimeter frequencies. The PXA provides a variety of IF and video outputs, including a fast log video output (rise time as fast as 14 nanoseconds) for time-based analysis of pulses such as radar and EW. With an IF bandwidth up to 900 MHz (much wider than its maximum digitizing bandwidth) the PXA can be used with wideband digitizers in a downconverting configuration, as shown in Figure 3. Signal analysis can be performed inside a digitizer such as the Agilent Infiniium oscilloscopes by the Agilent 89600 VSA software.

Oscilloscopes and other wideband digitizers generally do not have equivalent performance (dynamic range, linearity, number of equivalent bits) to the internal digitizers in signal analyzers. Distortion measures may be approximately 40 to 45 dB rather than the 75 to 80 dB of internal digitizers. This makes these external digitizers well-suited for in-band measurements such as modulation quality and pulse parameters of wideband signals. Out-of-band measurements can then be made using the normal spectrum analysis capabilities of the signal analyzer.

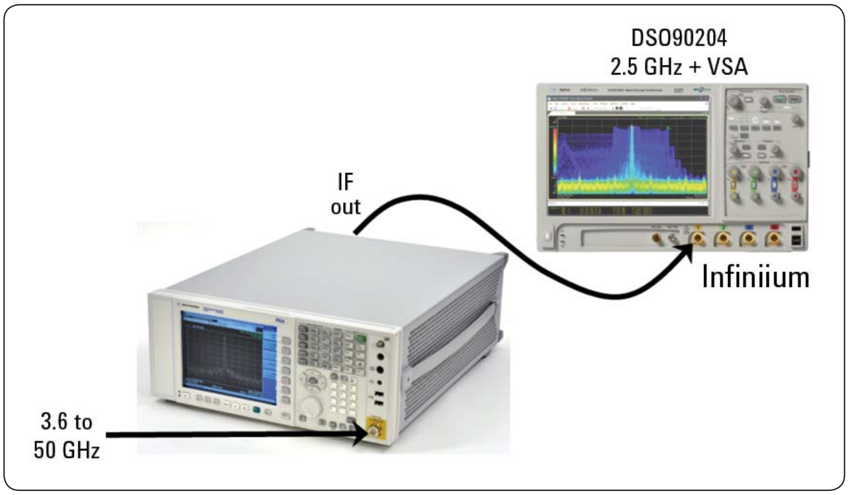



*Figure 3. Agilent PXA signal analyzer is used as a wideband downconverter. IF bandwidths as wide as approximately 900 MHz are available for digitizing with external solutions such as oscilloscopes. Signal processing for spectrum, vector, and demodulation measurements is performed by Agilent 89600 VSA software in the oscilloscope or a host PC.*

## Dedicated upconverters and downconverters

Some ultra-wideband signals (typically in the millimeter frequency range) call for a combination of bandwidth, sensitivity, and operating frequency that is not available from signal analyzers operating directly or as downconverters. Modulation bandwidths reach 2 GHz or more, greatly narrowing the range of solutions.

Dedicated upconverters and downconverters are available on a special order basis from Agilent to satisfy these needs. To provide adequate performance the solutions are customized rather than offered as an off-the shelf product. These dedicated converters provide high sensitivity (low conversion loss) for applications where no external connector is available and therefore connections must be made through an antenna. This sensitivity is combined with the very wide bandwidth required for ultra-wideband applications.

The dedicated downconverters have a number of limitations including limited frequency operating range. Instead they are generally customized for the operating frequency of a specific application. They are not preselected and are therefore not optimized for out-of-band measurements such as spurious. These millimeter downconverters are not integrated solutions, and require separate local oscillators.

The output of these millimeter downconverters is then sampled by a wideband digitizer, typically an oscilloscope. Spectrum measurements and demodulation are then performed by software such as the Agilent 89600 VSA.

An example of a dedicated downconverter is shown in Figure 4. This millimeter downconverter has a waveguide input and in the figure it is equipped with a horn antenna for close-range analysis of a signal that is not available from a waveguide or coaxial connector.


*Figure 4. Agilent millimeter frequency ultra-wideband downconverter. The waveguide input with a horn antenna is at the upper right. This downconverter is driven by an external microwave local oscillator and its output is fed to an external digitizer such as an oscilloscope.*

## Coaxial Versus Waveguide Connections

Signal and spectrum analyzers generally provide coaxial connectors for the SUT, and these connectors are chosen for compatibility with the highest frequency covered by the analyzer. The ready availability of coaxial-to-waveguide transitions plus the potential use of external mixers (usually with waveguide SUT inputs) means that the user has choices to make in the method of signal connection.

Waveguide is usually implemented as a hollow rigid metal structure with a precision rectangular interior whose cross section is of the proportions 2:1. Its operating frequency covers about one octave and dimensions get smaller as operating frequency increases. Waveguide is operated with a single mode of propagation. The "cutoff" frequency is the minimum frequency of the desired propagation mode, and waveguide behaves like a highpass filter around this cutoff frequency. Above the normal operating frequency range multiple modes of propagation are possible, each with different transmission characteristics.

Both coaxial and waveguide connections have significant benefits and drawbacks. In particular, waveguide is often chosen when there is a requirement for high power handling or lowest signal loss. For higher millimeter frequencies and into the terahertz region it may be the only practical choice. Table 2 summarizes the advantages and disadvantages of these connection methods.

*Table 2. Comparison of coaxial and waveguide connections*

| | Coax | Waveguide |
|---|---|---|
| Advantages | Flexible, easy to change routing | Low signal loss |
| | Wide frequency range | Ability to handle high power |
| | Light weight | Mechanically rugged |
| | Can carry DC bias for power or control | — |
| | Can be less expensive | — |
| | Suited to probing or component measurements | — |
| Disadvantages | Lossy; loss increases with frequency | Inflexible |
| | Can be delicate (due to small dimensions of high frequency cables) | May require custom construction (expensive) |
| | — | Time delays involved in fabrication and reconfiguration |
| | — | Frequency range ≤ 1 octave |
| | — | Transitions needed to connect to analyzers, other coaxial elements |

# Choosing and Using the Appropriate Cables and Connectors

## Cables, connectors and adapters

Accurate and consistent measurements depend on the use of cables and adapters designed for the frequencies involved. Their materials, structures and geometries are specially designed for a specific operating frequency range, to yield consistent impedance and reduce signal loss. Avoid compromising the performance of an expensive test system with poor-quality or inappropriate cabling and accessories.

Since most millimeter-wave spectrum analyzers are used in an environment that also includes work at lower frequencies, it can be tempting to use hardware designed for these lower frequencies. However, smaller wavelengths demand smaller dimensions in the cables and connectors. To avoid a phenomenon called "moding," (excitation of the first circular waveguide propagation mode in the coaxial structure) the diameter of coaxial connectors and cables must be much smaller than the signal wavelength. For millimeter-wave measurements, this means that common SMA and precision 3.5 mm accessories should not be used. Figure 5 shows a comparison of the insertion loss of SMA and 2.4 mm assemblies over the frequency range of 30 to 50 GHz.

It is interesting to note in the measurements of Figure 5 that the insertion loss of the SMA assembly is usually slightly lower than the 2.4 mm assembly, but is much less consistent. The insertion loss peak just below 36 GHz is significant, very narrowband, and would be inconsistent in its frequency, amplitude and phase. This would be a troublesome problem for any measurements in this frequency range. For example the amplitude and phase inconsistencies of this insertion loss peak would distort any modulated signal that it coincided with.

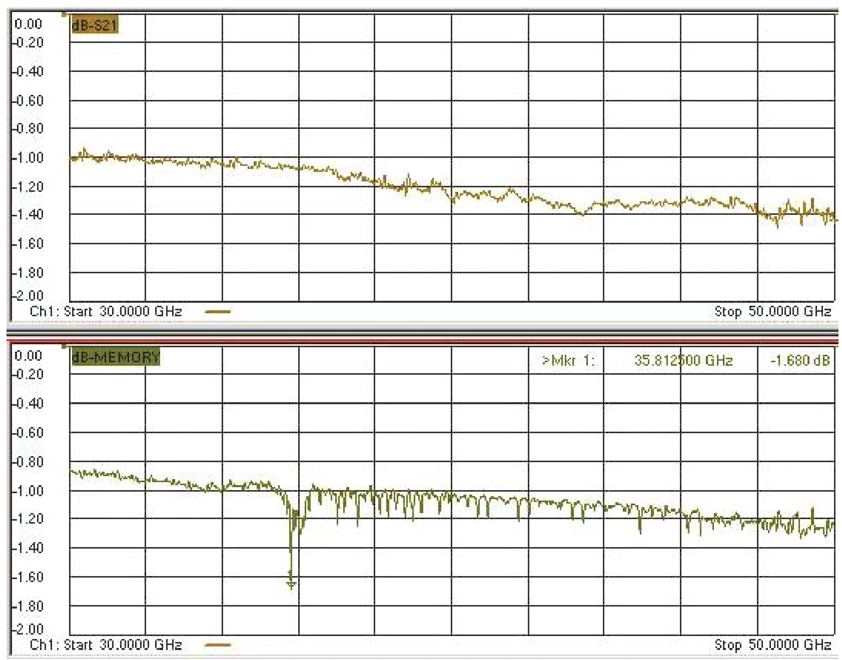



*Figure 5. Cables and connectors matter. This insertion loss measurement covers 30 to 50 GHz and shows the effects of using an SMA cable and adapters instead of appropriate 2.4 mm hardware. Note the multiple amplitude drop-outs in the lower trace at approximately 36 GHz and above. This phenomenon will create significant errors in both signal and network measurements.*

A summary of common microwave and millimeter connectors, their frequency ranges, and permissible intermating is provided in Table 3.

You may consider using 2.92 mm equipment for frequencies to 40 GHz, and take advantage of the fact that 2.92 mm connectors intermate with SMA and 3.5 mm for a degree of flexibility and compatibility when lower frequency measurements are made. However, for best performance and repeatability to 50 GHz, precision 2.4 mm accessories are recommended.

For mixed-frequency environments you may want to standardize on 2.4 mm accessories, using between-series adapters to make connections where needed. Though they have slightly more insertion loss than SMA and 3.5 mm (primarily above 30 GHz), 2.4 mm accessories can be used to cover all lower frequencies and offer superior repeatability.

Especially at millimeter frequencies it is important to consider the insertion loss of cables and adapters. As described later in this note, a single adapter may have insertion loss of 0.5 to 1 dB at frequencies approaching 50 GHz. For the most accurate measurements, this loss should be accounted for, and measured if possible, since analyzers are, by necessity, specified at their front panel connectors, without adapters.

*Table 3. Summary of microwave connector types*

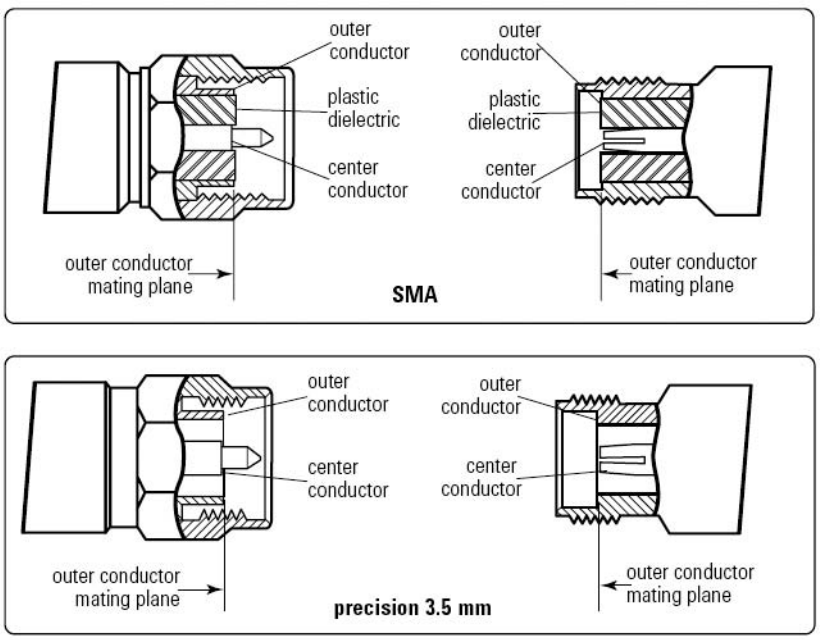
| Connector type | Frequency range | Mates with | Avoid mating with |
|---|---|---|---|
| SMA | Variable, 18 to 24 GHz | 3.5 mm, 2.92 mm | 2.4 mm |
| 3.5 mm (APC 3.5) | 34 GHz | SMA, 2.92 mm | 2.4 mm |
| 2.92 mm or "K" | To 40 GHz | SMA, 3.5 mm | 2.4 mm |
| 2.4 mm | To ≥ 50 GHz | 1.85 mm only | SMA, 2.92 mm, 3.5 mm |
| 1.85 mm | 65 to 70 GHz | 2.4 mm only | — |
| 1 mm | 110 GHz | — | — |

*Note: SMA connectors are a common and inexpensive type, but their lack of precision affects their durability and performance, and can cause increased wear when intermated with other (precision) connectors. SMA connectors are rated for only a very limited number of connection cycles, and should be examined before each use.*

## Cable and connector grades and construction

Precise tolerances and different materials and structures are required for microwave and millimeter assemblies. The materials, structures and geometries of these cables and adapters are specially designed for higher frequencies. This precision is proportional to the smaller wavelengths of these signals, and it yields more consistent impedance and reduces variance in insertion (signal) loss.

For example, you can see by visual inspection that SMA connectors use a PTFE (polytetrafluoroethylene) dielectric, while precision 3.5 mm and 2.4 mm connectors use an air dielectric, perhaps with a bead (sometimes difficult to see) supporting the center conductor. However you can't see the more precise dimensional tolerances of these accessories. You also might not notice, because they are extremely small, the different structures of the pins and collets, and their tapers and shoulders.




***SMA vs. precision 3.5 mm connectors***
*These cross-section diagrams demonstrate the difference between SMA and precision 3.5 mm connectors. Note the difference between the plastic dielectris of the SMA connector and the air dielectric of the 3.5 mm connector.*

There are more differences between production, instrument and metrology grade connectors but they are beyond the scope of this document.

The precision and small dimensions of millimeter-wave accessories inevitably make them somewhat less mechanically strong and considerably more expensive than lower frequency versions. While this is an unfortunate consequence of high-frequency measurements, it is very important to avoid compromising the performance of an expensive test system with poor-quality or inappropriate cabling and accessories.

## Connector torque

Using the appropriate torque wrench ensures proper connector torque, improving measurement repeatability and extending connector life. Though the metal bodies of connectors and adapters may seem perfectly rigid, there is always a small amount of flexibility in these structures. The short wavelength of very high frequency signals makes measurements of them more sensitive to this flexing. Repeatable measurements require consistent torque from measurement to measurement and on all the connections in a setup. A torque wrench also avoids damage due to over-tightening and helps connectors achieve their rated lifetimes. The small dimensions of high frequency connection structures means that they do not have great mechanical strength, and may be deformed or even permanently damaged by excessive torque.

Two common torque values handle most measurements below 70 GHz. They are 90 N-cm (8 in-lb.) for 2.4 mm, 1.85 mm, and precision 3.5 mm connectors, and 56 N-cm (5 in-lb.) for SMA connectors. Torque wrenches are available preset to these torque values.

SMA connectors are frequently used in combination with 3.5 mm and/or 2.92 mm connectors due to their ability to be intermated. In this situation the proper torque for these intermating operations depends on the gender of the male connector. Thus 56 N-cm. torque wrench should be used when connecting male SMA connectors to either 3.5 mm or 2.92 mm (K) connectors or to other SMA connectors, while a 90 N-cm torque wrench should be used when connecting male 3.5 mm or male 2.92 mm connectors to mating female connectors including SMA.

Note: When making connections *take care to rotate only the nut, and never rotate the body of the connectors when their mating surfaces are in contact*. Use another wrench on the flats of one connector to prevent rotation.

The difference made by proper torque can be only a fraction of a dB for a single connection, but the errors or loss from multiple connections can add, to become significant considering the high accuracy of today's analyzers and the accuracy expected of modern measurements. Good accuracy at millimeter wave frequencies is a challenge, and proper torque eliminates one source of additional error.

## Connection consistency

Wherever possible use the same cables, connectors, and cable routing for the most consistent measurement results. Even the highest quality cables and adapters have measurable insertion loss and affect impedance (return loss). These effects generally increase with frequency. The smaller dimensions of millimeter-wave cables and hardware prevent amplitude drop-outs due to moding, but contribute to signal loss. This loss can be more than 3 dB per meter of coaxial cable (not counting connectors) and more than 0.5 dB per adapter or connector pair at 40 GHz. Even in situations where comparable connection length is maintained, different cable/connector combinations with the same end-to-end gender can result in different insertion loss and return loss.

The situation is similar when using different types or brands of cables, and even when comparing good cables to those that might be worn or damaged. Bending, kinking and stretching cables can also affect results–in some measurements you can see a difference in real time just by flexing a cable while a measurement is in progress. Since repeatability is as important as absolute accuracy in many measurements (especially where some sort of substitution may be used to improve accuracy), it is always a good idea to use the same cables and connectors in the same configuration from measurement to measurement. Not surprisingly, the use of semi-rigid coaxial cable can improve many measurements by reducing incidental movement and making more consistent connections.

Connect the analyzer to the circuit using the shortest, simplest, straightest path possible. Fewer connectors or adapters, and shorter cables reduce the chance for problems and minimize the non-ideal behavior of each element. Cables should not be so short, however, that they are kinked or bent over a radius tighter than recommended by the manufacturer. Sharp bends will cause physical discontinuities which result in localized impedance problems, and can permanently damage cables or mechanically distort the cable-connector interface.

When different connections are being made between measurements, and especially for relative measurements, it is important to understand the measurement plane. For this, it is key to know what parts of the measurement connection change from measurement to measurement.

# Electrical and Mechanical Damage Hazards

## Electrical damage

Electrical damage is a particular concern for analyzer inputs that use high frequency components and assemblies that are physically small and cannot dissipate significant power or withstand high voltages. The problem is more acute at millimeter frequencies because protective measures such as a DC block are not automatically included due to their effect on analyzer performance. If the SUT has a DC component a DC block should be added by the user, perhaps as part of a "connector saver" assembly as described below.

ESD or "static zap" is a significant concern at high frequencies, as the small size of microwave and millimeter components makes them more vulnerable. Typical ESD precautions include using table mats, wrist and heel straps, and ensuring a proper ground connection for the analyzer.

Some signal sources can pose a special hazard even when producing low power, due to their production of much larger transients during switching. If this is a concern, one mitigation technique is to switch to higher levels of analyzer input attenuation when making source changes or connections.

A special frustration with electrical damage is that the resulting performance degradation may not be complete or obvious. Some damage will impair analyzer performance in a significant but non-obvious way.

## Mechanical damage

The small and precise dimensions of microwave connectors also make them subject to expensive mechanical damage. Unfortunately, some degree of damage and a certain amount of wear are inevitable after many connect/disconnect cycles. One practical solution is to protect the analyzer's front-panel connector by making external connections through a sacrificial adapter called a connector saver. A typical connector saver at these frequencies is a 2.4 mm adapter with female connectors at both ends, and that is why millimeter-wave spectrum analyzers often have male connectors on their front panels. In addition, the male connector is more durable and less likely to be damaged by attempted mating with an incompatible connector type or damaged connector.

The connector saver is usually left in place on the front of the analyzer, with frequent connections made to it instead of the analyzer's permanent connector. This dramatically reduces the number of connect/disconnect cycles that the analyzer's connector experiences, and can put off the need for comparatively expensive replacement of the analyzer's connector (and associated recalibration) nearly indefinitely. Several examples of adapters as connector savers are shown in Figure 6.

*Figure 6. For millimeter-wave applications, the most common connector savers will have female connectors on both ends. Shown here are adapters to connect an analyzer with 2.4 mm front panel connectors to type-N and 2.4 mm accessories.*

In a mixed environment of 2.4 mm (or 1.85 mm) connectors and SMA connectors, a special intermating damage hazard exists. The SMA connector is mechanically similar to the 2.4 mm or 1.85 mm connector, and intermating of a male SMA connector is prevented only by the fact that the SMA nut is too small to be threaded to the higher frequency connector. The protection provided by this size difference is lost if the SMA nut is not captive and is allowed to slide away from the other parts of the connector. This hazard is shown pictorially in Figure 7.

The SMA male connector in these pictures has a non-captive nut, allowing it to be inserted into the smaller collet of the 2.4 mm female connector, causing damage. The situation is the same for 1.85 mm connectors. Note that the thread pitch and end relief distance are different on the 2.4 mm and 3.5 mm ends of the adapters.

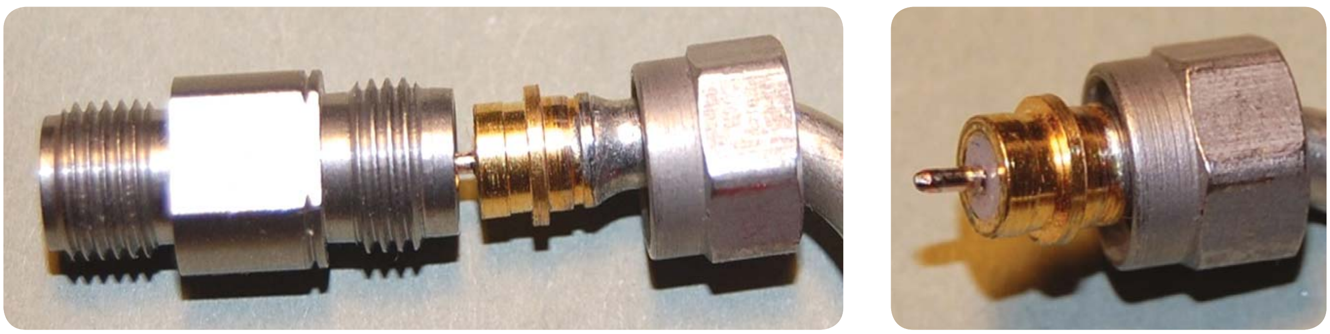


*Figure 7. Figure 7a shows a 2.4 mm-to-3.5 mm adapter with the 2.4 mm end of the adapter on the right. The male connector at right is an SMA. The SMA male connector in Figure 7b has a non-captive nut and a male conductor which is displaced axially (too long) and is slightly bent, perhaps from the bending of the semi-rigid cable adjacent to the connector.*

# Improving Measurement Performance through Analyzer Features and Signal Processing

Modern spectrum and signal analyzers have a number of features, options, and alignment functions that can optimize performance in different measurement situations. Some are universal and part of all measurements, such as automatic alignments. Others are options, user-selected functions, or user initiated operations. Several of the most useful examples are discussed here.

## Choose whether to use a preamplifier, attenuator, or both

A signal analyzer will be most sensitive when 0 dB of input attenuation is selected. Sensitivity can be further enhanced by using an external or internal preamplifier, since a preamplifier with significant gain and low noise figure can substantially improve the analyzer's effective sensitivity or noise figure. Internal preamplifiers are not optimized for a particular measurement situation but offer convenience benefits and are included in the analyzer calibration and alignments.

While preamplifiers generally offer the best sensitivity when combined with a 0 dB analyzer attenuator setting, several accuracy, sensitivity, and distortion trade-offs are involved when choosing input attenuation and preamplification. For example, with attenuation set to 0 dB the signal under test is effectively coupled directly to the analyzer's first mixer. The mixer's input is not as close to a 50-ohm resistive impedance as the attenuator, and therefore the analyzer's reflection coefficient will be higher when no attenuation is used. This higher reflection coefficient will lead to a greater potential mismatch error when measurement sensitivity is maximized.

Use of the input attenuator will improve the analyzer's impedance match, with the match (and mismatch error) improving as attenuation is increased. Of course the disadvantage of using the attenuator is a loss of sensitivity. One dB of sensitivity is lost for each dB of input attenuation.

The analyzer's built-in preamplifier, if available, may allow both sensitivity and mismatch error to be optimized. With the preamplifier providing a fixed gain following the input attenuator, the attenuation can be increased to a value that provides adequate sensitivity while improving reflection or coefficient or match. This will reduce potential amplitude accuracy errors due to mismatch.

## Alternative input paths to optimize sensitivity versus distortion and other parameters

Some general improvements in the functionality and reliability of spectrum analyzers can cause the analyzer noise figure or displayed average noise level (DANL) to be slightly degraded. Examples would include the switching and path losses needed to implement an internal microwave preamplifier, and the associated switching for low band (non harmonically-mixed) operation and a low band preamplifier. Another example (in the Agilent PXA for example) is the change to solid-state input switching in some cases, to improve reliability and repeatability. Solid-state switches typically have slightly higher insertion loss than hardware switches at microwave frequencies. The switching and path losses increase with frequency and while they can be characterized and corrected to preserve amplitude accuracy, they still affect the noise floor of the analyzer and thus the accuracy of low-level signal measurements.

Preamplifiers can compensate for this loss and improve signal/noise for small signals, generally offering the best DANL or noise figure throughout the microwave and millimeter frequency ranges. However they are generally limited to measurements when no large signals are present at the analyzer input. Large signals can exercise nonlinearities in the preamplifier, creating distortion products that can be mistaken for those from the signal under test. These large signals can cause distortion problems even when outside the selected frequency span.

In the Agilent PXA this problem is solved through an optional low noise path which uses hardware switches to bypass lossy elements normally found in the input chain. The result is the highest sensitivity possible without a preamplifier, and a measurement configuration suitable for situations when larger signals are present. The low noise path applies to all "high band" frequencies of 3.6 GHz and higher and an example of the improvement in noise floor is shown in Figure 8.

## Signal processing to subtract analyzer noise power

An analyzer's own noise floor is a limiting factor in some measurements, and the conversion loss from harmonic mixing causes this noise floor to increase with frequency. Noise limits the low end of dynamic range, along with the accuracy of measurements on small signals. When large signals are present, it is common to increase analyzer attenuation as way to limit distortion due to overload, but this brings small signals closer to the analyzer's own noise, and thus the analyzer noise limits the amount of attenuation. Noise can also have a large impact on measurement speed, potentially requiring narrower RBWs for measurements such as spur searches, since these narrow RBWs require slower sweeps due to increased RBW settling time.

As a result, reducing the analyzer's contribution to noise power in a measurement can help both low-level and high-level measurements. Alternatively it can allow low-level measurements to be made without the cost and potential distortion contributions of a preamplifier.

A standard, user-selectable feature in Agilent PXA analyzers is noise floor extension (NFE). This feature automatically performs a scalar subtraction of the analyzer's noise power from spectrum measurements. The PXA combines real-time measurement processing with a built-in model of analyzer noise power (noise floor) for all measurement configurations. Thus the analyzer can subtract the majority of its noise power contribution to measurements without the convenience penalty of a separate noise floor measurement. There is no effect on measurement speed, and the benefit is available for all frequencies the analyzer covers. An example of the improvements from noise floor extension and low noise path is shown in Figure 9.

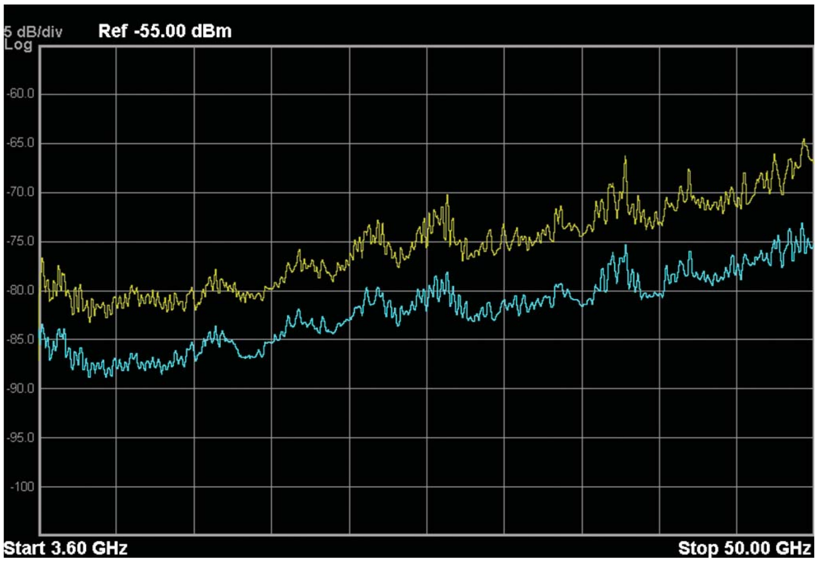



*Figure 8. This measurement covering 3.6 to 50 GHz at 5 dB/div illustrates the noise floor improvement when the PXA low noise path is selected.*

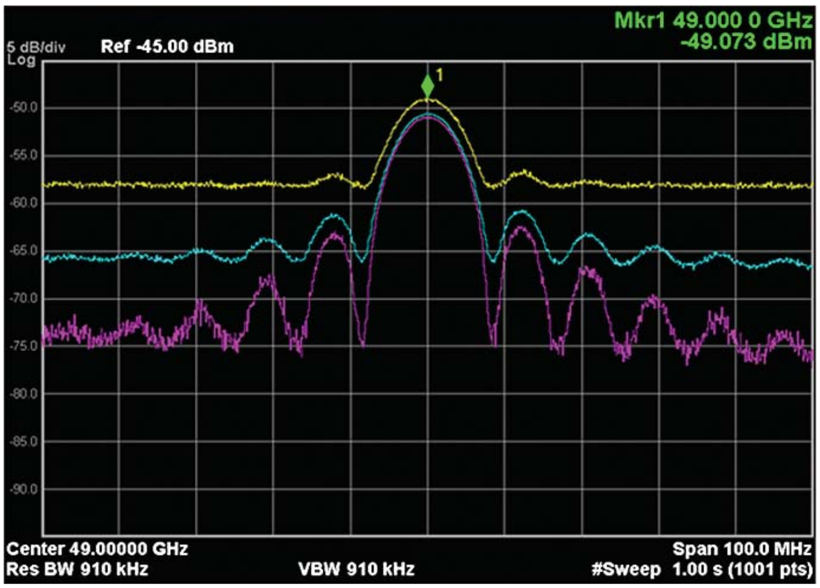



*Figure 9. Measurements of this low level signal at 49 GHz are improved significantly through the use of the low noise path and noise floor extension features of the Agilent PXA. The top trace is a normal measurement, the middle trace is made with the low noise path selected, and the bottom trace shows the benefit of adding the noise floor extension feature.*

## Bypassing the preselector

As mentioned previously, some microwave and millimeter frequency signal analyzer include a microwave preselector bypass option. This bypass path removes the tunable preselector filter from the measurement path and is essential for wide bandwidth measurements.

The dynamic range benefits and costs of bypassing the preselector depend on the individual measurement specifics. While bypassing the preselector removes its insertion loss contribution it also removes some amount wideband noise filtering. The effect on analyzer noise figure should be evaluated on a case-by-case basis if noise is a concern. Bypassing the preselector can also allow mixer images and other signals into the final IF for measurement. If there is confusion in signal identification one can tune to the desired signal with the preselector present and then bypass the preselector for final measurements.

## Alignments to optimize analyzer performance

Periodic alignments are an important element in the performance of microwave and millimeter signal analyzers. The alignments are performed automatically according to time and temperature parameters monitored by the instrument itself. In some situations these alignments are inhibited by the user to prevent their interrupting signal measurements. In these cases the user is responsible for initiating alignments when allowable. In general, the best measurements are made when the analyzer temperature has stabilized and a calibration or alignment is performed shortly before the measurement itself.

## Preselector alignment or centering

The (typically YIG-tuned) filters that serve as preselectors in most millimeter wave spectrum analyzers run in an open-loop mode, and are therefore prone to some degree of drift. The "preselector centering" operation is thus an important one and should be performed when the center frequency is changed. Though the analyzer itself performs the centering, the operator must initiate the process before a final measurement is made. "Preselector tuning" is an operation where the analyzer optimizes the overall tuning parameters for the preselector over the analyzer's full operating range, and need not be done often.

# New Research on Mismatch Error Calculations Yields Tighter Accuracy Specifications

Estimating and optimizing measurement accuracy is a particular challenge for microwave and millimeter measurements. Major performance figures such as amplitude and frequency accuracy (or phase noise), flatness, noise level (or signal/noise), and repeatability degrade as frequency increases. Analyzer architectural changes such as the use of higher-order harmonics tend to widen the inherent bandwidth of measurements and reduce sensitivity. Cabling and connectors contribute to both signal loss and flatness variations due to impedance or return loss uncertainty. These sources of error add to those from any uncertainties produced by the imperfect impedance of the source under test.

Understanding power measurement accuracy or uncertainty at microwave and millimeter frequencies is somewhat complex, and automated calculations are available to simplify the task. See "*Power Measurement Uncertainty Per International Guidelines*" in the "For More Information" section at the end of this document.

Mismatch uncertainty is a particularly important parameter, and is often the largest component of amplitude measurement uncertainty. Newly published research from Agilent Technologies provides a better understanding of the accuracy effects of mismatch uncertainty. In the past this uncertainty has been modeled in several different ways, which overestimated the magnitude of the error due to mismatch. A new statistical method using a Rayleigh distribution has been validated by experimental evidence to more accurately estimate mismatch error. Importantly, the method reduces the error contribution due to mismatch to between one third and one sixth of its previous value.

This new method applies in the common scalar analyzer case where reflection coefficient phase is not known, and reflection coefficient magnitude must be assumed from manufacturer data across a wide range of frequencies.

Complete information and a link to an uncertainty calculator program is available in Agilent application note 1449-3 "*Power Measurement Uncertainty per International Guidelines,*" as updated April 2011.

# For More Information

## Web resources

PXA signal analyzers:
**www.agilent.com/find/pxa**

Smart harmonic mixers:
**www.agilent.com/find/smartmixers**

Coaxial connector overview:
**www.home.agilent.com/upload/cmc_upload/All/CoaxialConnectorOverview.pdf**

What mates with what comparison guide:
**http://na.tm.agilent.com/pna/connectorcare/What_mates_with_what.htm**

Connector grades:
**http://na.tm.agilent.com/pna/connectorcare/Connector_Grades.htm**

*Intermateability of SMA, 3.5 mm and 2.92 mm Connectors*, Microwave Journal (Cables & Connectors Supplement), March 2007, available at **www.gore.com**

Average power sensor uncertainty calculator:
**www.home.agilent.com/upload/cmc_upload/All/Average_Power_Sensor_Uncertainty_calculator_Rev6.xlsx**

## Related literature

*Fundamentals of RF and Microwave Power Measurements (part 3) Power Measurement Uncertainty Per International Guidelines AN-1449-3*, literature number 5988-9215EN

*Connector Care Quick Reference Card*, literature number 08510-90360

*Principles of Connector Care*, literature number 5954-1566

*Making Wideband Measurements: Using the Agilent PXA Signal Analyzer as a Down Converter with Infiniium Oscilloscopes and 89600 VSA Software*, application note

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