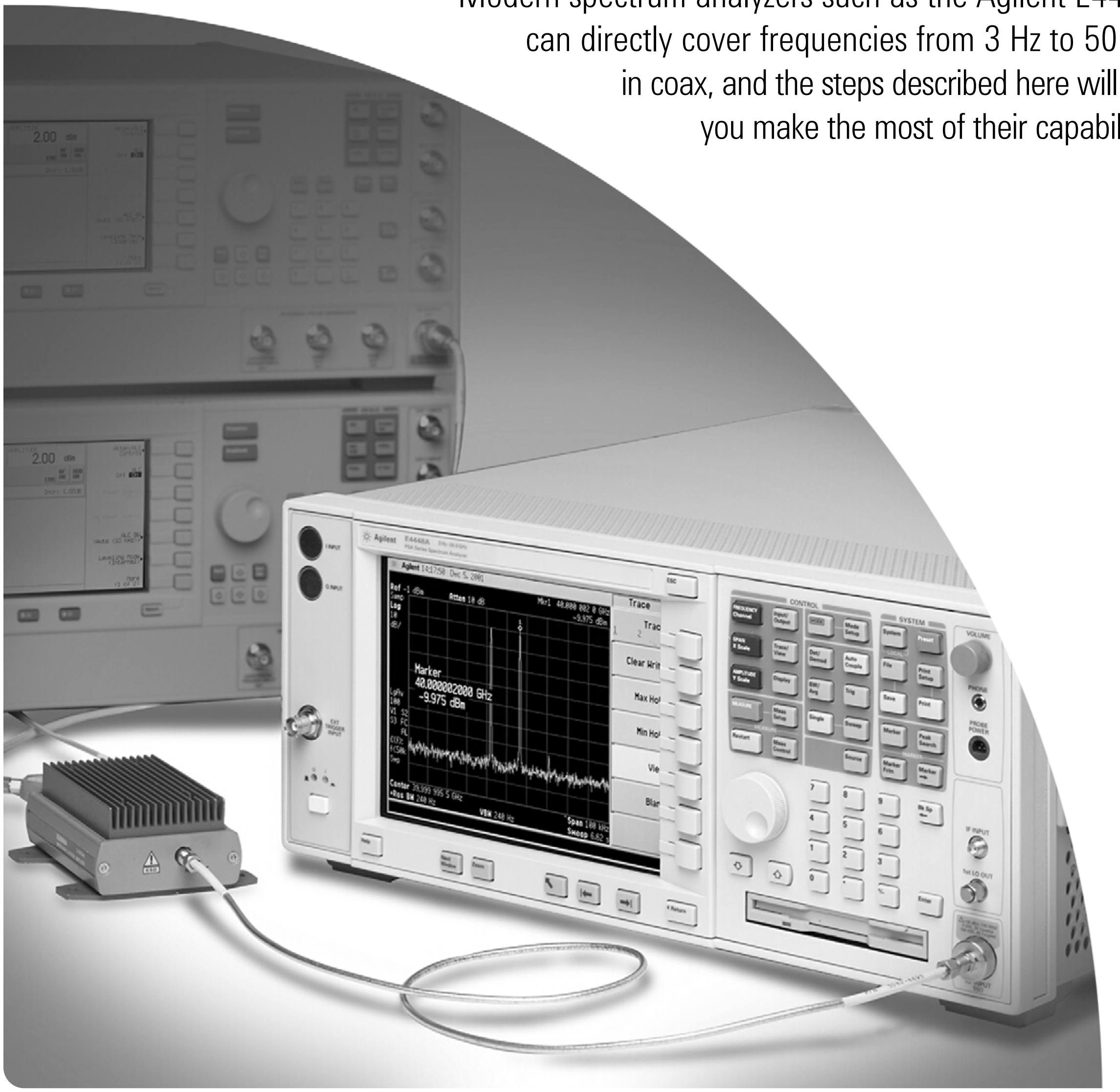
8 Hints for Better Millimeter-Wave Spectrum Measurements

Application Note 1391

Modern spectrum analyzers such as the Agilent E4448A
can directly cover frequencies from 3 Hz to 50 GHz
in coax, and the steps described here will help
you make the most of their capabilities.



Agilent Technologies

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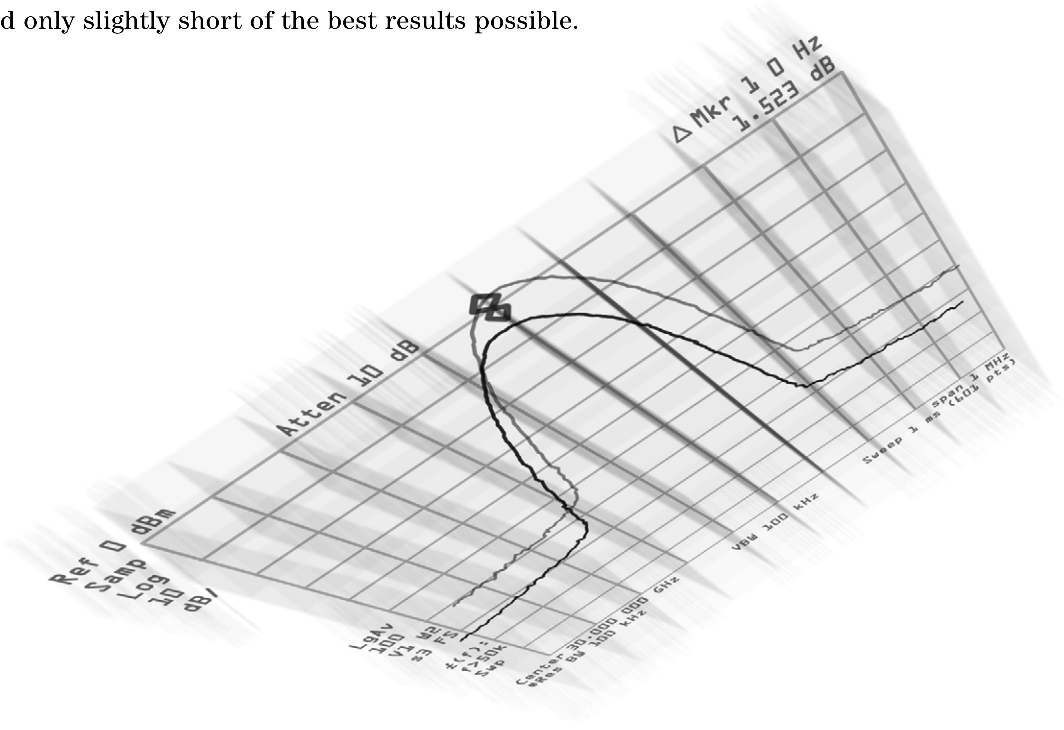
Introduction

Making good spectrum measurements gets tougher as frequencies get higher, and there are special challenges in the millimeter-wave region. Nonetheless, it's possible to make good millimeter-wave measurements with a minimum of trouble: Just combine good basic microwave measurement practice with a few things distinctive to these higher frequencies. As with so many other situations, avoiding the most common pitfalls can allow even inexperienced users to make measurements which are well optimized and only slightly short of the best results possible.

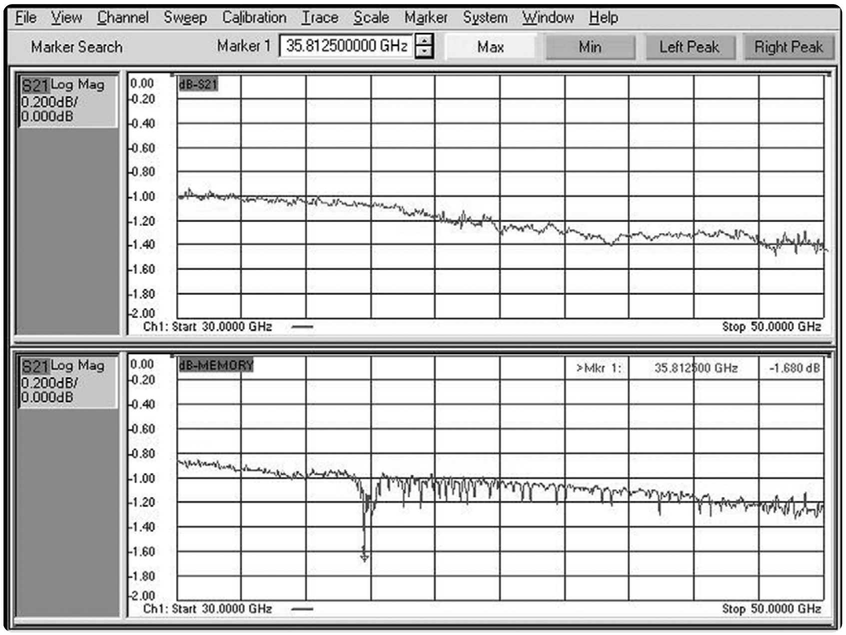
What is "millimeter-wave?"

Definitions of millimeter-wave vary, but the term generally refers to frequencies of 26.5 GHz or 30 GHz and above. That is where signal wavelengths fall below approximately 10 mm, and thus the terminology changes from centimeters to millimeters. This document covers millimeter-wave measurements to approximately 50 GHz.



This application note is primarily concerned with measurements made in coaxial environments by millimeter-wave spectrum analyzers to 50 GHz. Modern spectrum analyzers are able to cover the entire range of design tasks for high frequency applications well, handling frequencies from IF and RF through millimeter-wave, so they are the ideal fundamental tools for designers in this frequency range. These measurement hints apply no matter what type of spectrum measurement you're making – signal power or frequency, noise level, distortion, or phase noise.

Since many millimeter-wave analyzers will be often used at lower frequencies because of their flexibility, summary material like this document may make it easier to transition effectively from lower frequency measurements to millimeter-wave ones.



Cables and connectors matter

This measurement from the new 50 GHz PNA series network analyzer 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 would create significant errors in both signal and network measurements.

8 hints – A summary checklist

This document is organized into eight subject categories, covering the major factors in making good measurements at these high frequencies. This summary page of categories or hints can also be used as a checklist, reminding you of the elements of good measurement practice whenever you need to refresh your memory. You might want to post this summary page near your analyzer to make it easier for every user to recall the elements of good measurement practice. More detailed information on each hint is in the pages that follow.

✓ Hint 1: Use only cables and adapters designed for millimeter-wave frequencies.

Accessories for mm-wave measurements are different (and typically more expensive!) from those used in RF/microwave measurements. The materials, structures and geometries of these cables and adapters are specially designed for these frequencies, to yield more consistent impedance and reduce signal loss. Avoid compromising the performance of an expensive test system with poor-quality or inappropriate cabling and accessories.

✓ Hint 2: Use a "connector saver" on the spectrum analyzer.

The small size and precise geometry of mm-wave connectors means that they are more delicate and more costly than the larger connectors used at lower frequencies. Millimeter-wave spectrum analyzers often have male connectors on their front panels to encourage users to semi-permanently attach a female-to-female adapter or DC block as a connector saver. Measurement cables are then attached to this connector saver, which can be easily replaced after it becomes worn or damaged.

✓ Hint 3: Use a torque wrench on all connections.

Proper torque improves measurement repeatability and extends connector life. The tightening torque on connectors has a significant effect on measurements at mm-wave frequencies, and repeatable measurements require consistent torque from measurement to measurement and on all the connections in a setup. A torque wrench avoids damage due to over-tightening and helps connectors achieve their rated lifetimes.

✓ Hint 4: 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) at mm-wave frequencies. 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, it's 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.

8 hints – A summary checklist

✓**Hint 5: Perform calibrations or alignments frequently, and whenever measurement conditions change.**

Virtually all mm-wave analyzers have auto-calibration and alignment functions in their firmware and hardware. Take advantage of these functions in each measurement to allow the analyzer to perform at its best. This is particularly important in higher measurement bands (where harmonic mixing is used) and where preselectors are used. Analyzers typically initiate calibrations and alignments on a timed basis, though they may also respond to detected changes in temperature. 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.

✓**Hint 6: Understand the measurement plane and its characteristics, and 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. When different connections are being made between measurements, and especially for relative measurements, it's important to understand the measurement plane. For this it's key to know what parts of the measurement connection change from measurement to measurement.

✓**Hint 7: Review instrument specifications and the individual measurement configuration to understand the actual level of performance you can expect.**

Major performance figures such as amplitude and frequency accuracy (or phase noise), flatness, noise level (or signal/noise), and repeatability will not be as good at mm-wave frequencies. Analyzer architectural changes such as the use of higher-order harmonics and preselectors tend to widen the inherent bandwidth of measurements and reduce the dynamic range available at mm-wave frequencies. 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.

✓**Hint 8: Make measurements carefully and begin with the best measurement practices that you would normally apply to RF and microwave measurements.**

Good practice at mm-wave frequencies is a superset of good practice at lower frequencies. Remember the factors that influence measurements are more difficult, sensitive, and variable at higher frequencies. Expect good measurements at these frequencies to take significantly more time and care. Inspect connections and cables frequently to detect wear or damage, and promptly replace gear that has reached the end of its rated life.

Detailed hints

Hint 1

Use only cables and adapters designed for millimeter-wave frequencies.

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, accessories for millimeter-wave measurements are different from those used in RF/microwave measurements.

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.

Connector summary

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 to70 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.

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.

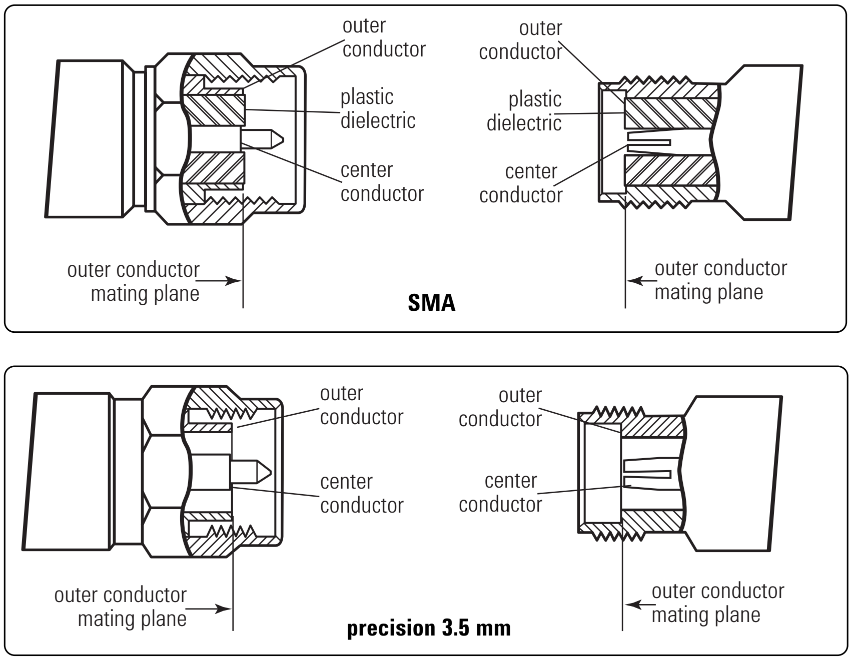
For mixed-frequency environments you may want to standardize on 2.4 mm accessories, using between-series adapters to make connections where needed. Though they are slightly more lossy than SMA and 3.5 mm (primarily above 30 GHz), 2.4 mm accessories can be used to cover all lower frequencies and offer superior repeatability. However, be careful when connections are made, to avoid damage from improper mating. For example, mating a 3.5 mm or SMA male connector to the (smaller but mechanically-similar) 2.4 mm female connector will probably damage the smaller female connector.

Precise tolerances and different materials and structures are required.

The materials, structures and geometries of these cables and adapters are specially designed for millimeter 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 Teflon dielectric, while precision 3.5 mm and 2.4 mm connectors use an air dielectric, perhaps with a bead 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. There are further differences between production, instrument and metrology grade connectors, though they are beyond the scope of this note.

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.



SMA vs. precision 3.5 mm connectors

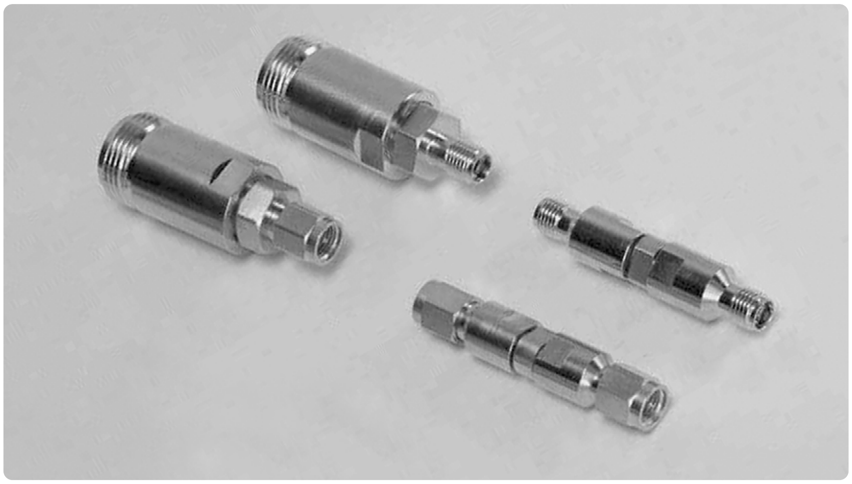
These cross-section diagrams demonstrate the difference between SMA and precision 3.5 mm connectors. Note the difference between the plastic dielectric of the SMA connector and the air dielectric of the 3.5 mm connector.

Hint 2

Use a "connector saver" on the spectrum analyzer.

Many microwave engineers are already familiar with the potential for expensive ***electrical*** damage to the input sections of their analyzers (For example, see hint 8 below, regarding the suggested use of an external DC block). 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.



Connector savers

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.

Other (between-series) adapters can also be used as connector savers, accommodating the typical use of the millimeter-wave analyzer at lower frequencies. The robustness of the larger, lower frequency connectors, and the potentially heavier cables attached to them make connector savers just as important for these measurements. Examples (all with female connectors at both ends) of connector savers are shown are shown in the table below.

Connect to	Adapter part number
2.4 mm female	11900B
2.92 mm female	11904B
3.5 mm female	11901B
K female	11904B
SMA female	(Use 3.5 mm 11901B)
Type N female	11903B

Example connector savers for 2.4 mm male front-panel connector:

At millimeter frequencies it is also worth considering the insertion loss of these adapters. As described in hint 6 below, 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.

This adapter 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 sees, and can put off the need for (comparatively expensive) replacement of the analyzer's connector nearly indefinitely. In the event a damaging mistake is made in connecting a signal to the analyzer, (for example, connection of the wrong type of cable such as a male SMA assembly, which would damage a female 2.4 mm connector) the damaged female connector can be quickly replaced, avoiding repair expense and down time, not to mention the possibility of erroneous measurement results.

Hint 3

Use a torque wrench on all connections.

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. In addition, 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.

Connector torque

SMA	56 N-cm (5 in-lb.)
3.5 mm	90 N-cm (8 in-lb.)
2.4 mm	90 N-cm (8 in-lb.)
1.85 mm	90 N-cm (8 in-lb.)

Some common torque values

The best way to ensure consistent connections, good repeatability, and long connector life, is to use a torque wrench on all connections (and to ensure that connections are always clean – see hint 8 below). Some common torque values are 90 N-cm (8 in-lb.) for 2.4 mm, 1.85mm, and precision 3.5 mm connectors, and 56 N-cm (5 in-lb.) for SMA connectors. Torque wrenches are available preset to these torques. Take care to rotate only the nut, and never rotate the body of the connectors when their mating surfaces are in contact.

Once properly torqued, most connections will stay that way, but attention should be given to any connections subject to vibration, twisting, repeated flexing, or thermal cycling. Especially in combination, these actions can loosen connections and affect measurement values.

The emphasis on proper connector torque is more typically found in network analysis, where even very slight changes in connector geometry can affect phase measurements. However, the security and repeatability of connections, and the importance of avoiding expensive damage are also valid concerns for spectrum measurements. As described in hint 7 below, good accuracy at millimeter-wave frequencies is a challenge, and proper torque eliminates one source of additional error.

Hint 4

Use the same cables, connectors, and cable routing for the most consistent measurement results.

Signal connections, no matter how carefully made, are less perfect at mm-wave frequencies. These imperfections impact both performance and repeatability, affecting absolute measurements such as signal power and relative measurements such as distortion.

The insertion loss of cables and connectors, for example, is significant and easily measurable at millimeter-wave frequencies. The smaller dimensions of millimeter-wave cables and hardware help prevent amplitude drop-outs due to moding, but contribute to signal loss. This loss typically rises with frequency, and 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 (impedance) figures. 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.

A major benefit of coaxial cable, when compared to waveguide, is its flexibility. However it is that very flexibility that contributes to potential impedance and insertion loss variations with different cable routing. Bending and stretching cables changes their dimensions, and thus affects signal propagation. This can be particularly true where cables meet connectors, and cable manufacturers typically provide some sort of strain relief to reduce the problem. To whatever degree this affects measurements, the impact of variations can be reduced by a consistent approach to connections and, as mentioned in hint 3, proper connector torque.

Another way to reduce connection variations is to use semi-rigid cable. The relative rigidity of the cable and the interface to its connectors reduces incidental movement and therefore improves repeatability. This is especially helpful where cabling might otherwise be disturbed during a measurement, such as by vibration or user interactions.

Hint 5

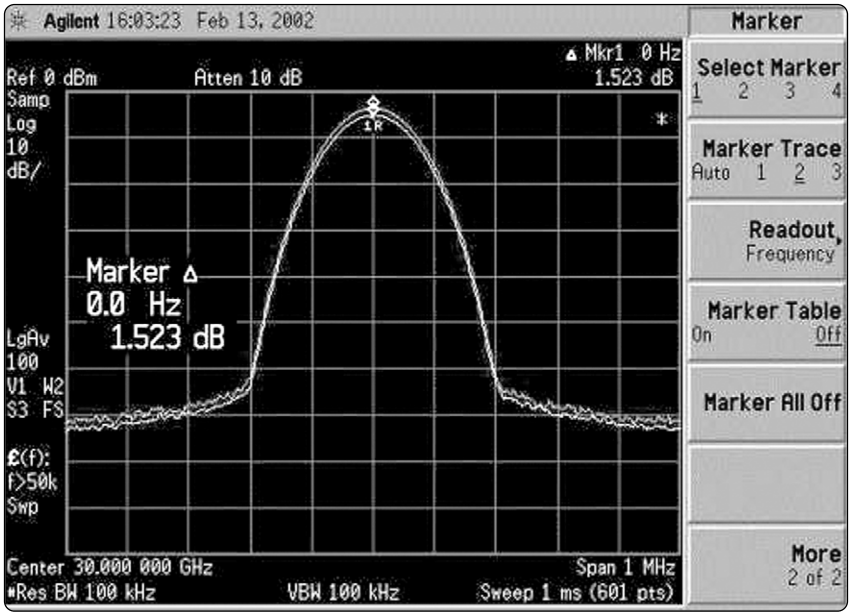
Perform calibrations or alignments frequently, and whenever measurement conditions change.

Sophisticated internal alignment and calibration routines, plus internal reference sources help today's spectrum analyzers achieve their high performance figures. The combination of preselectors and higher measurement bands (higher harmonics of the spectrum analyzer local oscillator, in analyzers using harmonic mixing) make millimeter-wave analyzers more sensitive to environmental and component variations. Analyzer hardware and firmware routines are designed to compensate for these variations to the maximum extent possible, and users should take advantage of them for optimum performance.

For example, 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.

Temperature has perhaps the greatest effect on alignment parameters and accuracy. Therefore it is desirable that measurements be made at a stable temperature close to the point at which the analyzer has performed its alignments and self-calibrations. Indeed, spectrum analyzers such as the Agilent PSA series actually measure their own internal temperature in addition to the elapsed time since the previous alignment and calibration. By combining these time and temperature factors with internal knowledge of changes in their input configuration, analyzers such as these can determine the need for calibration to maintain optimum accuracy.

The optimum conditions for accuracy include stable environmental conditions for the analyzer, device under test (DUT), and interconnections. In this case the analyzer can be left to control its own calibrations. If measurement conditions are changing, it may be better to explicitly control the timing of calibrations and alignments to occur just before measurements are made.



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Ref 0 dBm Atten 10 dB

Δ Mkr1 0 Hz 1.523 dB

Samp Log 10 dB/

Marker Δ 0.0 Hz 1.523 dB

LgAv 100 V1 W2 S3 FS £(f): f>50k Swp

Center 30.000 000 GHz Span 1 MHz

#Res BW 100 kHz VBW 100 kHz Sweep 1 ms (601 pts)

Amplitude error without preselector centering
This example shows the importance of preselector centering in millimeter-wave measurements.
The blue trace shows a measurement after centering, removing an error of over 1.5 dB at 30 GHz.

Hint 6

Understand the measurement plane and its characteristics, and connect the analyzer to the circuit using the shortest, simplest, straightest path possible.

When compared with waveguide, coaxial cable (or even semi-rigid cable) is flexible and convenient. By using coaxial cable and adapters one can quickly and easily measure a wide range of frequencies through different connection configurations. However, as mentioned in previous hints, coaxial connections are not an ideal (constant impedance), lossless path to the analyzer. Therefore, the best and most consistent measurement results will be obtained with the most direct connection to the analyzer.

These direct connections can be optimized through the use of cables of different lengths and, as appropriate, different connectors. This is a significant issue for measurement performance, and not only convenience. Using cables which match the available type and gender of analyzer and DUT connectors eliminates the need for multiple adapters, which add insertion loss and impedance match (return loss) uncertainties to the measurement. 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.

Maintaining high accuracy while using different cables and adapters means that the user must understand the effective measurement plane in each measurement. While spectrum analyzers are specified at their front panel connectors, DUT connections are made at the end of cable/adapter combinations. These cable/adapter combinations are likely to be different for different measurements, so for optimum accuracy it may be necessary to estimate or measure differences in insertion loss, or to use a calibration signal to extend the measurement plane to a known point at or near the DUTs themselves. These techniques are useful for both absolute and relative signal level measurements.

Hint 7

Review instrument specifications and the individual measurement configuration to understand the actual level of performance you can expect.

It is fair to summarize the situation by saying that everything is more difficult (for both those who use and those who manufacture test equipment) at millimeter-wave frequencies. Compared to RF and microwave frequencies, the accuracy limits for higher frequency measurements are wider, and dynamic range measures are lower.

Some specification reductions are a consequence of the architecture of millimeter-wave analyzers. Preselector filtering introduces an additional insertion loss parameter, reducing sensitivity. The higher LO harmonics which are used for higher bands (in analyzers which use harmonic mixing) also reduce sensitivity because mixer conversion loss increases with increasing harmonic number. In addition, these higher harmonics increase analyzer phase noise by multiplying the phase noise of the LO.

Other specification reductions are a consequence of the increasing effect of impedance uncertainties at higher frequencies and frequency response errors over very wide frequency ranges. These differences are of greatest significance for absolute power measurements and comparisons of power from different sources, since errors at a single frequency and from a single source (where there are no impedance differences) will tend to cancel each other out. The table below shows some typical performance differences between millimeter-wave and lower frequency measurements.

For high-sensitivity measurements where no input attenuator is used, the impedance (VSWR) or return loss and accuracy specifications should be examined for this special case. For most analyzers, this figure is degraded when attenuator values are small or zero. This effect is present, though smaller, at all frequencies.

Finally, bear in mind that measurement accuracy effects due to DUT connections (such as VSWR mismatch) will add to those described here and (as mentioned in the hints above) these connection effects are larger at millimeter-wave frequencies. Accurate results are still possible at these high frequencies, but they are inevitably more difficult.

Performance parameter	Spec. reduction, 50 GHz vs. 5 GHz
Absolute accuracy	Calibrator unchanged, see flatness
Flatness	2.5 dB (uncertainties are 2.5 dB greater)
Displayed average noise level	20 dB
Phase noise/noise sidebands	Approximately 20 dB
Harmonics, spurious	5 to 20 dB

Typical performance differences, comparing 5 GHz measurements to 50 GHz measurements

Hint 8

Make measurements carefully and begin with the best measurement practices that you would normally apply to RF and microwave measurements.

As mentioned in the summary above, good measurement practice at mm-wave frequencies is a superset of good practice at lower frequencies.

Use good quality cables, connectors, and accessories, and inspect them frequently for damage or wear.

Connector gauges are available to go beyond visual inspection, and network analyzers can be used as additional verification. Take care to keep connections clean (use only 99.5% isopropyl alcohol on foam-tipped swabs and dry with canned air), and consider separating the millimeter-wave accessories from others (or marking them) to prevent improper connections or damage. The simple and inexpensive step of using dust caps on all connectors can prevent expensive damage and keep skin oil and debris out. Consider using external DC blocks and attenuators, along with connector savers or between-series adapters, to protect the delicate front-ends of analyzers. These accessories, though they are significant trouble and expense, can save many times their cost in repair bills, down-time and bad measurement results.

Additional Agilent literature

Cable and Connector Care,
literature number 5988-4167EN

Fundamentals of RF and Microwave Power Measurements,
Application Note 64-1C,
literature number 5965-6630E

Spectrum Analysis Basics,
Ap-Note AN-150
literature number 5952-0292

RF and Microwave Test Accessories Catalog,
literature number 5968-4314EN

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