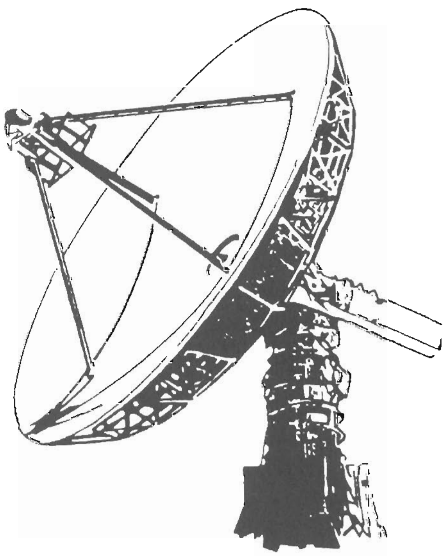
MEASURING PHASE NOISE AND ADJACENT CHANNEL POWER WITH THE 8901B MODULATION ANALYZER.

Bob Burns

RF & Microwave Measurement Symposium and Exhibition

HEWLETT PACKARD



MEASURING PHASE NOISE AND ADJACENT CHANNEL POWER WITH THE 8901B MODULATION ANALYZER.

This paper describes a method for measuring the phase noise of RF and microwave signals using a new version of the 8901B modulation analyzer. This approach is an extension of the adjacent channel power measurements commonly made on communications systems signals, and actually measures total SSB noise at offsets greater than 5 kHz away from the carrier. Advantages and limitations of this technique are discussed and compared with other methods of measuring noise around RF and microwave signals.

OUTLINE:

1. Why measure phase noise and/or adjacent channel power?
   - What is phase noise? Adjacent channel power?
   - Why is this type of noise undesirable?
   - Why are these measurements required?
2. Existing methods for making these measurements (advantages and disadvantages):
   - Spectrum analyzers
   - Phase noise measurement systems
   - Modulation analyzers
3. How to make this measurement using the 8901B:
   - Block diagram with noise/adjacent channel power option
   - Spectral representation
   - Measurement algorithm
     - adjacent channel power
     - phase noise
   - Using an external L.O.
   - Measuring microwave signals
   - Advantages of this technique
4. Limitations
   - Accuracy and dynamic range
     - amplifier and detector linearity and noise floors
     - L.O. noise and settability: internal vs. external
     - filter response
   - Image response
   - Spurious
5. Automating noise and adjacent channel power measurements:
   - System block diagram
   - Applications.

SPOKANE DIVISION
HEWLETT · PACKARD

As the communications spectrum becomes more crowded, noise performance of communications signals becomes increasingly important as a way to ensure overall system performance. The intent of this paper is to describe a method for measuring this performance. This method is compared to other measurement techniques, and the relative advantages and disadvantages of these methods are discussed. An automated system for making carrier noise measurements is described, and examples given.

AGENDA

- Why measure noise and/or adjacent channel power
- Techniques for measuring signal noise
- Measuring carrier noise with the 8901B
- Limitations of this technique
- Automating the measurement

733

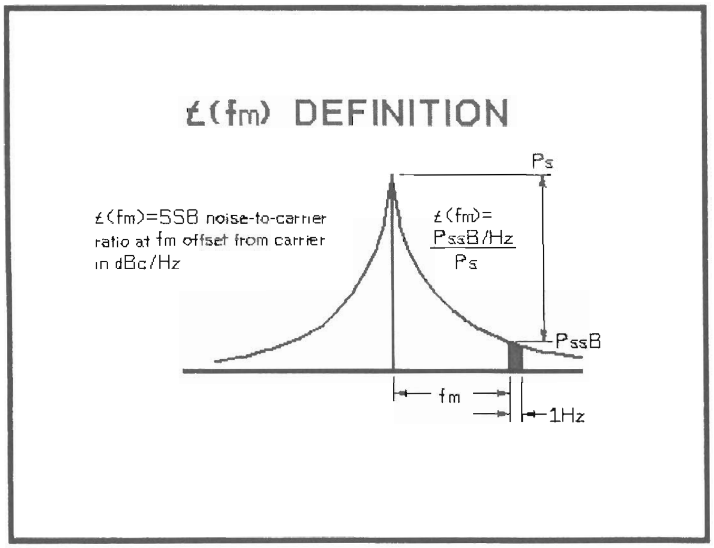
Noise around a signal can be represented as fluctuations of either the amplitude or phase of the carrier. This noise is commonly referred to as phase noise, since fluctuations in phase are typically the dominant source of noise close to the carrier.

SIGNAL REPRESENTATION

$$V(t) = V_S\,[1+\Delta V(t)]\ \mathrm{COS}\ [2\pi f_o t + \Delta\phi(t)]$$

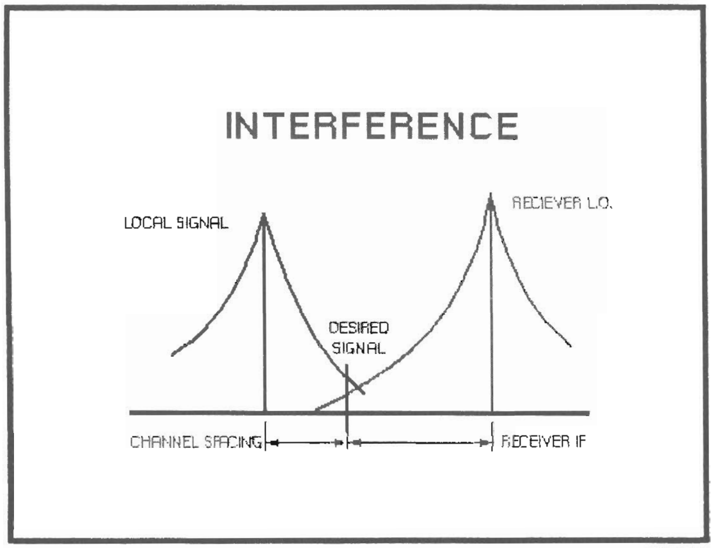
= Signal with amplitude and phase fluctuations, $\Delta V(t)$ and $\Delta\phi(t)$

734



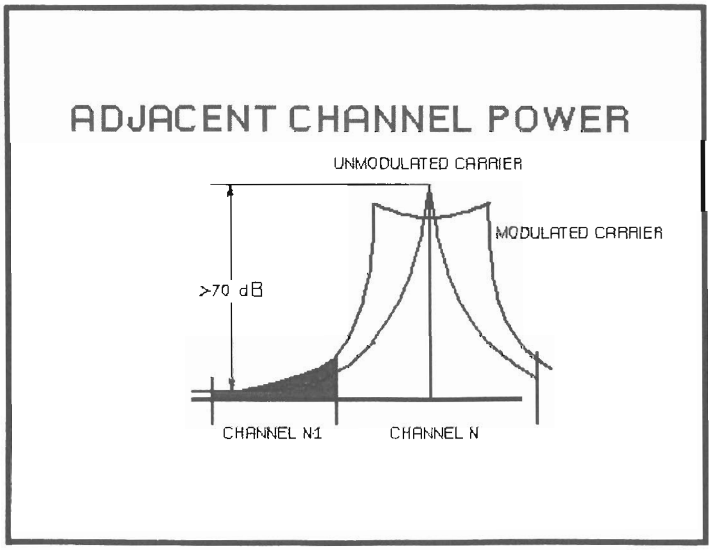
735

$\mathcal{L}$(fm) defines the ratio of power in a 1 Hz bandwidth fm Hz away from the carrier to the carrier power. This is SSB power which can be caused by fluctuations in the amplitude or phase of the source, as well as additive broadband noise. $\mathcal{L}$(fm) is usually the important measure of noise around communications signals.



736

Noise around communications LOs can limit the communication system performance when receiving weak signals. Noise at adjacent channel offsets on a locally transmitted signal can prevent clear reception of a distant signal in the adjacent channel. Noise on receiver LOs at offsets equal to the IF frequency can limit the receiver's overall sensitivity. Fast and accurate measurement of this noise is necessary for identifying these causes and improving system performance.



737

Regulatory agencies are recognizing the need to require minimum adjacent channel interference performance on equipment used in communications systems to ensure that all users can make full use of allocated channels. Measurement of transmitted noise is required to guarantee conformance to regulations that are likely to become increasingly stringent with time.

There are many types of commercially available test equipment that can be used to measure noise of communications signals. The spectrum around a signal can be measured directly on a spectrum analyzer. Systems of spectrum analyzers and interfaces providing low noise references and sensitive detectors are available. Modulation analyzers also can be used to measure residual FM, and this can be related to phase noise.

NOISE MEASUREMENT USING:

Spectrum Analyzers

Phase Noise Measurement Systems

Modulation Analyzers

738

Spectrum analyzers are valuable for a qualitative quick evaluation of signals if the noise of interest is not too low. The phase noise of the spectrum analyzer LO limits many RF spectrum analyzers to performance in the neighborhood of −100 dBc/Hz for $\mathscr{L}(f)$ measurements. Care must be used in correcting for attenuator and IF linearity errors, and for using the proper equivalent noise bandwidth correction factor for the IF filter in use. If the analyzer logs the signal prior to detection, additional correction factors need to be used for noise measurement. These limitations can prevent the use of a spectrum analyzer for making fast, calibrated measurements of low noise signals.

DIRECT SPECTRUM MEASUREMENT

Advantages:

- Fast and Easy
- Shows "Big Picture"
- Flexible

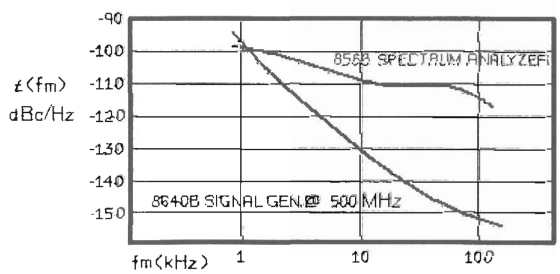
Disadvantages:

- Limited Dynamic Range
- No Phase Information

739

This plot shows the noise performance of the LO in a high-performance spectrum analyzer. At many offsets this noise is too large to allow measurement of some typical communications signals.

ANALYZER L.O. NOISE



740

NOISE MEASUREMENT SYSTEMS

Advantages.

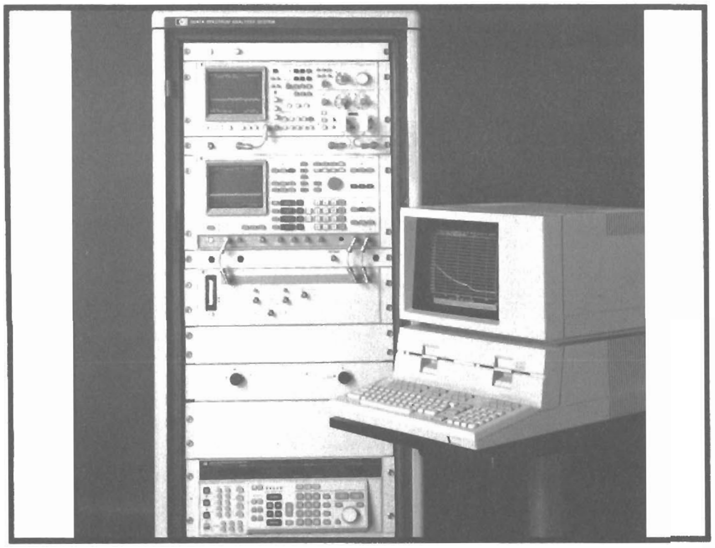
- Very High Performance, Low Noise
- Accurate, Calibrated Output in dBc/Hz
- Can Distinguish AM From PM Noise

Disadvantages:

- Requires Two Sources or Appropriate Reference
- Can be Large, Expensive, Slow
- Many Pitfalls to Watch Out For

741

Noise measurement systems such as the HP 3047A can be used to obtain accurate and detailed noise information of very low noise RF and microwave signals. The expense of such systems has kept them from enjoying widespread popularity in all but the most critical testing applications. Additionally, there are many possible pitfalls that can be encountered in using such systems, leaving operation to relatively sophisticated users. When a phase-locked signal is required, tuning characteristics of the oscillator must be considered, as well as its ability to be injection-locked.



742

This is a picture of a high performance phase noise measuring system manufactured by HP. Although very accurate and useful for measuring extremely low noise, it may not be appropriate for some less demanding applications.

RESIDUAL MODULATION MEASUREMENTS

Advantages.

- Quick, Easy Qualitative Check of Spectral Purity
- AM and FM Can Be Distinguished

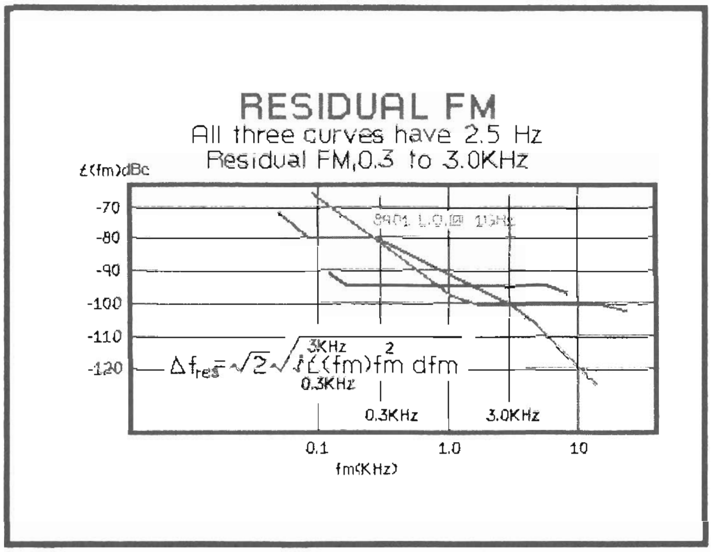
Disadvantages.

- Results Dependant Upon Noise Slope
- Requires External L.O. for Low Noise Measurement
- Requires Specialized Filtering for Detailed Information

743

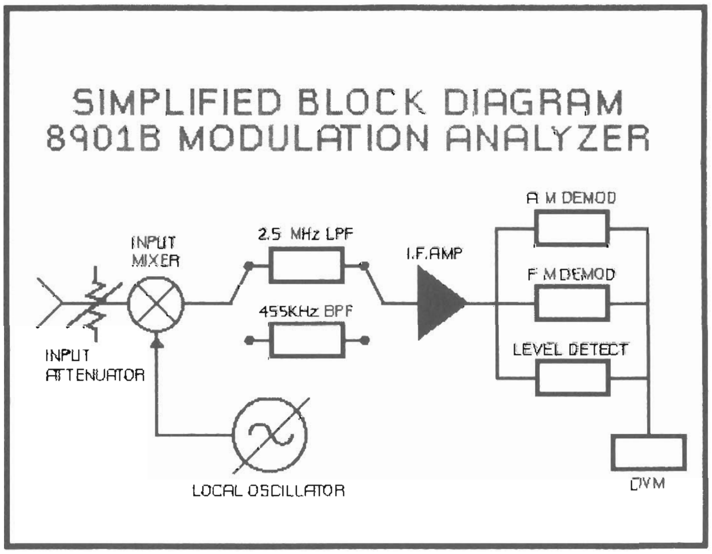
A modulation analyzer such as the HP 8901 can be used to measure residual FM or AM. This is an easy and fast measurement to make, and gives a quick qualitative check of the purity of low to medium performance signals. If relatively low phase noise is to be measured, this technique has several limitations. Since residual FM is the integrated power spectral density of frequency fluctuations over the demodulation bandwidth, the relationship between residual FM and $\mathcal{L}(f)$ at any given offset is complex. Complex filtering is required if detailed information regarding the shape of the sideband noise is desired. An external LO is needed for measuring low noise sources, and fractional Hz outputs are typical results.

Residual FM does not tell the whole story. This plot shows the noise performance of the internal LO in the 8901 at 1 GHz. Two other noise plots are also shown. Although the noise at most offsets is different for these plots, the residual FM from 0.3 kHz to 3 kHz is roughly the same for all three sources.



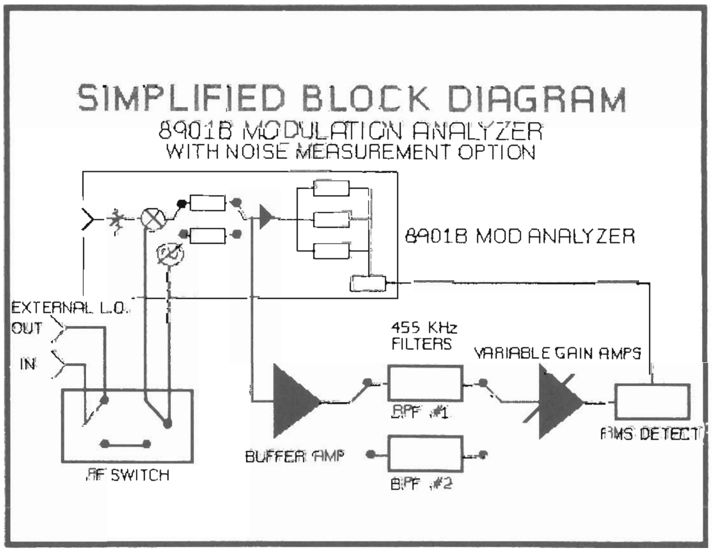
744

Options to the HP 8901B Modulation Analyzer have been designed to allow using this instrument to measure $\mathscr{L}$(f) at adjacent channel offsets directly as well as residual modulation measurements. The 8901 is a heterodyne receiver which down-converts signals up to 1300 MHz to one of two IFs: 455 kHz or 1.5 MHz. This IF signal is then fed to AM, FM, or level detectors to allow demodulation and analysis.

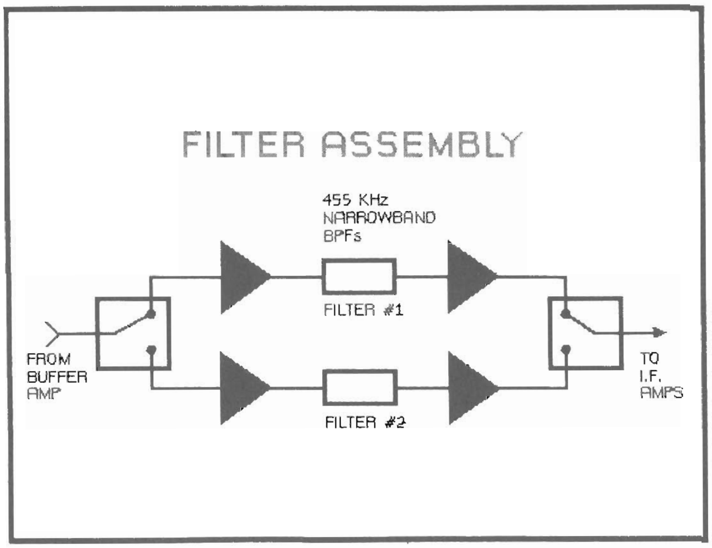


745

The 8901B options for measuring adjacent channel power and noise consist of an RF switch for an external LO input, buffer amplifiers in the IF to allow splitting the IF signal, added narrowband filters, variable gain precision amplifiers, and an RMS detector. The RF switch allows use of an external LO when lower noise and/or finer resolution frequency settability is required than is provided by the internal local oscillator. The narrowband filters provide rejection of the large down-converted signal when noise near this signal is being measured. The precision variable-gain amplifiers provide a method for making calibrated measurements with the rms detector over a wide dynamic range.

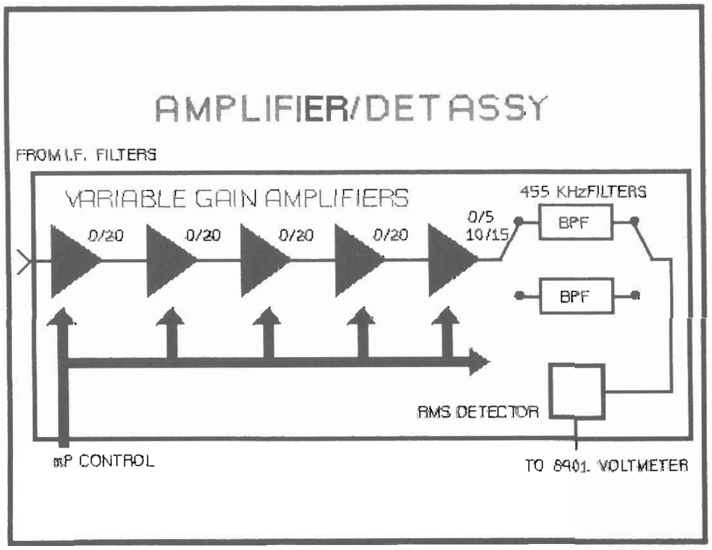


746



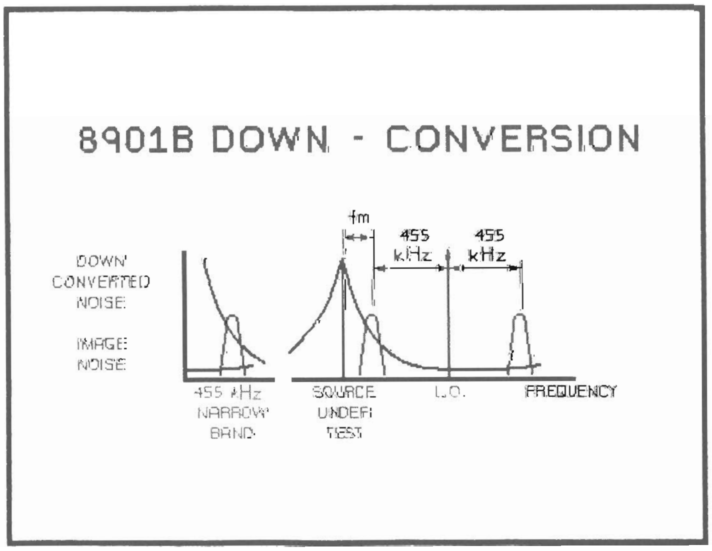
747

Any one of three filter combinations are available with the 8901B for making noise measurements. One combination is equipped with two standard filters which allow recommended adjacent channel power measurements to be made for any of three channel spacings: 25 kHz, 20 kHz, and 12.5 kHz. Additionally, a narrow filter of approximately 2.5 kHz bandwidth may be substituted for either of the standard channel filters. This narrow filter allows measurements as close as 5 kHz to the carrier, and is useful for making general purpose noise measurements. The effective noise bandwidth of approximately 34 dB relative to a 1 Hz bandwidth can be compensated for by the instrument firmware, permitting direct readings in dBc/Hz. Amplifiers are provided to compensate for insertion loss in these filters, and to keep system S/N high.



748

95 dB of auto-ranging IF gain, variable in 5 dB steps, is provided between the narrowband IF filters and the rms detector. The detector can operate accurately over approximately 20 dB of dynamic range. Summing the 95 dB of available variable gain, 20 dB of detector range, and 34 dB of noise bandwidth yields 149 dB for measurement range of noise in a 1 Hz bandwidth relative to the carrier power level. Additional filtering is provided between the amplifiers and detector to reject broadband amplifier noise and to provide additional carrier rejection.



749

When the LO of the 8901B is tuned to a given frequency, it converts signals separated from the LO by the IF frequency into the IF passband. This can be thought of as two IF filters at the LO frequency + and − the IF frequencies. The signal that appears at the detector is the sum of the signals in these two passbands. If the LO is tuned such that the desired signal is in one of these passbands, the peak signal power is detected. If the LO is then moved 20 kHz, noise 20 kHz to one side of the signal being measured is then detected by the IF detector.

To measure noise, first set the instrument to a known state, such as automatic operation in frequency measuring mode. Feed a signal to the input port, and allow the 8901B to automatically tune to this signal. Alternately, the frequency of the 8901B can be manually tuned to the desired signal. Use the special function keys to enter the noise measurement mode and to select the appropriate narrowband IF filter. The instrument will read the peak signal strength at the IF rms detector in volts. The amplifiers and input attenuator will autorange to keep this level between 1.5 and 3.0 Volts. This number is then used as the reference level for making relative noise measurements. The LO can now be moved to the offset of interest by entering this offset in kHz and pushing the kHz UP key. Enter the special function for the filter to be used to measure noise. The IF amplifiers will range automatically to maintain the power in the filter bandwidth in the linear range of the detector. The display will show this level in decibels relative to the peak signal power reference level previously measured. A separate special function may be used to display this level in dBc/Hz if the narrowband filter is used.

MEASUREMENT/ALGORITHM

Command	Function
Auto/Frequency	Set instrument to known state
24.0 Spcl	Initializes instrument for noise measurement
24.1/3/5 Spcl	Measures signal reference power with one of three filters
KHz UP or KHz Down	Tune 8901B L.O. to desired offset
24.2/4/6/7 Spcl	Displays noise in one of three filters BWs or in 1Hz BW relative to signal in dB

750

USING AN EXTERNAL L.O.

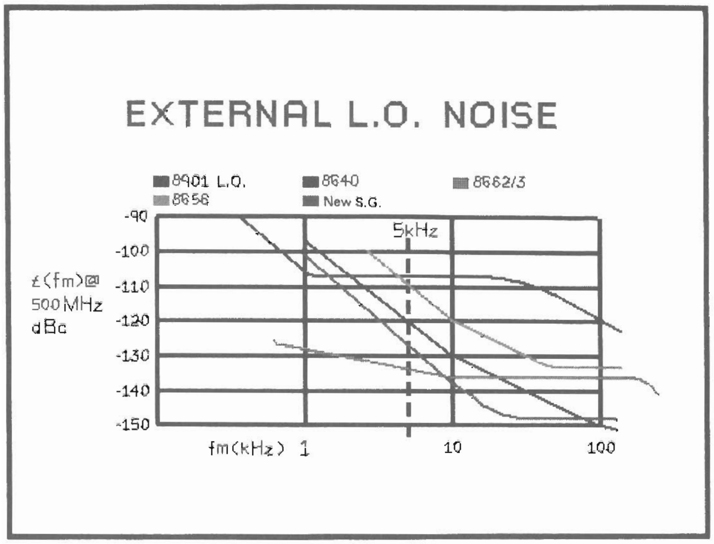
- Especially Useful Above 100MHz
- Allows Better Frequency Settability Resolution
- Improves Measurement Noise Floor
- Can Extend Range to 2.1 GHz

751

The noise measurement option for the 8901B includes a programmable RF switch for selecting an external source to be used as the local oscillator. This switch, LO amplifiers, and internal mixer will all operate to 2.1 GHz, thus offering one method of extending the 8901B measurement range above the 1300 MHz limit of the internal LO. The 8901B internal LO frequency resolution can be as coarse as 2 kHz at 1300 MHz, decreasing linearly with frequency. When using the 2.5 kHz wide filters for measuring phase noise, frequency setting resolution better than 1 kHz is desirable to peak the signal in the IF passband. An external LO with fine frequency resolution allows this for higher measurement frequencies.

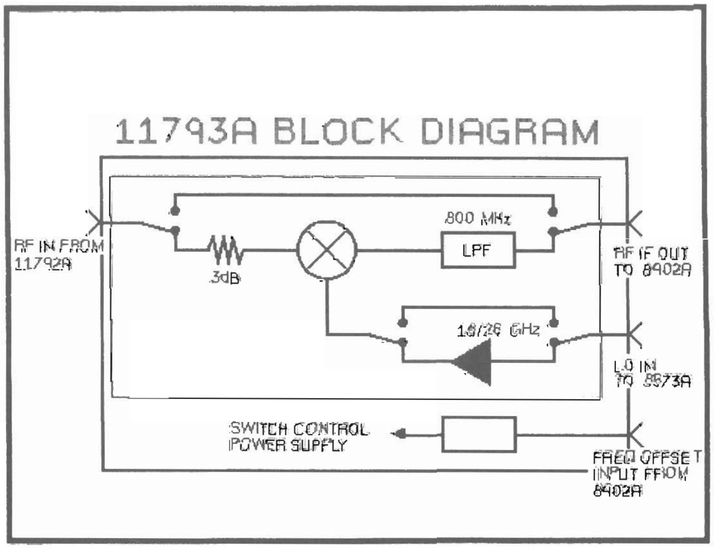
To use an external LO, select 23.1 SPCL prior to entering noise measurement mode. Tune the external LO 455 kHz above the desired signal frequency. Set the reference level as before, then increase the frequency of the LO by the desired offset frequency.

The phase noise on the LO internal to the 8901B limits the instruments dynamic range below the capability allowed by the other critical components in the measurement path. Use of an external low noise LO and careful attention to the RF attenuator and IF detector settings during reference level setting allows measurement floors approaching −150 dBc to be obtained. Since the external LO is amplified and used as the large signal input to the mixer, AM noise is suppressed. There are many high-quality signal sources available with UHF noise performance that is superior to the 8901 LO noise performance at offsets addressed by this technique, as is illustrated in this plot.



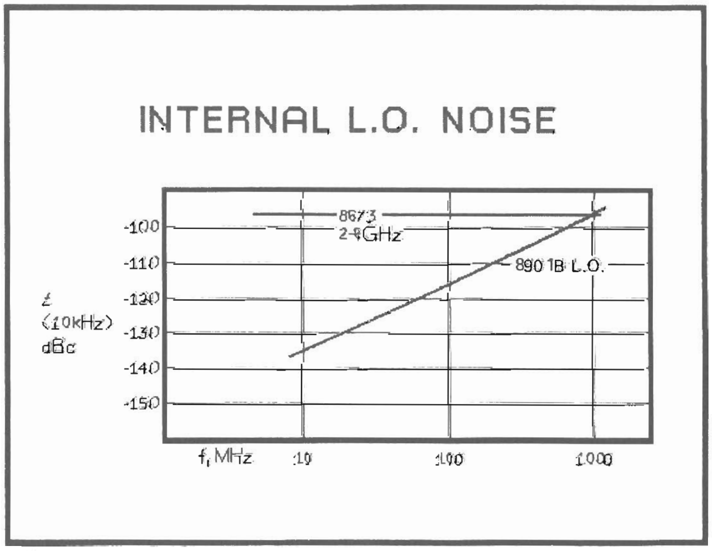
752

Extending this measurement technique to microwave frequencies simply requires a microwave mixer and a stable, microwave source with phase noise lower than the source-under-test. The difference frequency can be tuned to the frequency range of the 8901B and analyzed directly. These components are included in the 11793A microwave down-converter. When coupled with a microwave LO such as the 8673A, the 11793A extends the range of all 8901B measurement capabilities to 26.5 GHz.



753

When down-converting a microwave signal for noise analysis by the 8901B, it's best to keep the difference frequency low (below 10 MHz) to take advantage of the lower noise of the 8901B's LO at the lower frequencies. Frequency setting resolution also becomes finer as the 8901 LO is tuned to lower frequencies. Keeping the difference frequency low also minimizes in-band mixer spurious, and makes the filtering job easier.



754

MEASURING SIGNAL SSB NOISE WITH THE 8901B

- Fast/Easy
- Moderate Cost
- Easily Automated
- Standard Adjacent Channel Power Tests Built-In
- Measures Total SSB Noise Power, Not Just AM or PM

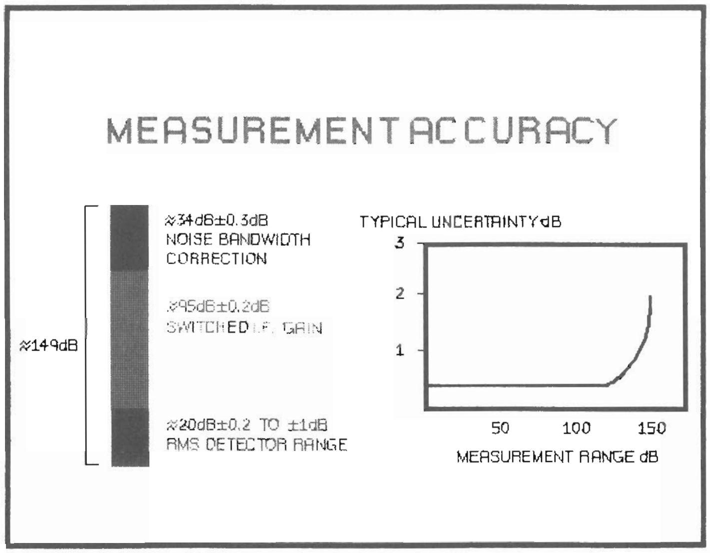
The noise measurement options on the 8901B allow extremely easy and fast measurement of SSB noise on RF and microwave signals. The measurement is relatively insensitive to many common pitfalls encountered in making noise measurements. There is no need to phase-lock signals. The data is displayed conveniently, either as −dBc in a 1 Hz bandwidth, or as total power in a standard channel test filter. Noise at a given offset is measured and displayed real-time, allowing adjustment of the device being tested. Although there are times when it is advantageous to separate the AM and PM components of noise, total SSB noise, regardless of type, is what is usually important when analyzing the limitations in communications systems. This is precisely what the 8901B noise measurement option measures.

There are several limitations involved in this technique which can render it inapplicable for some test situations. The bandwidth of the IF filters prevents this instrument from measuring noise closer than 5 kHz to the carrier before IF feedthrough begins to saturate the detector. Dynamic range limitations in the RF and IF paths prevent measurement of noise below −150 dBc even with a noiseless LO. Since the LO and signal under test are not locked to each other, both must have good frequency stability. Otherwise, the offset frequency being measured will drift as the signal drifts, and results will be inaccurate. (However, many non-phase locked sources are stable enough with adequate warm-up.) This technique rejects neither AM nor PM noise, thus the measured result is the sum of both of these types of noise. If neither type of noise is dominant, and only one type is of interest, a different technique must be used. Also, if noise at the image frequency (910 kHz away) is comparable to noise at the offset of interest, the image noise will sum into the IF and the result will be affected. This typically happens at larger offsets where white noise predominates, and the image noise adds 3 dB to the result. Finally, any discrete signals, such as spurious sidebands, may be interpreted inaccurately by this method. This is because the filter noise bandwidth correction factor (34 dB for 2.5 kHz filter) applies only to evenly distributed noise throughout the filter passband. Discrete signals therefore will be measured as 34 dB lower than the actual value.

8901B LIMITATIONS

- Offsets must be greater than 5KHz
- Dynamic range limited to less than 150dB
- Source must be stable to within 1KHz
- Total noise measured, not just phase noise
- Noise at image is also measured
- Poor identification and resolution of spurious

756



757

The main components affecting accuracy of this measurement are the accuracy of the noise bandwidth correction for the narrowband IF filter, the accuracy of the IF amplifier gain steps, and the accuracy of the rms detector. The effective noise bandwidth of the IF filter is stored in battery backed-up memory, and can be changed by using a special function. The 3 dB bandwidth of the filter can be measured by setting a reference when tuned to a synthesized source with fine frequency resolution. Tuning the source back and forth through the IF passband until the 8901B reads −3 dB yields the 3 dB bandwidth of the filter. The filter rolloff is steep enough that the effective noise bandwidth is within 0.3 dB of the 3 dB bandwidth.

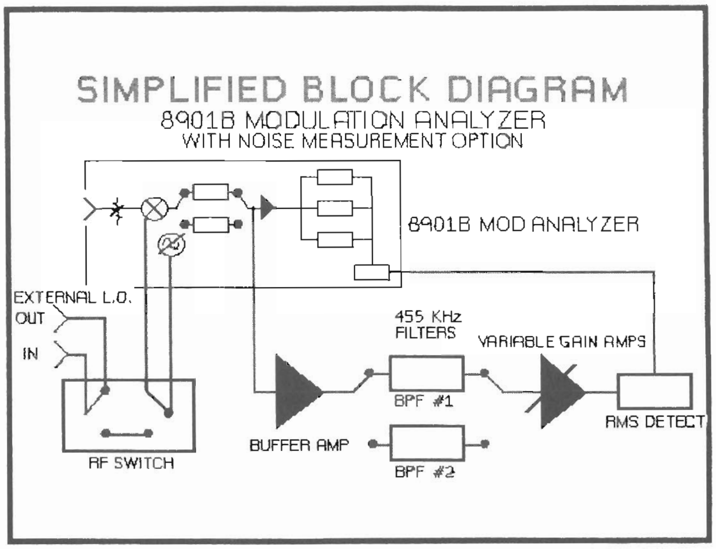
The programmable gain-step IF amplifiers are precision amplifiers with accuracy in the range of 0.01 dB/10 dB change in gain. The maximum gain error will then be roughly 0.2 dB if the entire 95 dB of gain change available is used.

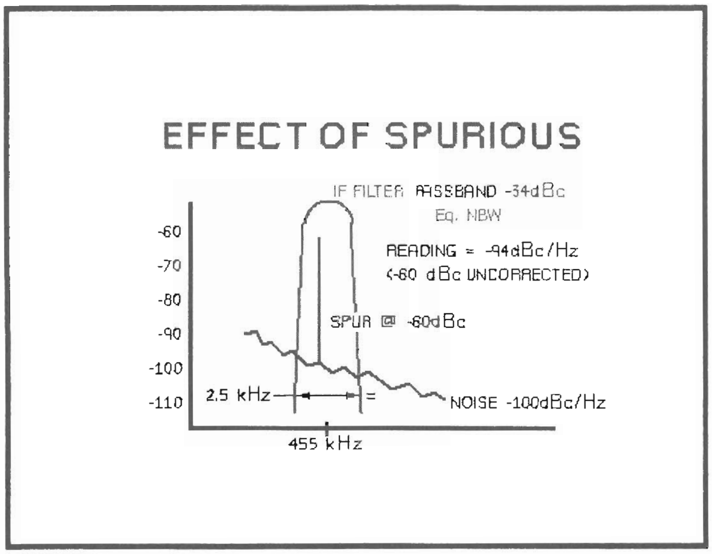
The rms detector is always kept within a 6 dB window during reference setting. The accuracy of the detector over this range is better than 0.2 dB. When measuring noise near the dynamic range limits of this instrument (−150 dBc), the detector will be making measurements over a range that is roughly 20 dB. The uncertainty at the limit of this range can approach 1 dB.

Adding these uncertainties together, it can be seen that the typical accuracy can vary from about 0.5 dB for measuring noisy sources to greater than 2 dB when the noise is less than −140 dBc. These uncertainties do not include errors resulting from unflatness of the noise throughout the filter passband, noise at the image frequency, or residual noise from the 8901B.

The equivalent input noise figure of the 8901B is approximately 24 dB. This is limited by the insertion losses encountered throughout the RF and IF paths, the maximum signal level that may be applied to the RF mixer, and the equivalent noise in the amplifiers. This requires that input signal levels should be greater than 0 dBm to take full advantage of the dynamic range available in the IF. The RF input attenuator should be manually adjusted (through special function keys) to ensure that the maximum signal level is being applied to the IF (no IF gain when setting a reference level). This is not normally necessary when making a standard adjacent channel power test, but is desirable when measuring phase noise. The 8901B will display an error message when the reference signal level is beyond the upper limit of the rms detector (error 17). The input attenuator should be adjusted just below the level needed to cause this error message.

Once a reference level has been set, the dynamic range can be quickly checked by removing the signal. The instrument should then display greater than 145 dB relative to the signal in a 1 Hz bandwidth. This number will then be approximately the measurement floor. As noise being measured approaches this level, this noise will sum into the result and will cause errors as this floor is approached. This check will not take into account the noise of the LO, as this noise is not down-converted into the IF when no input signal is present.





759

The noise measurement option of the 8901B receiver measures total power passed through the IF filter to the rms detector. When using the noise bandwidth correction factor for this filter, the assumption is made that the noise in this filter is evenly distributed, and therefore the noise power in a 1 Hz bandwidth at the center of the filter is equal to the total power in the filter passband minus the noise bandwidth correction factor. This is not always the case. Phase noise from 5 kHz to 100 kHz from a UHF signal will typically vary from $1/f$ to $1/f^2$. This causes very little measurement error if the filter bandwidth is small compared to the offset being measured. Even if the noise changes from a 9 dB/octave slope to 6 dB/octave in the filter passband, the error introduced will be less than 0.15 dB.

Of more concern is the effect of a noise "hump" or spurious sidebands. If a spur falls into the filter passband that is well above the noise power in the filter passband, the rms detector will accurately measure the peak spur power, i.e., the noise bandwidth correction factor is no longer valid. Therefore, when measuring a known discrete spurious signal that is well above the noise power in the IF filter bandwidth, the noise bandwidth correction factor should not be applied. Many times spurs can be identified, as they will cause the result to increase suddenly as the frequency offset is increased. In the absence of spurs, noise readings will generally decrease smoothly or remain constant with increasing offset. Spurs less than 30 dB above noise in a 1 Hz bandwidth will not be detected.

In summary, the measurement floor of this technique is limited by the noise of the LO and by the equivalent input noise of the 8901B. The internal LO of the 8901B is a good choice at lower center frequencies. However, an external LO will improve the measurement floor at UHF. The input level and input attenuators should be carefully adjusted to maximize dynamic range when setting the reference level.

The accuracy of the IF detection scheme varies from typically 0.5 dB when measuring higher noise levels to approximately 2 dB at the lower levels.

Attention must be paid to the effect of discrete spurious and very steep or non-monotonic noise slopes. The noise bandwidth correction may not apply in some of these cases. Spurs less than 30 dB above noise in a 1 Hz bandwidth will not be seen at all.

Noise at the image frequency (910 kHz away) also sums into the IF filter. If white noise is being measured, this will add 3 dB to the result. Also spurious signals at the image frequency will be detected as if they were at the offset of interest.

Finally, the accuracy of the offset frequency being measured is only as good as the accuracy of the difference frequency between the LO and source under test. Both must remain stable during the time between reference setting and measuring at the desired offset.

ERROR SUMMARY

- L.O. Noise
- 8901B Equivalent Input Noise Figure
- Accuracy and Linearity of Filter BW
  If Gain, RMS Detector
- Noise Slope and Spurious Signals
- Image Noise
- Frequency Settability and Stability
  of L.O. and Source

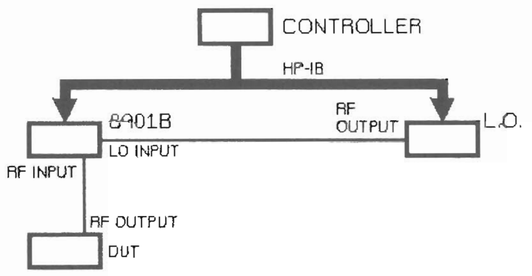
APPLICATIONS

- Transmitter testing
- Production testing of sources
- Signal generator calibration or characterization
- R&D evaluation

761

With this measurement capability, we can now make adjacent channel power measurements on transmitters. Specifically, CEPT standards can be met with the required filters. Phase noise can be easily checked on the production line for different types of sources. Because of HP-IB, the 8901B can be put into an automatic system. Because of the capability to make the measurement real time, the 8901B can be used for calibration and design evaluation.

AUTOMATED NOISE MEASUREMENT



762

Here is a block diagram for making an adjacent channel power measurement or a phase noise measurement with an external LO. If the internal LO of the 8901B is used, then there is no special connection. To automate the system a controller is connected through HP-IB.

HEWLETT PACKARD

Printed in U.S.A.