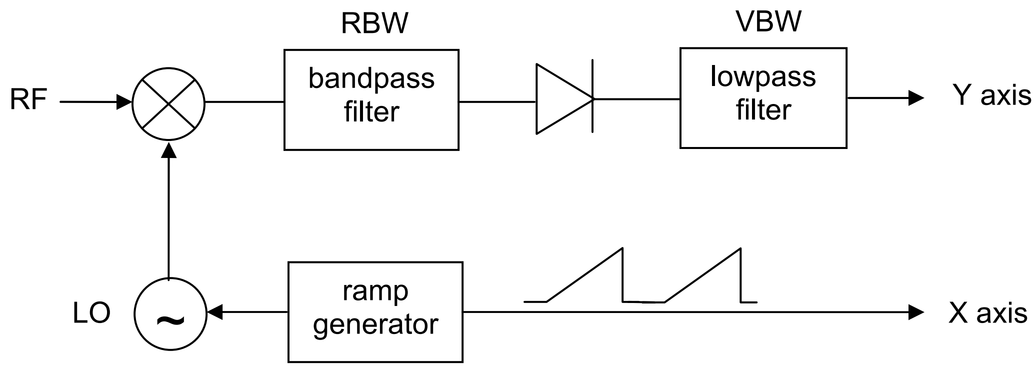
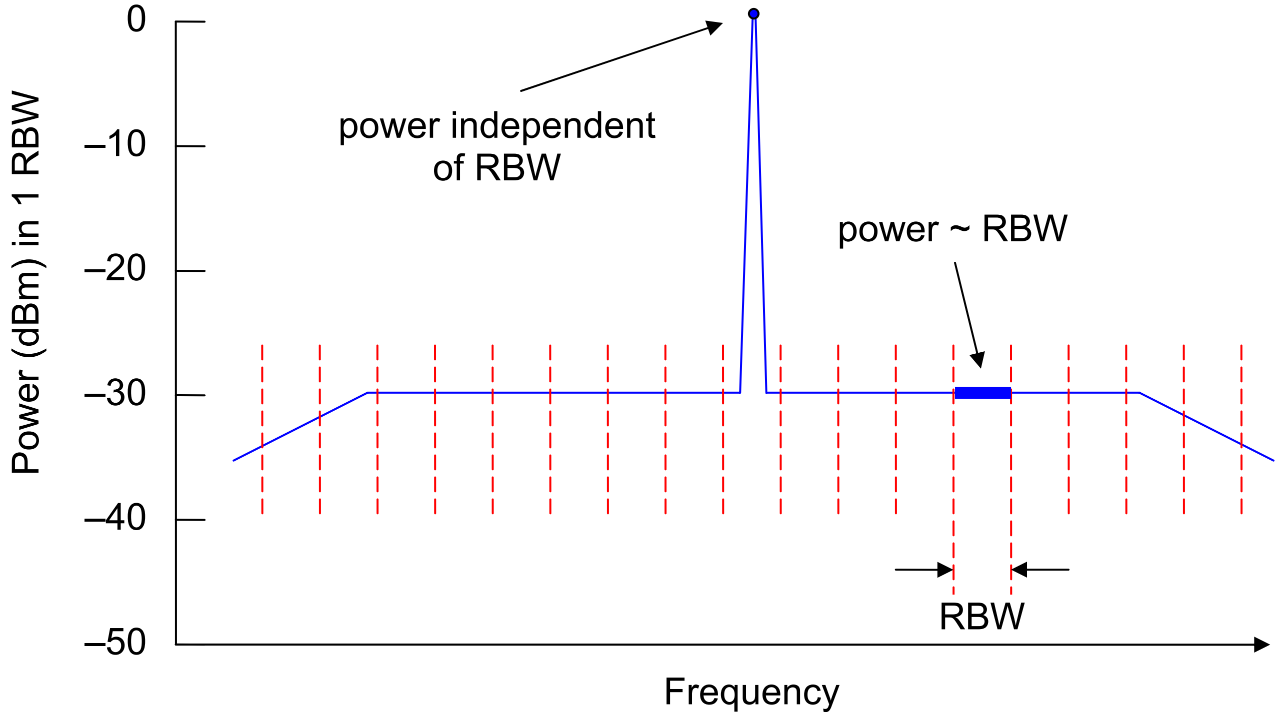
Basic parameters and functions of a spectrum analyzer



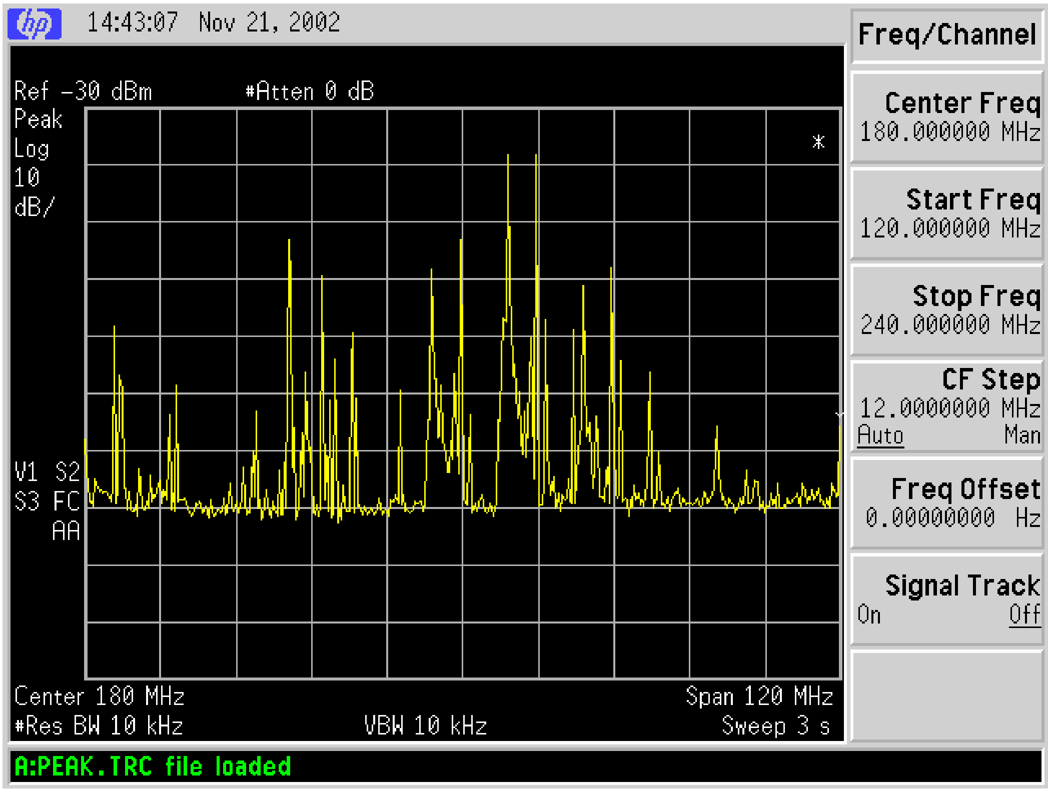
Function	*Description*
`start/stop frequency`	Displayed frequency range on x-axis.
`center frequency/span`	Ditto.
`reference level`	Power level at y-axis reference position, usually at top of display.
`scale type`	Logarithmic or linear scale on y-axis.
`scale/div`	Units per vertical division, usually 1, 2, 5, or 10 dB/div.
`attenuation`	Input attenuation. Decrease it to lower noise floor.
`resolution bandwidth`	Signal bandwidth of each instantaneous power measurement. Decrease it to improve sensitivity to narrowband signals.
`video bandwidth`	Cutoff frequency of lowpass filter following power detector. If video BW < resolution BW, output is smoothed, and sensitivity to impulsive signals is reduced.
`video averaging`	Display average spectrum from multiple sweeps.
`sweep time`	Time interval to draw trace once across screen. In order to maintain proper amplitude calibration, analyzer sets sweep time as a function of frequency span, resolution BW, and video BW.
`max hold`	Display max level measured at each frequency over repeated sweeps.
`zero span`	Configure analyzer as a fixed, tuned receiver to display power vs. time for the frequency range specified by center frequency and resolution BW.
`marker`	Use marker to measure frequency and power at selected points.

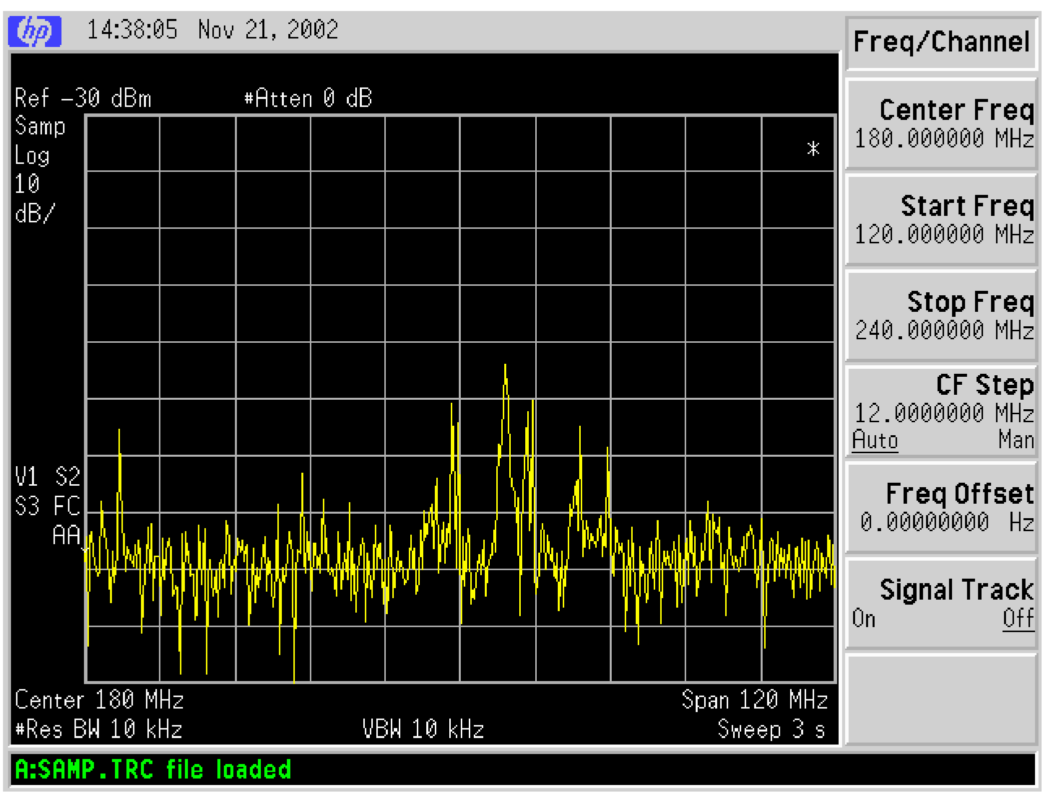
Resolution bandwidth



- For broadband noise, power is proportional to RBW.
- For CW (carrier) signals, power is independent of RBW.

RFI-rich spectrum using peak (top) & sample (bottom) detection



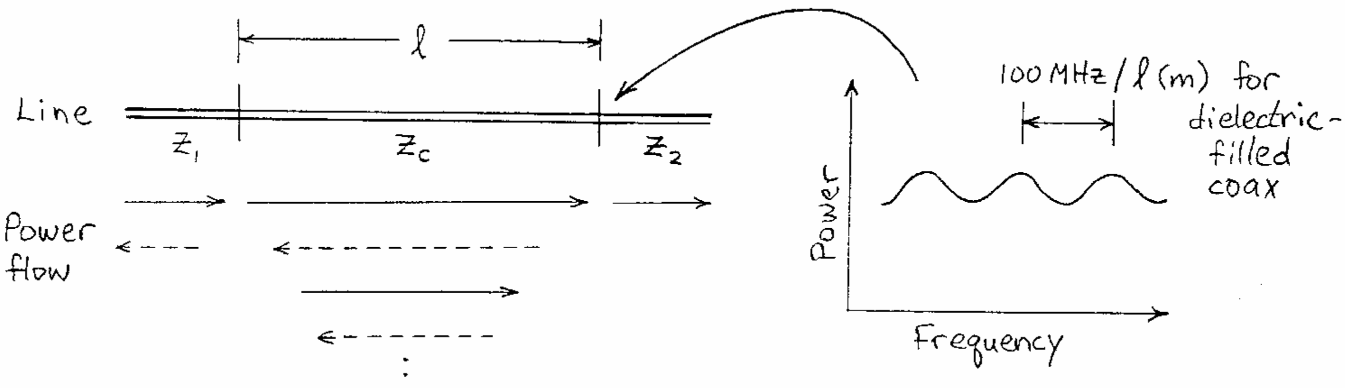


Some spectrum analyzer applications in VLBI

- Measure frequency response of active and passive components, e.g., filters and amplifiers.
- Measure cable loss, e.g., in cables to antenna.
- Look for ripple in broadband RF or IF signals as evidence of impedance mismatches.
- Measure LO phase noise and estimate LO phase jitter. (See "Notes on Phase Modulation of LO Signals" and IF3 LO phase noise example.)
- Test for presence of phase cal or LO modulation by measuring the carrier–to–noise power ratio of a phase cal tone and comparing against broadband power measurements. (See notes on "Using a spectrum analyzer to test for LO or phase cal modulation.")
- Search for sideband modulation on a CW-type signal. For example:
  - 50 or 60 Hz sidebands on an LO, phase cal tone, or reference frequency signal (e.g., 5 or 500 MHz).
  - 5 kHz sidebands on phase cal tones due to MkIV cable measurement system.
  - CW sidebands on LO signal originating in phase–locked loop (e.g., 10 kHz sidebands on LO in VLBA BBC or MkIV VC).
- Search for spurious phase cal signals by turning off phase cal or unlocking the receiver LO and then looking for signals at normal phase cal frequencies.
- Search for RFI in IF or baseband signals.
- Use zero–span mode to examine temporal variability in a narrow frequency range.
- Use the analyzer as a power meter, to measure the total power over a specified frequency range, or as a frequency counter, to measure the frequency of narrowband signals.

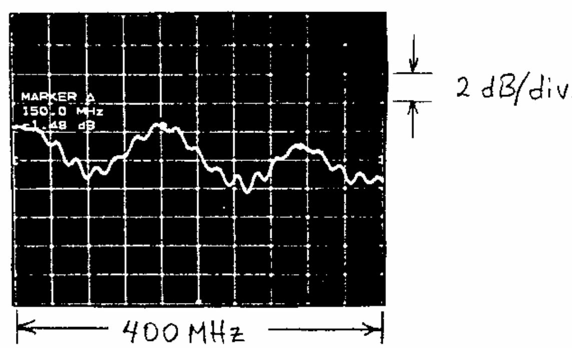
Impedance Mismatches and Reflections

- Coax or waveguide transmission lines have constant characteristic impedance $Z_c = V/I$. ($Z_c = 50\ \Omega$ is common for coax.)
- If line is terminated with active or passive device having impedance Z_c, all incident power will be absorbed without reflection.
- If device has impedance $\neq Z_c$, or if line has a break or bad connector, some power will be reflected.
  $\Rightarrow$ Gain is decreased, and amplifier driving line may oscillate.
- If multiple abrupt impedance changes are present, multiple reflections cause ripple in power and phase spectra.



Example:

Ripple in IF power spectrum due to multiple reflections over 0.7-meter and 5-meter cable lengths.



- Multiple reflections are particularly serious if they occur before the phase cal injection point, either between feed and coupler or between phase cal antenna unit and coupler.
- Even more serious are unstable, time-dependent changes in phase ripple caused by multiple reflections, which can affect measured group delay.

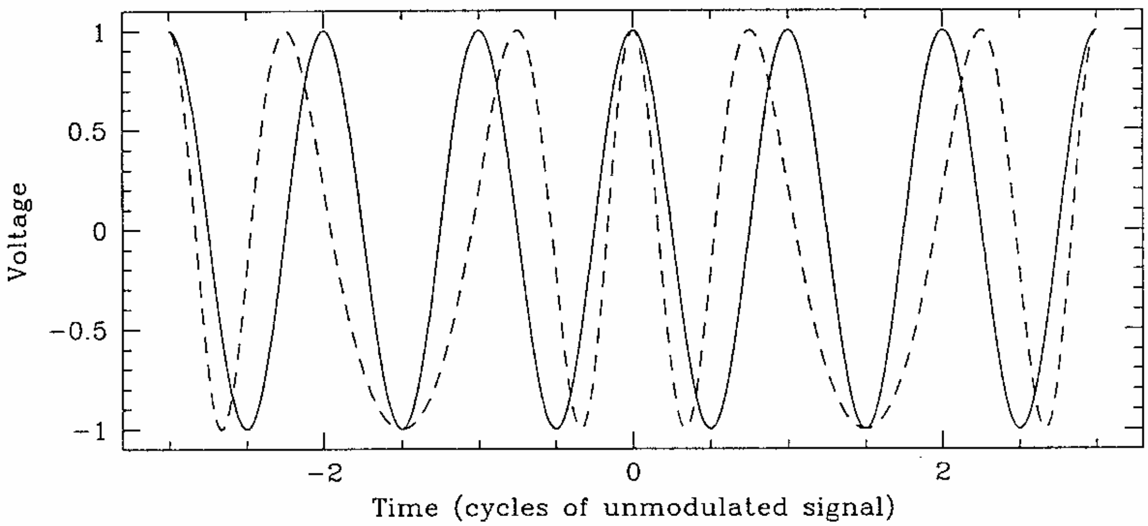
Phase Modulation of LO Signals

$$V_{LO}(t) = \cos[\omega_{LO} t + \phi + mod(t)]$$

Example of phase modulation in time domain:

——— Unmodulated pure sine wave

- - - - Modulated sine wave with $mod(t) = (\pi/2 \text{ radians}) \times \sin \omega_{LO} t/3$



For $mod(t) = \alpha \sin \omega_m t$ and $\alpha \ll 1$ radian,

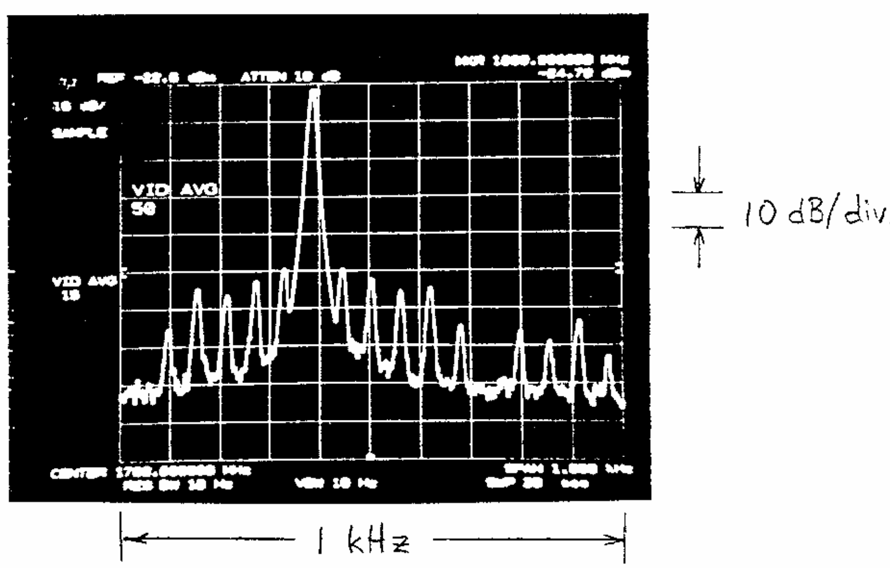
$$V_{LO}(t) \approx \cos(\omega_{LO} t + \phi) + \frac{\alpha}{2}[\underbrace{\cos(\omega_{LO} + \omega_m)t}_{\text{USB}} - \underbrace{\cos(\omega_{LO} - \omega_m)t}_{\text{LSB}}]$$

In general case, for arbitrary $mod(t)$,

- spectrum of modulated signal has upper and lower sidebands on either side of LO frequency, and
- amplitude of $\cos \omega_{LO} t$ term is reduced compared to unmodulated case.

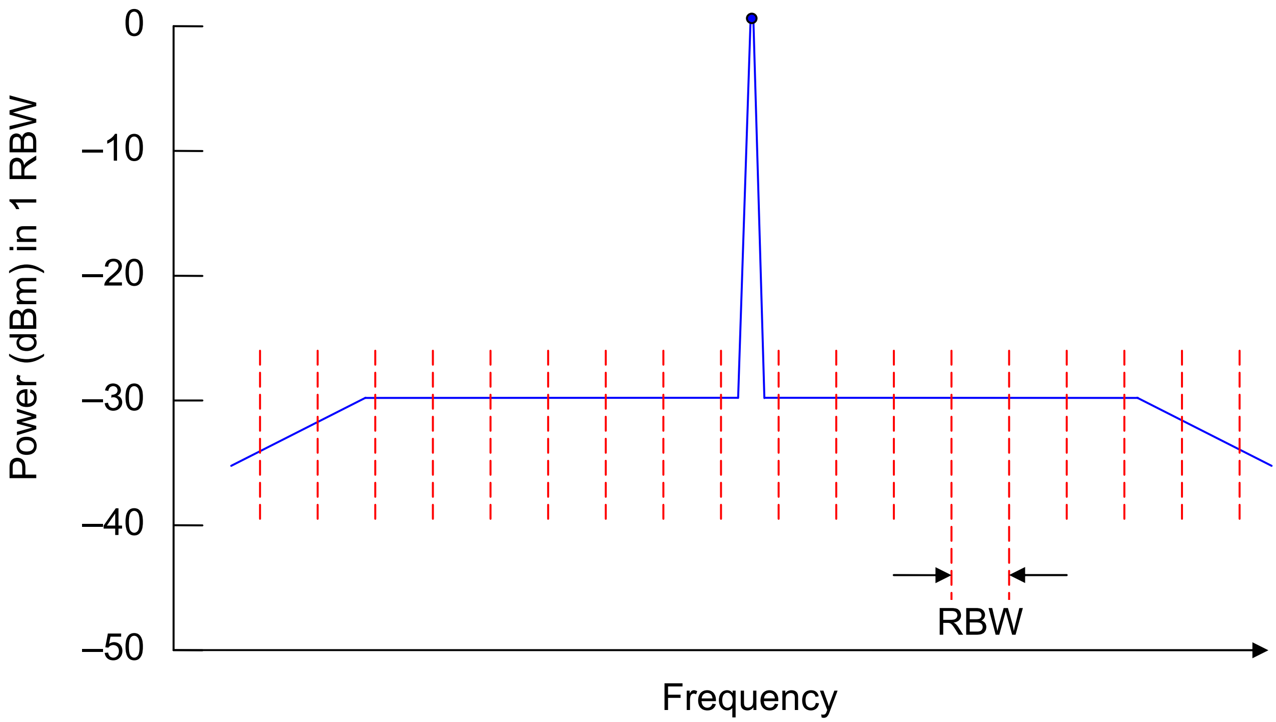
LO Phase Modulation in Geodetic VLBI

- Modulation of LO in receiver or in VC/BBC causes
  - loss of phase coherence in baseband signals relative to signals at other VLBI stations
  - degradation of VLBI sensitivity
  - shifting of signal power to modulation sidebands.
- Low–level modulation of a low–frequency LO reference signal can lead to strong modulation at high LO frequencies:
  When frequency f_1 is multiplied up to f_2, phase noise (in degrees or radians) is multiplied by ratio f_2/f_1, and strength of modulation sidebands is increased by $20\log_{10}(f_2/f_1)$ dB.
  - Example: Modulation sidebands on a 5 MHz LO reference will be $20\log_{10}(8080/5) = 64$ dB stronger at $f_{LO} = 8080$ MHz.
- A common source of modulation is 50/60 Hz hum in power supplies.
  - Example: Power spectrum of 1700 MHz LO locked to 5 MHz reference signal with weak 60 Hz modulation –



- **LO modulation sidebands in VLBI systems should be > 30 dB below the LO carrier.**

Measuring carrier phase noise



- Phase noise of a carrier = total power in two modulation sidebands
- RMS phase jitter of a carrier in radians =
  sqrt [(power in 2 sidebands) / (power in carrier)]

Example: Calculate carrier phase noise for spectrum above, out to the "knees" in the spectrum

Phase noise level is -30 dBm/RBW out to 6 RBWs away from carrier.
→ power in 2 sidebands = 2 x (0.001 mW / RBW) x (6 RBW)
= 0.012 mW
In practice, power is usually calculated from frequency span & RBW.
For example, if span = 12 kHz and RBW = 1 kHz,
power in 2 sidebands = (0.001 mW / 1 kHz) x (12 kHz) = 0.012 mW

Power in carrier = 0 dBm = 1 mW

RMS phase jitter of carrier = sqrt [0.012 mW / 1 mW] radian
= 0.11 radian = 6 degrees

Notes on Phase Modulation of LO Signals

Brian Corey / Haystack Observatory

11 May 1998

The output from any oscillator exhibits phase noise, *i.e.*, it is not a pure, noise-free sinusoid. The level of phase noise, or phase jitter, depends on the quality of the oscillator and of any reference signal to which the oscillator is locked, and on the oscillator control electronics. Phase modulation refers to deviation of the phase from that of a pure sinusoid. Oscillator signals may be phase–modulated either by design, as in communication systems, or unintentionally, due to intrinsic oscillator noise or poor–quality reference signals, for instance. For geodetic VLBI, the LO signals should have minimal phase modulation, in order to maximize the phase coherence of the baseband signals with those from other stations.

Phase jitter

Phase modulation appears in the time domain as jitter in the signal phase. If the signal is displayed on an oscilloscope that is triggered off a phase-stable source at the same frequency (or a subharmonic of that frequency), the zero-crossing times of a phase-modulated signal will be observed to vary about some mean value. A useful quantity to measure is the *root-mean-square (rms) phase jitter* $\Delta\phi_{rms}$ defined as

$$\Delta\phi_{rms} = \sqrt{\text{average value of (phase deviation from mean value)}^2} \ .$$

A rough guide that is good enough for many purposes is that

$$\Delta\phi_{rms} \approx \frac{1}{4} \times (\text{peak}-\text{to}-\text{peak phase jitter}) \ .$$

In the frequency domain, phase modulation appears as sidebands on either side of the carrier. There is a direct relation between the size of the sidebands and the phase jitter (strictly valid only in the case of weak modulation):

$$\Delta\phi_{rms}(radians) = \sqrt{\frac{\text{total power in both sidebands}}{\text{carrier power}}} \ .$$

If the value of $\Delta\phi_{rms}$ estimated in this manner with a spectrum analyzer is significantly lower than the value measured directly on an oscilloscope, then you probably missed some sidebands that lie outside the analyzer frequency range over which you searched. Note that spectrum analyzers have intrinsic phase noise themselves, so sidebands observed may originate in the analyzer and not in the signal you want to measure!

There are specifications for the maximum phase noise of most LO signals in geodetic VLBI systems. For example, $\Delta\phi_{rms}$ for the LO in a Mark III/IV video converter is specified to be $< 4°$ at 100–450 MHz and $< 9°$ at 450–500 MHz.

To illustrate how phase jitter is calculated from the modulation sidebands observed on a spectrum analyzer, consider a carrier with symmetric noise sidebands that extend from zero to 10 kHz on either side of the carrier. Assume the sidebands are –30 dBc down (*i.e.*, 10^{-3} as strong as the carrier) when measured with a resolution bandwidth of 1 kHz. The noise/carrier power ratio is then $2 \times 10^{-3} \times$ (10 kHz) / (1 kHz) = 0.02, where the factor of 2 comes from the two sidebands. $\Delta\phi_{rms}$ is then $\sqrt{.02} = 0.14$ radian, or 8 degrees.

If the modulation occurs at one or more discrete frequencies (modulation bandwidth < analyzer resolution bandwidth), rather than over a broad frequency range, then the calculation is carried out without including the (sideband BW)/(resolution BW) factor. Such discrete-frequency modulation is often observed at harmonics of the line frequency or, in the case of a VC/BBC LO, at harmonics of 10 kHz.

Tests for phase modulation of an LO in a VLBI system

1. Look for phase jitter at baseband of a test signal injected into the RF or IF part of the system. (Phase cal is generally too weak to use in this way, except in the case of gross phase modulation.)

2. Use a spectrum analyzer to look for sidebands in a baseband phase cal signal or in the LO signal itself.

3. The following simple test is sensitive to modulation sidebands >1 kHz from the carrier of a phase cal or other test signal:

   a. Set a VC/BBC LO precisely to the IF frequency of the phase cal or test signal (*not* 10 kHz away).

   b. In the phase cal case, set the VC/BBC bandwidth to 0.5 or 0.25 MHz. (Not all VC's have the appropriate filters.)

   c. Turn the phase cal or test signal off. If the baseband power level drops, there is measurable power in the sidebands. (A VC or BBC is insensitive to signals at its LO frequency, so in this case the carrier power does not contribute to the baseband power level when the signal is turned on.)

How to determine whether it is the LO or phase cal that is modulated

1. Inject a test signal derived from a signal source independent of the maser (*e.g.*, rubidium, cesium, or crystal oscillator), and examine the test signal at baseband. In the absence of such a source, use a separate output from the maser as the driving signal to generate the test signal. At the least, try a different 5 MHz signal from the 5 MHz distributor to drive the LO or phase cal antenna unit, and see whether the modulation changes. Note that the antenna unit will generate phase cal pulses when driven with just 5 MHz. The ground unit is needed *only* for cable measurement.

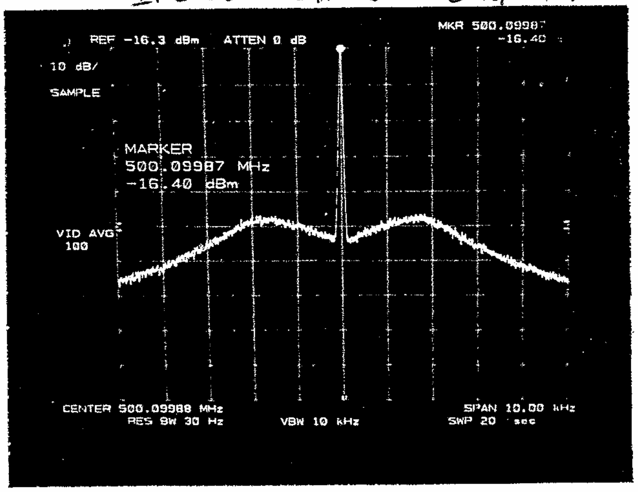
2. Look at the LO signal directly with a high-quality spectrum analyzer.

3. Try changing the LO tuning or running the LO or phase cal from a new power supply. Does the modulation change?

Beware!! The modulation may originate in the maser or its associated buffer amplifiers, in which case both the LO and phase cal signals will be modulated, and any modulation observed in a baseband or IF phase cal signal is likely to be only a small fraction of the modulation occurring to the RF phase cal signal or receiver LO. If both the RF phase cal signal and LO signal are driven by a common modulated reference signal, the phase jitter at IF or baseband will be smaller than in the LO by the ratio $|f_{RF} - f_{LO}|/f_{LO}$ (provided the modulation frequency is lower than the loop bandwidth of any phase-locked oscillator).

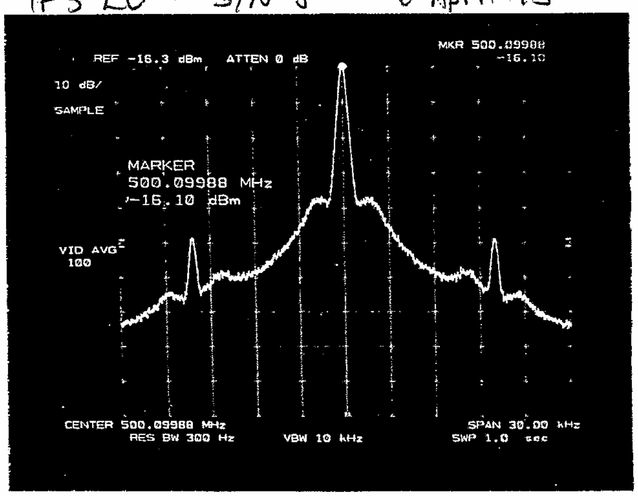
Phase noise spectra of 500.1 MHz LO in IF3 module S/N 8 -- 6 April 1993

IF3 LO - S/N 8 - 6 April 93



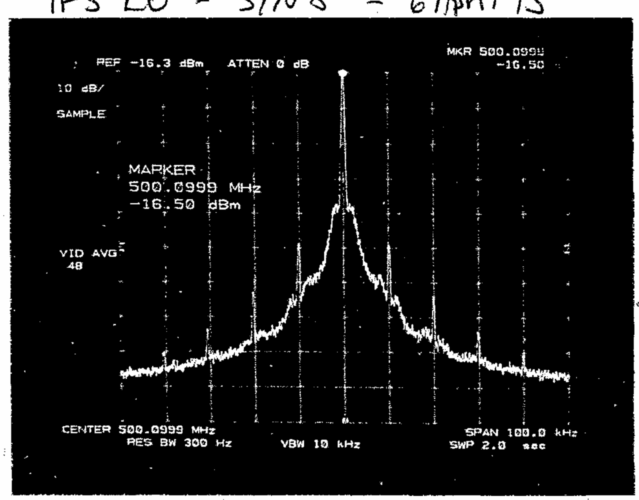
10 kHz span
30 Hz RBW

IF3 LO - S/N 8 - 6 April 93



30 kHz span
300 Hz RBW

IF3 LO - S/N 8 - 6 April 93



100 kHz span
300 Hz RBW

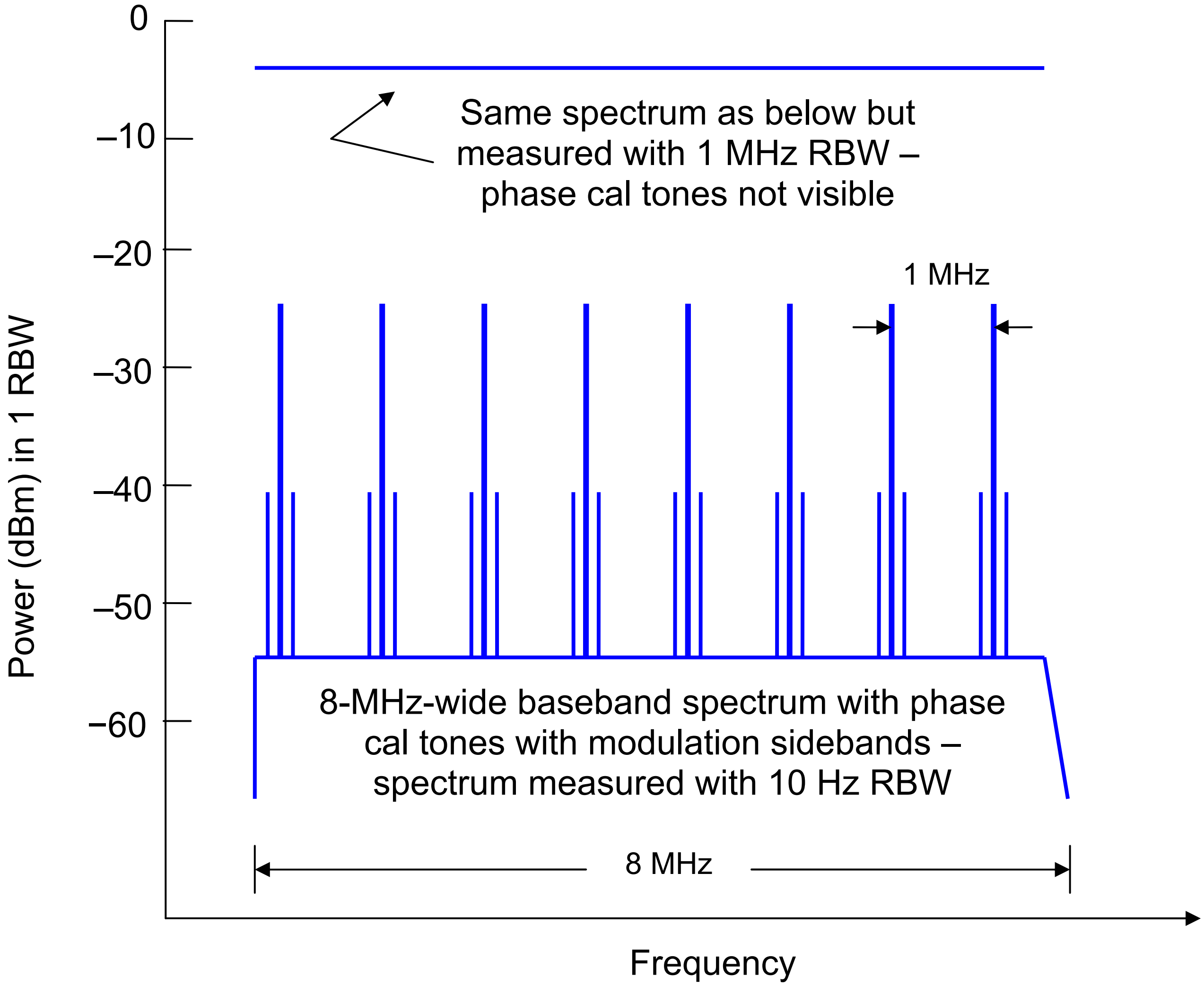
Phase noise of 500.1 MHz LO in IF3 module S/N 8

6 April 1993

Freq(kHz)	dBc/kHz	dNoise	Cum.noise	rms phase (deg)
0.000	-38.8	0.000000	0.000000	0.00
1.700	-32.8	0.001124	0.001124	1.92
3.000	-40.8	0.000796	0.001919	2.51
4.000	-46.8	0.000105	0.002024	2.58
5.000	-50.8	0.000029	0.002054	2.60
6.000	-53.8	0.000013	0.002066	2.60
9.000	-54.8	0.000023	0.002089	2.62
12.000	-60.8	0.000013	0.002101	2.63
15.000	-67.8	0.000003	0.002104	2.63
20.000	-70.8	0.000001	0.002105	2.63
30.000	-75.8	0.000001	0.002107	2.63
40.000	-79.8	0.000000	0.002107	2.63

Noise spectrum measured on HP8568A spectrum analyzer.

Indirect detection of severe phase cal modulation



Measure the strength of phase cal relative to system noise in two ways:

1. Measure height of phase cal tone relative to broadband system noise with a narrow RBW. Typically phase cal is about 30 dB above noise with a 10-Hz RBW. From this measurement, calculate ratio of phase cal tone power to system power over a 1-MHz bandwidth. Value should be approximately –20 dB, i.e., phase cal is ~1% of total system power.
2. Using total power detector, measure change in baseband power level as phase cal is turned on and off.

Compare the estimates of the pcal/system power ratio from the 2 methods. If the first ratio is smaller than the second ratio by >1 dB, phase cal power is probably being lost to modulation sidebands, which might not otherwise be easily observed due to their unknown frequency range and structure.

Using a spectrum analyzer to test for LO or phase cal modulation

Modulation of a phase calibration or LO signal due to a malfunctioning power supply or other problem can sometimes be severe enough to reduce the amplitude of the signal by > 1 dB. The following technique can be used to detect such losses.

1. Display a phase cal tone at IF or baseband frequency on a spectrum analyzer, and make two measurements:
   - Measure the power level at the peak of the tone. Call it P_{pcal}.
   - Measure the power level of the noise floor surrounding the tone. Call it P_{noise}. The measurement should be done with a precision of < 1 dB. Achieving this low an error may require using either video averaging or a very narrow video bandwidth. For this to be a valid test, the noise floor must be due to the incoming signal and not to internal analyzer noise.

2. Let B_{res} be the resolution bandwidth with which the noise floor measurement was taken. Also, let r_{pcal} be the pulse repetition rate of the phase calibration system (typically 1 MHz, although the DSN, for instance, often uses other values). Using the results from step 1, calculate the fractional system power f_1 due to phase cal:

   $$f_1 = \frac{P_{pcal}}{P_{noise}} \times \frac{B_{res}}{r_{pcal}}$$

   On a dB scale,

   $$f_1(\text{dB}) = P_{pcal}(\text{dBm}) - P_{noise}(\text{dBm}) + 10 \log B_{res}/r_{pcal} \; .$$

   Example: For $P_{pcal} = -45$ dBm, $P_{noise} = -75$ dBm, $B_{res} = 10$ Hz, and $r_{pcal} = 1$ MHz, $f_1 = -20$ dB, or 0.01.

3. Using a square-law detector connected to the same IF or baseband signal (e.g., TPI detector in a VC/BBC), measure the fractional change in power f_2 as the phase cal system is turned on and off: $f_2 = P_{on}/P_{off} - 1$. f_2 is typically in the range 0.01 – 0.02. The measurement accuracy on f_2 needs to be better than ~25%, or 1 dB, so it may be necessary to take repeated readings.

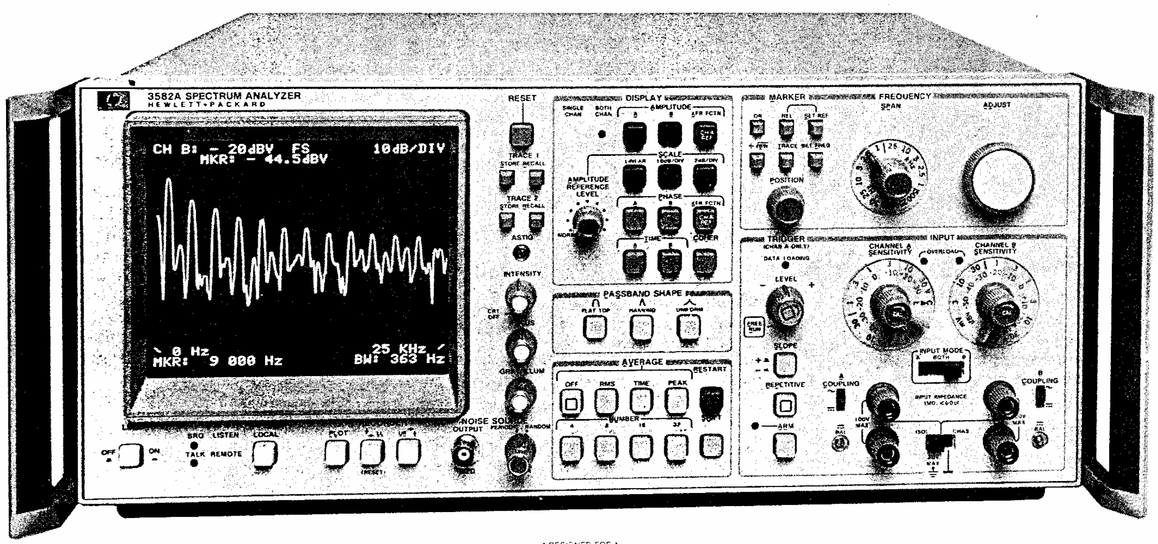
4. Compare f_1 and f_2. Ideally, f_1 and f_2 should agree.
   - If f_1 and f_2 agree to within 25% (1 dB), then there is no severe loss of signal power.
   - If f_2 is greater than f_1 by more than 25–50% (1–2 dB), then not all of the phase cal power is going into the tones spaced r_{pcal} apart. Instead, it is likely that severe modulation of either the LO or phase cal signal has caused power in that signal to be lost to modulation sidebands. Closer examination of the IF or baseband signal may reveal the location of the sidebands.
   - If f_1 is greater than f_2 by more than 25–50% (1–2 dB), then there was probably an error in the measurements!

SIGNAL ANALYZERS

Dual-Channel, Dynamic Signal Analyzer 0.02 Hz to 25.5 kHz

Model 3582A

- Transfer function magnitude and phase measurements
- Coherence function measurement
- Phase spectrum measurement
- Transient capture and frequency domain analysis
- Internal periodic and random noise source
- Band selectable analysis for 0.02 Hz resolution
- Alphanumeric CRT annotation and marker readout



DESIGNED FOR HP-IB SYSTEMS

Description

The 3582A is a powerful dual-channel, real-time spectrum analyzer that solves bench or systems measurement problems in the frequency range of 0.02 Hz to 25.599 kHz. Sophisticated LSI digital filtering combined with microcomputer execution of the Fast Fourier Transform (FFT) provides exceptional measurement capability and performance.

Exceptional Frequency Resolution

The ability to resolve closely spaced spectral components is often critical in the study of subtle phenomena such as structural transfer functions. Unlike conventional dynamic signal analysis which extends from DC to some maximum frequency, the Model 3582A can "zoom in" to analyze any selected band of frequencies with dramatically improved resolution. The start or center frequency of the 5 Hz to 25 kHz band analysis spans can be adjusted in 1 Hz increments to cover the entire frequency range of the instrument. This provides resolution down to 20 milliHertz across the entire range for spectrum analysis or 40 milliHertz for transfer functions, representing as much as 5000 to 1 improvement over conventional "baseband" analysis.

Excellent Low Frequency Coverage

Many electrical and physical measurements have signficant spectral information in the audio and sub-audio range. With frequency ranges from 25 kHz down to 1 Hz full scale, the Model 3582A is extremely well suited to these types of measurements. The display shown in fig. 1 represents the phase noise of a frequency synthesizer over the range of 0 to 1 Hz with a frequency resolution of 6 milliHertz.

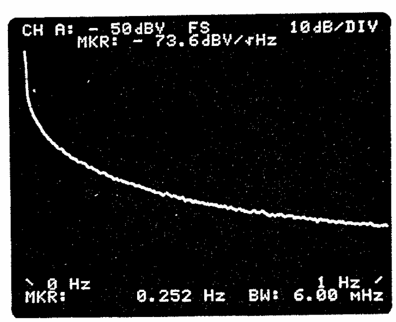


Figure 1: Phase Noise Measurement

Real Time Measurement Speed

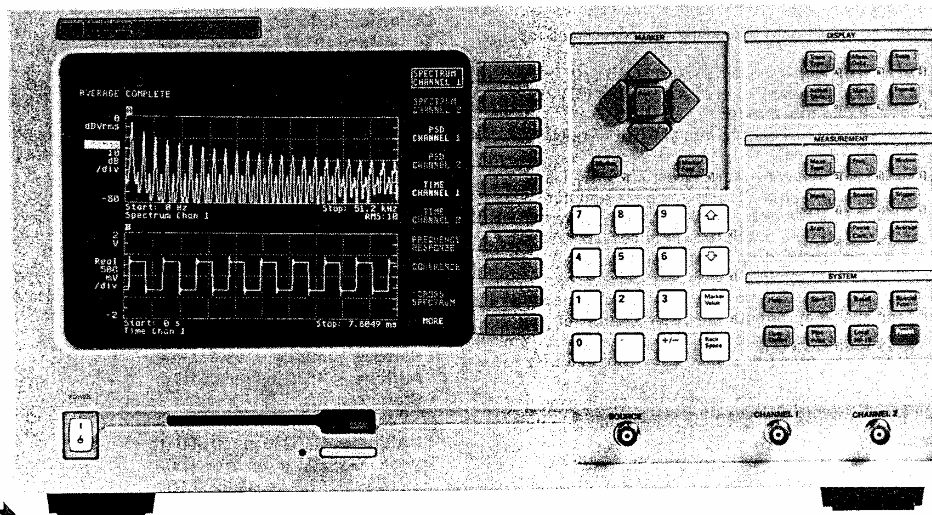
Long measurement times can be a major limitation of swept low frequency spectrum analyzers. In high volume testing or in applications requiring substantial on-line tuning these long measurement times are both expensive and inconvenient. Since the Model 3582A uses an advanced microcomputer to execute the Fast Fourier Transform (FFT), it can perform equivalent measurements as much as one to two orders of magnitude faster than a swept analyzer.

SIGNAL ANALYZERS

Dual-Channel, Dynamic Signal Analyzer 244 μHz to 102.4 kHz

Model 35660A

- Network and spectrum analysis
- 102.4 kHz single channel measurements
- 51.2 kHz dual channel measurements
- 401 line resolution
- 70 dB dynamic range
- ± 0.5 dB amplitude accuracy
- ± 0.4 dB and ± 1.0 degree channel match
- Frequency accuracy of ± 30 ppm



DESIGNED FOR HP-IB SYSTEMS

HP 35660A

HP 35660A Dual-channel Dynamic Signal Analyzer

The HP 35660A Dynamic Signal Analyzer is an FFT-based instrument that provides spectrum and network measurements in electronics, mechanical test, acoustics, and other low frequency application areas. The analyzer also offers built-in test and automation features, traditionally available only with a computer. These features include an internal programming language (HP 35680A Instrument BASIC), a built in disc drive, limit testing and data tables. With automation built in, the HP 35660A can save you both time and money.

The HP 35660A performs spectrum analysis from 488 μHz to 102.4 kHz and network analysis from 244 μHz to 51.2 kHz. The FFT provides 401 lines of resolution in both one- and two-channel modes. Complete alias protection and digital zoom ensure high resolution measurements with warranted accuracy. Measurements include linear spectrum, power spectrum, frequency response, gain/phase, group delay, time history, and power spectral density. A built-in 3.5 inch disc drive, compatible with HP Series 200/300 workstations, stores traces, tables, states, and application programs.

Electrical Spectrum Analysis

The HP 35660A is typically 10 to 100 times faster than swept spectrum analyzers for equivalent measurements, and provides higher resolution (244 μHz throughout the 102.4 kHz frequency range). This speed and resolution contribute to the quality of HP 35660A tests for distortion, spur level, frequency drift, intermodulation, and other signal parameters. Amplitude accuracy of ± 0.5 dB and frequency accuracy of ± 30 ppm guarantee precision in tests of such devices as headsets, modems, telephone components, speakers, transducers, and electrical motors.

Electrical Network Analysis

With two input channels and a built-in source, the HP 35660A can quickly measure the response of low-frequency filters and networks. Source signals provided are random noise, periodic chirp, and fixed sine. Periodic chirp is useful for testing non-linear responses such as output clipping of amplifiers. Random noise is ideal to get a linear approximation of a non-linear network. Fixed sine lets you test response at a specific frequency.

The HP 35660A is also a good choice for low-frequency transmission measurements in telecommunications and other areas. To ensure highly accurate magnitude and phase measurements, the HP 35660A offers ± 0.4 dB gain and ± 1.0 degree input channel phase match. For custom analysis of these measurements, the HP 35660A provides waveform math, including conjugation, FFT, inverse FFT, square root, and frequency domain integration and differentiation.

Machinery Vibration

The HP 35660A is an excellent fit for applications that require vibration monitoring at full load. With the analyzer's built-in limit tables, users can implement vibration and health monitoring of engines, machine tools, and other equipment, without an external computer and without programming. The analyzer's internal disc drive makes it easy to record, store, and recall limits for production or maintenance testing.