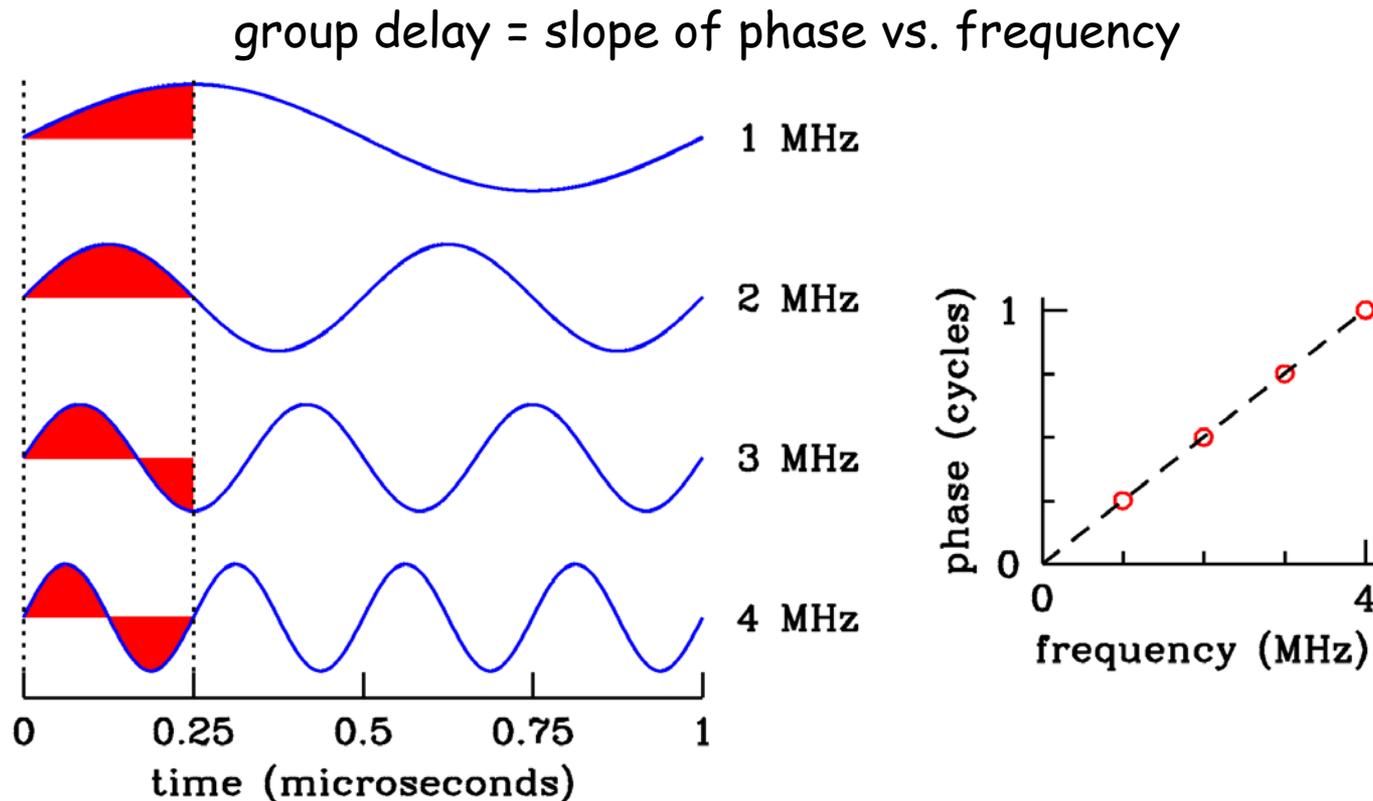


Phase Cal Basics  
and  
RF System Testing

Brian Corey

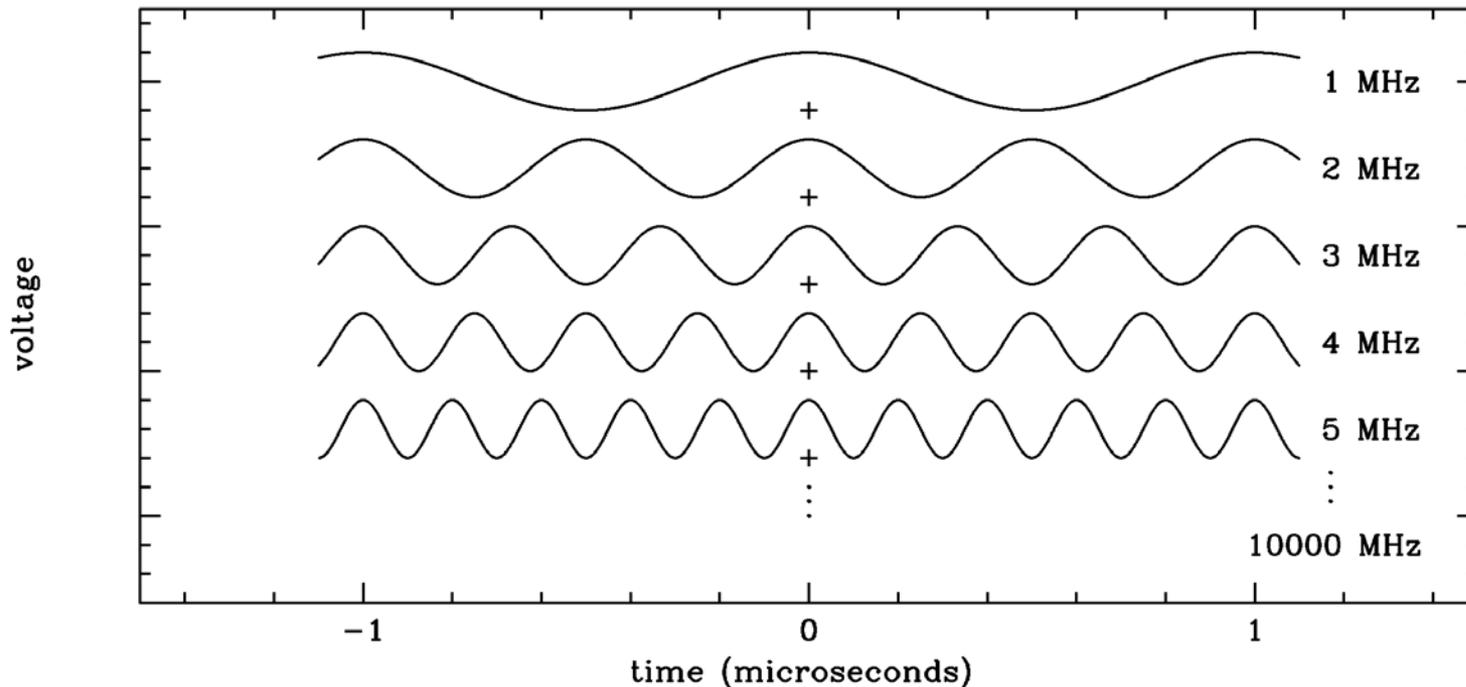
## Phase/delay calibration systems in VLBI

- Astrometric and geodetic VLBI rely on accurate measurement of phase and delay, devoid of errors caused by instrumentation.
- In absence of perfectly stable systems, calibration signals can be used to measure, and hence correct for, instrumental time and frequency variations of phase and delay.



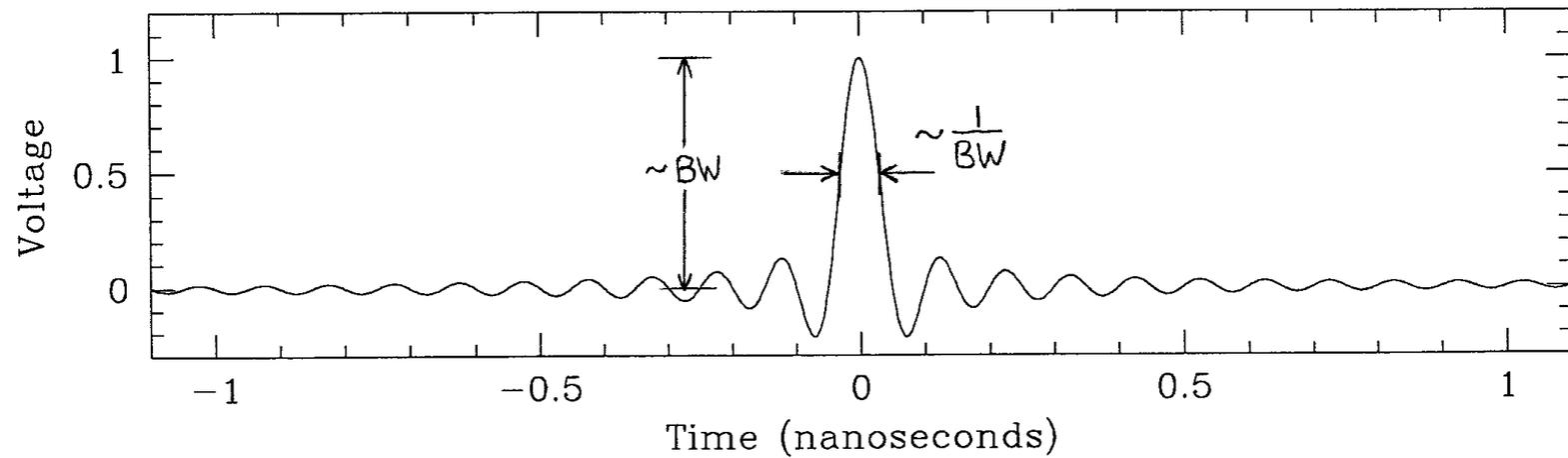
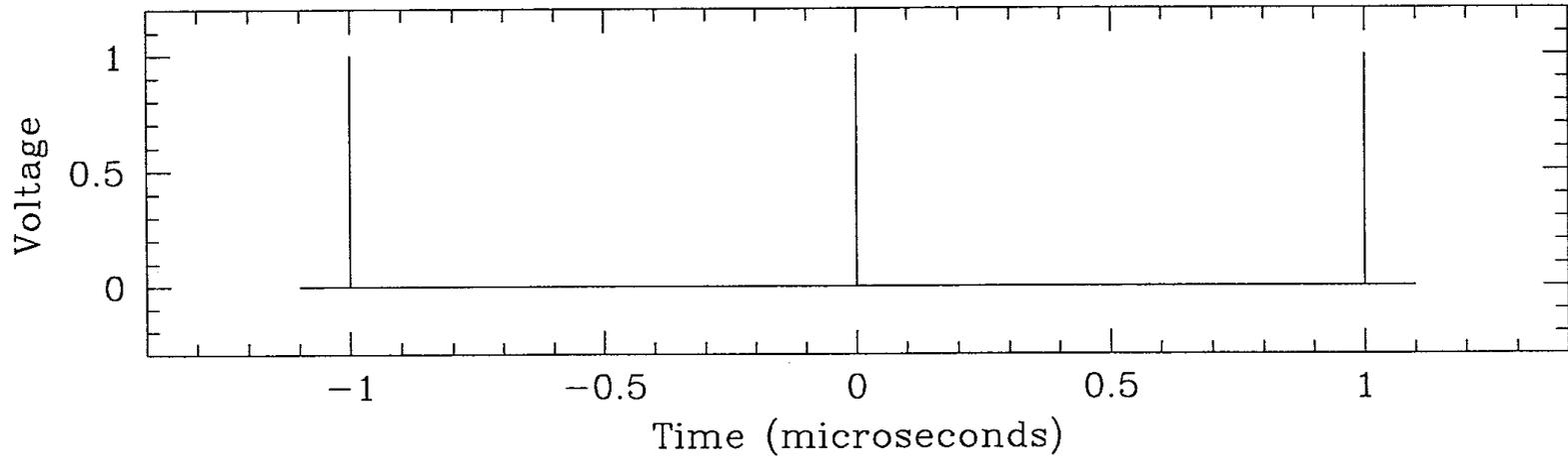
## Phase cal signal in time domain, as sum of sinusoids

Say we want a calibration signal every 1 MHz, up to 10 GHz:

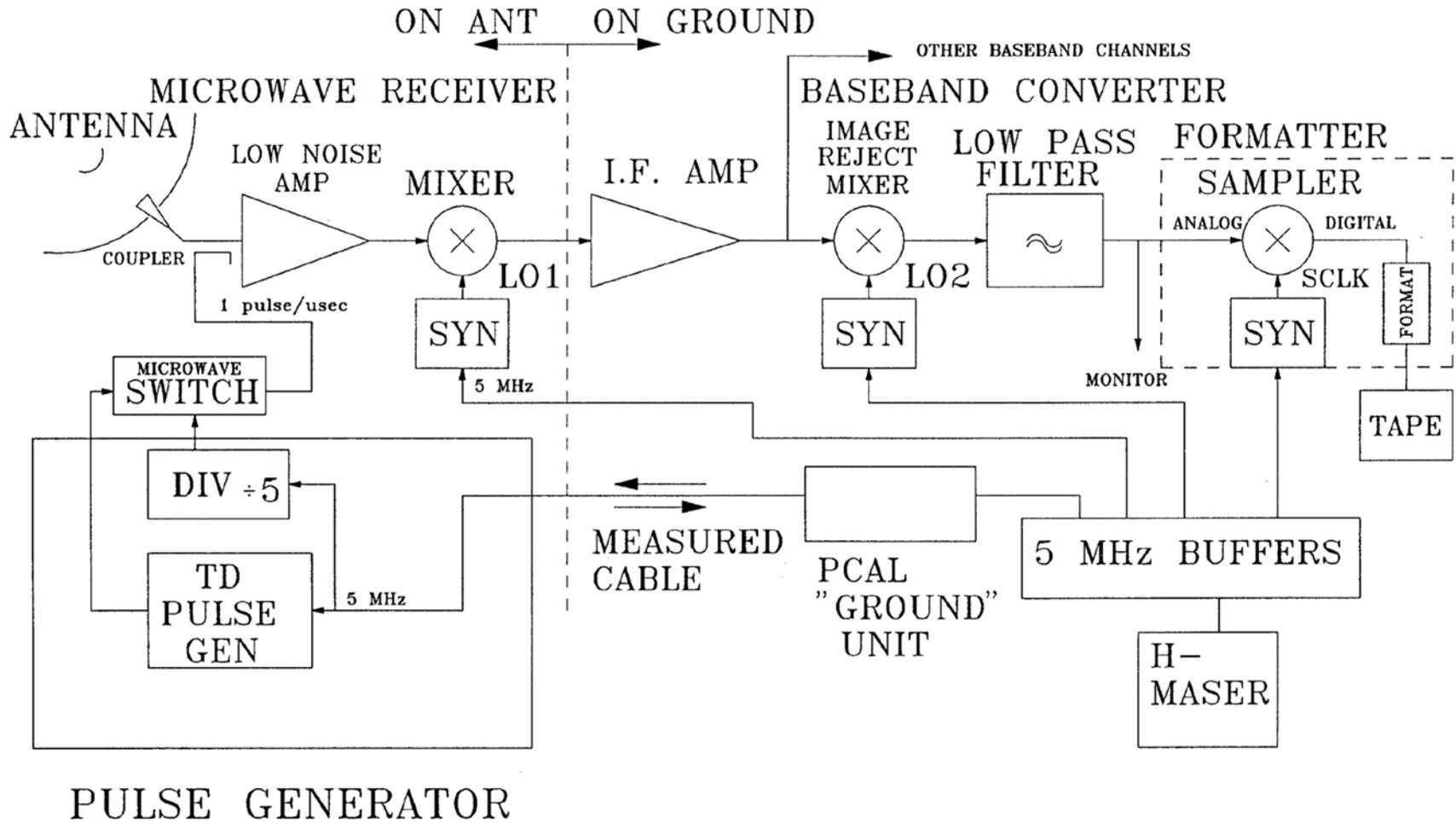


Add up all 10000 tones and you get...

## Phase cal in time domain, as pulses

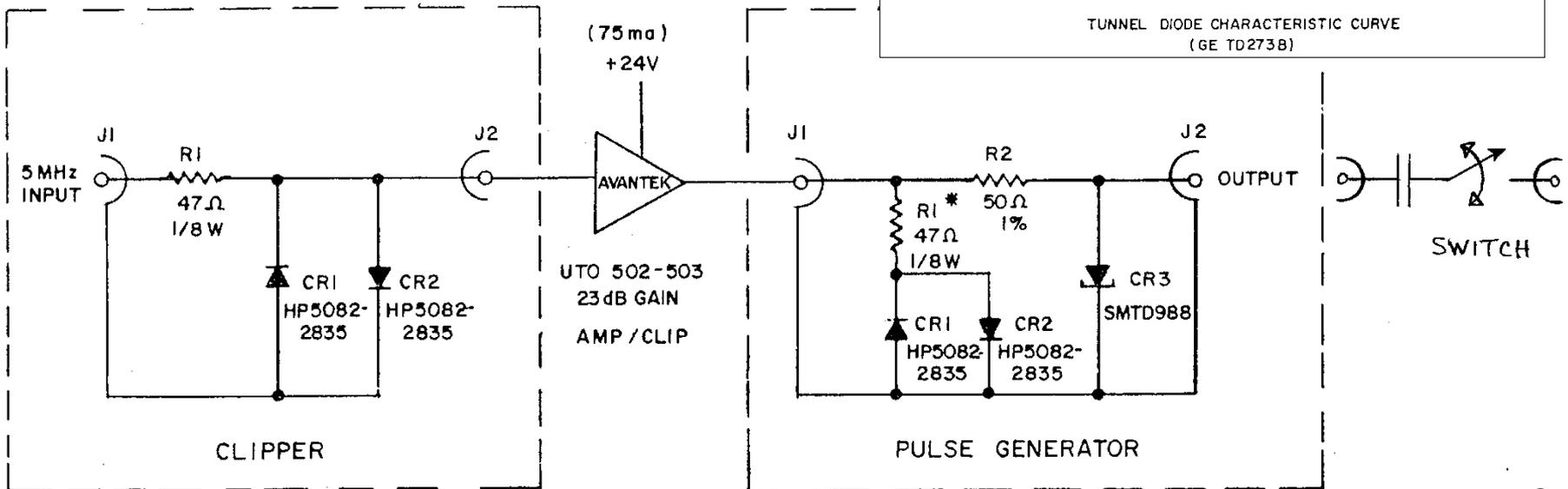
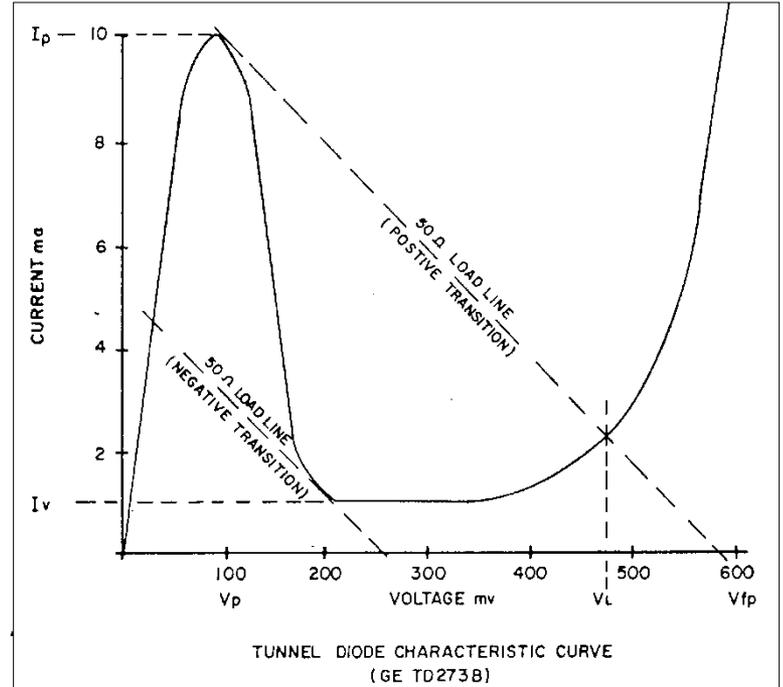


# Phase/delay calibration at a VLBI station



# Tunnel diode pulse generator

- 1970s-era circuit below illustrates how a 5 MHz sinewave is converted to a 1 MHz pulse train.
  - Tunnel diode creates a 5 MHz square wave with fast rise/fall.
  - Capacitor "differentiates" to make positive & negative pulses.
  - Switch passes every 5<sup>th</sup> positive pulse. → 1 MHz pulse train



## What is phase cal phase sensitive to?

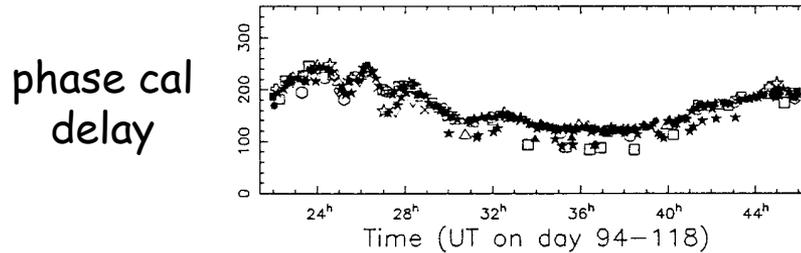
- Phase cal phase, measured at baseband, depends on:
  - 5 MHz phase at output of “ground unit” in control room
  - Electrical length of cable up to antenna unit
  - Phase delay through antenna unit
  - Phase delay from antenna unit to cal injection point
  - Phase of receiver LO
  - Phase delay through receiver, from cal injection point to IF output
  - Electrical length of IF cable from receiver to control room
  - Phase delay through backend electronics (e.g., IF up- or down-converter, IF distributor, VC/BBC)
  - LO phase in backend mixers
- Any instrumental phase/delay that affects quasar (fringe) signal also affects phase cal signal except for
  - delay through antenna structure and
  - delay from feed to cal injection point.

## What is phase cal amplitude sensitive to?

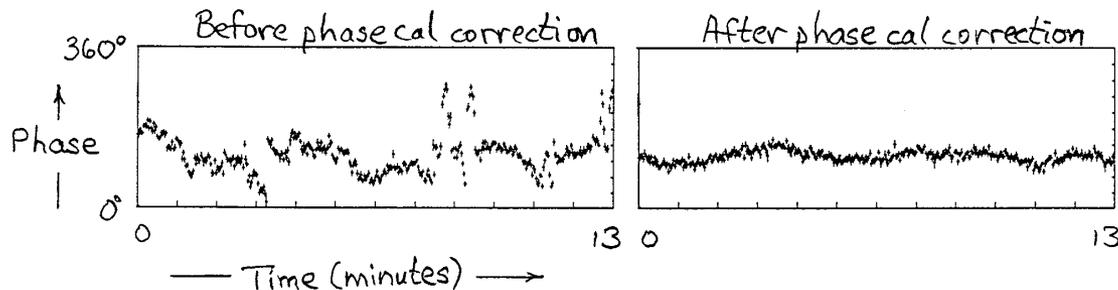
- Phase cal amplitude, as measured in **analog** baseband, depends on:
  - Phase cal voltage at antenna unit output
  - Loss between antenna unit and cal injection coupler
  - Coupling strength of cal injection coupler
  - Gain/loss through receiver, antenna cables, and backend
  - Coherence loss due to unstable LO in receiver or backend
  - Reflections in RF or IF path from antenna unit to backend
  - USB/LSB image rejection in downconverters
  - Interference from spurious signals
- Phase cal amplitude, as measured in **digital** bit stream (sign bit or 2 bits with AGC), is the ratio between the analog phase cal amplitude and rms noise voltage.
  - Normalizing by the noise voltage makes the digital phase cal amplitude
    - insensitive to gain/loss through the receiver and backend (item 4 above), but now
    - sensitive to system temperature (including increase due to RFI).

## Phase cal applications

- Measure changes in instrumental phase/delay during and between scans.
  - Example: Change in antenna IF cable length at some antenna orientations.



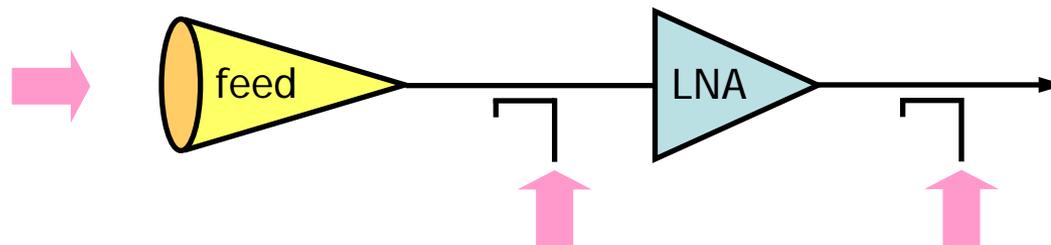
- Improve fringe phase coherence by correcting for LO phase variations
  - Example: Correction of LO jumps caused by intermittent cable connection.



- Check for LO modulation sidebands that can degrade phase coherence and VLBI sensitivity.
- Test USB/LSB image rejection in downconverters.
- Provide second-by-second estimates of  $T_{\text{sys}}$  in each frequency channel.
- Enable phase/gain equalization for generating circular polarization from linear.

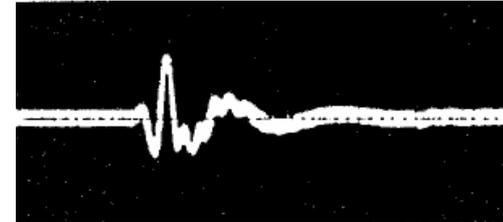
## Phase calibration in VGOS (formerly known as VLBI2010)

- Primary function remains as always: Measure instrumental phase variations over time and frequency.
- Phase differences between channels will be far more stable in VGOS than in S/X VLBI, thanks to digital IF-to-baseband conversion in FPGAs.
- But digital back-ends have not made phase cal obsolete!
  - Phase cal needed in VGOS to measure
    - LO phase drifts between bands
    - Phase/delay drifts in RF/IF analog electronics and cables/fibers
- Increase pulse repetition rate from 1 to 5 or 10 MHz (and pcal tone spacing from 1 to 5 or 10 MHz), to reduce danger of saturation.
  - Because baseband channels are wider (~32 MHz) than in S/X, each channel will still include many pcal tones.
- Broadband pcal generator has been deployed in NASA VGOS test-bed receivers at GGAO and Westford.
- Options for pcal injection point:



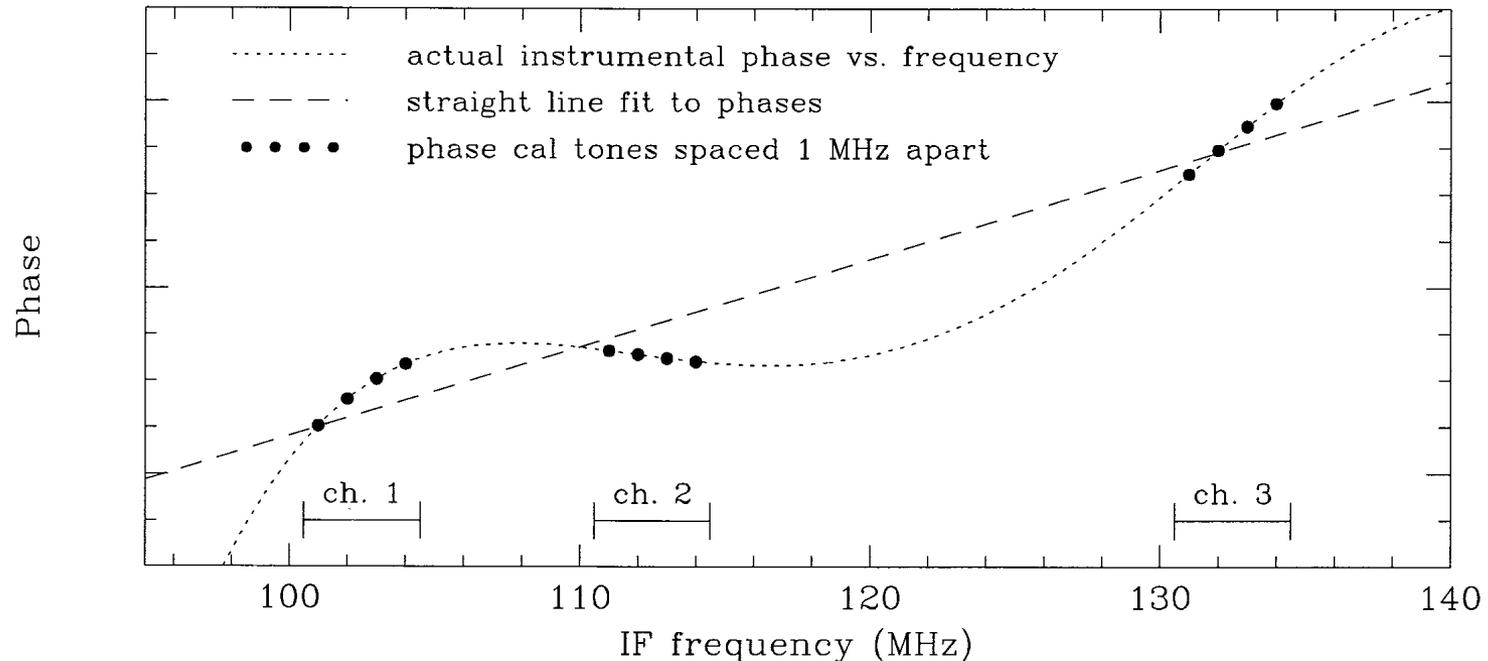
## Pulse repetition rate and headroom

- As RF bandwidth increases, pulse intensifies.
  - For 1-MHz pulse rep rate & 1-GHz BW, peak pulse voltage  $\sim 10\times$  rms noise.
  - For VLBI2010 RF BW of 12 GHz, peak pulse voltage  $\gg 10\times$  rms noise.
- With insufficient analog headroom, pulse drives electronics into nonlinear operation.  $\rightarrow$  spurious signals generated that corrupt undistorted pcal signal
- Options to avoid driving electronics into saturation:
  - Reduce pulse strength
    - Phase cal SNR reduced  $\rightarrow$  noisier phase extraction
    - More prone to contamination by spurious signals
  - Reduce pulse strength *and* increase pulse repetition rate to 5 or 10 MHz
    - Fewer tones spaced 5 or 10 MHz apart
- With 5 or 10 MHz rep rate, baseband tone frequencies can differ from channel to channel when channel separation =  $2^N$  MHz.
  - Fringe-fitting is more complicated if only one tone per channel is extracted .
  - Software solution: Use multiple tones per channel and correct for delay within each channel, as well as between channels.
- General recommendation: peak pcal pulse power / P1dB  $< -10$  dB



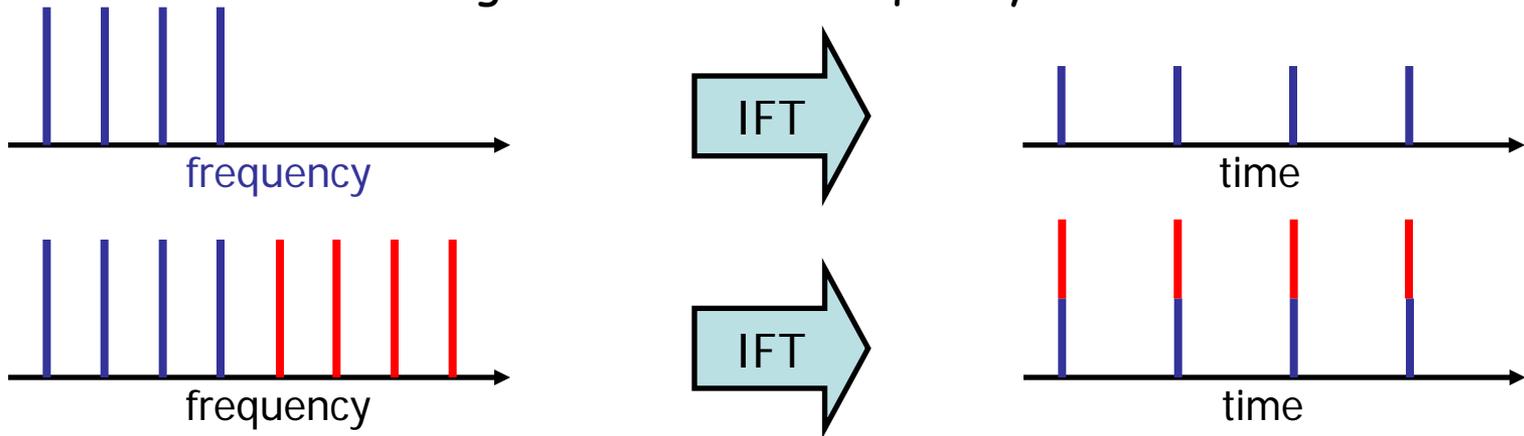
## Using multiple phase cal tones in each frequency channel

- With one phase cal tone per channel, only a phase offset can be estimated.
- But a simple phase offset may be inadequate if
  - instrumental phase varies rapidly over frequency, or
  - baseband tone frequency varies from channel to channel.
- Solution: Measure phase of multiple tones in each channel and solve for the frequency dependence of the phase.
- Advantages: Higher SNR and improved phase VLBI phase/delay stability.

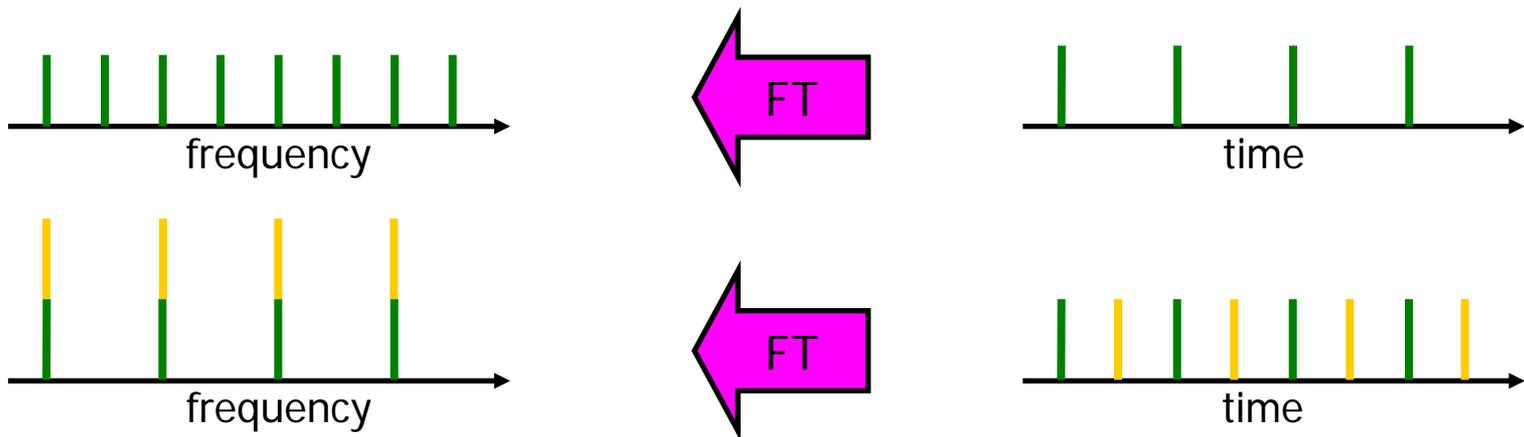


# Effects on phase cal of changing bandwidth or pulse rate

Pulse voltage scales with frequency bandwidth -

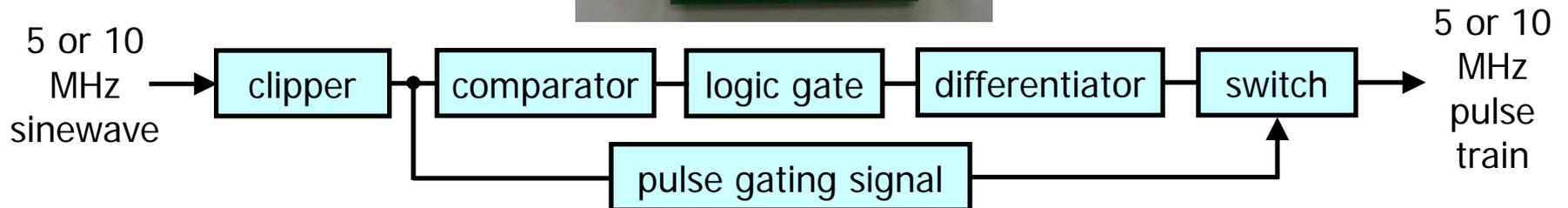
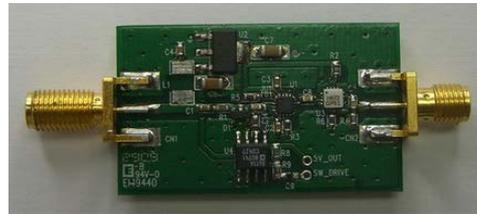


Amplitude and spacing of frequency tones scales with pulse rate -



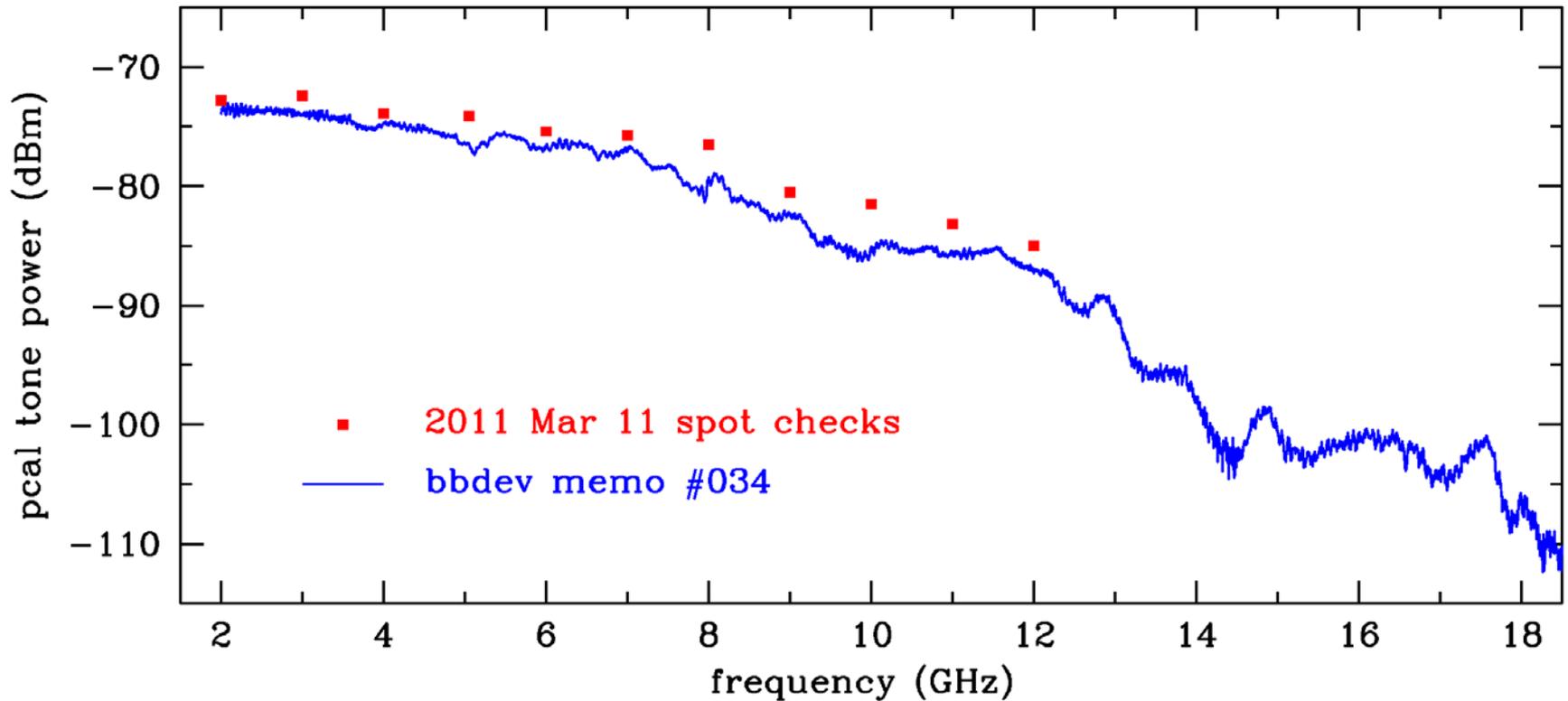
## Haystack "digital" phase calibrator

- Tunnel diodes at heart of many older pulse generators are no longer available.
- High speeds of today's logic devices allow a generator to be built around them.
- "Digital" phase calibrator designed by Alan Rogers (Haystack).
- 5 or 10 MHz sinewave input; output pulse train at same frequency.
- Output spectrum flatter than in tunnel diode design.
- Pulse delay temperature sensitivity  $< 1 \text{ ps}/^\circ\text{C}$  with no external temp. control.
- No support for cable measurement system (unlike previous phase cal designs).
- Circuit diagram and details available at [http://www.haystack.mit.edu/geo/vlbi\\_td/BBDev/023.pdf](http://www.haystack.mit.edu/geo/vlbi_td/BBDev/023.pdf).



# Digital phase calibrator output power spectrum

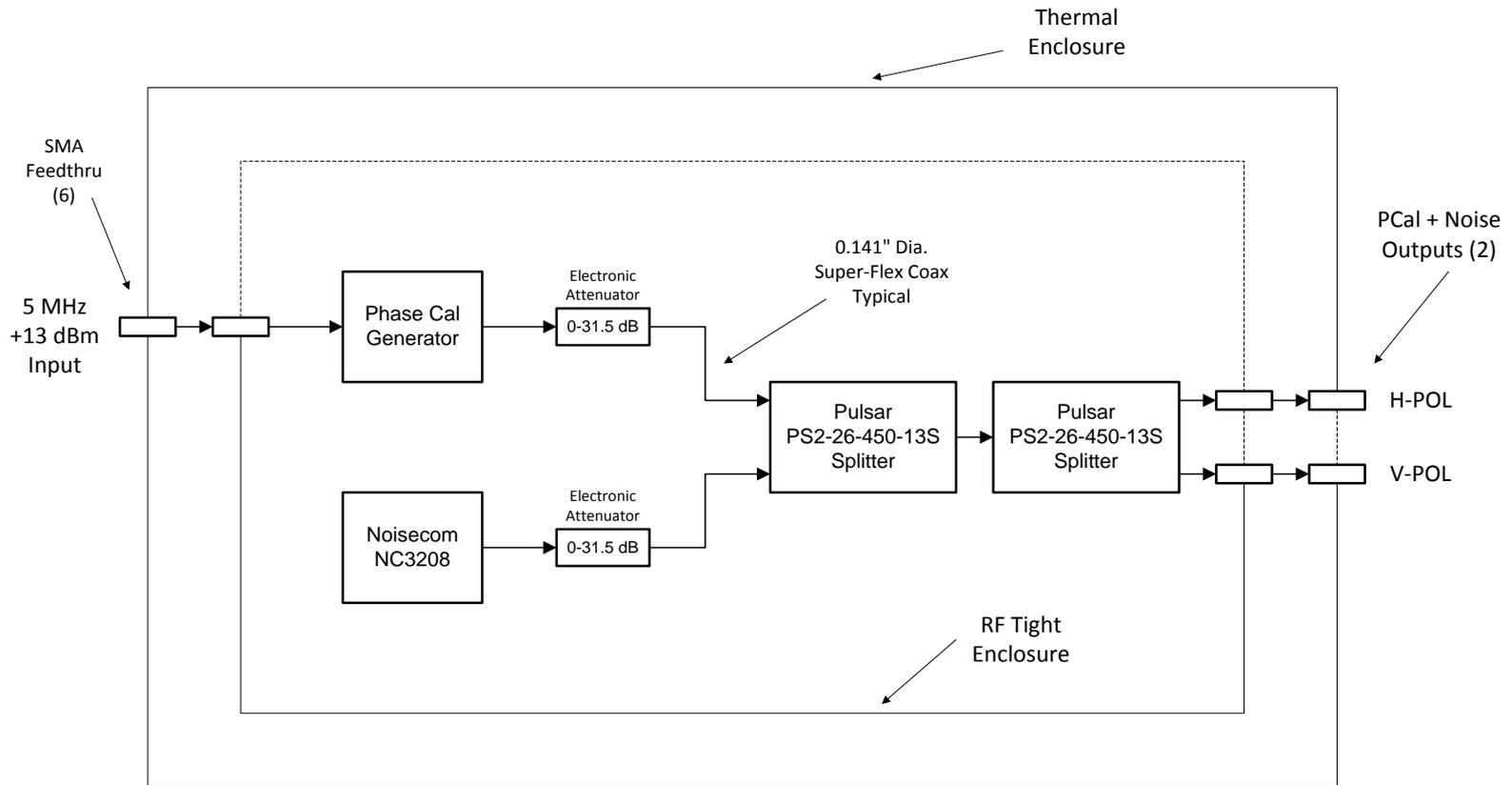
digital pcal generator tone power with 5 MHz input



## Broadband phase/noise calibration unit

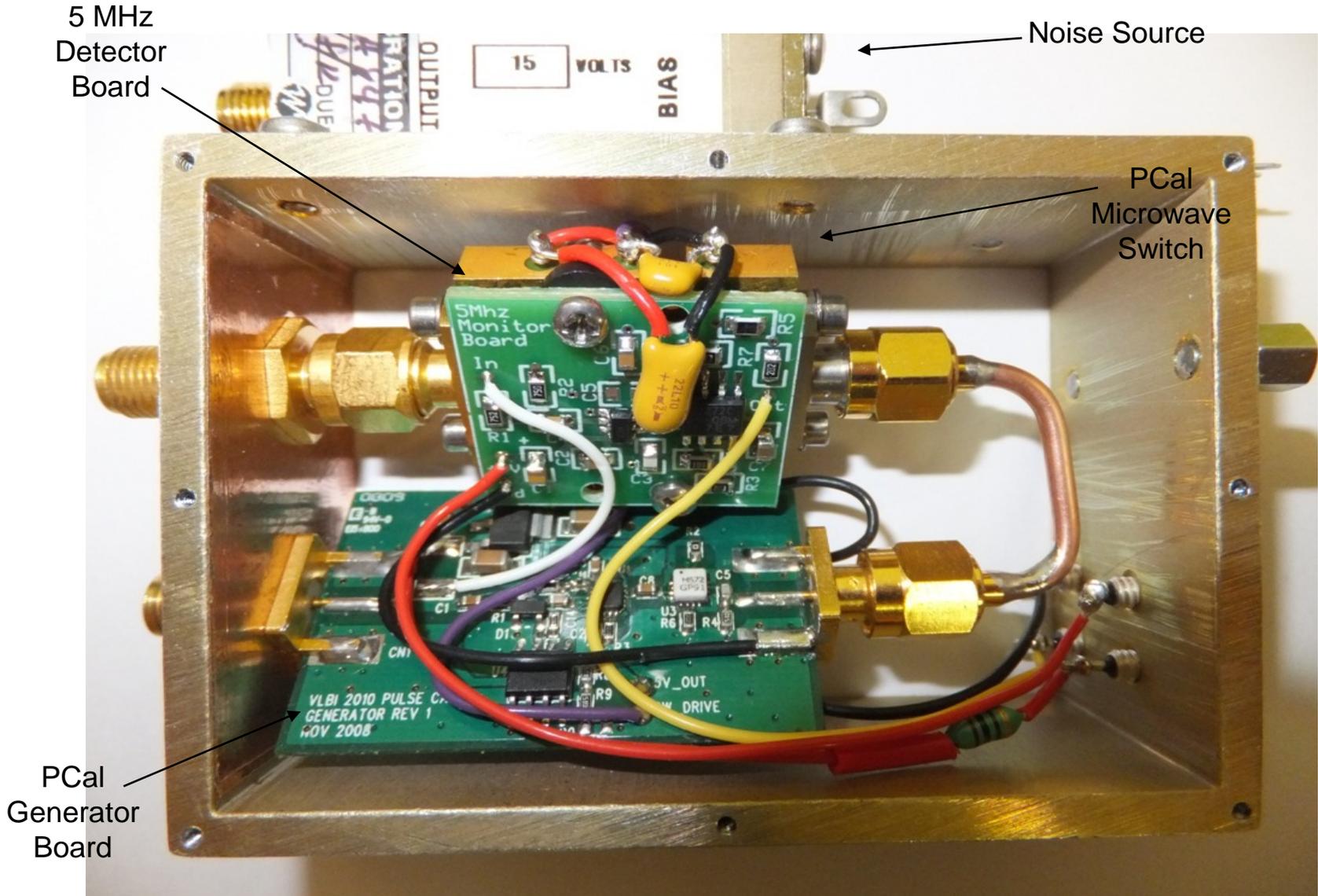
- "Cal box" developed by Honeywell Technical Solutions Inc (HTSI) and Haystack Observatory for broadband front-ends
- Cal box includes
  - digital phase calibrator
  - noise source
  - 0-31.5 dB programmable attenuators on phase and noise outputs
  - noise and phase cal gating
  - RF-tight enclosure
  - Peltier temperature controller ( $\Delta T < 0.2^{\circ}\text{C}$  for  $20^{\circ}\text{C}$  change in ambient T)
  - monitoring of temperature, 5 MHz input level, attenuation, gating
- Two identical RF outputs with combined pcal+noise
- Equalizers for phase or noise cal signals can be added if necessary.

# Broadband phase/noise cal box: RF connections

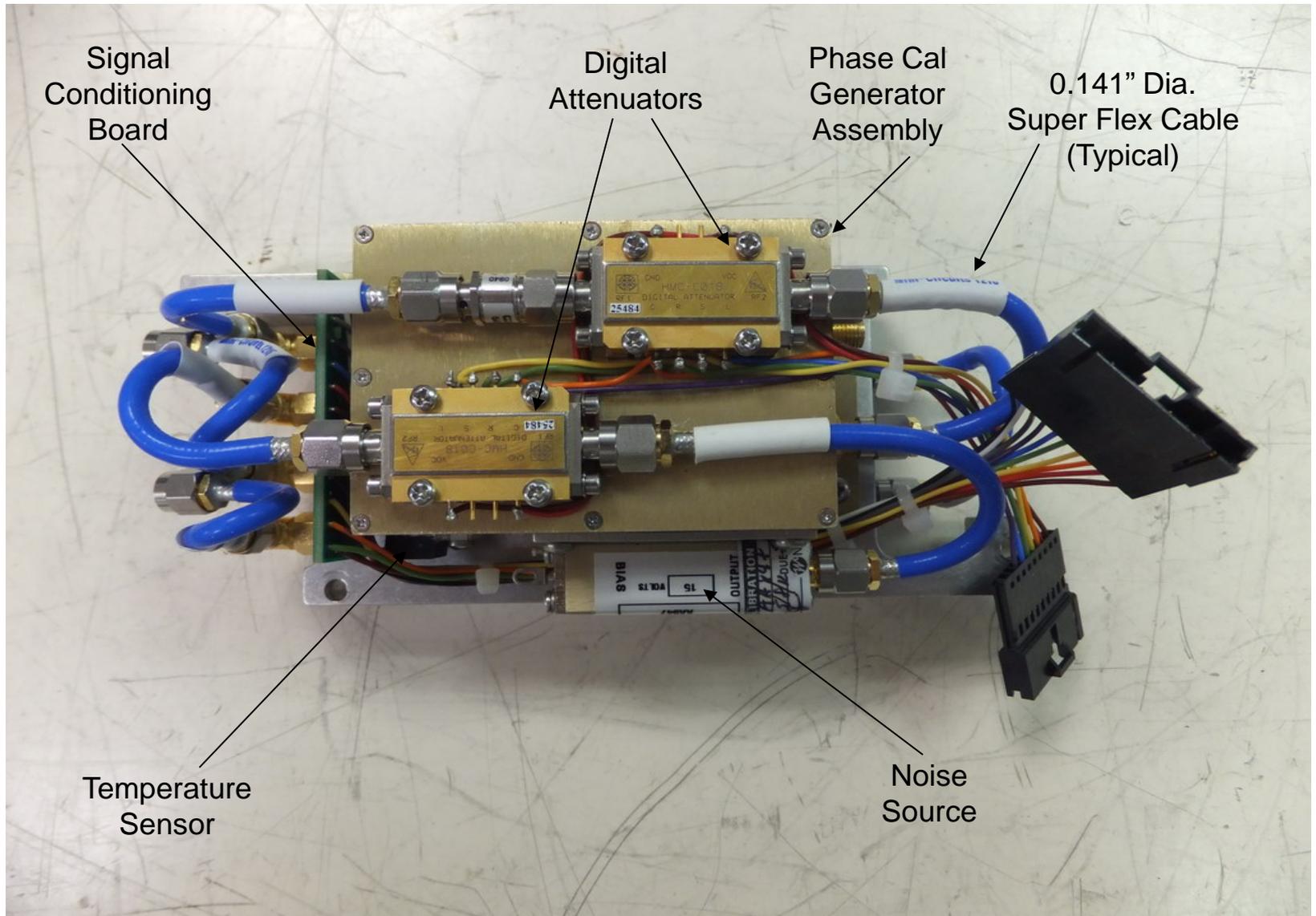


**Broadband Phase/Noise Calibration Unit**  
RF Wiring Diagram

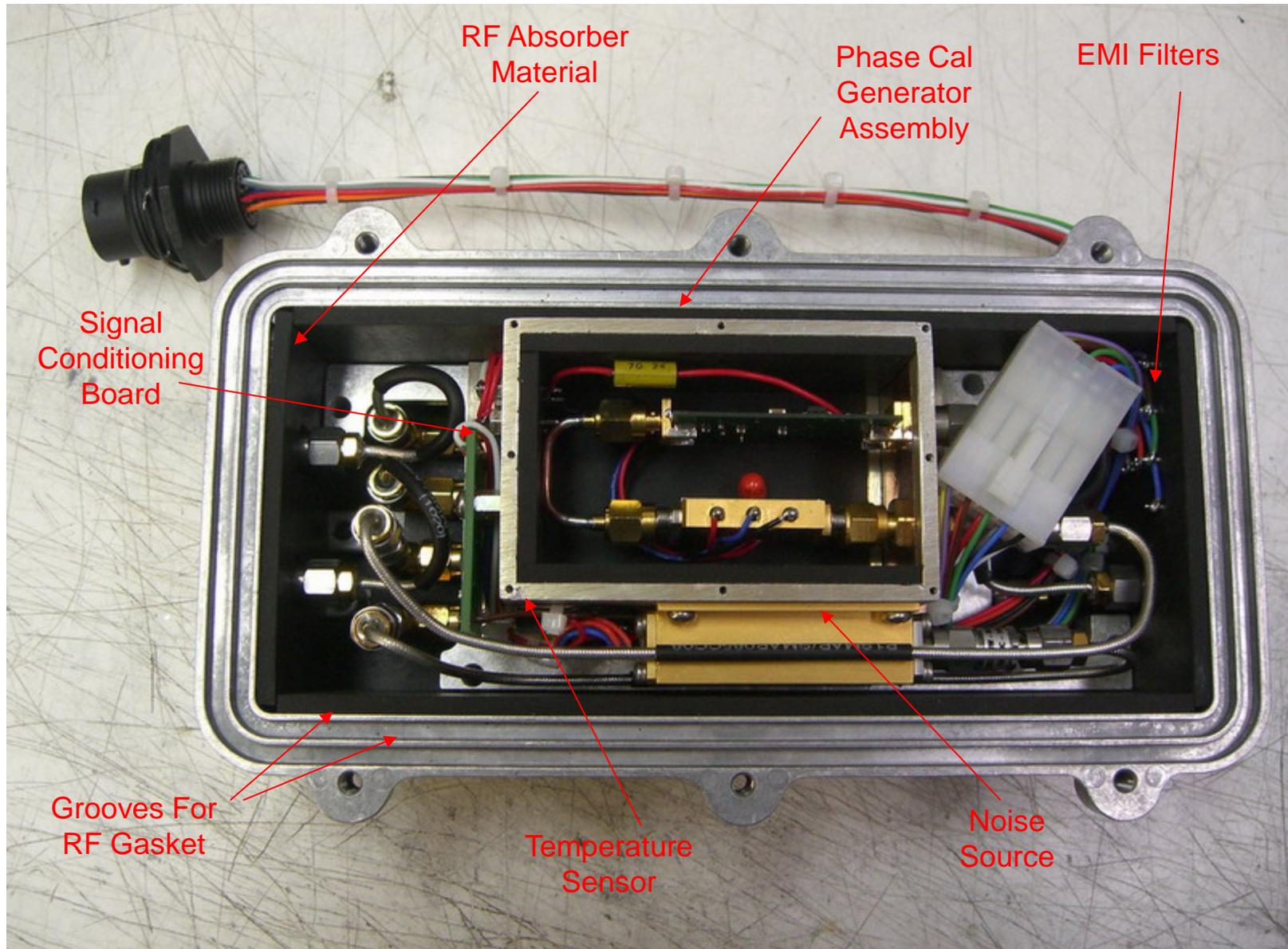
# Phase cal generator, microwave switch, & 5 MHz detector



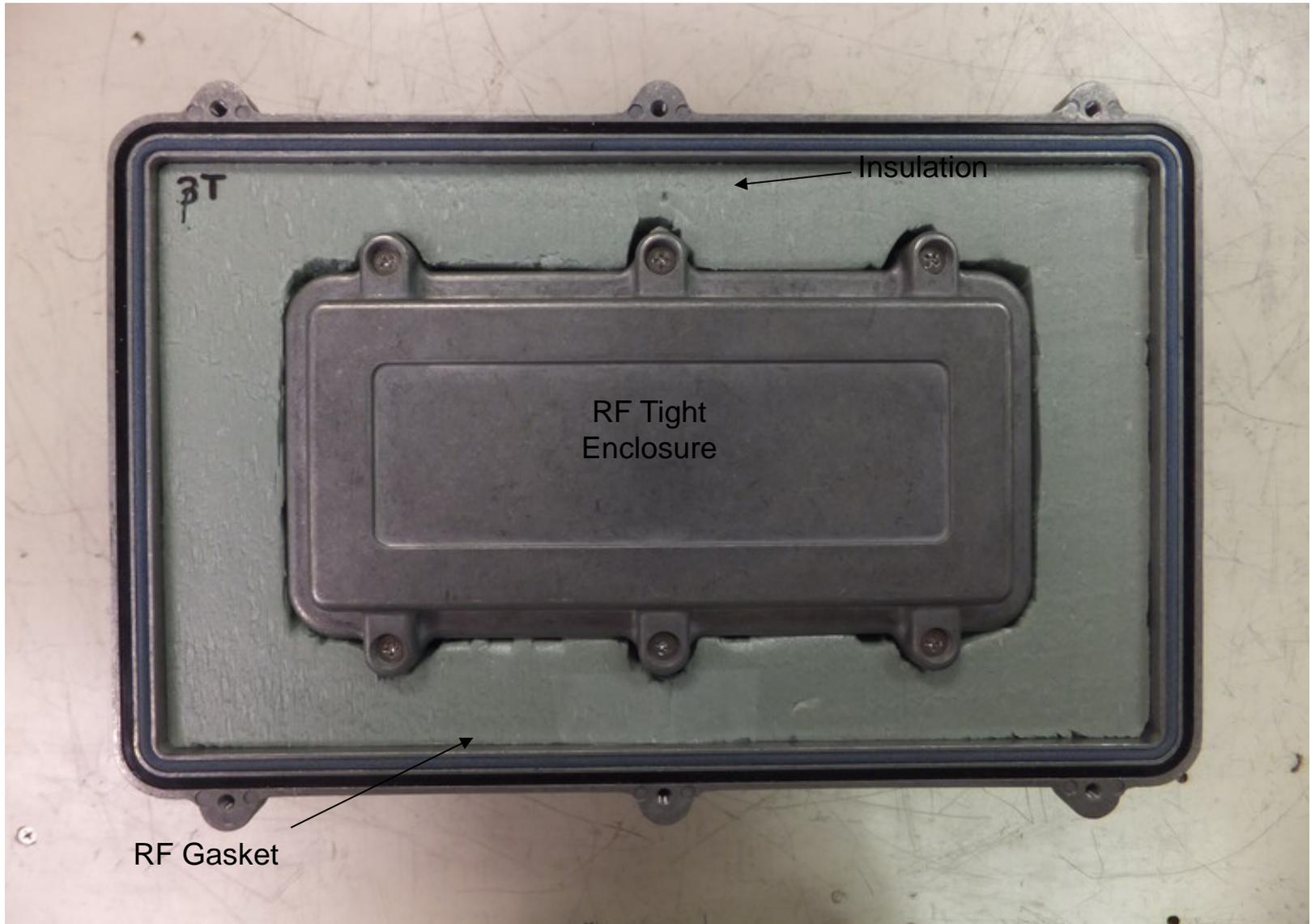
# Phase/noise calibrator assembly



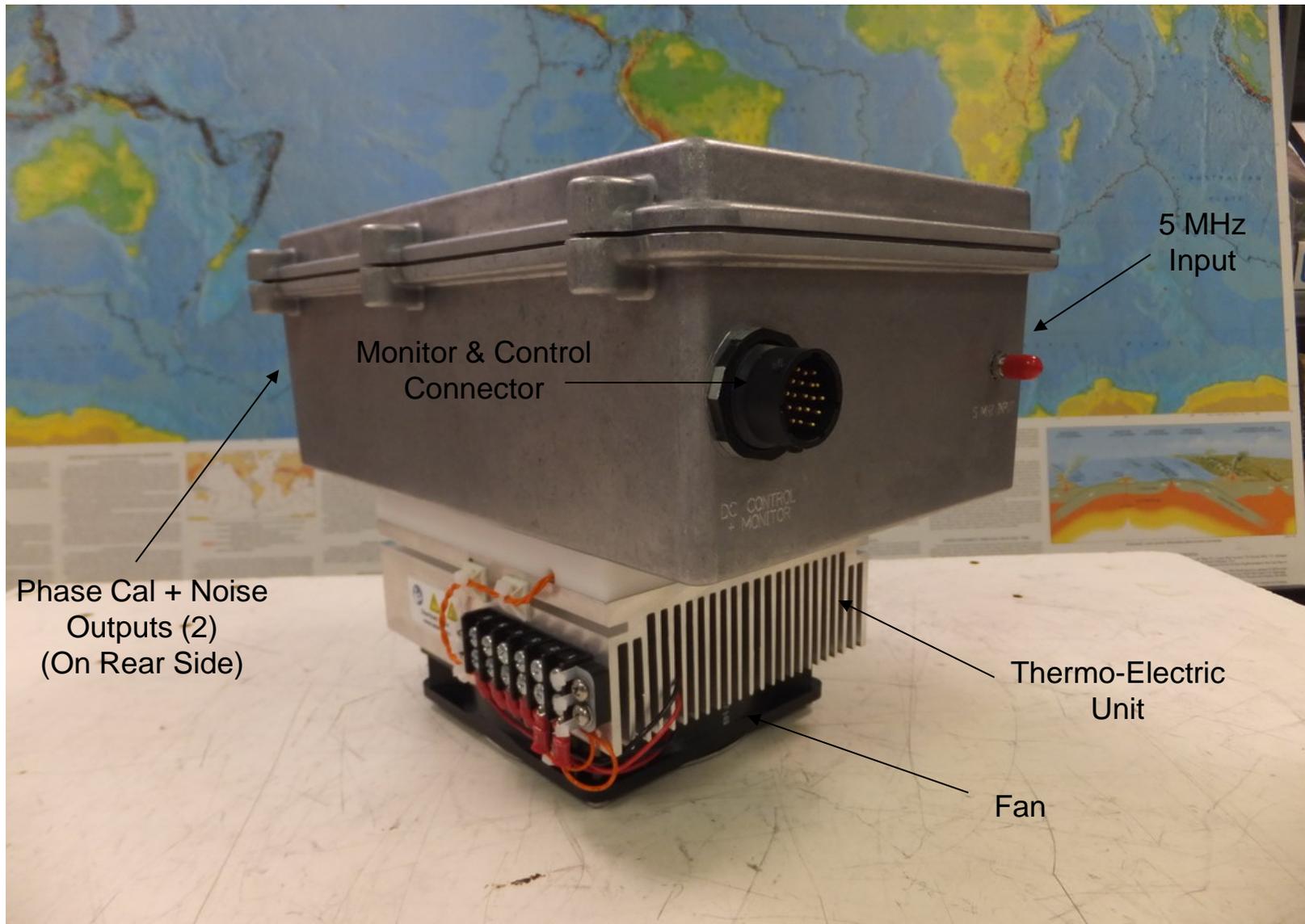
# Phase/noise calibrator in RF-tight inner enclosure



[A box in [a box in [a box]]]

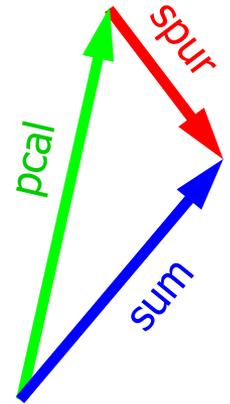


# Complete cal box assembly with thermoelectric unit



## Spurious phase cal signals

- Definition: Spurious signal is
  - a monochromatic signal
  - at the same RF, IF, or baseband frequency as a pcal tone
  - coherent over at least ~1 second with the pcal tone
  - but not the pcal tone that traversed the desired signal path.
- Spurs corrupt measured phase cal phase and amplitude.
  - For a -20 dBc spur, error in measured pcal signal is up to
    - 6° in phase
    - 10% in amplitude
- Examples of spurious signal sources:
  - Maser-locked signals generated in VLBI electronics (e.g., 5 MHz harmonics)
  - Phase cal images
  - Phase cal intermodulation/saturation
  - Secondary injection paths from pulse generator
  - Multipath from radiated phase cal
  - Cross-talk from other polarization
- Goal: Spurious signals >40 dB below phase cal.



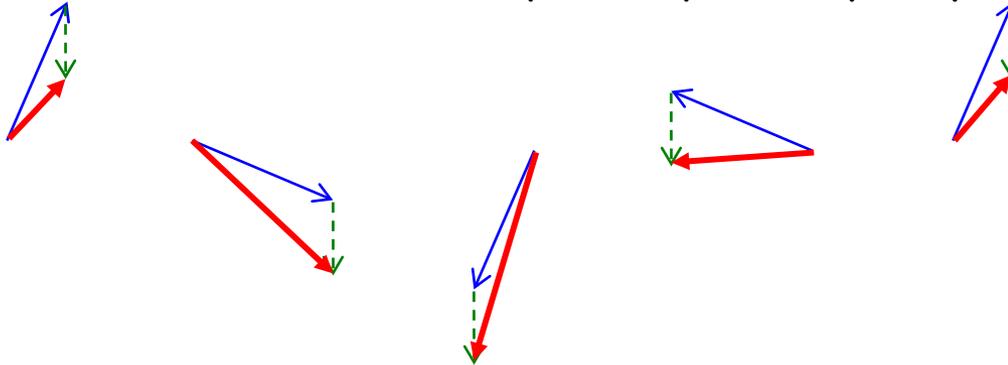
## Diagnostic tests for spurious signals

- At a station -
  - Measure power level of a pcal tone on a spectrum analyzer.
  - Observe how far the level drops when steps are taken that **should** make pcal completely disappear. Examples:
    - Disconnect reference signal to pcal antenna unit.
    - Turn off pcal with ground unit switch (Mark4 cable cal systems).
    - Unlock receiver LO.
    - Offset receiver LO frequency from integer MHz.
    - Disconnect cable from antenna unit to cal injection coupler.
  - Level should drop  $>40$  dB.
    - Analyzer resolution BW  $< 100$  mHz may be needed to keep analyzer noise floor low enough to see a 40 dB drop.
- At a station or a correlator -
  - Plot pcal amplitude vs. pcal phase for pcal data extracted from recordings for many observations.
  - Look for quasi-sinusoidal pattern in amp vs. phase plot.

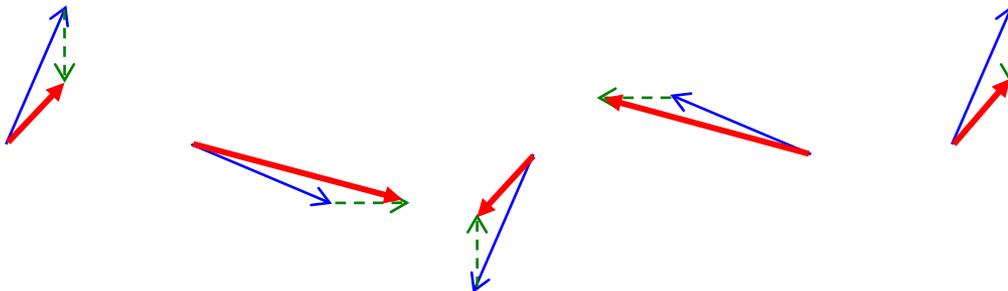
# Origin of pcal amp vs. phase quasi-sinusoids

- Legend:
- True phase cal, rotated in steps of  $90^\circ$
  - - -→ Spurious signal
  - Vector sum of true phase cal & spurious signal

- Case 1: Spurious signal of constant amplitude and phase
  - Amplitude of vector sum varies by one cycle as pcal phase varies  $360^\circ$ .



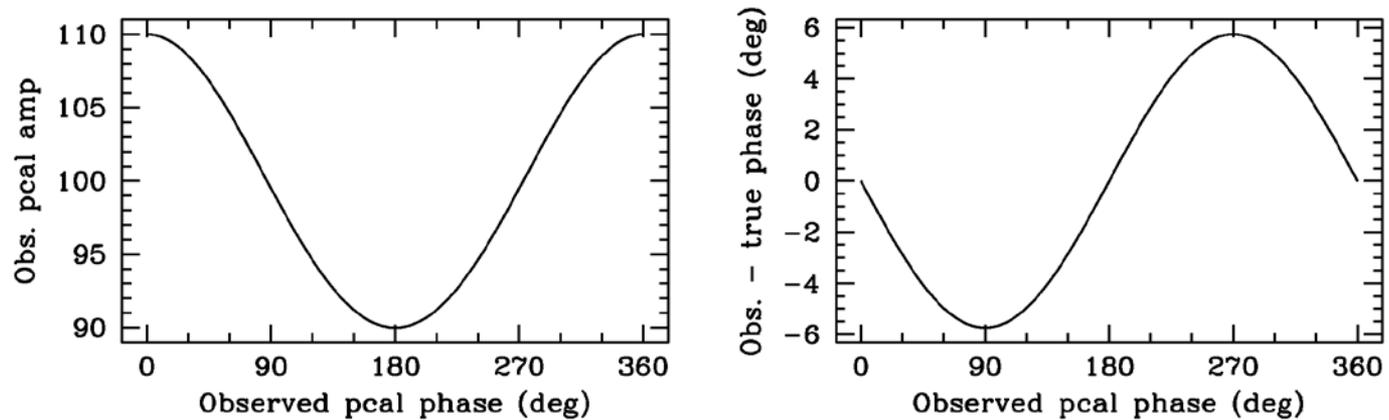
- Case 2: Spurious signal = phase cal at image frequency
  - Amplitude of vector sum varies by two cycles as pcal phase varies  $360^\circ$ .



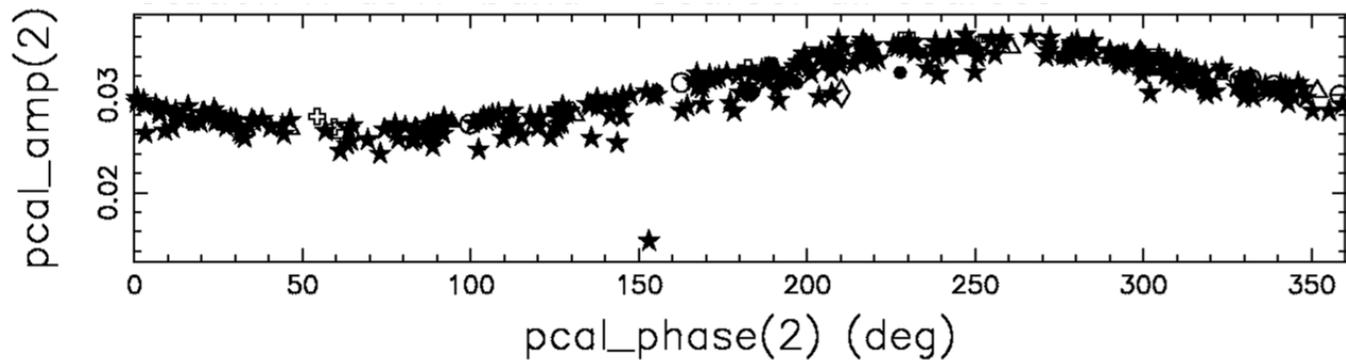
# Spurious signal example: constant spur

Theory:

Pcal constant spur model for true pcal amp = 100 and spur amp = 10



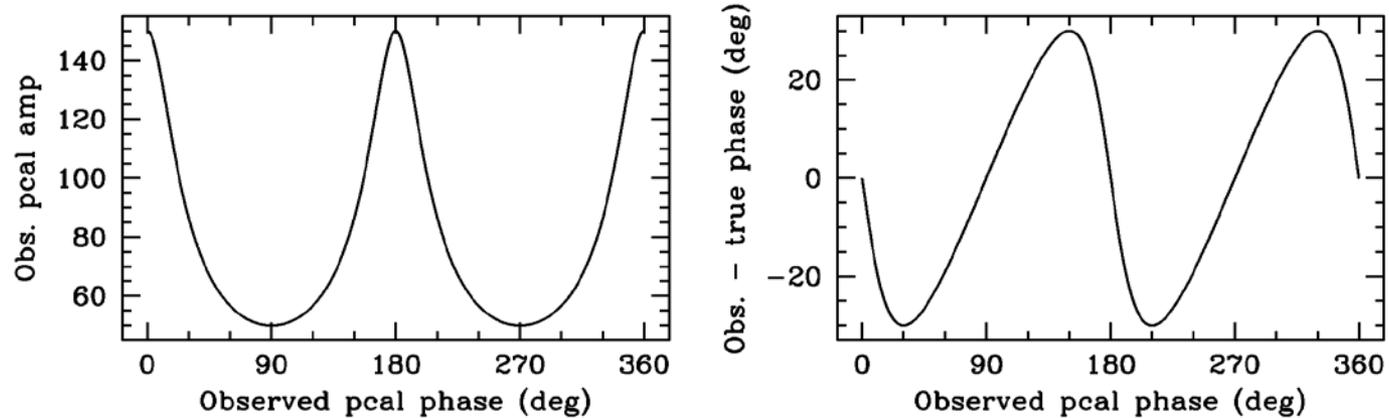
Observation:



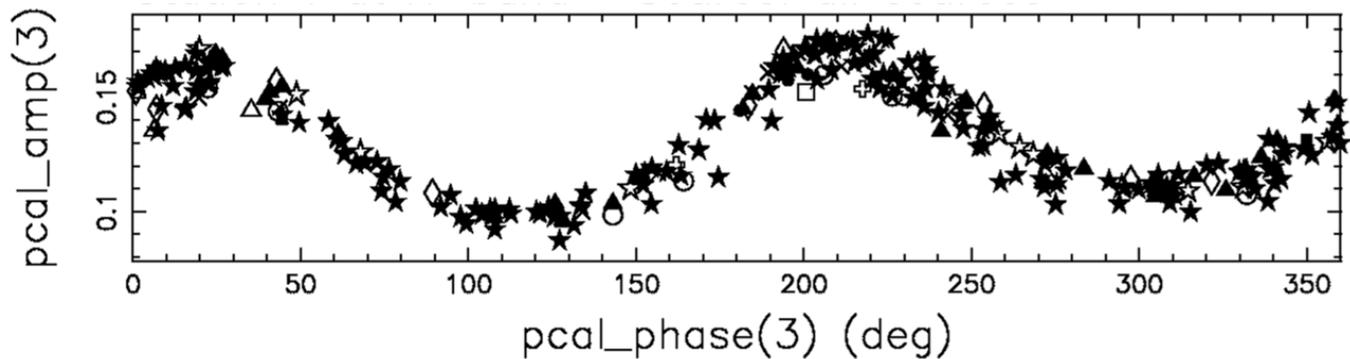
# Spurious signal example: image spur

Theory:

Pcal image spur model with pcal amp = 100 and image amp = 50



Observation:



## Cable calibration system

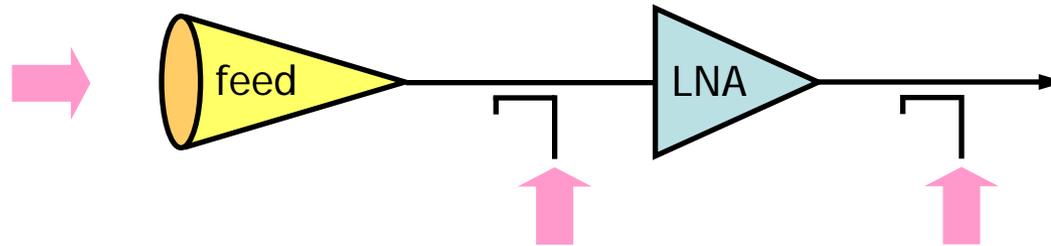
- Electrical length of cable carrying phase cal reference signal (or phase cal signal itself) from control room to frontend must be
  - stable or, if not,
  - measured for post-observation data correction.
- Measurement techniques include:
  - Use vector voltmeter in control room to measure phase difference between reference signals sent to receiver and returned from receiver.
    - If a single cable is used for transmitting both directions, reflections along the way can cause measurement errors.
    - If two cables are used, they may not behave in same manner.
  - Modulate reference signal in antenna unit before returning it to control room, to distinguish it from a reflected signal.
    - This is method used in Mark4 cable cal system.
- A cable measurement system will almost certainly be needed for VGOS to achieve the necessary delay measurement precision.
  - Tests of LMR-400UF cables carrying 5 MHz on GGAO and Westford antennas show orientation-dependent delay variations  $\gt \sim 10$  ps, which exceeds the VGOS limit of  $< 0.3$  ps.

## Representative cable cal systems deployed or under development

- Some system stabilize the transmitted phase rather than measure variations.
- Most optical fiber systems send the same frequency up and down separate fibers due to directional crosstalk in a single fiber.
  - Do lengths of up and down fibers change by the same amount?
- Modulation in the frontend allows the return signal to be distinguished from a reflected signal on a single coax or fiber.

<i>System</i>	<i>Cable no./type</i>	<i>Frequencies</i>	<i>Comments</i>
Mark 4	1 coax	5 MHz & 5 kHz	Does not meet VLBI2010 spec.
VLBA	2 coax	500 MHz & 2 kHz	Modulates 500 MHz in frontend.
Koike Park	2 fibers	500 MHz	
NRAO 14-m	2 fibers	500 MHz	
JPL DSN	1 fiber	modulated 1 GHz	Phase stabilization
EVLA	2 fibers	512 MHz	
Arecibo	2 fibers	1.45 GHz	
KVG	1 coax or fiber	2 near 700 MHz	Phase stabilization or meas.

## Noise/phase cal signal injection points



- Radiated into feed -
  - Facilitates phase/gain equalization for linear-to-circular pol conversion.
  - Motion between feed & radiator mounted on subreflector can be measured.
  - Phase/delay characteristics of feed can be measured.
  - Phase calibration may be adversely affected by variable multipath.
- Injected via directional coupler between feed and LNA -
  - Conventional injection point in VLBI receivers.
  - Broadband stripline couplers have typical insertion loss of 0.5-1.0 dB.
    - Coupler must be cooled to cryogenic temperature to reduce added  $T_{sys}$ .
    - At 20 K physical temperature, added system noise is 2-5 K.
- Injected via directional coupler after LNA -
  - LNA gain and phase must be stable.
  - Cal signal level must be higher than for pre-LNA injection by LNA gain.

# Spurious Phase Calibration Signals: How To Find Them and How To Cure Them

Brian Corey  
Haystack Observatory  
12 November 1994  
Last revised 30 July 1999

This memo describes some of the causes of spurious phase calibration signals in geodetic VLBI systems, tests that can be performed at the stations to detect the signals, and measures that can be taken to reduce their levels. The discussion assumes a Mark III/IV calibration system with a “ground unit” in the control room driving an “antenna unit” in the receiver; the antenna unit generates narrow pulses spaced 1  $\mu$ sec apart, which are injected into the RF signal path via a directional coupler. Most of the discussion is also applicable to other systems, with some minor modifications.

## What are spurious signals?

As used in this memo, the term “spurious phase calibration signal” (or, in interests of brevity, “spur”) means a signal that interferes with the true phase cal generated by the means described above, and which thereby can cause a systematic error in the measurement of the phase of a baseband phase cal signal. More specifically, it is a narrowband signal that is coherent with, and has the same frequency as, the true phase cal. Note that this definition excludes noise-like signals (e.g., RFI) that can degrade the measurement precision but will not bias the measurement systematically.

## How weak should they be?

Ideally, spurious signals should be at least 50 dB below the true phase cal, i.e.,  $< -50$  dBc. Under such conditions, the effect of a spur on the measured phase is  $< 0.2$  degree. A level under  $-40$  dBc is acceptable. A  $-30$  dBc spur is serious cause for concern, and a  $-20$  dBc spur may well render the phase cal unusable in the geodetic analysis of the VLBI data.

## What causes them? What cures them?

1. **Externally generated spurs in the control room:** Often the strongest spurious signals originate in control room electronics that are not a part of the calibration system, but that use a frequency reference signal from the maser as an input and so are able to generate signals coherent with the phase cal system. The formatter in particular is a potent source of spurs, as it generates harmonics of the sample clock (usually  $N \times 4$  MHz) and the sample+parity clock (usually  $N \times 4.5$  MHz), as well as harmonics of 5 MHz. For example, when observing with the standard narrowband S/X frequency sequence and with receiver LO frequencies of 2020/8080 MHz, it is common to observe strong spurious signals in X channel 3 and S channel 1, because the two IF phase cal frequencies (171 and 198 MHz, respectively) are both harmonics of 4.5 MHz.

These externally generated spurs usually enter the signal path at IF frequencies, although on occasion a spur is picked up at RF frequencies by being radiated into the receiver feed. For

instance, a spur has been observed at 2268 MHz (the phase cal frequency for S channel 4 in the narrowband sequence), which was due to the 12th harmonic of the 189 MHz clock on the tape transport control board being radiated out of the control room and into the feed.

When a spur originates at IF frequencies, it is usually picked up at the point in the control room where the IF signal level from the receiver is lowest, i.e., at the input to the IF distributor. One test for helping to locate where the spur is being picked up is to change the attenuation in the IF distributor: if the amplitude of the spur does not change relative to the broadband IF or baseband noise level, it is being picked up before the IF attenuator.

Cures:

- a. Raise the IF level from the receiver by adding amplifier stages in the receiver or at the point where the signal enters the control room.
  - b. Put filter capacitors on the IFD power supply lines. In a Mark III/IV IFD, be sure the capacitors called for in NASA/CDP VLBI CCR #031 are present on the power lines and on the bias lines to the normal/alternate switches.
  - c. Check for cables with broken outer shields or bad connectors, where spurs may leak in.
  - d. Use double-shielded cables for running IF signals, including on the IFD patch panel.
  - e. Put a ferrite bead on the 1 pps line going into the IFD.
  - f. Run the offending spur generator off a frequency reference source other than the maser. (This was the solution for the 2268 MHz spur.)
  - g. Turn off the spur generator, if possible!
  - h. If all else fails, change the frequency sequence to avoid spur frequencies, in collaboration with the experiment scheduler and other stations.
2. **Receiver LO electronics spurs:** Receiver LO electronics can be a source of spurs at harmonics of the LO reference frequency. For example, the CTI 2020/8080-MHz oscillator used in many NASA receivers radiates harmonics of 5 MHz well up into the S-band frequency range, and they may be picked up at RF.

Cures:

- a. Avoid observing at RF frequencies for which the phase cal frequency is a harmonic of the LO reference frequency (an action to be taken by the experiment scheduler, not just by an individual station!).
  - b. Lower the level of radiated spurs by using copper tape on the seams of the oscillator, putting the LO in a Faraday cage, etc.
  - c. Ensure the integrity of all connectors and cables.
3. **Phase cal images:** If the LO frequency in a downconverter is an integer number of MHz, two RF phase cal tones will contribute to each tone in the IF: (1) the desired RF tone at frequency  $f_{RF}$  and (2) the image tone in the opposite sideband at frequency  $f_{RF,image} = 2f_{LO} - f_{RF}$ . The image tone is a spurious signal. An image rejection filter is generally placed ahead of the mixer to attenuate the image tones.

Cures:

- a. Ensure the image rejection filter attenuates image frequencies by  $>50$  dB.

- b. Offset the LO from an integer number of MHz. If  $f_{LO} = (N + x)$  MHz, where  $N$  is an integer and  $0 < x < 1$  ( $x \neq 0.5$ ), the desired and image phase cal tones will be at different frequencies in the IF. For instance, the LO frequency of the IF3 downconverter is set to 500.1 MHz; the 0.1 MHz offset is there to separate the desired and image tones in the IF3 output.

- 4. **Amplifier saturation spurs:** When the phase cal pulse is on, the total system power level at RF or IF is momentarily higher (typically 10-20 times higher at X-band) than when the pulse is off. The pulse may drive an amplifier close to saturation, in which case the amplifier will distort the pulse waveform. This distortion is a source of spurs, the phases of which generally differ from those of the undistorted phase cal. For a pulse repetition rate of 1 MHz, the spur frequencies are harmonics of 1 MHz.

Often the strongest spurs arise in the final IF amplifier in a receiver, where the IF power level is highest. The isolation amplifier in a Mark III/IV video converter typically generates spurs at the  $-40$  to  $-45$  dBc level.

Cures:

- a. Use amplifiers capable of higher output levels.
  - b. Lower the RF/IF system gain. (But this may conflict with cure 1a.)
  - c. Attenuate the RF phase cal level. There is no need for the phase cal level to be higher than 1-2% of the  $T_{sys}$  noise power.
  - d. Offset by a fractional MHz the LO frequency of a mixer preceding an offending amplifier.
- 5. **Mixer feedthrough:** If the RF and IF frequency ranges of a mixer overlap each other (not good practice, generally speaking!), imperfect balance in the mixer diodes will allow some direct feedthrough of RF phase cal signals into the IF, without any frequency up- or down-conversion.

Cures:

- a. Offset the LO frequency from integer MHz.
  - b. Redesign the circuit!
- 6. **Multiple RF injection paths:** The RF phase cal signal from the antenna unit may inadvertently be injected into the main RF signal path via routes other than through the calibration coupler. For instance, the antenna unit radiates well into the X-band frequency range (even when the ground unit switch is turned off!), and radiated tones may be picked up by the feed.

Cures: Highly dependent on specific case.

- 7. **Antenna unit spurs:** The antenna unit itself may generate additional signals that interfere with the desired phase cal signal. The tunnel diode pulse generator in a Mark III/IV antenna unit actually puts out a positive-voltage pulse every 200 ns, and a negative-voltage pulse approximately midway between each pair of positive pulses. A microwave switch following the generator allows only one of every 5 positive pulses, and no negative pulses, to pass, thereby creating the usual 1 MHz pulse train. If the switch is not functioning properly, however, and does not attenuate the negative pulses sufficiently, the negative pulse train may be a significant source of spurs.

Cure: Fix the antenna unit!

8. **Reflection in phase cal injection path:** If there are multiple impedance mismatches in the signal path between the antenna unit and the cal injection point, reflections in the path will cause multiple, time-delayed replicas of the pulse to be transmitted to the coupler, and the phase cal phase will be corrupted.

Cure: Eliminate reflections by ensuring cables and connections are good. Attenuators may also be of use.

9. **Phase cal pick-up at IF frequencies:** The antenna unit generates phase cal tones at frequencies from 1 MHz to above 10 GHz, including tones in the IF frequency range. These IF tones may leak out of the antenna unit and may then be picked up in the receiver IF, without passing through the RF electronics. In one case, for instance, tones were observed to be injected into the S-band IF via the LO detector port on the MITEQ mixer/preamp used in many NASA receivers.

Cures:

- a. Improve the filtering on the power supply, monitor/control, and other DC lines to the antenna unit and to the IF electronics.
- b. Offset the LO frequency from integer MHz.

10. **Crosstalk between IF signals:** There may be insufficient isolation between two IF signals (e.g., S- and X-band, or two polarizations in the same band), with the result that the phase cal in one IF may contaminate the phase cal in the other IF and act like a spur. Such crosstalk between S- and X-band has been observed to originate in a receiver on an antenna and in a dual-IF upconverter in a VLBI backend.

Cure: Improve the isolation. Details depend on the specific case.

## How can spurious signals be detected?

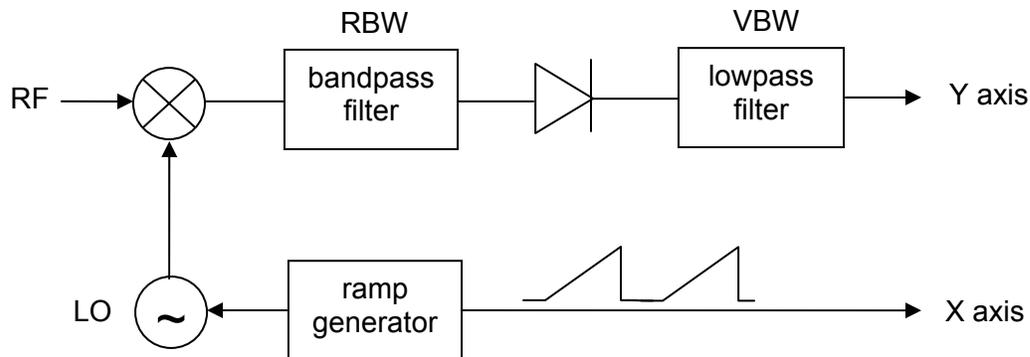
Most station tests for the presence of spurs involve using a spectrum analyzer (or, if an analyzer is not available, an oscilloscope with a narrowband filter) to measure the power level at the baseband phase cal frequency, which is typically 10 kHz. The general idea behind most tests is to change something in the system that should make the phase cal disappear (e.g., disconnect the reference signal to the antenna unit), and then see if it did disappear. If a signal at the phase cal frequency is still present above the analyzer noise level after the change, then a spur is present.

Some of the tests that can be performed at the stations to detect spurious signals are:

- A. Turn off the phase cal with the ground unit switch. If a spur persists, it is type 1 or 2 or, less likely, 6 or 7.
- B. Disconnect the cable from the ground unit to the antenna unit. If a spur persists, it is type 1 or 2.
- C. Turn off the phase cal as in test A or B, and disconnect the IF cable either at the output from the receiver or at the point where the IF enters the control room. If a spur persists, it is type 1.
- D. Unlock the receiver LO by disconnecting its reference signal. Any spur still present is type 1 or 4.

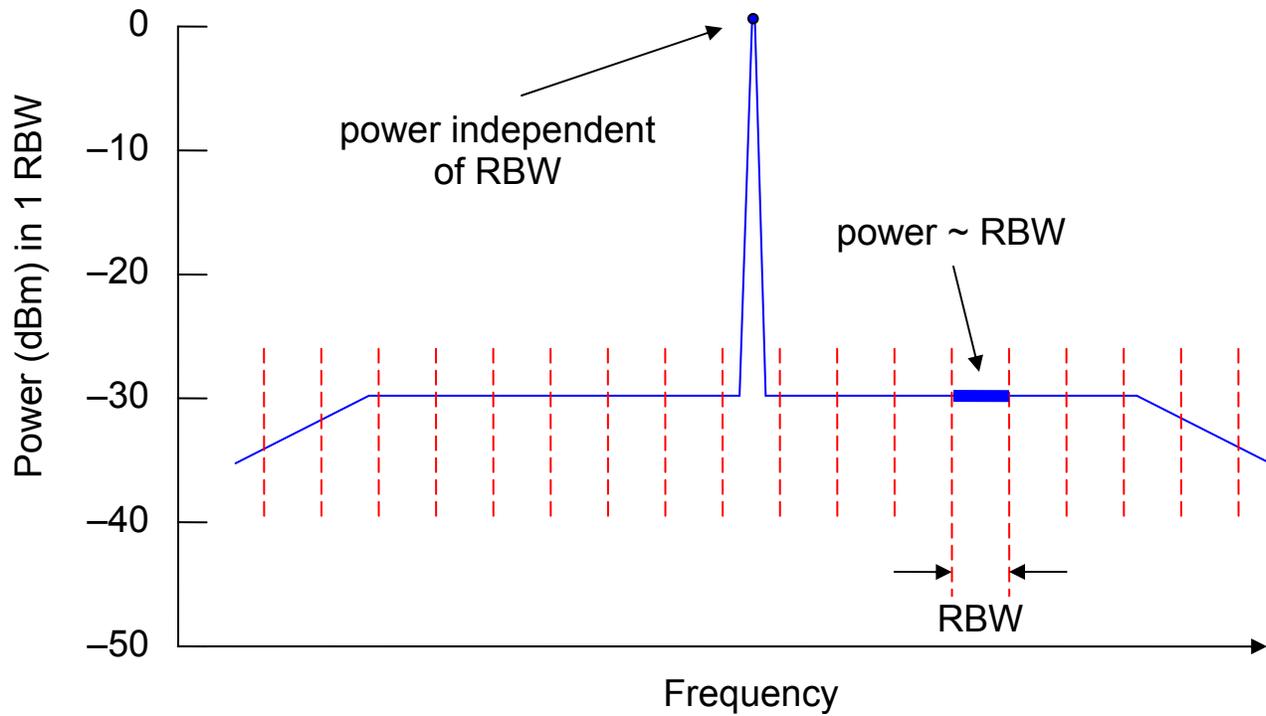
- E. Disconnect the cable from the antenna unit to the calibration coupler. Any spur still present is type 1, 2, 6, 9, or 10. While this test may be difficult to carry out, as it requires access to the receiver, it is probably the most reliable means for detecting spurs of types 6, 9, and 10.
- F. Set the LO frequency on a video converter to observe a phase cal tone whose RF frequency is an integer multiple of 5 MHz. Repeat test A. If the power level drops less than 20 dB, and if no spur is present at that level when test B is done at the same frequency, then the microwave switch in the antenna unit is probably defective (type 7 spur).
- G. Offset the receiver LO from integer MHz by, e.g., using a high-quality crystal oscillator to supply the LO reference, instead of the maser. If the baseband phase cal tones are observed to shift by  $x$  MHz in frequency, the image tones will shift by  $-x$ , and type 1 and 4 spurs will remain unshifted. A type-2 spur will shift, but by an amount different from  $x$ .
- H. Use an adjustable line in the receiver LO reference line to vary the receiver LO phase. For selected baseband phases over the  $360^\circ$  range, measure the phase cal amplitude and phase (using, e.g., an FFT analyzer or the Field System commands `pca1` or `dqa`). Plot the amplitudes versus phases. The amplitude should be independent of phase, in the absence of spurs. An externally generated spur of type 1, with stable amplitude and phase, will cause a single-cycle sinusoidal variation in amplitude over  $360^\circ$  of phase, as will spurs of types 4, 5, and 9. A spur from a phase cal image causes a two-cycle sinusoid over  $360^\circ$ . A type-10 spur in IF band 1 (e.g., S or X) caused by crosstalk from IF band 2 will have a period of  $360^\circ / |f_{LO2}/f_{LO1} - 1|$ , provided the same LO reference signal serves the two LO's.
- I. Wiggle connections in the receiver and look for phase or amplitude variations.
- J. The phase cal amplitude should have no strong frequency dependence within a band (S or X). If the amplitude varies from channel to channel, and particularly if it does so with a quasi-sinusoidal dependence on frequency, then there may be multiple reflections in the cal injection path (type 8 spurs).

## Basic parameters and functions of an analog spectrum analyzer



<i>Function</i>	<i>Description</i>
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



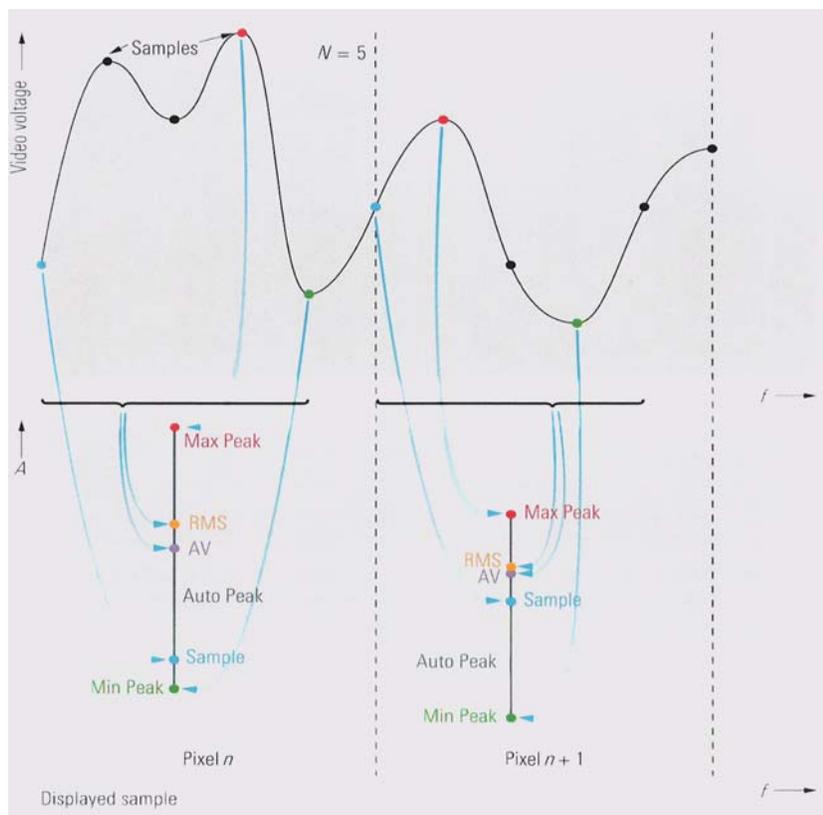
- For broadband noise with  $BW > RBW$ , power is proportional to RBW.
- For narrowband (e.g., CW) signals with  $BW < RBW$ , power is independent of RBW.

## Detectors in spectrum analyzers with digital displays

Most modern spectrum analyzers use LCDs to display spectra, rather than the CRTs of older (purely analog) analyzers. With digital displays, the display resolution in both frequency and power is more limited.

The finite number of pixels in an LCD (as opposed to the effectively infinite number for a CRT) means that, for wide frequency spans and narrow RBWs, each pixel has to represent the spectral information for many sample points that lie within the frequency span of the pixel. It is left to the user to select which point to display in each pixel. Typical options include:

- *Max peak* (or simply *peak*) – the sample with the maximum power
- *Min peak* – the sample with the minimum power
- *Sample* – a “typical” value, usually either the first (in frequency) or central sample for each pixel
- *RMS* – power corresponding to the square of the RMS (root-mean-square) voltage magnitude of the samples for each pixel
- *Average* – power corresponding to the average mean voltage magnitude of the samples



From *Fundamentals of Spectrum Analysis* by Christoph Rauscher, Rohde & Schwarz, 2007

Which detector type to use depends on the nature of the signal.

- In the presence of narrowband signals, *max peak* ensures that no signal is missed.
- When only broadband, noise-like signals are present, *sample*, *RMS*, or *average* detection better represents the spectrum than does *max peak*, which will show the upper envelope of the spread in power.

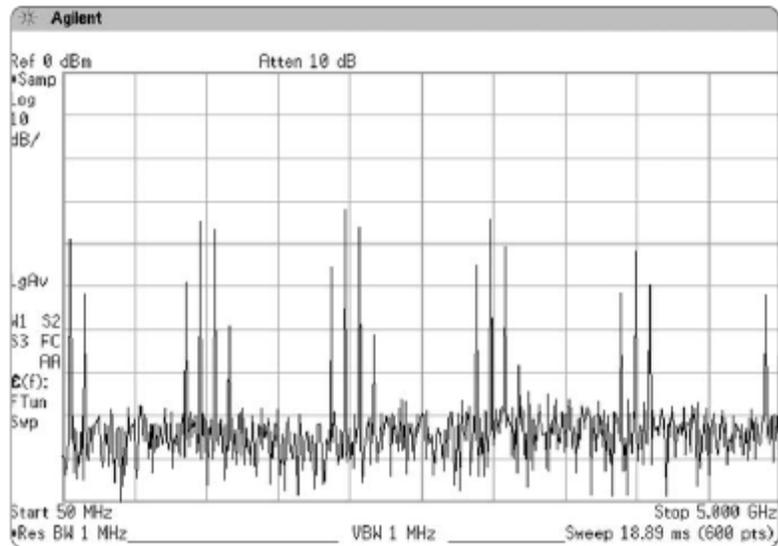


Figure 2-22a. A 5 GHz span of a 100 MHz comb in the sample display mode

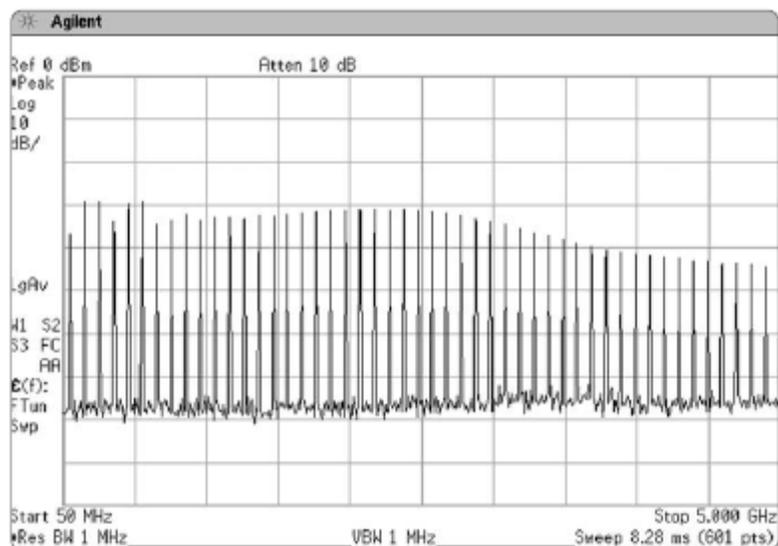
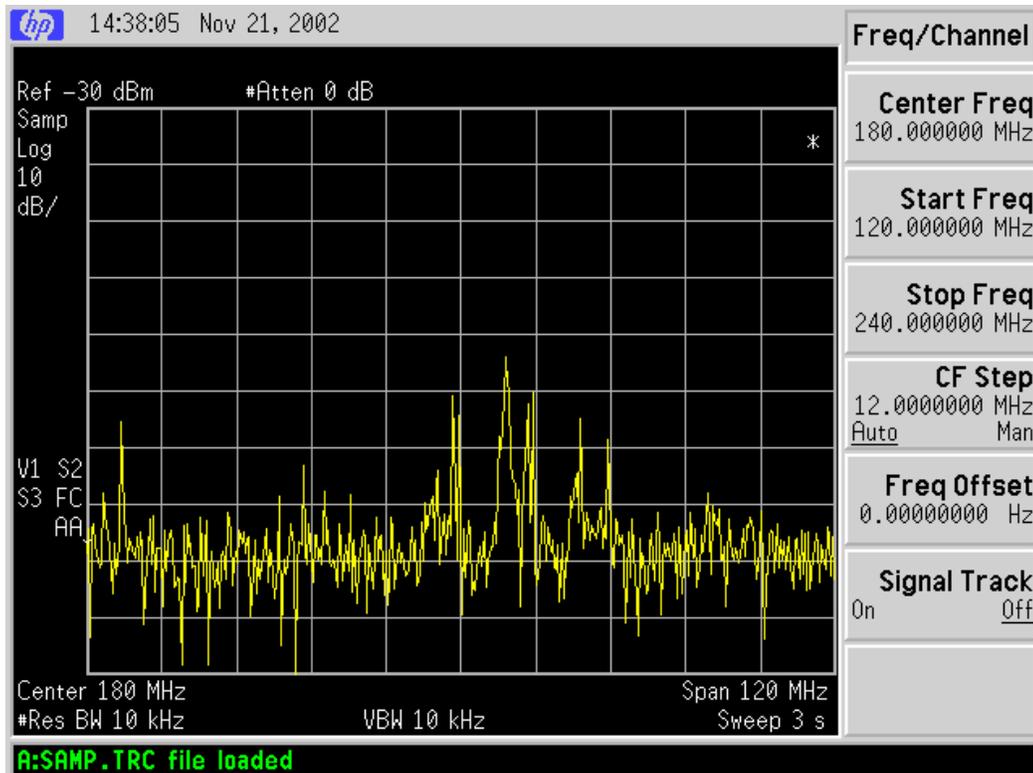
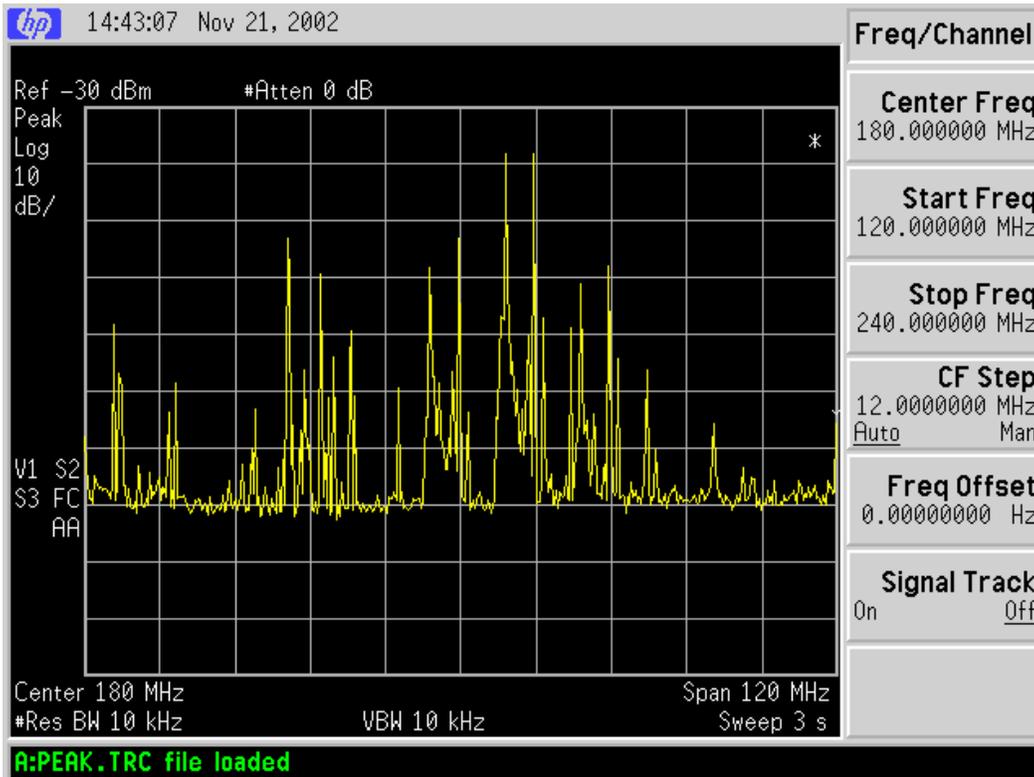


Figure 2-22b. The actual comb over a 500 MHz span using peak (positive) detection

From Agilent Application Note 150: Spectrum Analysis Basics

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

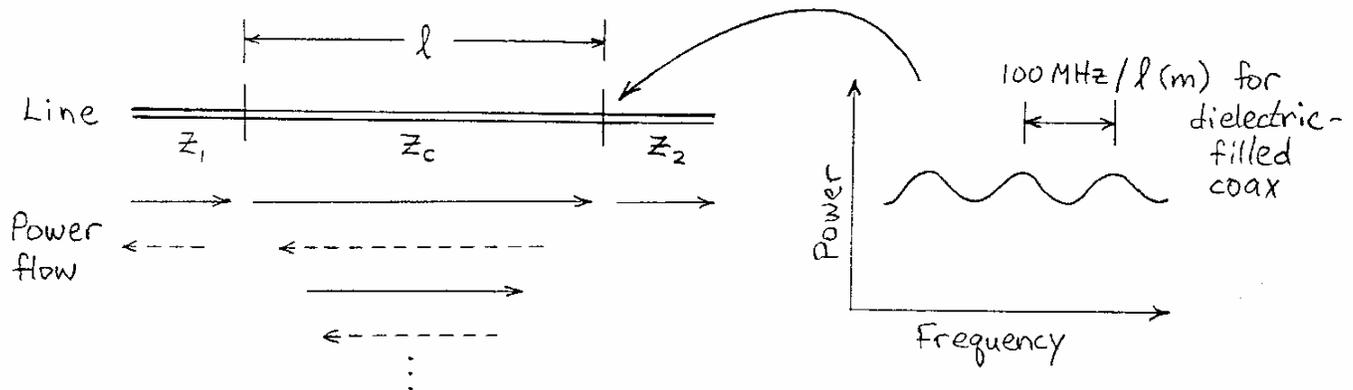


## Some spectrum analyzer applications in VLBI

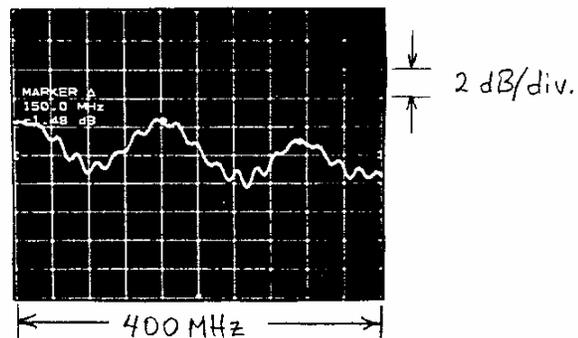
- Measure frequency response of active and passive components, e.g., filters and amplifiers.
- Measure cable loss, e.g., in cables to antenna.
- Look for ripple in broadband RF or IF signals as evidence of impedance mismatches.
- Measure LO phase noise and estimate LO phase jitter. (See “Notes on Phase 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.



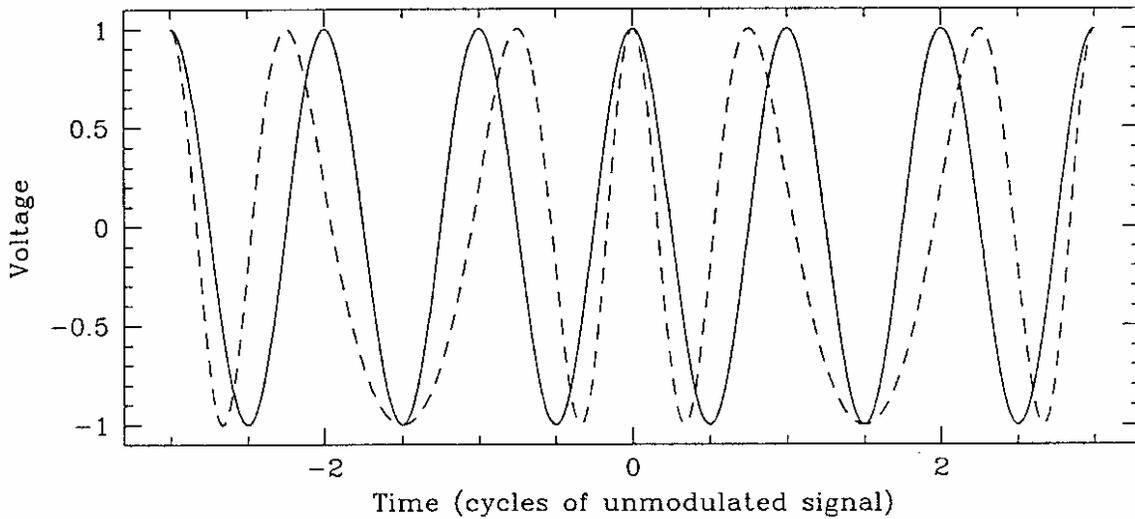
- Multiple reflections are particularly serious if they occur before the phase cal injection point, either between feed and coupler or between phase cal antenna unit and coupler.
- Even more serious are unstable, time-dependent changes in phase ripple caused by multiple reflections, which can affect 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 [  $mod(t) = 0$  ]
- - - - 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,

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

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

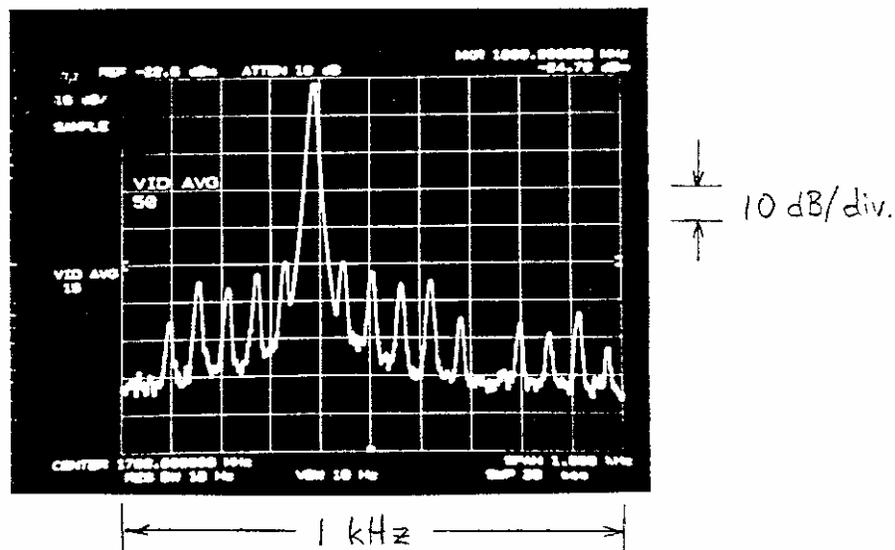
- spectrum of modulated signal has upper and lower sidebands on either side of LO frequency, and
- amplitude of  $\cos \omega_{LO}t$  term is reduced compared to unmodulated case.

## 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:
 

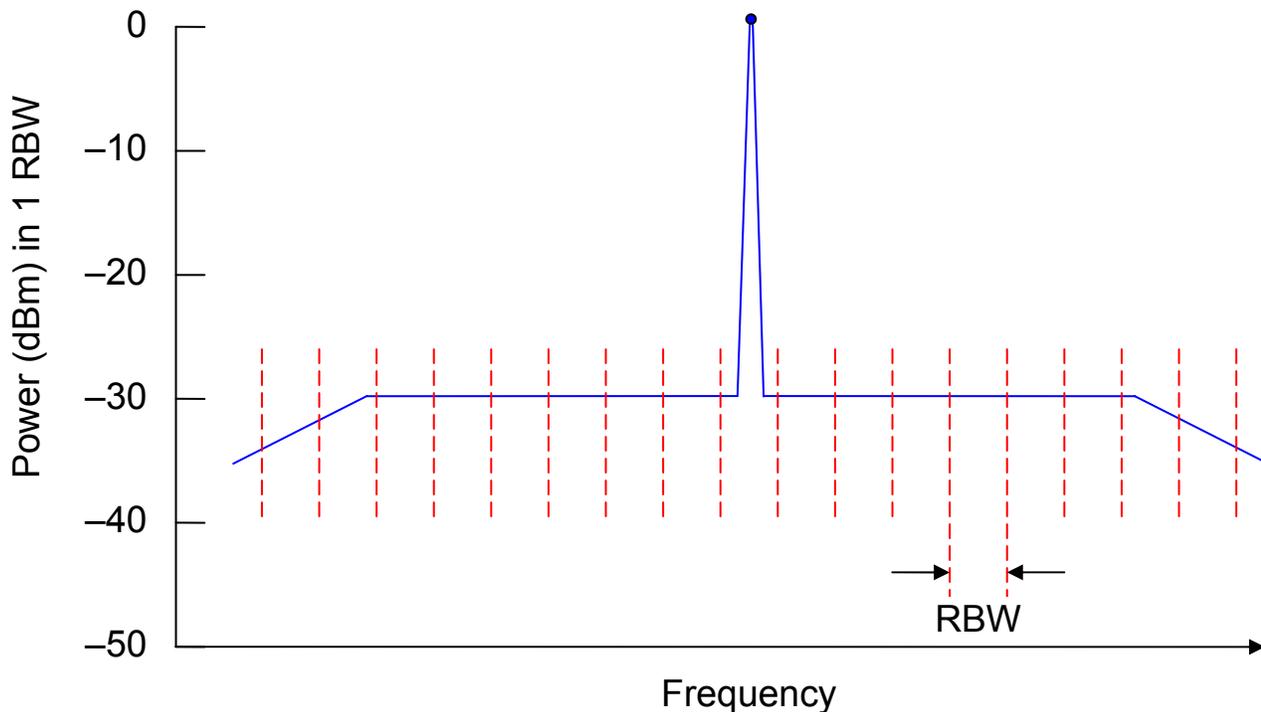
When frequency  $f_1$  is multiplied up to  $f_2$ , phase noise (in degrees or radians) is multiplied by ratio  $f_2/f_1$ , and strength of modulation sidebands is increased by  $20 \log_{10}(f_2/f_1)$  dB.

  - 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 =  
 $\sqrt{(\text{power in 2 sidebands}) / (\text{power in carrier})}$

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 =  $2 \times (0.001 \text{ mW} / \text{RBW}) \times (6 \text{ RBW})$   
= 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 =  $(0.001 \text{ mW} / 1 \text{ kHz}) \times (12 \text{ kHz}) = 0.012 \text{ mW}$

Power in carrier = 0 dBm = 1 mW

RMS phase jitter of carrier =  $\sqrt{0.012 \text{ mW} / 1 \text{ mW}}$  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

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

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):

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

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  $< 4^\circ$  at 100–450 MHz and  $< 9^\circ$  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  $2 \times 10^{-3} \times (10 \text{ kHz}) / (1 \text{ kHz}) = 0.02$ , 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.)

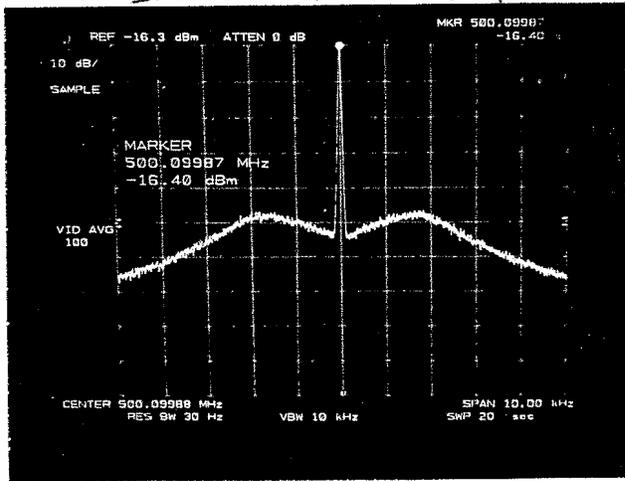
### How to determine whether it is the LO or phase cal that is modulated

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

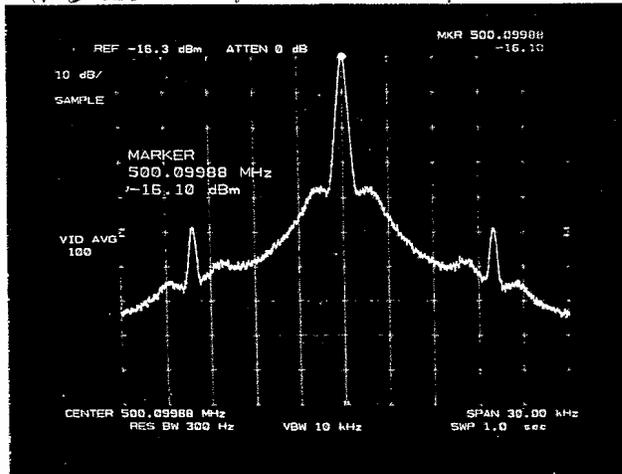
to the RF phase cal signal or receiver LO. If both the RF phase cal signal and LO signal are driven by a common modulated reference signal, the phase jitter at IF or baseband will be smaller than in the LO by the ratio  $|f_{RF} - f_{LO}|/f_{LO}$  (provided the modulation frequency is lower than the loop bandwidth of any phase-locked oscillator).

IF3 LO - S/N 8 - 6 April 93



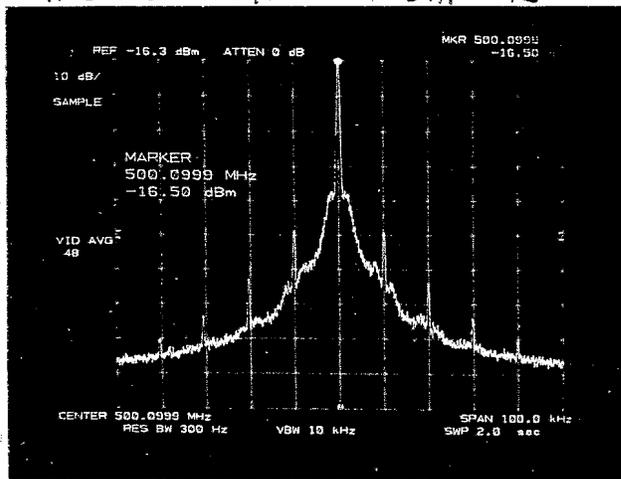
10 kHz span  
30 Hz RBW

IF3 LO - S/N 8 - 6 April 93



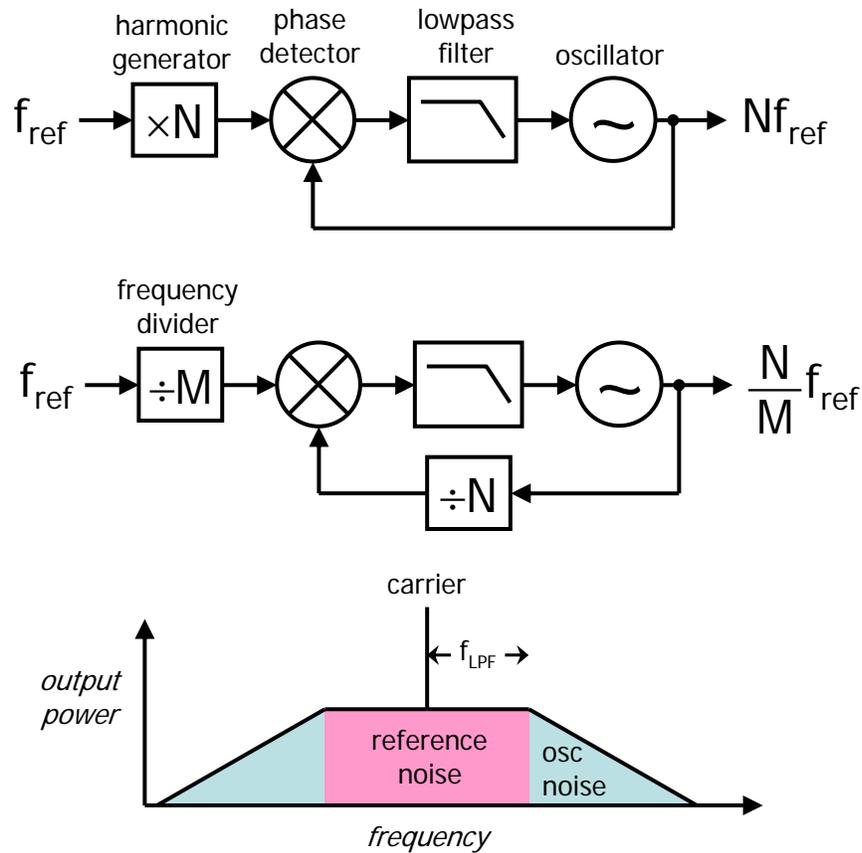
30 kHz span  
300 Hz RBW

IF3 LO - S/N 8 - 6 April 93



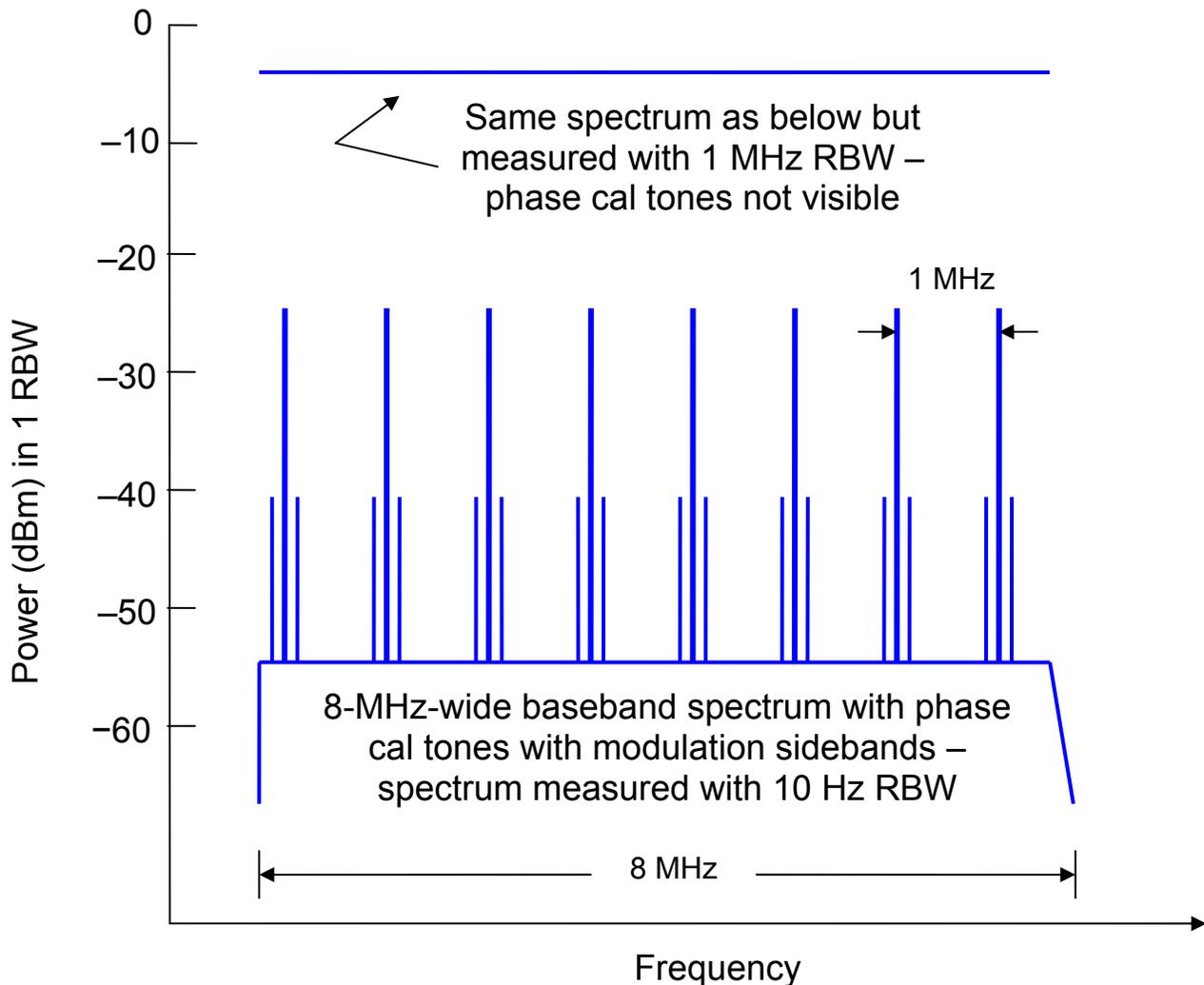
100 kHz span  
300 Hz RBW

## Phase-locked oscillators



- PLOs use a reference frequency to steer an oscillator on long time scales ( $> \mu\text{s}$  to  $\text{ms}$ ).
- PLO phase noise outside the loop BW (= lowpass cutoff frequency) is generally lower than that of reference signal multiplied up to output frequency.
- First circuit above is common in receiver LOs.
- VC/BBC PLO uses second circuit with  $f_{\text{ref}} = 5 \text{ MHz}$  and  $M = 500$ .  
 → Output can be varied in steps of 10 kHz.

## 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  $\sim 25\%$ , 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!

## Analyzers for phase cal spurious signal detection

- Detecting phase cal spurious signals at -50 dBc requires, for typical phase cal power levels, an analyzer resolution BW of order 10 mHz.
- Typical big-box analog analyzers have a minimum RBW of 1-10 Hz.
- Analyzers with narrower RBW suitable for spurious signal detection include:
  - Low-frequency (up to ~1 MHz) FFT analyzer such as antique HP 3582A and HP 35660A.
  - Software-defined radios (SDRs)
    - SDRs and their uses in VLBI diagnostics are the subject of a TOW lecture by Tom Clark and Rick Hambly.