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

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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 μsec 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° range, measure the phase cal amplitude and phase (using, e.g., an FFT analyzer or the Field System commands `pcal` 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° 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°. 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 $360°/|f_{\mathrm{LO}2}/f_{\mathrm{LO}1} - 1|$, 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).