Reducing Phase-Measurement Errors due to RF-Source Band Breaks

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***Abstract*— A signal source can introduce phase-measurement errors when its output crosses through internal frequency-band breaks. The source phase lock circuits in this band-break region sometimes report approximate phase lock before complete phase lock occurs. The result of this approximate phase lock is a minor error in the output frequency, which can lead to phase-measurement errors at the system level. The magnitude of the phase errors depends on the amount of frequency offset and the difference in electrical lengths between the measurement system's signal and phase-reference paths.**

If this behavior were deterministic, then the resulting phase errors might be tolerable. Unfortunately, it was found that the final settling time (measured in many hundreds of milliseconds) was not consistent, depended in part on the two specific frequencies surrounding the band break, became more confused if a second sweep encountered the band break before the first break had settled, and of course changed behavior if the frequencies were sequenced in reverse order or measured one at a time.

The design approach described herein reduced to negligible the phase-measurement errors due to frequency errors in two large multioctave test systems. The approach relies on managing range transmission line lengths so that propagation time is sufficiently equal among the various signal and reference paths. Measured data are presented that show the advantage of the optimized system design.

I. Introduction

When making RF measurements that require accurate phase, one of the error contributions will be frequency inaccuracy in the signal and/or local-oscillator (LO) sources. This paper explores the sensitivity of a phase-referenced acquisition system to those errors, and suggests one mechanism to minimize that sensitivity.

Of particular interest are frequency errors that vary with time, such that the measured phases over a data set are not merely offset by a scalar. One example of such a frequency error might occur when crossing a signal source's band break, where the frequency might rapidly settle to be very close to the commanded frequency, but finish its settling after a more substantial delay. Such an apparent band-break behavior was the impetus for this effort.

The chosen mitigation mechanism begins with equalization of the electrical lengths carrying the radiated RF signal to the signal and reference mixers, and similar equalization for the two LO/IF paths. As we will show, the measured phase error is proportional to the difference in electrical length traveled to the two mixers from the source(s) with the frequency error.

Figure 1. illustrates four electrical lengths L_S, L_R, L_{PR}, and L_{PS} carrying waveforms to the signal and reference mixers, plus two more electrical lengths L_{IFS} and L_{IFR} from the mixers to the receiver's A/D converters. Path L_S goes from the signal (RF) source to the signal mixer, and includes the range antenna, free-space transmission, antenna under test, plus any RF cabling in that path. Note that any AUT translation during the measurements will generally cause L_S to change. Path L_R goes from the RF source to the reference mixer. Path L_{PS} goes from the LO (pump) source to the signal mixer, and path L_{PR} goes from the LO source to the reference mixer. Path L_{IFS} goes from the signal mixer to the receiver's signal-channel input, and path L_{IFR} goes from the reference mixer to the receiver's reference-channel input.

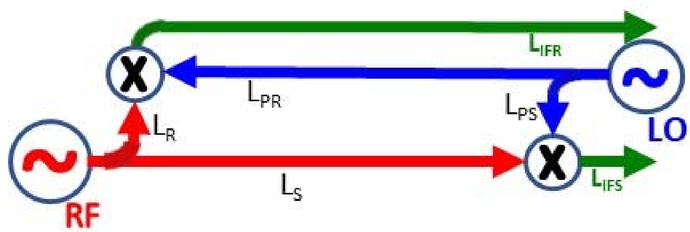

Figure 1. Block diagram of RF path

The phase delay ϕ in degrees (in the engineering phase convention) through an electrical length L at frequency f is given by (1):

$$\phi = -\frac{360^o}{\lambda} L = -\frac{360^o}{c} f L. \quad (1)$$

Thus, if the test or radiating frequency f is in error by Δf_{RF}, then the phase error is given by (2):

$$\Delta\phi = \frac{-360^o}{c}(\mathrm{f} + \Delta f_{RF})L - \frac{-360^o}{c} f L = -\frac{360^o}{c}\Delta f_{RF} L. \quad (2)$$

The mixing process is addressed in the literature [1]-[4] and will not be repeated here. If we begin with an assumption that only the RF source has a frequency error, and that the IF path lengths are the same for signal and reference, then our phase error in a phase-referenced (A/R) measurement will be ang(Δsignal / Δreference) as shown in (3):

$$\Delta\phi_{\frac{A}{R}} = -\frac{360}{c}\Delta f_{RF}(L_S - L_R) \quad (3)$$

If we assume fundamental mixing, then we can quickly see that a frequency error Δf_{LO} on the LO source would also lead to a phase error based on the electrical-length mismatch between the paths carrying the LO signal to the two mixers (with IF and RF paths matched):

$$\Delta\phi_{\frac{A}{R}} = -\frac{360}{c}\Delta f_{LO}(L_{PS} - L_{PR}) \quad (4)$$

With harmonic mixing and harmonic number N, the phase error in (4) due to LO-source frequency error would be multiplied by N.

The pair of IF paths will also contribute to phase error with proportionality to the difference in IF path length ($L_{IFS} - L_{IFR}$). The frequency error Δf_{IF} in the IF path is found in (5):

$$\Delta f_{IF} = N\Delta f_{LO} + \Delta f_{RF} \quad (5)$$

If we suspect that both signal sources might have frequency errors, then the total phase error due to frequency errors in an A/R measurement is:

$$\Delta\phi_{\frac{A}{R}} = \frac{360}{c}\begin{pmatrix} N\Delta f_{LO}(L_{PS} - L_{PR} + L_{IFS} - L_{IFR}) - \\ \Delta f_{RF}(L_S - L_R + L_{IFS} - L_{IFR}) \end{pmatrix} \quad (6)$$

where N is again the harmonic number used in the remote mixing.

A. Phase Measurement Error

Often in antenna measurements, the propagation time differs significantly along signal and reference paths L_S and L_R. This can lead to varying phase errors if f_S changes during the measurement. Figure 2. evaluates equation (3) for the range layout of signal and reference electrical lengths differing by about 85 m [280ft] It predicts an error of about 5 degrees if the signal source moves 50 KHz during a measurement.

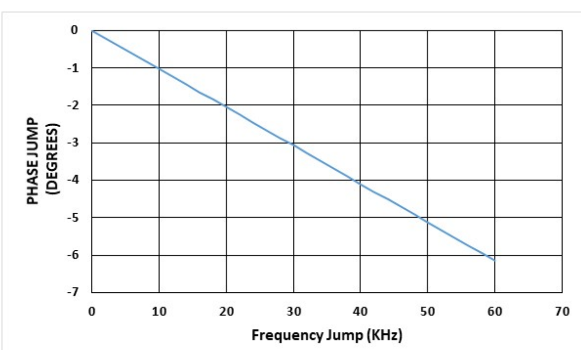

Figure 2. Phase error due to L_S and L_R path-length imbalance (equation 3)

On the other hand, equations (3) and (4) tell us that if we suspect frequency errors of 50 KHz and decide it is necessary to constrain phase jumps to less than 0.5 degrees, then we conclude that the electrical-length imbalance must total less than 7.6 m [25ft]. That is the criterion we set about to impose on our antenna range.

II. Measurement Evidence

Figure 3. is a plot of measured data that illustrate the observed phase errors. A 'Beam' in this measurement system commands the DUT to a particular state. For this test, that DUT state was constant for every beam number. Each of the plotted traces is normalized to the beam-1 reading in that trace, such that the expected plot should show phase=0 everywhere. The frequency list was set to alternate between 5 and 6 GHz, because earlier testing suggested that frequency change within that span led to phase anomalies. During the measurement, the Beam Number was cycled most rapidly (512 identical measurements) and then the frequency index. The elapsed time between Beams in this test was approximately 20 ms. The annotations on the plot are not relevant here (and are blurred due to lack of repeatability in the phase errors), but indicate the Beam Number where a trace initially exceeded five degrees of phase change.

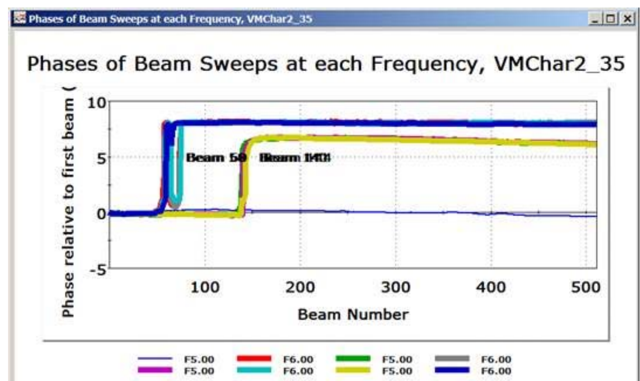

Figure 3. Measured Phase Errors

The first trace in Figure 3. is a thin blue line that is everywhere close to zero as expected. The RF and LO sources would have been commanded to 5 GHz for more than three seconds prior to the first trace's 512 measurements, so we would expect both sources to be fully settled throughout that trace with fixed (perhaps zero) frequency error. The other seven traces started their 512 measurements immediately after a frequency transition through 5.5 GHz. The four traces that first change state around beam 50 are all commanded to 6 GHz, and the three that change state near beam 140 are all commanded to 5 GHz. Note that the sweep through the 512 repeated states appears to be long enough (about 10 seconds) that any band switch would be fully settled

Figure 4. shows results of a similar test, this time testing several frequencies near the suspected band break. This plot is evidence consistent with frequency errors due to a band break in at least one of the sources between 5.5 and 6 GHz. Again, note that the sweep through the 512 repeated states appears to be long enough (about 10 seconds) that any band switch would be fully settled.

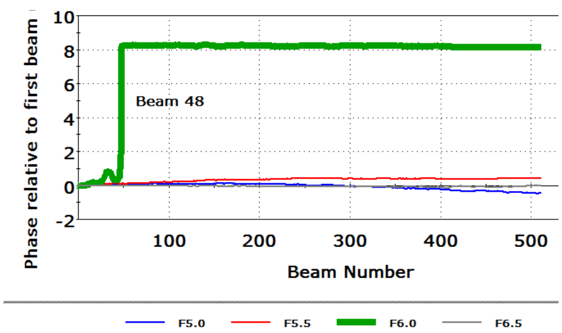

Figure 4. Measured Phase Errors in Frequency Sweep

Figure 5. shows the response when the time per beam is reduced from 20 ms to about 3 ms, reducing time per frequency from 10 seconds to about 1.5 seconds. This plot suggests that repeated rapid frequency sweeps that span the band break might tend to randomize the phase errors among the frequencies in each sweep, and such behavior was also observed.

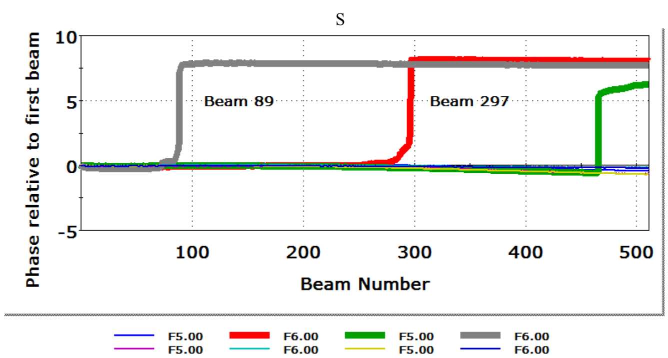

Figure 5. Faster Frequency Cycling

The collection of symptoms measured and illustrated in Figures 3-5 suggested that there was no reliable yet efficient procedure that could be used to collect large quantities of data with frequencies spanning the band break. Until the hardware fix was implemented, separate measurements were used above and below the break, and even then, measurements near the break were questionable.

III. Design Approach; A Case Study

In order to illustrate the applicability of a hardware solution, a case study is discussed. The goal is to reduce the phase errors resulting from this apparent band-break behavior to acceptable values. This case study targeted an electrical length $|L_S - L_R| \leq 7.62$ m. Consider a part of equation (6)

$$\Delta L_{LO} = |L_{PS} - L_{PR} + L_{IFS} - L_{IFR}|. \quad (7)$$

$$\Delta L_{RF} = |L_S - L_R + L_{IFS} - L_{IFR}|, \quad (8)$$

The case study examines a simple measurement system with the signal and reference mixer positioned at the opposite ends of the RF path. Figure 6. depicts the measurement system with a large ΔL. Consider the reference mixer is positioned close to the coupler and the signal mixer positioned close to the receiver. This establishes the large electrical-length mismatch between the signal and reference path. Let the electrical length of the signal path from the coupler to the signal mixer be $L_S = 76.16$ m [250 ft] and the reference path from the coupler to the reference mixer be $L_R = 0.91$ m [3.0 ft]. Let the electrical length of the signal LO path from the signal mixer to the receiver be $L_{PS} = 29.56$ m [97 ft] and the reference LO path from the reference mixer to the receiver be $L_{PR} = 92.35$ m [303 ft].

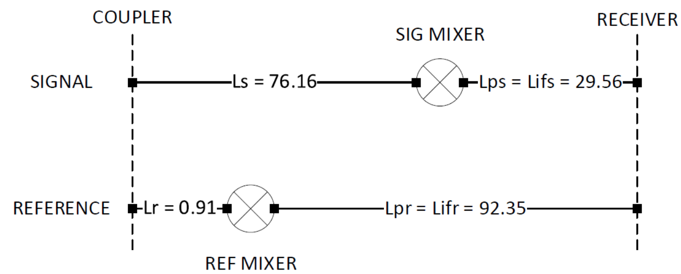

Figure 6. Case Study Measurement System Original

The large mismatch in electrical length denoted as $\Delta L_{RF} = |L_S - L_R + L_{IFS} - L_{IFR}| = 12.46$ m [40.9 ft]. The LO/IF path also exhibits a large mismatch in electrical length denoted as $\Delta L_{LO} = |L_{PS} - L_{PR} + L_{IFS} - L_{IFR}| = 125.58$ m [412 ft]. This electrical-length mismatch of original ΔL_{RF} and ΔL_{LO} equates to a phase error $\Delta\phi_{A/R} = 6.78$ degrees if both frequency error, Δf_{RF} and Δf_{LO}, is 50 kHz, per equation (6) with fundamental mixing ($N = 1$).

The hardware solution to reduce the electrical length was to position the signal and reference mixers at similar electrical lengths from the coupler. Ideally, the signal mixer would be positioned close to the receiver for high RF system fidelity. Therefore, the reference mixer was moved toward the receive end of the range to closely match the electrical length of the signal path. Given spatial constraints, the reference mixer was positioned at $L_R = 70.86$ m [232 ft] from the coupler (Figure 7.).

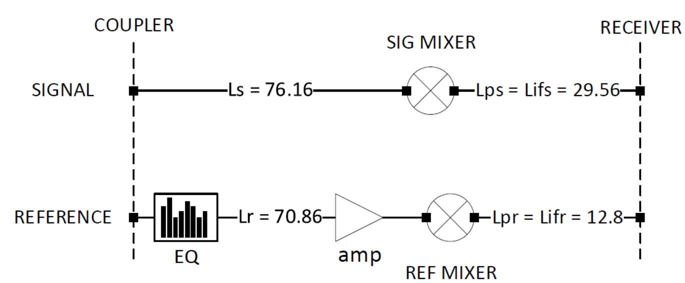

Figure 7. Case Study Measurement System Modified

One challenge in relocating the reference mixer is maintaining the proper amplitude level over a wide frequency range. A long RF cable path introduces a sloped frequency response. One approach is to implement an amplitude equalizer with amplifier to mitigate the negatively sloped frequency response. This solution was chosen to maintain a flat frequency response by largely canceling the long RF cable's attenuation.

The new reference mixer position is set at $L_R = 70.86$ m [232 ft]. The modified system design reduced the electrical length $\Delta L_{RF} = |L_S - L_R + L_{IFS} - L_{IFR}| = 22.06$ m [72.4 ft]. The LO/IF path also benefited with the reduced electrical length $\Delta L_{LO} = |L_{PS} - L_{PR} + L_{IFS} - L_{IFR}| = 33.52$ m [110 ft]. Inserting these numbers into equation 6 yields a phase error $\Delta\phi_{A/R} = 0.68$ degrees if both frequency error, Δf_{RF} and Δf_{LO}, are 50 kHz, with fundamental mixing (N = 1).

This satisfies the original target goal of an electrical length $|L_S - L_R| \leq 7.62$ m [25 ft], and, further, results in phase error $\Delta\phi_{A/R} \leq 0.32$ degrees given a 50 kHz frequency error.

Testing of frequency sweeps with the modified RF path showed no signs of the band break. Sweeps were acquired below, above, and through the band break, and all phases overlaid.

IV. Future Considerations

During this effort, it became apparent that numerous path lengths affect this type of phase error, $|L_S\text{-}L_R|$ being one of several, as shown in equation (6). It may be beneficial for the antenna measurement community to follow the guidance of equation (6) during design of very large broad-band ranges.

V. Conclusion

Phase-measurement errors have been reduced to negligible through managing transmission path length differences below a threshold set by the anticipated maximum frequency error of the range RF and LO sources.

Acknowledgement

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References

[1] Bert Henderson and Edmar Camargo, Microwave Mixer Technology and applications,, Artech House, Inc, 2013, ISBN 978-1-60807-489-1

[2] Stephen A. Maas, Microwave Mixers, Artech House, Inc, 1986, isbn 0-89006-171-8.

[3] Bert Henderson, “Mixers: Part 1 Characteristics and Performance,” Watkins-Johnson Tech-notes, March/April 1981.

[4] Erik L. Kollberg, editor, Microwave and Millimeter-Wave Mixers, IEEE Press, 1984, ISBN 0-87942-179-7.