FREQUENCY AND PHASE STABILITY IN A MILLIMETRE WAVE NETWORK ANALYZER

Pekka Eskelinen[1] , Jussi Säily[1], and Pekka Sjöman[2]

[1]Helsinki University of Technology, Institute of Digital Communications (IDC)
[2]Helsinki University of Technology, Metsähovi Radio Research Station
PO Box 3000, FIN-02015 HUT, Finland
Email: pekka.eskelinen@hut.fi

ABSTRACT

A principle of constant frequency offset between the receiver and transmitter microwave sources is used in a commercial millimetre wave vector network analyzer, mostly canceling the effects of oscillator drift through subtraction. Despite the selected scheme, the internal crystal oscillators seem to cause some short-term phase and frequency uncertainties at millimetre wave frequencies. Phase drifting of close to 2 degrees at 100 GHz during a measurement period of 4 hours is observed. Antenna pattern measurements with near-field methods over periods up to tens of hours may suffer from these analyzer instabilities.

Keywords: Network analyzers, phase stability measurements, frequency measurements, millimetre wave measurements, oscillators

1. INTRODUCTION

Millimetre wave frequencies are getting increasingly popular due to the rapidly increasing need for wideband communications and because the present allocations below 40 GHz simply have become too crowded. Also, at higher millimetre and submillimetre frequencies the available antenna sizes and atmospheric propagation characteristics have been found attractive. Satellite transponders, imaging devices and vehicular radars are typical applications. E.g. planned satellite missions like ESA´s Herschel Space Observatory and PLANCK in the next full decade will make use of submillimetre wave instruments. One of the main technological challenges is to be able to accurately measure the common electromagnetic parameters of components, subassemblies and systems also at these bands and to keep the cost of test instrumentation within reasonable limits. However, a very limited number of high performance test facilities for, say, antenna measurements beyond 300 GHz and diameters exceeding 1 m are currently available.

The best tool for the measurements is a vector network analyzer with which the scattering parameters of a two-port device can be measured. For millimetre wave work, only one or two commercial designs are available, the construction of which is somewhat different from that of state-of-the-art RF analyzers sold for cellular business. Figure 1 shows a schematic presentation of the particular device, which has been studied in this evaluation. Its operating principle is documented e.g. in [1]. The analyzer basically utilizes two microwave YIG (Yttrium Iron Garnet) sweepers covering 8-18 GHz and a harmonic generator, which produces the final millimetre wave test signal. The second sweeper is used as the local oscillator for a harmonic mixer whereby a lower frequency is regenerated for the vector receiver. As is seen, the manufacturer has chosen not to phase-lock the local oscillators. Instead, a phase comparator is connected to the difference of those two microwave sources. This means that the center frequency of one sweeper (and thus the millimetre wave test signal as well) may freely drift as long as the frequency difference between the two sweepers equals the selected reference. The design is based on the assumption of identical sweepers, noise-free digital dividers and associated phase-locks and is motivated by lower cost. According to the manufacturer [1], any phase errors within the sweeper arrangement will be cancelled out before the signal reaches the vector receiver. This assumption is made from the calculated phase-noise ϕ_{IF} for the IF-signal (see equation (3) below), and is valid for high signal-to-noise ratio (SNR) in the receiver.

Because many specialized pattern measurements of millimetre and submillimetre wave antennas, see e.g. [3, 4], require a distinct and stable frequency and phase, an external frequency counter (EIP 575B) is used in the analyzer system to frequency steer the first sweeper but without a phase-locking feature. The counter has its own internal crystal time base. Alternative technical solutions to the frequency-generating problem within the higher microwave bands can be found in [5] and [6]. For our purposes, [7] serves as a classical text book on frequency synthesis. A comprehensive discussion of typical phase and amplitude error budgets and their computation for near-field pattern measurement arrangements can be found in [8] where, however, no pre-processed numerical values are given.

If the phase-noise of the first YIG-sweeper is ϕ_{LO1}, N the harmonic rank, and ϕ_{HG} the phase noise of the diode harmonic generator, then the phase noise of the transmitted millimetre wave signal can be formulated as

$$\phi_{mm} = N\phi_{LO1} + \phi_{HG} . \qquad (1)$$

According to the noise analysis principles presented in [2], the phase-noise of the IF-signal after downconversion in the harmonic mixer is

$$\phi_{IF} = \phi_{mm} - N\phi_{LO2} + \phi_{HM} . \qquad (2)$$

Substituting (1) to (2) we get

$$\phi_{IF} = N(\phi_{LO1} - \phi_{LO2}) + \phi_{HG} + \phi_{HM} . \qquad (3)$$

The phase-noise contribution from (3) is dependent on the harmonic rank, the phase-noise difference between the YIG sweepers, and the phase-noises of the harmonic generator and mixer. The latter are negligible compared to the multiplied YIG-noise. The value of N ranges from 1 to 10 in normal operation between 18–180 GHz. In addition to the increased multiplication and harmonic mixing losses due to rising *N* and resulting in lower SNR, problems with phase stability also increase with *N*.

The single-sideband (SSB) phase-noises for both YIG sweepers were measured. The results are shown in Figure 2. The increased phase-noise of the LO_2 compared to the LO_1 is seen clearly, and it is due to the PLL loop between the oscillators. The added phase-noise varies between 2–5 dB across the measured offset frequencies of 5–100 kHz. Close-carrier phase-noise of the free-running YIG-oscillator could not be measured. The effect of the added phase-noise on the observed phase unstabilities is not clear, but it may increase the phase measurement uncertainty at low received signal levels.

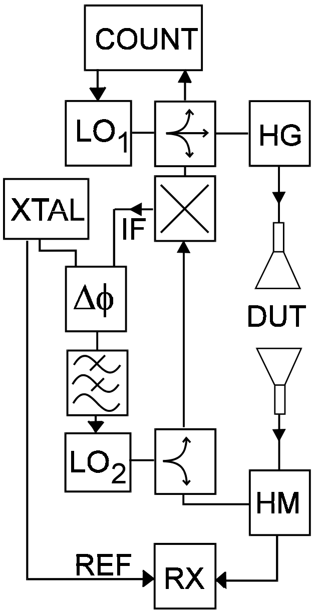

Figure 1. *A schematic block diagram of the evaluated millimetre wave vector network analyzer. Two microwave sweepers (LO_1 and LO_2) are used to generate the test signal in the harmonic generator (HG) and to regenerate a lower frequency replica of it in the harmonic mixer (HM). The difference of the two local oscillator frequencies is phase-locked to a low-cost crystal unit (XTAL). Additional coarse frequency steering is provided by the external counter (COUNT) to LO_1.*

2. THE TEST ARRANGEMENT

Millimetre wave component measurements and experiments with a submillimetre wave compact antenna test range (CATR) suggested that there might be some phase stability problems within the analyzer. Phase recordings (up to several hours) of e.g. straight waveguide sections showed either a drift of measured phase or alternatively abrupt jumps of arbitrary duration. An analysis of the problem is rather complicated because we basically need a second, considerably better millimetre wave source for a direct comparison. Even if such a device were at hand, the operating principle of the analyzer practically precludes this kind of a test as the original signal comes from a more or less free-running oscillator. As a substitute, an attempt has been made to trace these phenomena back to the system's internal reference oscillators and particularly down to their frequency and phase characteristics. For most of the measurements, the basic, simplified setup of Figure 3 was used. A very stable oven oscillator serves as the laboratory standard and the momentary phase error is obtained through a balanced RF mixer into which the various reference signals from the millimetre wave analyzer are fed.

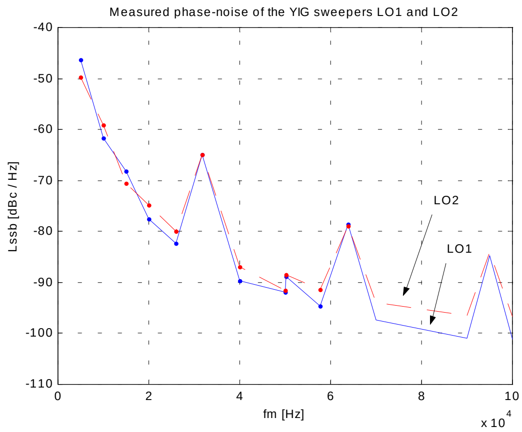

Figure 2. *The measured single-sideband phase-noise of the YIG sweepers LO_1 and LO_2 between offset frequencies of 5 kHz – 100 kHz. The measurements were done with the TEK2782 spectrum analyzer at 17 GHz (RBW=1 kHz, VBW=30 Hz, averaging=10). The added phase noise in LO_2 due to the PLL loop varies between 2–5 dB.*

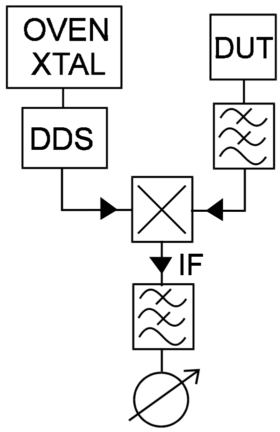

Figure 3. *In order to be able to perform the phase tests with the quite arbitrary oscillator frequencies, an external digital low-frequency synthesizer was connected between the laboratory primary reference and the balanced mixer, which was used in the common way as a phase detector.*

The test arrangement was supplemented by an adjustable synthesizer to eliminate the effects of the intrinsic frequency offset of about 10^{-6} in the millimetre wave analyzer's 10 MHz clock. An overview of the complete instrumentation can be seen in Figure 4 with the DDS synthesizer low in the front. Much of the test procedures were adopted from the author's recent work in GPS timing, which is described in [9]. Measurement noise could be effectively reduced e.g. by the method of [10] but as it will be shown below, the DUT performance really did not require this. Helpful ideas regarding short-term phase fluctuations were obtained from [11].

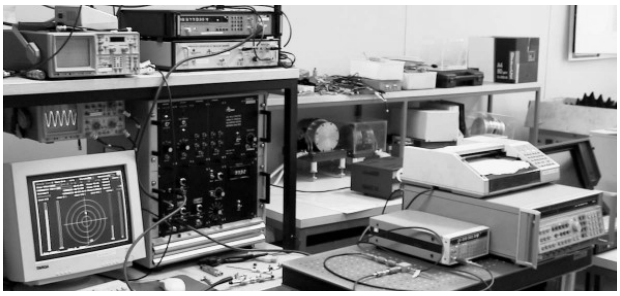

Figure 4. *A view of the laboratory installation showing the MVNA (dark) in the middle, the DDS generator and the time-base generator to the right. The microwave counter is on top of the shelf.*

First, the residual phase drift of the digital synthesizer was measured against the oven oscillator. Very satisfactory performance was observed as can be seen in Figure 5 and we felt confident with our setup regarding actual experiments with the network analyzer. The full scale deflection would have been 550 mV for a 180 degree phase difference but actual measurements were performed near the zero crossing value due to the best sensitivity and linearity.

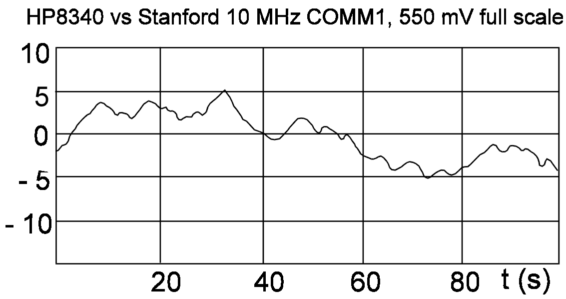

Figure 5. *A verification run of the low frequency digital synthesizer confirms its suitability for the evaluation setup. Typically, the phase uncertainty across time intervals up to 100 seconds is one tenth or less compared to the respective values of the tested network analyzer.*

3. SOME OBSERVATIONS

First of all we noted that there is a direct correlation between the phase of the analyzer's internal oscillator (marked XTAL in the schematic of Figure 1) and that of the millimetre path as measured by the analyzer system itself. A straight waveguide section was used throughout the experiments and the test frequency was set to 100 GHz for mechanical convenience although any changes in the sweeper phase would be multiplied by even larger integers if a higher output frequency was chosen. Figure 6 demonstrates a recording over 100 seconds during which we notice a frequency drift and a couple of phase jumps - the most interesting at around 80 seconds. It seems that a linear, slow shifting in reference phase is not coupled to the output whereas rapid deviations are.

The measured phase response of the straight waveguide section at 100 GHz during a 4 hours long measurement period is shown in Figure 7. The warm-up time for the system was 24 hours. First, a phase jump of about 0.5 degrees is observed when the sampling period starts. This is due to the fact that the analyzer relocks the YIG-oscillators each time a new data-taking session begins. A more serious problem is the observed phase drift of close to 2 degrees. The drifting is believed to be caused by drifting of the analyzers internal reference crystal and the frequency counters timebase crystal.

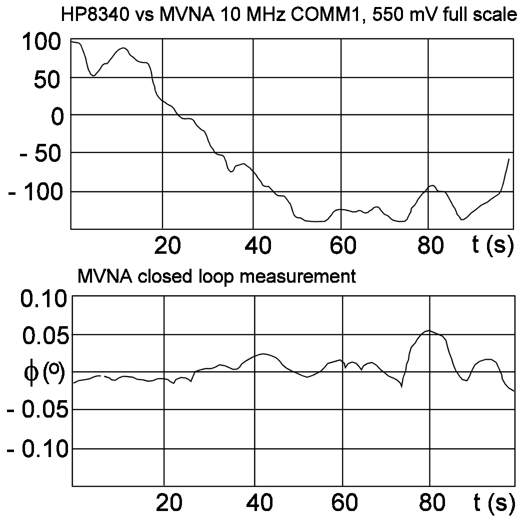

Figure 6. *Phase changes in the millimetre path (lower plot) correlate well with those of the analyzer's internal crystal reference; see e.g. the jumps at around 40 and 80 seconds. The linear drift, caused by a difference in the reference frequencies seems to be filtered out.*

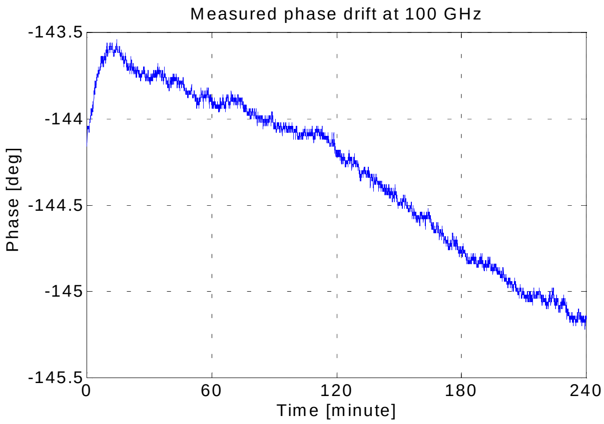

Figure 7. *Measured phase response through a straight piece of waveguide at 100 GHz during a 4 hours sampling period (after warmup time of 24 hours). Phase drift of close to 2 degrees is observed.*

Load-pulling effects were studied from the analyzers 10 MHz and 50 MHz output ports. Inside the analyzer, there is an internal 50 MHz crystal oscillator from which e.g. the distributed 10 MHz is obtained through digital division. This 50 MHz clock in the analyzer suffers from load pulling effects (applied at the 10 MHz output) as can be seen in Figure 8. The problem is quite astonishing as the clock circuit looks like having two cascaded isolation amplifiers and a complete chain of TTL dividers for the separation of the 10 MHz output and the 50 MHz oscillator signal.

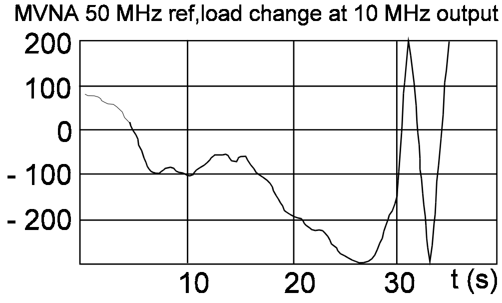

Figure 8. *One of the most primitive defects of the network analyzer's synchronization scheme is the heavy dependence of the 50 MHz reference oscillator's output frequency on the loading (changed at 30 seconds) of adjacent 10 MHz lines, which do not have a direct connection to it. Such load pulling effects seriously hamper any sensible frequency calibration efforts.*

The dependence of the observed millimetre wave phase at 100 GHz on the EIP counter 10 MHz reference crystal oscillator was also studied. As is demonstrated in Figure 9, there is only minor correlation between the counter phase and the millimetre wave result.

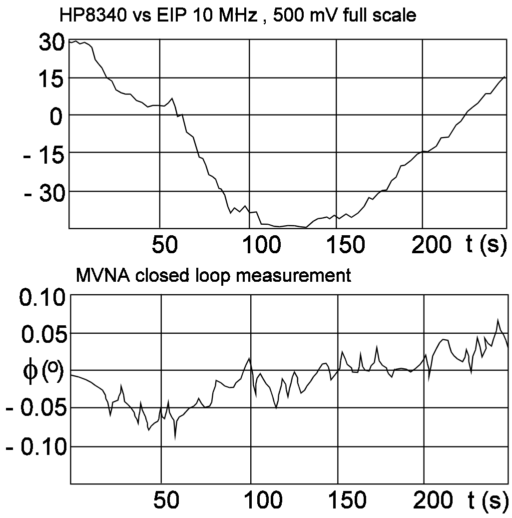

Figure 9. *The external frequency steering counter has a really small effect - if any at all - on the phase stability. The two discontinuities to the left and right of 50 seconds on the upper plot (phase of counter timebase) can be correlated with the phase lag of 0.05 degrees on the lower millimetre wave plot.*

4. CONCLUSIONS

Our brief tests have indicated that the performance of a commercial vector network analyzer suffers from a connection between the observed millimetre wave phase and the 10 MHz/50MHz reference oscillator characteristics. This happens despite the manufacturer's technical choice of mutually tracking frequency-locked generators, a method which should cancel out the oscillator fluctuations. Although linear drift terms of either phase or frequency seem to be filtered away, more instantaneous deviations lasting from five to twenty seconds, tend to have an influence on the output signal as well. In the evaluated configuration, the effects of the internal 10MHz/50MHz synthesizer reference and the associated electronics are expected to be dominating. The measured phase drift at 100 GHz during a measurement period of 4 hours was close to 2 degrees.

The described behavior is believed to be caused by problems in the synthesizer electronics including reference clock distribution. The selected operating principle limits the possibility of external phase comparisons of the YIG-oscillators. The observed phase drifting may disturb e.g. several hours long millimetre wave antenna measurements. A straightforward improvement to the analyzer stability is thought to be possible by replacing the individual low-cost crystal oscillator units with a centralized rubidium standard, supplemented by e.g. optically isolated outputs and dividers. A GPS-stabilized rubidium reference clock system for the analyzer is being developed at the time of writing.

REFERENCES

[1] Goy P. and Gross M., ”Millimeter and/or submillimeter network vector analyzer”, French Patent Sep 1st, 1989, US Pat No 5119035 Jun 2nd, 1992

[2] Kroupa V.F., ”Noise properties of PLL systems”, *IEEE Transactions on Communications*, Vol. Com-30, No. 10, Oct. 1982, pp. 2244–2252

[3] Säily J., Ala-Laurinaho J., Häkli J., Tuovinen J., Lehto A., Räisänen A.V., ”Test results of a 310 GHz hologram compact antenna test range”, *Electronics Letters*, Vol 36., No. 2, Feb. 2000, pp. 111–112

[4] Säily J., Ala-Laurinaho J., Häkli J., Tuovinen J., Lehto A. and Räisänen A.V., ”Instrumentation and testing of submillimeter wave compact antenna test ranges”, in *Proc. Eleventh International Symposium on Space Terahertz Technology*, Ann Arbor, May 2000, pp. 590–597

[5] Schitov A., ”1.5 - 40 GHz multifunctional microwave sampling converter”, in *Proc. IEEE International Frequency Control Symposium*, April 1999, pp. 604–606

[6] Tan G., ”A highly stable, phase coherent, wideband microwave synthesizer for radio astronomy applications”, in *Proc. IEEE International Frequency Control Symposium*, April 1999, pp. 607–610

[7] Crawford J. , *Frequency Synthesizer Design Handbook*, Norwood, Artech House, 1994

[8] Newell A.C., ”Error analysis techniques for planar near-field measurements”, *IEEE Transactions on Antennas and Propagation*, vol. 36, No 6, June 1988, pp. 754–768

[9] Eskelinen P., ”Problems in estimating some timing uncertainties of commercial frequency and time standards”, *IEEE Transactions on Instrumentation and Measurement*, vol.48, Feb. 1999, pp. 62–65

[10] Fest D., Groslambert J. and Gagnepain J., ”Individual characterization of an oscillator by means of cross-correlation or cross-covariance method”, *IEEE Transactions on Instrumentation and Measurement*, vol 32, Sept. 1983, pp. 447–450

[11] Walls F., Wanwright A., ”Measurement of short term stability of quartz crystal resonators and the implications for oscillator design and applications”, *IEEE Transactions on Instrumentation and Measurement*, vol 24, Mar. 1975, pp. 15–20