Center for Astrophysics

Harvard College Observatory
Smithsonian Astrophysical Observatory

MEMORANDUM

April 27, 1989

To: SMA Distribution
From: Colin CM
Subject: Design Study Memo #3: Local Oscillator Phase Stability

This memo investigates the difficulties in providing stable local oscillator signals for the SMA, and concludes that adequate systems can be built at frequencies where Gunn oscillators can be used.

Local Oscillator Phase Stability for the SMA

COLIN MASSON

Introduction

Operation of the SMA at frequencies up to ~1 THz will require more stable local oscillators than those in current radio interferometers. In this memo, I explore the practical limits to LO purity, based on previous experience, and available components. At the very highest frequencies ($\gtrsim$500 GHz), the only existing receivers use Schottky diodes and laser local oscillators. It would probably be very difficult to phase-lock such lasers reliably in the several elements of the SMA, although phase locked lasers have been used for 10 μm interferometry at Berkeley. I shall therefore consider only a scheme in which Gunn oscillators running at a frequency near 100 GHz are multiplied and the output is used to feed an SIS receiver. With present technology, this approach is certainly good up to 500 GHz, and we can estimate the limits to performance quite reliably. At higher frequencies, operation of the array will probably have to wait for technological improvement both in receivers and local oscillators. If the present rapid pace of receiver development continues, it is highly likely that multiplied Gunn local oscillators will be available over the entire frequency range by the time the array is completed.

A Generic LO chain

The diagram in Figure 1 shows a generic local oscillator chain. In the base station there is a master oscillator which provides the frequency reference for the whole interferometer. For local interferometry this does not have to be more stable than roughly 1 part in 10^7 (determined by astronomical line widths), but for VLBI, much higher stability is required, and a maser must be used. The signal from the master oscillator is usually not convenient in frequency or purity for transmission to the antennas, so it is used to lock a transfer oscillator, usually at a higher frequency. The signal from this transfer oscillator is then split and transmitted to the antennas, along some cables or fibers whose lengths are stabilized. Because cable losses increase with frequency and fiber systems have an upper limit of a few GHz, the transmission frequency must be lower than the final frequency of the interferometer, and it is necessary to have one or more phase lock loops (PLLs) in each antenna at successively higher frequencies leading up to the final Gunn oscillator. These PLLs also serve the purpose of filtering the phase noise in the reference signal, using each oscillator as a flywheel to smooth over fast fluctuations in the reference.

Figure 2 shows a generic phase noise plot for a PLL. The phase noise is presented in units of power per 1 Hz bandwidth, relative to the carrier, as a function of frequency offset. A typical signal source has phase noise which increases rapidly toward low frequency offsets, due to drifts, and a noise floor at high frequency offsets, which is due to thermal noise. When a signal is multiplied in frequency by a factor of N, the phase noise increases by a factor of N^2. In the limit of low phase noise, it is easy to see why this is so. Since time delays in the signal are unaffected by the multiplication, phase jitter must be proportional to multiplication factor. Sideband power is proportional to the square of the phase jitter, and therefore to the square of the multiplication factor. Since well-designed oscillators tend to have similar noise floors, the result of multiplication is that multiplied, low-frequency signals usually have higher noise levels at large frequency offsets than do unmultiplied, high-frequency signals. However, the most stable oscillators are available at low frequencies. Thus, on the phase noise plot, the multiplied, low-frequency signal is usually superior at small offset frequencies, while the unmultiplied high-frequency signal is superior at large offsets.

PLLs are designed to take the best characteristics of each oscillator. A PLL can be viewed as a type of servo, which forces the high frequency oscillator to follow the low-frequency one, within the bandwidth of the loop, but which allows the high frequency oscillator to run freely at offsets beyond the bandwidth of the loop. By choosing the bandwidth to be near the crossover point in the phase noise plot, then, the phase noise of the locked oscillator can be better than either the reference or the free-running unlocked oscillator. In the chain of transfer oscillators, the bandwidths of the PLLs usually increase steadily as the crossover points move to higher offset frequencies.

One consequence of this is that the transmission bandwidth increases along the chain of oscillators. There is no limit on the bandwidth, except at the point where the reference signal is transmitted to the antennas. Unless some attempt is made to equalize the lengths of the cables to the various antennas, there will be a differential time delay proportional to the difference in lengths. If the maximum length difference is 1km, and we require that the phase difference be less than 0.1 radian, then the maximum transmission bandwidth is roughly 3 kHz. We must therefore impose the requirement that the signal generated in each dish be sufficiently pure that no significant decorrelation is produced by noise at offsets greater than 3 kHz. If the cable lengths were approximately equalized, then the bandwidth could be increased in inverse proportion to the length difference.

The graph in figure 3 shows the phase noise characteristics of some typical oscillators. The phase noise levels have all been adjusted to a common frequency of 100 GHz, by allowing for the effect of any required frequency multiplication. Also marked on the plot is a line marking the threshhold for a signal/noise ratio of 100 at 1 THz. The significance of this line is that, for each octave it is just crossed by the phase noise curve, the decorrelation of the LO signal in an interferometer would decrease the measured fringe amplitude by 1%. In a local interferometer, as described above, phase noise at frequency offsets below 3 kHz is common to all the antennas and does not produce any decorrelation.

From the curve for a typical Gunn oscillator it can be seen that the phase noise does not fall below the line until the frequency offset reaches approximately 1 MHz, which is therefore the minimum bandwidth for the final lock loop. Phase noise curves for two high quality synthesizers are also given on the plot. It can be seen that the HP 8662 is almost adequate as it stands, although it is a bit too noisy at large offset frequencies. The HP 8642 is superior at high frequencies, but quite poor at small offsets. The best intermediate oscillators are cavity or YIG oscillators runing at frequencies of a few GHz, though these have noise levels which are too high at an offset of 3 kHz to be locked directly by the transmitted reference signal. A suitable system, therefore, would also have a crystal oscillator in each antenna to provide long term stability. If the low-noise crystal shown in the plot is used, then it should be used to lock the cavity or YIG oscillator with a bandwidth of approximately 50 kHz, and the cavity or YIG oscillator would be used to lock the Gunn, with a loop bandwidth of 1-2 MHz. Provided that the reference signal from the base station was transmitted with a bandwidth of at least 500 Hz, such a local oscillator chain should degrade the signal/noise ratio of the interferometer by no more than 1%, even at frequencies as high as 1 THz.

Phase Drifts

The above analysis shows that it is possible to construct LO systems with sufficient purity for the SMA, at least at frequencies where multiplied Gunn oscillators can be used. There is another difficulty, however, which is the problem of long-term phase drifts. The longest term drifts are removed by regular observations of calibrators, but it is impractical to calibrate more often than every 20 minutes or so, and the local oscillator system must therefore be stable enough not to drift between calibrations.

The two major sources of such drifts are cables and components such as mixers, amplifiers and frequency multipliers. Except for avoidable causes such as bad connectors, the largest influence on the phase is temperature. If we assume that the equipment cabin is stabilized within 2 K, then it is possible to estimate maximum tolerable cable lengths. I assume that the main part of the cable from the base station to the antenna is stabilized by some system which measures its electrical length, but that in the part of the LO system beyond the end of that transmission cable, any further cable drifts are uncompensated

If we specify that any drifts over 30 minutes should contribute less than 1% loss, the rms phase should be less than 6°, which corresponds to a path length error of 6 μm at a frequency of 800 GHz. For reasonably good cable with a temperature coefficient of about 10 ppm/K, the allowable length is only 30 cm. While some improvements on these numbers are possible, the unavoidable implication is that the transmission cable must have its length stabilized up to a point very close to the receiver, to minimize the length of uncompensated cable.

Component drifts are also significant. For example, in the OVRO system described by Padin, Woody and Scott (1988), the most critical components contribute 20°/K at 115 GHz. Such a drift would be intolerable when multiplied to 800 GHz, and must be avoided either by controlling the temperature of such critical components, or by applying the phase reference as far up the LO chain as possible. For example, if ~~the reference~~ was transmitted over an optical fiber at the frequency of the YIG oscillator, drifts in the chain below the YIG frequency would not matter in the final phase of the system. Figure 4 shows a block diagram of a suitable LO chain for the SMA, assuming that a high frequency reference signal can be transmitted over an optical fiber.

Conclusions

The brief analysis presented here demonstrates that there are no fundamental obstacles to the provision of a stable local oscillator system for the SMA, for frequencies where multiplied Gunns can be used. Care must be taken in the construction, however, particularly to avoid drifts in cables and components. One possible system would have a complete synthesizer in each antenna, starting with a 100 MHz crystal oscillator, locking a YIG oscillator at a few GHz. If the reference is transmitted from the base station at the YIG frequency over an optical fiber, then it could be compared directly with the YIG signal, bypassing any drifts in the multiplication chain.

For the highest frequencies, where laser local oscillators are currently used, there may be no easy way to operate an interferometer at present. In a few years, however, it will almost certainly be possible to use SIS receivers at all proposed SMA frequencies, and multiplied Gunns can then be used to provide a suitably stable LO signal.

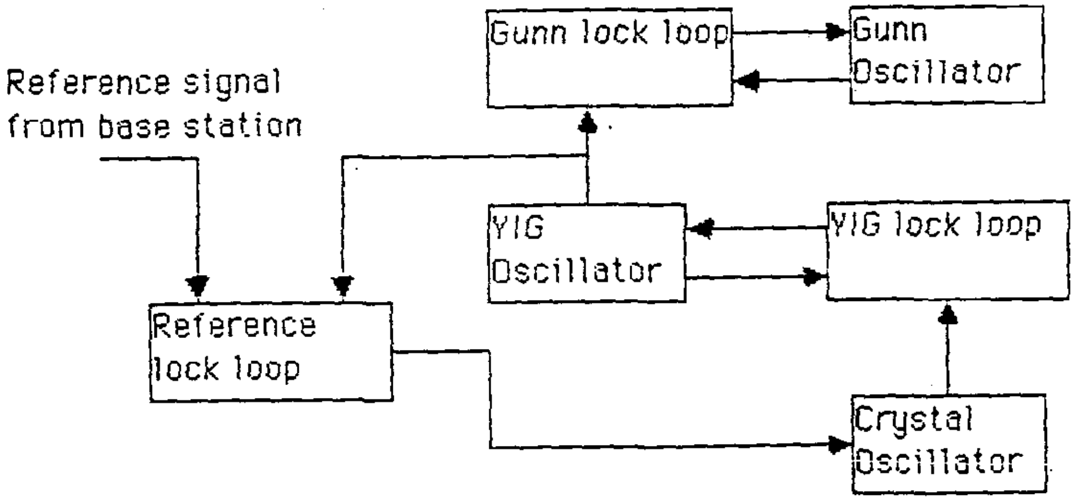

Figure 4. Outline of an LO chain which employs a high frequency reference signal to synchronize the antennas. This avoids phase drifts occurring below the YIG oscillator. The necessary flexibility in frequency is provided either by a synthesizer in the YIG lock loop or by a separate variable reference frequency transmitted from the base station.

12/24/88

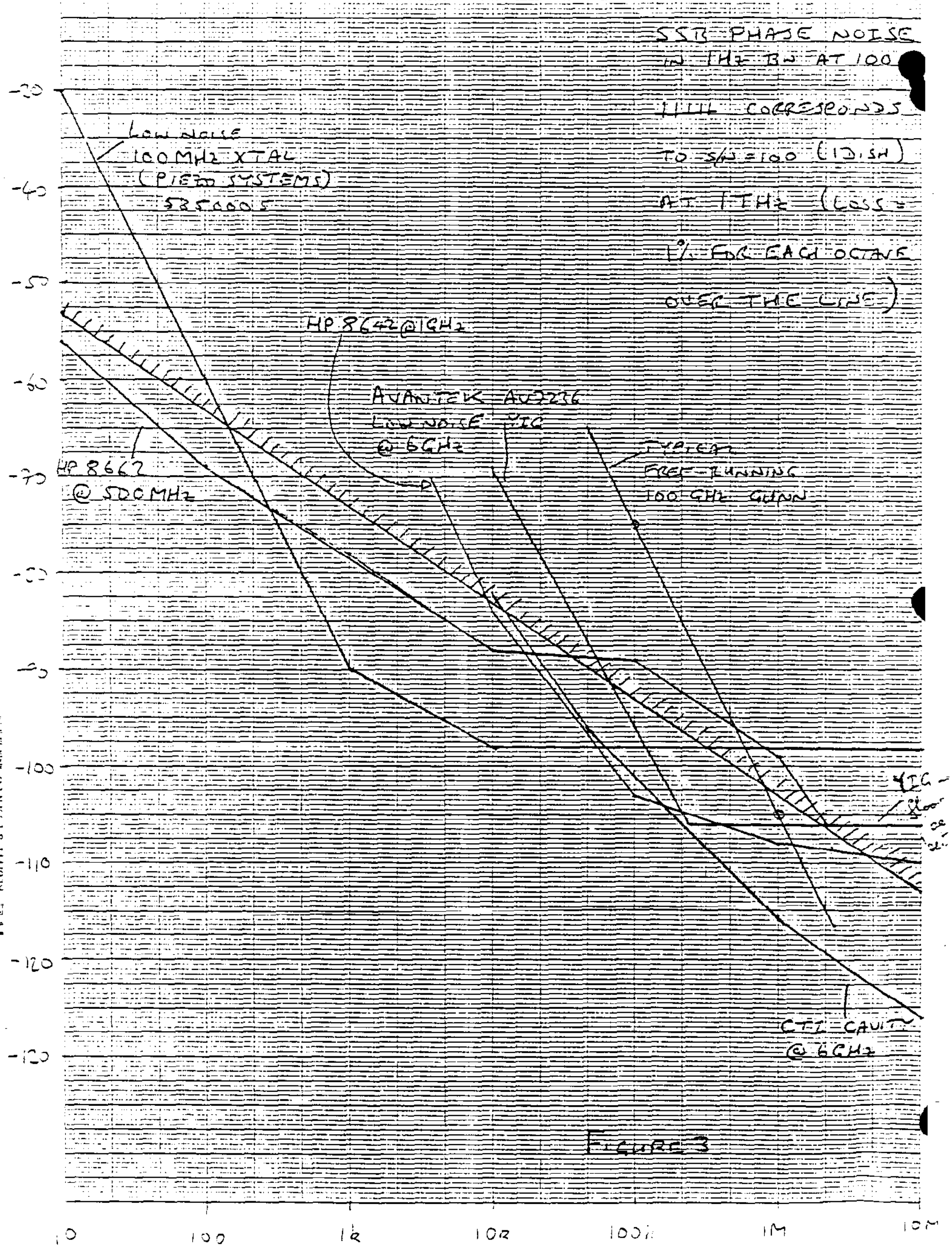

FIGURE 3

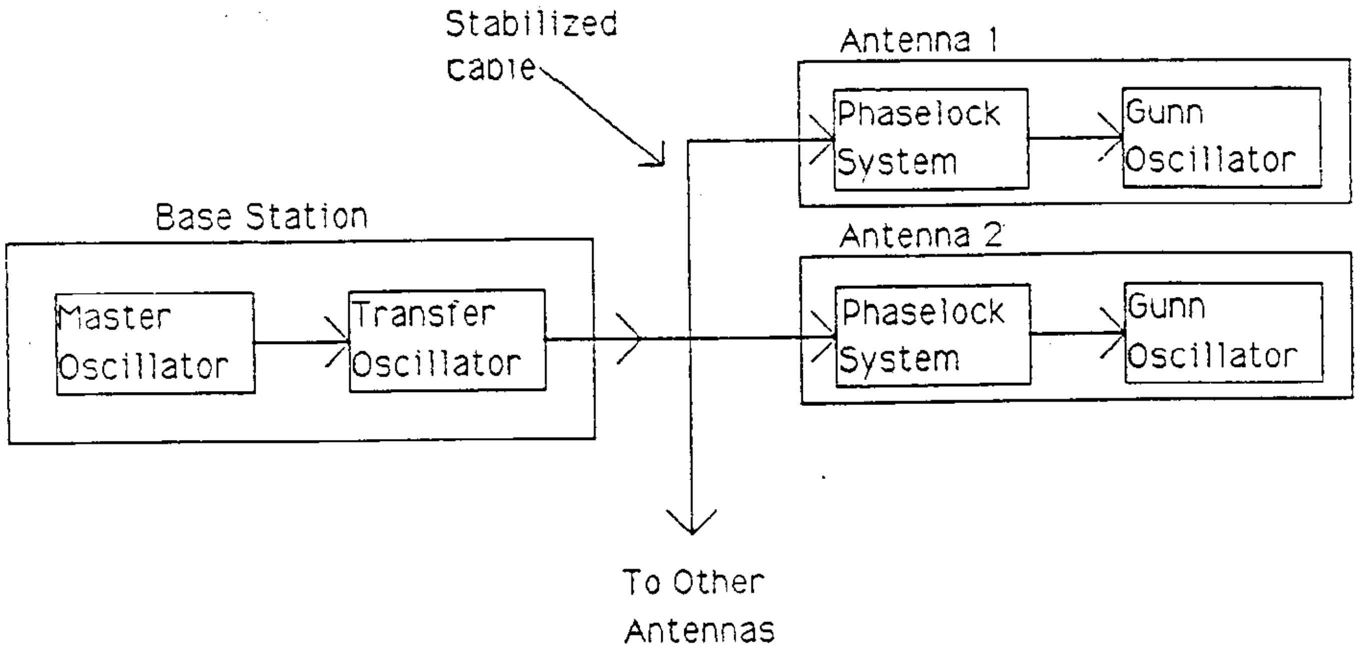

Figure 1. Generic LO system for a connected-element interferometer.

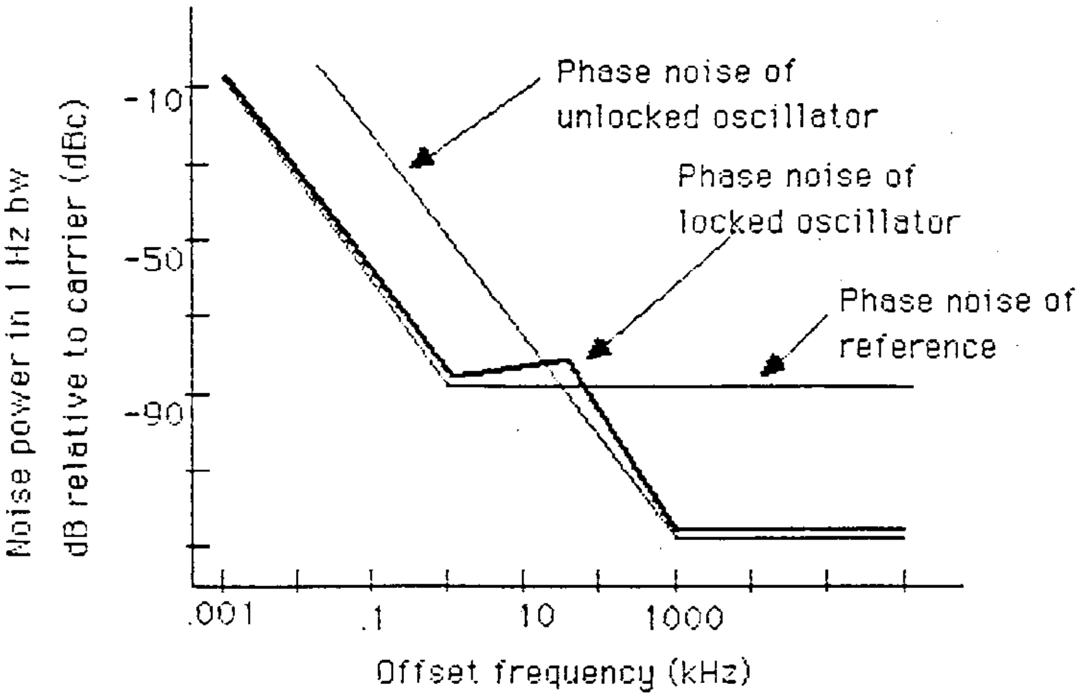

Figure 2. Phase noise in a typical PLL. The thin lines show the phase noise of the reference and the unlocked oscillator, while the heavy line shows the resulting noise of the locked oscillator.