# Detection of Weak Signals with an Injection Locked Oscillator

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**Zusammenfassung:** A software ring oscillator with a capture range of more than ± 5% can regenerate injected signals with SNR = -20 dB and identify even weaker signals with SNR = -27 dB. Injection Locked Synchronous Oscillators correspond to a first-order PLL and are always stable. Therefore no calculations or adjustments are necessary. An ILO is very easy to implement: no phase detector, no varactor, no loop filter.

**Introduction:** NMR signals in the earth's magnetic field are extremely weak and can only be detected with very narrow-band filters. With a large bandwidth, the filter allows too much interference to pass and the signal disappears in the noise. A low frequency Injection Locked Oscillator (ILO) easily reaches bandwidths smaller than 0.01 Hz and has the advantage that its frequency follows the signal frequency within certain limits.

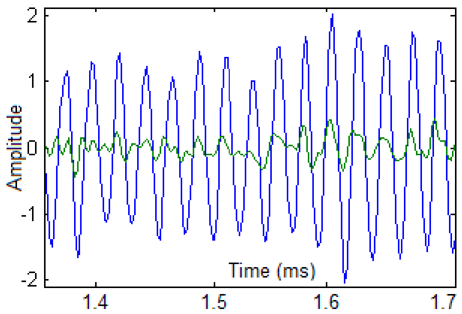


*Fig 1: Comparison of a noisy signal and ILO result in the locked state.*

The function of an ILO is easy to describe: A signal interferes with a harmonic oscillator of similar frequency. If the signal amplitude is large enough and the frequency difference is small enough, the signal can synchronize the oscillator. Then both frequencies match and the noise creates a variable phase difference. Suitable as ILO are oscillators whose frequency can be easily influenced because frequency changes cause only a small phase shift in the frequency-determining part of the circuit. In technical terms: the quality factor of the frequency-determining parts of the circuit should be as low as possible. Therefore RC oscillators are better suited than quartz or LC oscillators. A ring oscillator is even more advantageous and is used in the following.

## Features of an Injection Locked Oscillator:

a) If the frequencies of signal and ILO differ too much, the spectrum of the ILO output voltage shows the two spectral lines of signal and oscillator. The latter is surrounded by a broad noise base, caused by the inherent phase fluctuations of the ring oscillator and the interference from the supplied signal.

b) The lock-in range is the frequency range from which the locked-in state can be reached. This transition to the synchronized state can take some periods of the signal.

c) The hold-in range is the frequency range in which the ILO works stable and locked in. Its frequency is identical with the signal frequency. The spectrum of the ILO shows a very narrow spectral line, accompanied by a noise base defined by the signal. The hold-in range is wider than the capture range.

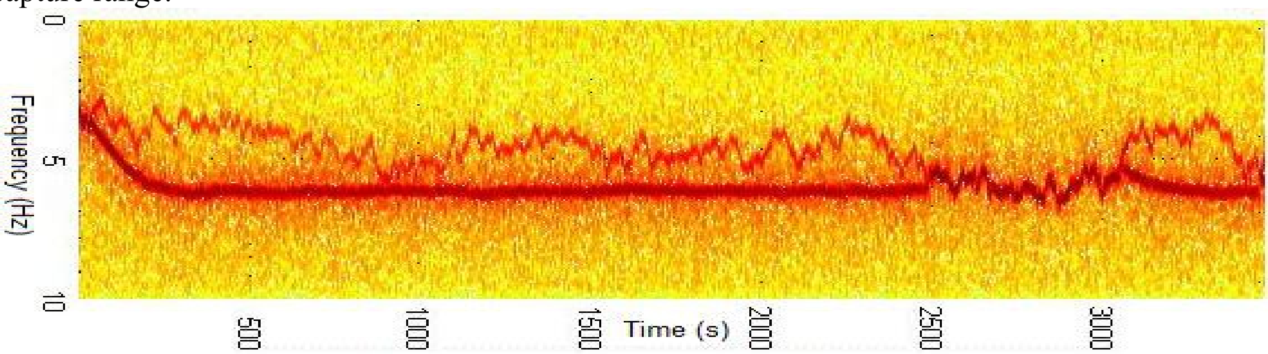


*Fig 2: Temporary synchronization of the ILO (below) by a weaker frequency variable signal.*

The spectrogram in Fig. 2 shows interesting details: A weak signal of highly variable frequency tries to "catch" an ILO. First, the synchronization fails because the signal frequency is outside the lock-in range (from time 0 s). The ILO then strives towards its preset, almost constant frequency near 6 Hz and ignores the signal because its frequency is outside the capture range. The reddish color fringes are caused by the strong phase noise of the disturbed ring oscillator. At time 2450 s the signal frequency reaches the capture range, whereupon the ILO synchronizes. From now on both frequencies are identical. At a later point in time (3040 s) the signal frequency exceeds the hold-in range and the lock-in state ends.

During the period from 2450 s to 3040 s, the more intense color indicates that the average amplitude of the ILO increases as long as the locked state is maintained. At the same time, the half-width of the spectral line decreases. Both may serve as proof of the locked state.

**Programming of the ILO:** If the signal is available in digitized form, the ring oscillator is not realized as hardware with electronic components but as a program. The basic circuitry of the oscillator is described in [[1]] and is specified in the following. An ILO has three control inputs and one output:

– Like a VCO, the value "z" changes the average frequency of a ring oscillator within certain limits. The range of values $0<z<1$ should be observed. The starting value of z is chosen so that the ILO synchronizes as fast as possible. Normally you know the frequency range in which you are looking for the signal. The frequency of the ring oscillator grows approximately proportional to "z". At a sampling rate of 50 Hz, the relationship is $f[Hz]=7.9\cdot z+0.8$ . For higher accuracy requirements in the range $0.1 < z < 0.9$, formula $f[Hz]=-2.11\cdot z^2+10\cdot z+0.29$ must be used. If the sampling rate is doubled, all coefficients in the above formulas must be doubled.

– The value "v" defines the nominal amplitude of the ring oscillator without signal. Because of the limiting property of the sigmoid function, the amplitude should be less than two. Above this value, the waveform is distorted and the frequency deviates from the calculated value. If the amplitude is too low, the amplitude stabilizing effect of the sigmoid function is reduced. However, the fed signal increases the amplitude of the ILO, which is why there is no temporary interruption of the oscil-lations. The lower the programmed amplitude of the ring oscillator, the wider the capture and hold range becomes. A target amplitude below 0.5 has proven to be effective. The value of "v" has to be adapted to the current value of "z". In the range $0.1<z<0.9$ use $v=-2.65\cdot z^2+6.13\cdot z-7.7$ . If the frequency range is limited to values around $z \approx 0.5$, the simpler formula $v=3.44\cdot z-7$ holds. The calculated value does not depend on the sampling rate.

– At each calculation step, the actual amplitude of the signal s(k) is added as interference to the calculated value of the ring-oscillator and should not be too large. Good results are obtained with $A_{Osci} / A_{Signal} \approx 10$ (see Fig. 1). It's worth experimenting a little here. The core of the MATLAB program[1] consists of a few lines:

```
for k=2:size(y,1)
  b=v*(1/(1+exp(-y(k-1,3)))-0.5); y(k,1)=z*b+(1-z)*y(k-1,1)+s(k);
  b=v*(1/(1+exp(-y(k-1,1)))-0.5); y(k,2)=z*b+(1-z)*y(k-1,2);
  b=v*(1/(1+exp(-y(k-1,2)))-0.5); y(k,3)=z*b+(1-z)*y(k-1,3);
end, plot(y(:,3))
```

Do not use channel `(y(:,1);` channel `(y(:,3)` is less noisy, because `(y(:,2)` acts like a low pass.

**Measurement of the capture range:** In the following examples, the value for "z" is selected so that the frequency of the ring oscillator *without signal* is 4.00 Hz. The amplitude should be less than 1. In contrast to a ring oscillator made of electronic components, the spectral line of the programmed ring oscillator is low-noise, there is also no temperature dependence.

1 H. Weidner, A Software-Ring oscillator, 2020

Sinusoidal signals of different frequencies are fed in and the spectrum of the ILO is measured. The blue curve in Fig. 3 shows the minimum amplitude an undisturbed signal has to achieve in order to "capture" the ring oscillator. Once this has been done, the ILO generates an almost noise-free signal, i.e. a sharp spectral line of narrow half-width. Therefore an ILO is very well suited for the regeneration of weak noisy signals. When the signal is frequency modulated, the ILO precisely follows any changes.

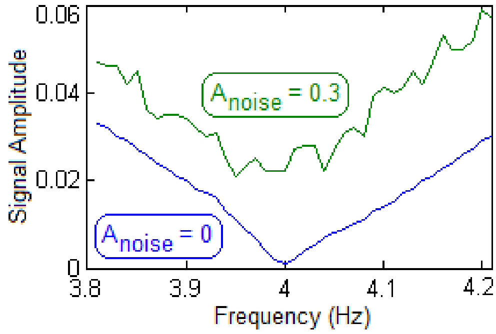


*Fig 3: Minimum signal amplitude as a function of frequency to achieve synchronization. Without signal the ring oscillator generates the frequency 4.00 Hz.*

The green curve in Fig. 3 shows the ability of the ILO to synchronize weak signals despite a much higher noise level. If the signal frequency is not exactly known and does not deviate more than 5% from the nominal frequency of the ILO, the accompanying noise amplitude may be at least 12 times stronger than the amplitude of the signal. The SNR = -21 dB of the signal is improved to about SNR = 0 dB of the ILO output voltage. With increasing frequency spacing, the signal amplitude must increase to achieve synchronization.

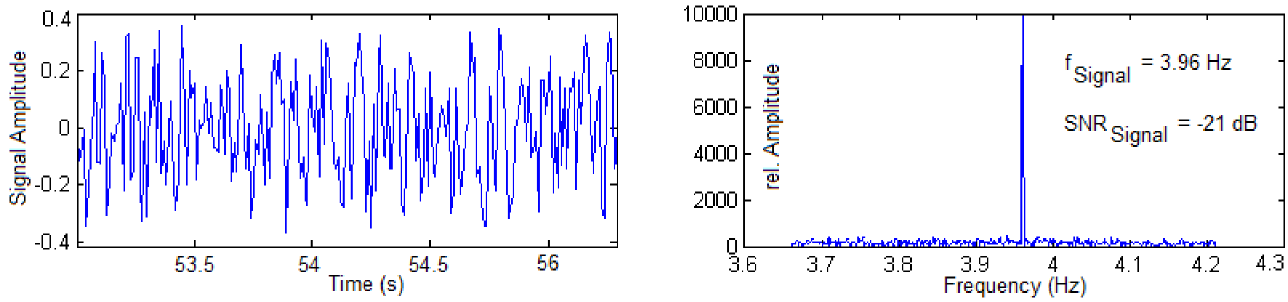


*Fig 4: Left: The injected signal (A=0.03) is not visible in the stronger noise (A=0.3) Right: The ILO is still synchronized, the signal frequency is clearly visible.*

Frequency changes of ± 5% can be followed by the ILO without any problems. In case of larger fluctuations, the average frequency of the ring oscillator must be tracked to prevent loss of synchronization (see Fig. 2). A suitable procedure is described in another article.

**The limits of sensitivity:** An ILO is able to detect weak signals in noise and determine their frequencies. In contrast to electronic components, a program is not damaged if the recommended range of values is exceeded. Many programs then produce nonsensical results, not so the ILO. Although the ILO is programmed in such a way that its (undisturbed) output amplitude has a value of about 0.5, a higher additional signal may be impressed. Of course, in view of this overload, no coherent sinusoidal oscillation can be expected as the output signal of the ILO. Nevertheless, the spectrum contains useful information.

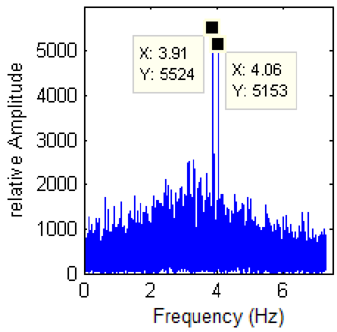


*Fig 5: Spectrum of the output voltage of the ILO at highly noisy signal*

In the next example this is the sum of noise (amplitude = 5) and two sinusoidal signals of the arbitrarily selected frequencies f1 = 3.91 Hz and f2 = 4.06 Hz. Both amplitudes have the same value 0.18. The ILO succeeds in detecting both signal frequencies simultaneously. The peaks exceed the noise background by at least twice the amount. The output signal of the ILO looks like noise and contains no indication of a sinusoidal oscillation. Nevertheless, the FFT program finds enough in-phase fragments of both signals and can identify them correctly despite SNR = -29 dB. A PLL circuit would not manage this.