ESTABLISHMENT OF NMR MAGNETOMETER FREQUENCY TRACEABILITY WITH THE LONG WAVE TRANSMITTER DCF77

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Key words:NMR magnetometer, DDS, sampling detector, DCF77 transmitter

Abstract: A simple, low power and cost-effective solution for the establishment of nuclear magnetic resonance magnetometer reference oscillator frequency traceability with the use of the long-wave DCF77 transmitter is described. The system assures a relative oscillator uncertainty of less than 10^{-7}. A low-cost direct digital synthesizer (DDS) is used to divide the reference signal and a binary counter is used to further divide the reference signal to obtain the signal for phase comparison with the DCF77 signal by means of a sampling detector. The signal from the sampling detector is amplified, digitized, filtered and analyzed by a microcontroller and a 12-bit analog-to-digital converter. The reference oscillator is not phase locked to the DCF77 signal, but only the difference of the two frequencies is measured as time of the period of the demodulated and filtered signal from the sampling detector. The frequency of the reference oscillator is calculated with the DDS frequency tuning word setting where the measured time of the period of the demodulated signal reaches the maximum value.

Vzpostavitev frekvenčne sledljivosti JMR magnetometra s pomočjo dolgovalovnega oddajnika DCF77

Kjučne besede: JMR magnetometer, DDS, vzorčevalni detektor, DCF77 oddajnik

Izvleček: V prispevku je predstavljena enostavna, energetsko varčna in cenovno ugodna rešitev za zagotavljanje sledljivosti referenčnega oscilatorja magnetometra, ki deluje na principu jedrske magnetne resonance, s pomočjo dolgovalovnega oddajnika DCF77. Sistem zagotavlja relativno negotovost oscilatorja manjšo od 10^{-7}. Signal referenčnega oscilatorja se deli s cenenim direktnim digitalnim sintetizatorjem (DDS) in binarnim števcem, dobljeni signal pa se fazno primerja z DCF77 signalom s pomočjo vzorčevalnega detektorja. Signal vzorčevalnega detektorja se ojača, digitalizira, filtrira in analizira z mikrokrmilnikom in 12-bitnim analogno-digitalnim pretvornikom. Referenčni oscilator ne deluje v fazno sklenjeni zanki z DCF77 signalom, ampak se meri razlika frekvenc obeh signalov, kot čas periode demoduliranega in filtriranega signala vzorčevalnega detektorja. Frekvenca referenčnega oscilatorja se izračuna z uporabo nastavitve DDS-a, pri kateri doseže merjeni čas periode demoduliranega signala največjo vrednost.

Introduction

The most accurate standards for magnetic flux density unit are based on magnetometers using nuclear magnetic resonance (NMR). The basic principle for measuring magnetic flux density with a NMR magnetometer is based on the conversion of magnetic flux density to frequency measurement. The magnetometer uses a reference oscillator as a reference source for frequency measurement.

When a NMR magnetometer is used as a part of the magnetic flux standard in an accredited calibration laboratory, its reference oscillator is periodically calibrated to assure the traceability of measurements (to the primary frequency standard).

The Laboratory for magnetic measurements uses an absorption type magnetometer /1/ for measurements of magnetic flux density. Its reference oscillator uncertainty should be in the order of 10^{-7} to have a minimal effect on the magnetometer measurement uncertainty.

A simple and cost-effective solution for assuring the traceability of the NMR magnetometer reference oscillator using the long-wave transmitter DCF77 is presented.

The frequency traceability of the NMR magnetometer is assured by means of the comparison of the divided NMR magnetometer reference oscillator signal with the signal from the DCF77 long-wave transmitter. There are also other ways of establishing frequency traceability of a reference oscillator such as the GPS signal /2, 3/ and short-wave transmitters /4/, but by using the long-wave transmitter the circuit implementation is relatively simple and no special receivers are required.

The DCF77 transmitter is transmitting the reference time and frequency signal at 77.5 KHz. The transmitter uses both amplitude and phase modulation of the carrier. The modulation does not influence the use of the carrier frequency for frequency comparison because the amplitude modulation is carried out by sinking the output power to 25 % of its maximum power (and not by interrupting the transmission) and the phase modulation is a pseudo-random phase modulation with a zero mean value /5/.

The DCF77 receiver

A block diagram of the DCF77 receiver is presented in Figure 1. The reference oscillator is a temperature compensated crystal oscillator (TCXO) operating at 40 MHz. Its frequency could be tuned electronically.

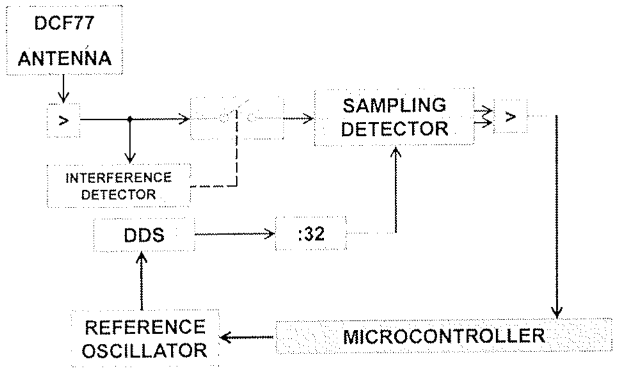

Fig. 1: Block diagram of the DCF77 receiver.

The reception of the DCF77 signal is ensured with a ferrite bar antenna, a three stage amplifier and a band-pass filter. The low-cost DDS used has a 10-bit DAC and a 28-bit frequency tuning word (FTW) to generate the reference signal for the demodulator based on the sampling detector /6/.

A DDS operating with a 40 MHz reference oscillator and with either a 28-bit, 32-bit or 48-bit FTW has a relative frequency resolution of $1.9\cdot10^{-6}$, $1.2\cdot10^{-7}$ or $1.8\cdot10^{-12}$ respectively. The calculations represent DDS output frequency resolutions relative to the DCF77 frequency. Without the binary frequency divider, the use of a DDS with a larger FTW would be necessary (more expensive, higher power requirements).

The DDS signal is filtered with a low-pass filter and further divided by 32 with a binary counter in order to increase frequency resolution of the DDS signal. In this way a square wave signal with a duty cycle of 50 % and with a relative frequency resolution of $6\cdot10^{-8}$ at 77.5 kHz is obtained. The square wave output signal drives the sampling detector based on a quad bilateral high-speed complementary metal oxide semiconductor analog switch. Two switches are used as a single pole double throw (SPDT) switch and are driven by a complementary 77.5 kHz signal. The other two switches are inserted between the SPDT switch and the capacitor of the sampling detector and are controlled by the interference detector circuit (noise blanker).

Instead of phase locking the NMR TCXO to the DCF77 signal, only the difference of the two frequencies is measured and displayed as time of the half-period (time between two reference crossings of the demodulated signal). It is also advantageous to measure time because the amplitude of the DCF77 received signal could be monitored at the same time. If the relative frequency uncertainty of the reference NMR oscillator is in the order of 10^{-7}, it can be neglected, compared to other NMR magnetometer measurement uncertainty contributions. This value of relative frequency uncertainty can be assured without phase locking the NMR TCXO.

The FTW of the DDS used in the DCF77 receiver is changed and the time of the period t_p of the demodulated signal is measured. The FTW at which the t_p reaches the largest value is used in calculation of the TCXO frequency.

The DDS is controlled by the microcontroller of the NMR magnetometer.

Experimental results

The prototype of the presented receiver was built and tested.

Figure 2 shows the schematic diagram of the DCF77 antenna circuit. Coil L1 is wound on a ferrite bar and together with the fixed capacitor C1 and trimmer capacitor C2 forms a resonant circuit tuned to 77.5 KHz. Transistor Q1 forms the first amplifier stage. Its output is fed via a coaxial cable to the DCF77 receiver.

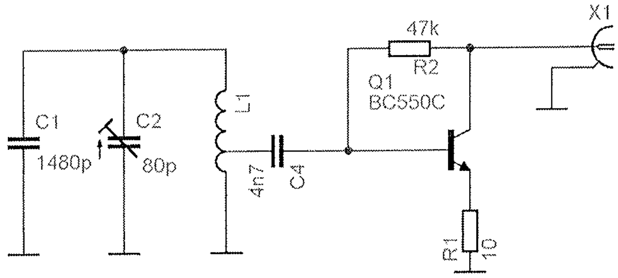

Fig. 2: Schematic diagram of the DCF77 antenna circuit.

Figure 3 shows the DDS circuit. The reference oscillator output is buffered and fed to the DDS (IC1) and to the NMR magnetometer (REF CLK). The control signals are generated by the microcontroller of the NMR magnetometer.

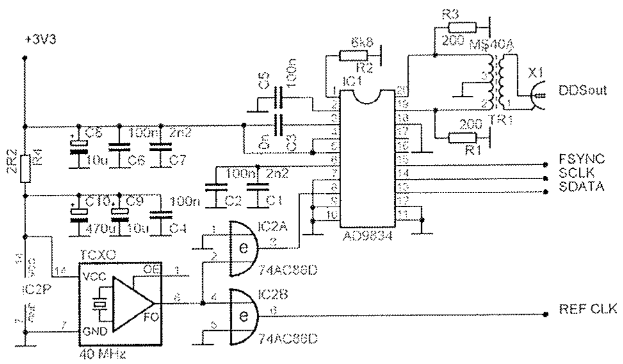

Fig. 3: Schematic diagram of the DDS circuit.

The DCF77 receiver schematic is shown in Figure 4. The constant current source for DCF77 antenna supply is built with a field-effect transistor Q2. The DCF77 signal amplitude at the source of Q2 is approximately 0.07 mV. The DCF77 signal is amplified in a two stage amplifier to approximately 8 mV and band-pass filtered with a resonant circuit tuned to 77.5 KHz (C2, TR1). The amplified signal is fed to a sampling detector built with a quad analog switch (IC1). Two switches operate at the receiving frequency,

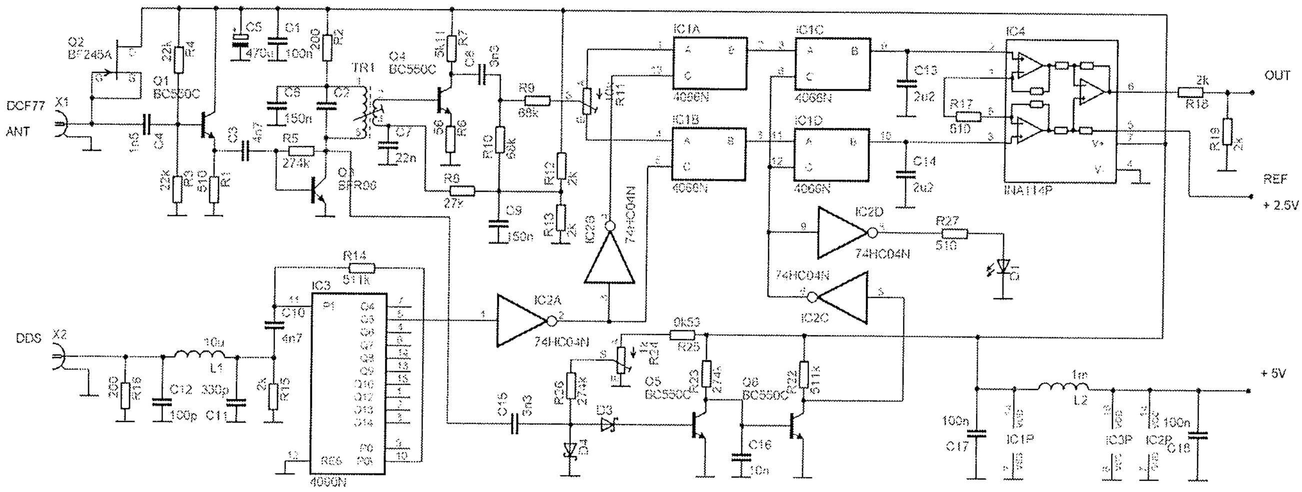

Fig. 4: Schematic diagram of the DCF77 receiver.

while the other two disconnect the sampling capacitors C13 and C14 in case of strong interferences and act as a switch of the noise blanker circuit. The direct current offset of the demodulated signal is adjusted to the mid-level with R11. The demodulated signal is amplified (40 dB) with the instrumentation amplifier IC4 and fed to the analog-to-digital converter (ADC) of the microcontroller via a resistive divider to adapt to the ADC input voltage range.

The reference signal for the sampling detector from the DDS is low-pass filtered (C12, L1, C11), converted to the square-wave and divided by 32 with the binary counter IC3. The divided output and the inverted output are used to control the analog switches of the sampling detector (IC1A and IC1B).

The noise blanker consists of a two-diode detector circuit (D3, D4), DC amplifier (Q5, Q6) and a signal shaper (IC2C). The level at which the noise-blanker is activated is adjusted with the potentiometer R24.

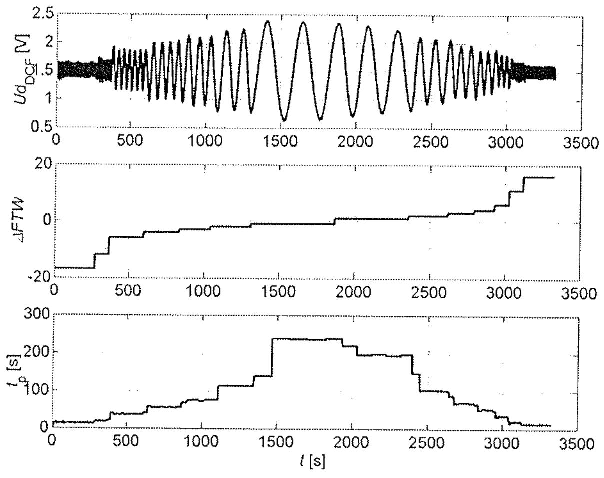

Fig. 5: Demodulated signal from the DCF77 transmitter Ud$_{DCF}$ and the time of one periode at different settings of the DDS FTW of the DCF77 receiver ΔFTW, ΔFTW = FTW - 16643112.

The DCF77 receiver uses 3.3 V and 5 V power supply. The current consumption of the 3.3 V power supply (used for the reference oscillator and the DDS) is 20 mA, the current consumption of the 5 V power supply (used for other circuity of the DCF77 receiver) is 23 mA.

The digitized demodulated signal from the DCF77 receiver and the FTW value were sent to the personal computer and stored on the hard disc for later processing and presentation.

The output frequency of the DDS is set to 77.5 kHz · 32 = 2.480 MHz. Assuming a TCXO frequency of 40 MHz, the calculated *FTW* is:

$$FTW = \frac{f_{OUT} \cdot 2^{28}}{f_{REF}} = 16642998 \qquad (1)$$

where f_{OUT} is the output frequency of the DDS and f_{REF} is the frequency of the reference oscillator (TCXO). Figure 5 shows the filtered demodulated signal from the DCF77 transmitter Ud_{DCF} and the time of one period t_p at different settings of the DDS FTW of the DCF77 receiver *DFTW*. The amplitude of the demodulated signal is changed because of the low-pass filter. The filter is a simple moving average filter, with the equation

$$Ud_{DCF} = (1 - kf_{DCF}) \cdot Ud_{DCF} + kf_{DCF} \cdot PSDdcf_{ADC}, \qquad (2)$$

where the $PSDdcf_{ADC}$ is the signal form the ADC and kf_{DCF} is an adjustable parameter of the filter. The t_p has the largest value when *FTW* = 16643112. This *FTW* is used in calculation of the TCVCXO frequency f_{REF}:

$$f_{REF} = \frac{f_{DCF77} \cdot 32 \cdot 2^{28}}{FTW} = 39.999726 \quad \text{MHz}. \qquad (3)$$

Figure 6 shows the spectrum of the demodulated and filtered signal Ud_{DCF} from the DCF77 transmitter. The peak at 0.088 Hz corresponds to t_p of 114 s. The peak at 1 Hz and its harmonic components are due to the amplitude modulation of the DCF77 signal used for transmission of the time code.

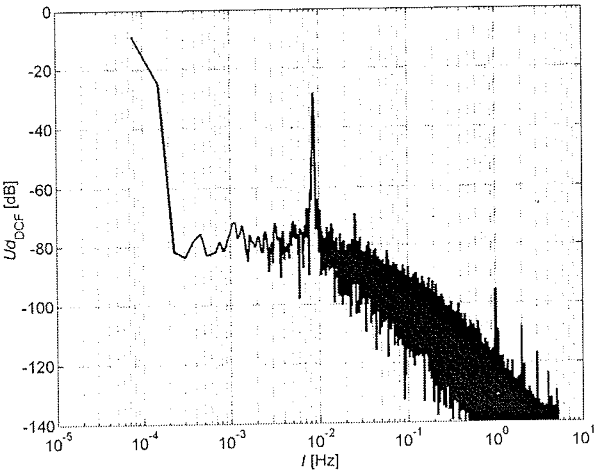

Fig. 6: Spectrum of the demodulated signal from the DCF77 transmitter.

The spectrum was obtained from the recorded signals during the measurement with the NMR magnetometer lasting over 3 hours and a half. The *FTW* was changed to 16643110 intentionally to obtain a stable periodic signal Ud_{DCF}. The time of one period t_p should not be less than 75 s in order to obtain a relative uncertainty of the reference crystal oscillator of less than 10^{-7}.

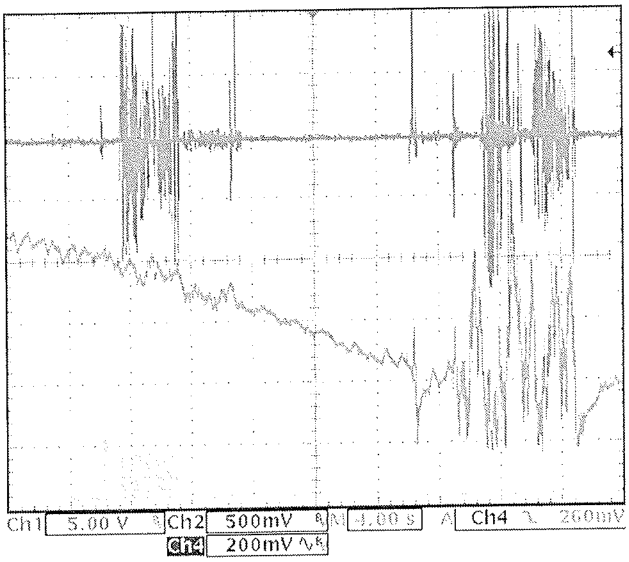

Fig. 7: Demodulated signal with enabled and disabled automatic interference filter.

The noise-blanker efficiently suppresses the interferences, as can be seen in Figure 7. The left half of the figure was recorded with the noise blanker enabled. The upper trace is the radio frequency signal present at the resonant circuit formed by TR1 and C2, the middle signal is the demodulated signal fed to the ADC and the lower signal is taken from the buffer IC2D and has high level when the analog switches disconnect the sampling capacitors due to the interferences received. On the right half of the figure the noise-blanker has been disabled. The received interferences cause high noise level superimposed on the demodulated signal. Low level variations of the demodulated signal are due to the amplitude modulation of the DCF77 signal.

Conclusion

Frequency traceability of the NMR magnetometer reference oscillator is established by means of the DCF77 long-wave transmitter with a relative uncertainty of less than 10^{-7}. Beside the DDS integrated circuit the DCF77 receiver uses only standard elements. The microcontroller used is part of the NMR magnetometer. The software is simple to implement as only a moving average filter and a counter to measure the time of one period of the demodulated signal are needed.

The presented system could be used also with other instruments that need reference oscillator traceability.

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