**RF Choke for VLF and LF Applications**

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## 1. Introduction

Very few places on Earth are not plagued by radio frequency interference (RFI) in the very low frequency (VLF, 3 to 30 kHz) and low frequency (LF, 30 to 300 kHz) bands. The RFI may be produced by switchmode power supplies, poor quality LED lights and light dimmers, motors, powerline network adapters, so-called smart home controls, a multitude of electronic devices and their chargers, and nearby powerlines. The RFI may be coupled to a coaxial cable transmission line as *common-mode* (longitudinal) currents and then appear at the input to a receiver where it can easily override weak signals.

An *RF choke* may reduce the interfering RF currents flowing on the cable. The chokes described in this article are lossy inductors made by winding small diameter coaxial cables through ferrite cores. The chokes are inserted in series with the coaxial feedline between the antenna and receiver, usually one at each end (figure 1). The inductors present a high impedance to the longitudinal currents. These currents are absorbed by the choke and dissipated as heat. The chokes have no effect on the desired signals (*differential mode* currents) between the center conductor and shield.

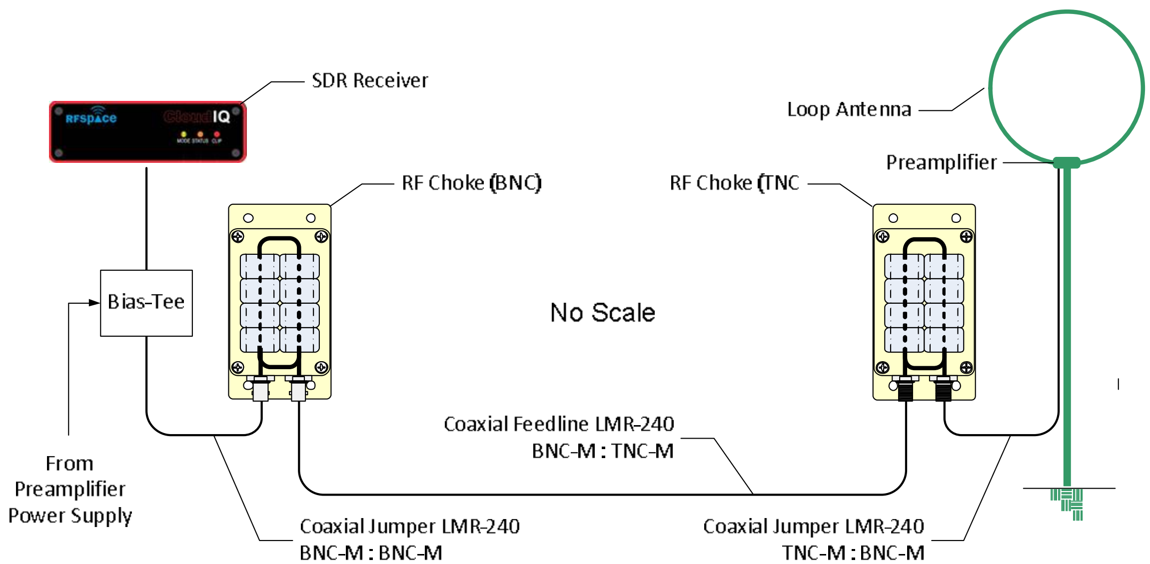


Figure 1 ~ Working diagram of choke application to reduce interference coupled to the transmission line. Sometimes only one choke is needed and its location is determined experimentally. ©2020 W. Reeve

If the antenna has a preamplifier that is powered through a bias-tee on the coaxial feedline, the dc flows in opposite directions on the center and shield conductors. Direct current flowing through ferrite core windings could generate a magnetic field that saturates the core and reduces the choke inductance; however, in this case, the magnetic fields are generated in opposite directions and cancel each other, thus having no effect on the choke inductance. For this to work as intended, it is important that the powering currents are confined to the coaxial cable and there are no stray paths.

The remainder of this article describes chokes that I built specifically for use with an HP 10509A loop antenna that originally was designed for reception of the time-frequency station WWVB at 60 kHz. The chokes are not limited to this specific application and may be usable with any antenna and receiver that uses a coaxial feedline and operates in the VLF and LF bands. The chokes also may be suitable for higher frequencies such as the MF and HF bands (300 kHz to 3 MHz and 3 MHz to 30 MHz, respectively) (see section 4 for measurements). At some locations only one choke may be needed to adequately suppress interference. The chokes described here are intended only for receiver circuits.

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## 2. Choke Types

Electrically, the choke is a lossy (low Q) inductor. At lower frequencies, its reactive impedance is proportional to the inductance and frequency, but the choke may be self-resonant and show capacitive reactance at frequencies above resonance (see {Reeve13}). To be effective at low frequencies, the inductance must be high to achieve a high impedance.

I initially considered three basic choke constructions (table 1). From a practical standpoint, only one type provides high impedance at low frequencies and that is the type made with multiple toroid cores and multiple coaxial cable turns on those cores. This construction is described in the next section.

Table 1 ~ Comparison of basic choke constructions

| Description | Construction | Impedance dependencies | Low frequency applications |
|---|---|---|---|
| Air core coil | Multiple windings of coaxial cable formed into an air core coil | Cable and core diameters and number of turns; has resonant effects | Requires extreme number of turns; not practical |
| 1-turn series string of toroid cores | Coaxial cable inserted through multiple toroid cores | Number of cores and core material | Requires extreme number of toroid cores; not practical |
| Toroid core coil | Multiple windings of cable through one or more toroid cores; requires small coax and large cores | Number of cores, core material and number of turns | Requires moderate number of turns and toroid cores |

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## 3. Choke Construction

My construction plan was simple: Pack as many toroid cores and as many windings as possible into the small weatherproof plastic enclosures I had on-hand. I did not target a specific choke impedance but hoped to achieve at least 1 kohm in the operating frequency range 10 to 100 kHz. My expectation was that the chokes would have no effect on normal signal transmission. There is nothing unique or original about the construction techniques described in the following paragraphs. I built two chokes, one with TNC connectors for outdoor use and the other with BNC connectors for indoor use.

I found that 8 pcs of Fair-Rite mix 75, p/n 2675821502, EMI suppression toroid cores would fit in the enclosures. I purchased the cores from Mouser Electronics for a little more than 1 USD apiece. The dimensions of each toroid are 31 OD x 19 ID x 15 T mm (1.22 x 0.748 x 0.591 in). These manganese-zinc (MnZn) toroids have high relative *permeability μ*, which is given as 5000 in the manufacturer's datasheet. Permeability indicates the ability of a material to become magnetized when placed in a magnetic field; a high permeability is necessary for attaining high inductance at low frequencies.

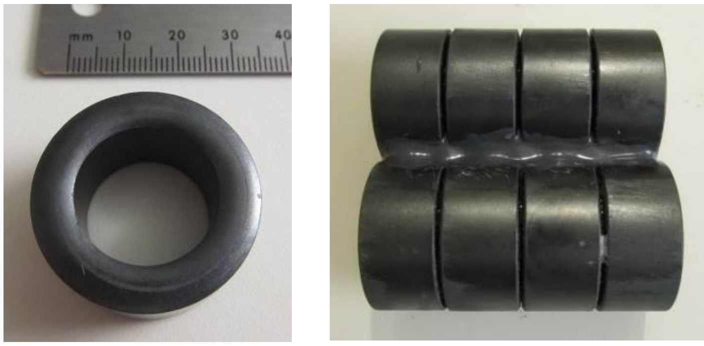


Figure 2 ~ Left: Fair-Rite toroid core, p/n 2675821502; Right: Binocular core formed from eight toroids in two rows. The cores in each row are first glued with superglue and after curing the two assemblies are then glued together with epoxy. ©2020 W. Reeve

Figure 3 ~ Alignment and clamping of each half of the binocular core. Two 1/2 x 2-3/4 in aluminum angles were clamped laterally in a vice and then the two blocks of four toroid cores each were placed on the angles for alignment. One of the angles is visible at the left-middle. Each block was held together with a non-metallic hobby clamp that uses a rubber band as seen with four toroids at the right-middle. The clamp was left in-place while the glue cured for 24 h. ©2020 W. Reeve

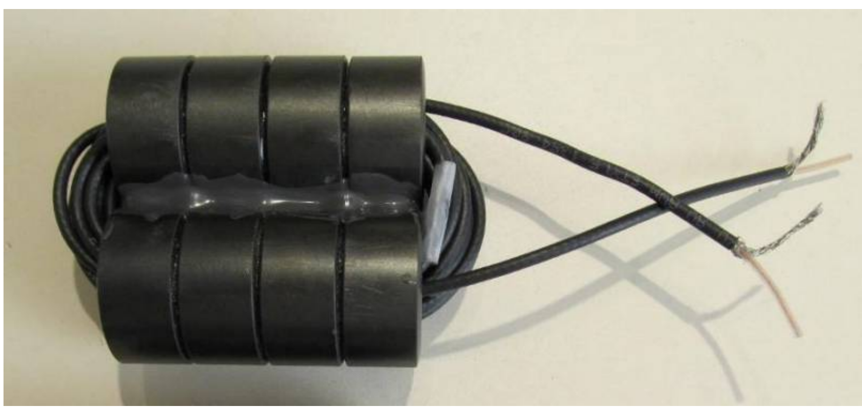

Figure 4 ~ Completed binocular core with windings ready for installation in the plastic enclosure. A piece of tape is seen at the center of the image. It was used to mark the center of the length of cable so that the core could be wound evenly from both ends. ©2020 W. Reeve

I glued the individual toroids into the form of a binocular core (figure 2). I used a small bead of Loctite SuperGlue Gel on the individual toroids to hold them in two blocks of four toroids per block. The toroids were first aligned on a piece of aluminum angle held in a bench vice (figure 3). A non-metallic hobby clamp held the toroids together while the glue cured. After 24 h two block assemblies were clamped together with non-metallic hobby clamps through their apertures while a mixture of 2-part epoxy was applied at the junction between the two assemblies. The epoxy was allowed to cure overnight. I built two complete binocular cores using this procedure.

After the epoxy had cured, the binocular core assemblies were cleaned with a cloth wetted with paint thinner. The finished binocular cores measure 60 L x 62 W x 31 H mm (2.364 x 2.440 x 1.22 in).

I wound the chokes with RG-174/U coaxial cable, which has 2.79 mm (0.11 in) outside diameter. I estimated that the average turn on the binocular core would require 7.25 in of cable (2x length of core block + 2x center-to-center spacing) and that 20 turns may be possible (each loop through both eyes of the binocular core is counted as 1 turn). This resulted in a total cable length of 145 in (just over 12 ft, or 3.7 m) for each choke. A 145 in piece of RG-174/U coaxial cable was cut from a spool and spread out on the floor for inductance measurements. The measured shield inductance with a Keysight U1733C LCR meter was 4.37 µH at 10 kHz and 4.33 µH at 100 kHz. This inductance may be compared to the later measurements of the completed chokes in section 4. The coax was then wound through each eye of the binocular assembly, resulting in 20 turns (as predicted) with approximately 100 mm long pigtails at each end (figure 4).

The measured dimensions of the weatherproof ABS plastic enclosures are 131 L x 69 W x 49 H mm (5.2 x 2.7 x 1.9 in) including the mounting flanges (figure 5). I acquired them through eBay for 3 USD each, and the listing showed the dimensions as 100 x 68 x 50 mm, not including the flanges. The enclosure is barely wide enough for the eight cores; in fact, the enclosure inside width is about 0.5 mm undersized, which required the binocular core to be tilted at a slight angle so as to not bend or stress the enclosure sides.

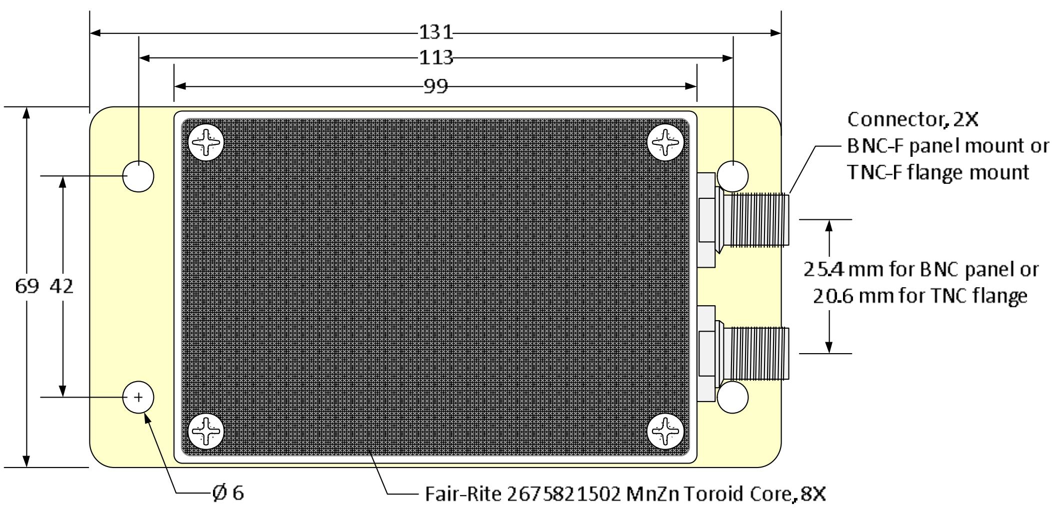


Figure 5 ~ 75% scale drawing showing basic enclosure dimensions (mm) as measured. The binocular core is not centered. Both connectors were placed at one end to ensure enough space for internally connecting the coax to the connectors and to allow the enclosure to shield the connections from rain. ©2020 W. Reeve

The enclosures were first prepared by cutting holes with brad-point drill bits on one end for the connectors. The holes for the BNC panel-mount connectors were cut with an undersized drill bit and then reamed so the connectors could be self-threaded into the plastic. The washer, ground lug and nut were then placed on the connector, tightened and secured with a small drop of superglue. The openings for the TNC flange-mount connectors were cut with a 1/8 in drill bit for the mounting holes and a 19/64 in drill bit for the center (figure 6). I used 3 mm fasteners (machine screw, internal star ground lug and nut) for the TNC flanges.

The binocular cores with windings were then placed in the enclosures. Before using hot glue to anchor the cores, I soldered the center and shield conductors to the connectors (figure 7). I originally hoped to use crimp connectors but the crimp sleeves were too long for the limited space between the connectors and the cores.

The final task was to install the supplied rubber seal in each top cover and fasten the cover to the units (figure 8).

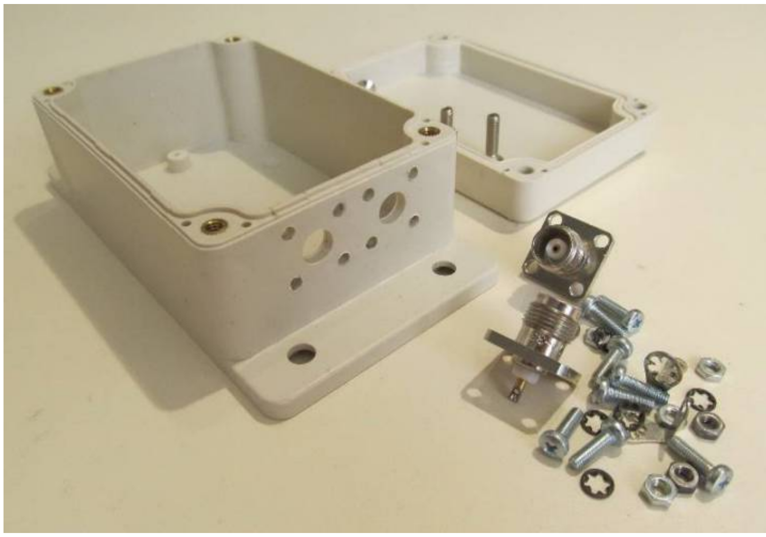

Figure 6 ~ Choke enclosure ready for installation of TNC flange-mount connectors. All connector holes were cut with brad-point drill bits and deburred. ©2020 W. Reeve

Figure 7 ~ Interior view of the choke with TNC connectors. Hot glue holds the binocular core in place. The coax shield is soldered to a ground lug on each connector flange. ©2020 W. Reeve

Figure 8 ~ Completed units ready for final testing, BNC on the left and TNC on the right. ©2020 W. Reeve

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**4. Measurements**

The shield inductance, Q and impedance of each completed choke was measured with the Keysight LCR meter at 10 and 100 kHz (table 2). The dc resistance was measured with the Keithley 2110 DMM setup for 4-terminal (Kelvin) resistance measurements. I also measured the same parameters for the center conductor and all measurements were very similar to the shield except the center conductor dc resistance was higher (about 1 ohm, as expected). The impedance measurements were in line with my expectations based on the core permeability. At the low end (10 kHz) the shield impedance is approximately 1 kohm and at the high end (100 kHz) is 15 kohm.

Only slight measurement differences are seen between the TNC and BNC chokes. For example, the difference between the impedances of the two chokes at 100 kHz amounts to only about 4.5%. The slight differences can be ascribed to the manufacturing variations in the toroid cores as well as the non-precision construction of the windings. Even variations in the coaxial cable construction contribute to the difference, although these are expected to be small for the high-quality cable used here (Coleman RG-174/U). For my application, the slight differences between the two chokes are not important.

Ideally, the choke impedance is proportional to frequency; for example, if the impedance at f1 is Z(f1), then the impedance at 10x f1 will be 10x Z(f1). However, it is seen from the tabulated data that the impedance Z(100 kHz) actually is 13.5x Z(10 kHz). This probably is due to the higher resistance at 100 kHz caused by skin and proximity effects (these also affect the inductance to some degree).

Table 2 ~ Shield conductor inductance, Q, impedance and dc resistance
Note the much lower Q at 100 kHz compared to 10 kHz due to higher losses

| **Frequency** | **TNC Choke** | **BNC Choke** | **Instrument** |
|---|---|---|---|
| Inductance, 10 kHz | 18.084 mH | 17.797 mH | U1733C |
| Inductance, 100 kHz | 24.17 mH | 23.10 mH | U1733C |
| Q, 10 kHz | 200 | 211 | U1733C |
| Q, 100 kHz | 27.4 | 29.0 | U1733C |
| Impedance, 10 kHz | 1.130 kohms | 1.113 kohms | U1733C |
| Impedance, 100 kHz | 15.201 kohms | 14.523 kohms | U1733C |
| Resistance, dc (20 °C) | 0.143 ohms | 0.142 ohms | 2110, 4-terminal measurement |

In addition to the basic measurements described above, I measured the reflection coefficients (S11 and S22) and transmission coefficients (S12 and S21) of each choke with a VNWA-3E vector network analyzer and S-Parameter Test Set (see {Reeve17} for a description of this instrument combination). I made two sets of calibrations and measurements, one from 5 kHz to 105 kHz and another from 100 kHz to 10 MHz. The purpose of these measurements was to confirm good transmission properties of the chokes (figure 9).

The measurements from 5 kHz to 105 kHz required special CoDec settings in the VNWA-3E (900 Hz sample rate and 1 x4 samples per IF period for a 225 Hz IF). For the measurements from 100 kHz to 10 MHz, I used default settings (48 kHz sample rate and 1 x4 samples per IF period for a 12 000 Hz IF).

My S-Parameter Test Set has SMA connectors so I used short (150 mm) jumper cables with SMA-M connectors on one end for connection to the test set and BNC-M on the other for connection to the chokes. I set the software for 1001 sweep frequency points and calibrated the VNA at the end of these cables with an SDR-Kits

*BNC Calibration Kit*. For the TNC choke I used BNC-F to TNC-M adapters and assumed the adapters have negligible effect at the low frequencies used in the measurements.

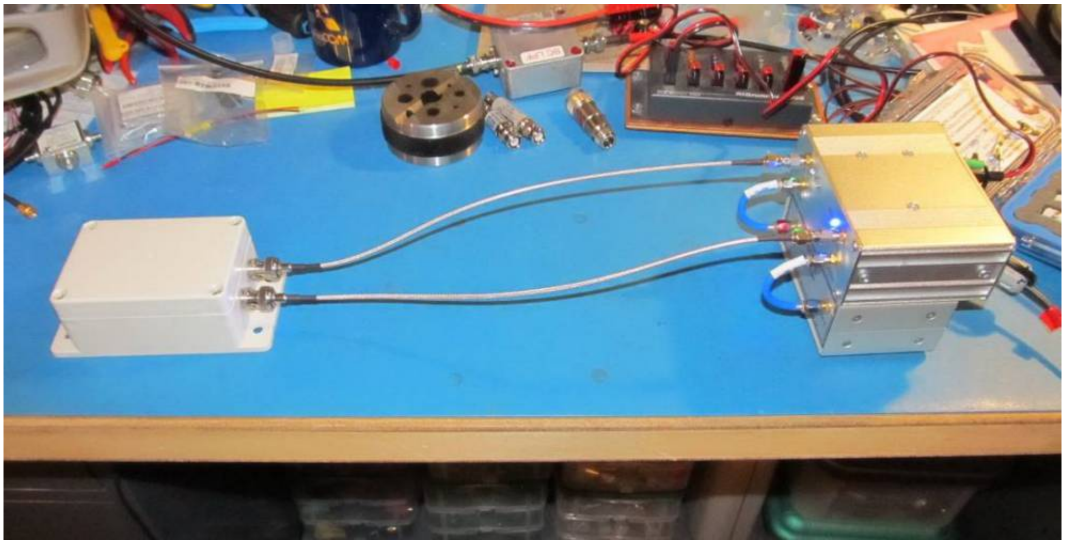

Figure 9 ~ BNC choke on the bench (left) connected to the VNWA-3E vector network analyzer with shop-built S-Parameter Test Set (right). The two jumper cables on the S-Parameter Test Set are made from RG-316 coaxial cable and are 150 mm long. ©2020 W. Reeve

The reflection and transmission coefficient measurements held no surprises and all plots are smooth with no resonant effects up to 10 MHz (figures 10 and 11). The S21 and S12 transmission coefficients in dB are equivalent to *insertion loss* in dB (IL = |S21| or |S12|) and negligible up to 100 kHz and < 0.4 dB up to 10 MHz. Similarly, the S11 and S22 reflection coefficients in dB are equivalent to *return loss* in dB (RL = |S11| or |S22|) and almost 40 dB at 100 kHz and still quite good at 25 dB up to 10 MHz. The forward (S11, S21) and reverse (S12, S22) measurements for both chokes were identical.

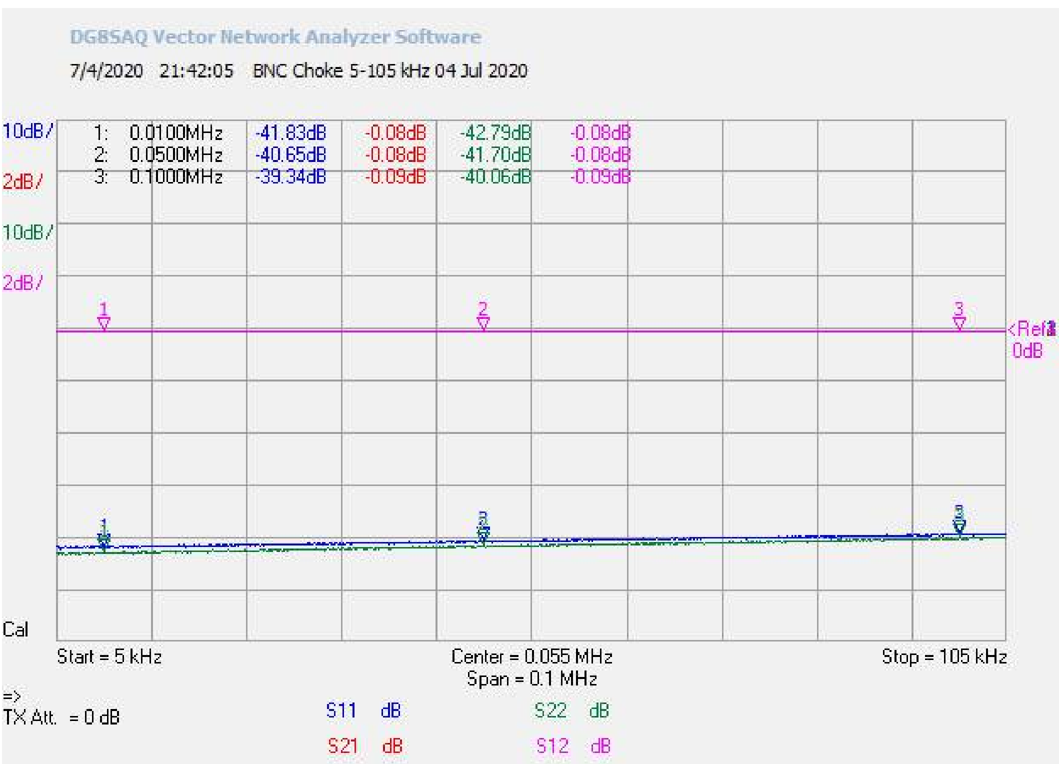


Figure 10 ~ S-parameter measurements for the BNC choke from 5 to 105 kHz. The scales for the reflection coefficients, S11 and S22, are 10 dB/div and for the transmission coefficients, S21 and S12, are 2 dB/div. The reference for all coefficients is the 6th division from the bottom. The marker table at the top-left shows the values for 10, 50 and 100 kHz.

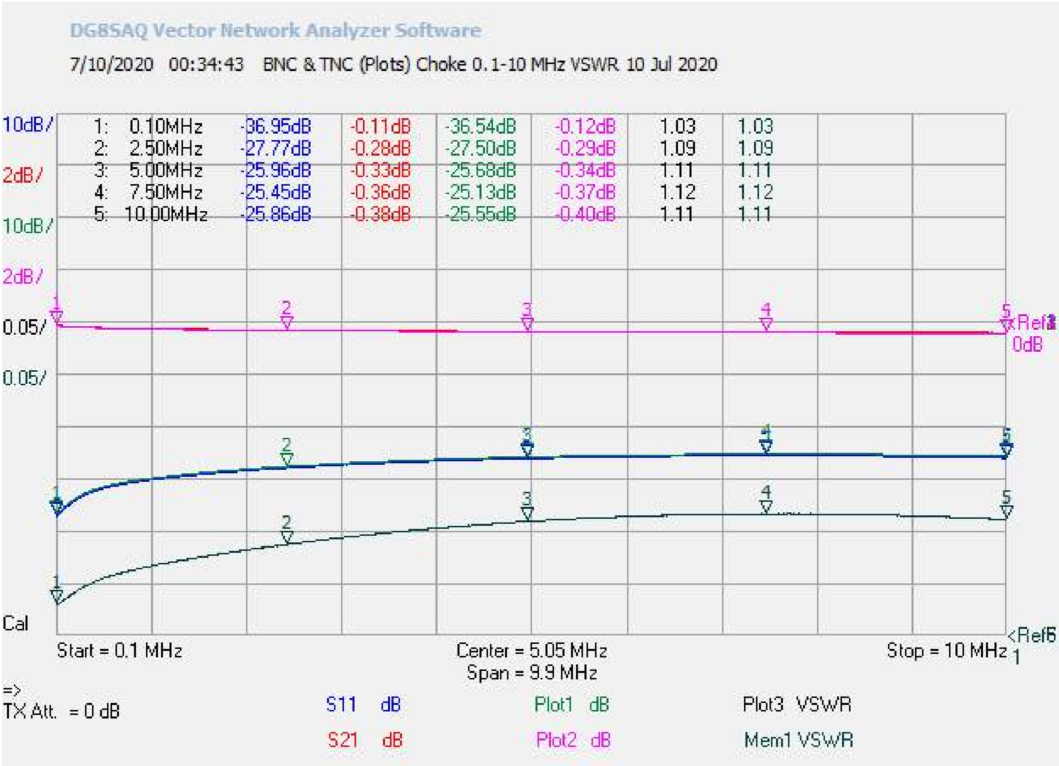


Figure 11 ~ S-parameter measurements for the BNC and TNC chokes from 0.1 to 10 MHz overlaid on the same plot. The traces marked S11, S21 and Mem1 VSWR are for the BNC choke. The traces marked Plot1, Plot2 and Plot3 VSWR are the same parameters for the TNC choke. The scales and references for S11 and S21 are the same as the previous figure. The scales for VSWR are 0.05/div with the 1.00:1 VSWR reference at 0 division.

The reflection coefficients (S11, S22) and the equivalent return losses represent the degree of impedance matching at the choke input and output. Impedance matching also can be represented by voltage standing wave ratio, VSWR, so I also plotted VSWR on the 100 kHz to 10 MHz plot. The VSWR never exceeded 1.12:1 throughout the frequency range 5 kHz to 10 MHz.

## 5. Conclusions

Two RF chokes were made from high-permeability ferrite round cable cores glued into the form of a binocular core. A 3.7 m length of RG-174/U coaxial cable was wound on each binocular core, which yielded an inductance of about 18 mH at 10 kHz and 24 mH at 100 kHz. Measurements with an LCR meter showed a shield impedance of about 1 kohm at 10 kHz and 15 kohm at 100 kHz, and measurements with a vector network analyzer up to 10 MHz showed no transmission degradation.

## 6. Weblinks and References


{Reeve13} Reeve, W. and Hagen, T., Applying and Measuring Ferrite Beads: Part I ~ Ferrite Bead Properties and Test Fixtures, 2013, available at: http://www.reeve.com/Documents/Articles%20Papers/Ferrite%20Beads/Reeve-Hagen_FerriteBeads_P1.pdf

{Reeve17) Reeve, W., Building Version 2 of an S-Parameter Test Set for the VNWA-3E, 2017, available at: http://www.reeve.com/Documents/Articles%20Papers/Reeve_S-ParamTestSet_V2.pdf

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