PART VI, Operation, Building and Testing the SWCTRL Module

Building and testing the zero-current hybrid FET-Relay switch control Board (SWCTRL)

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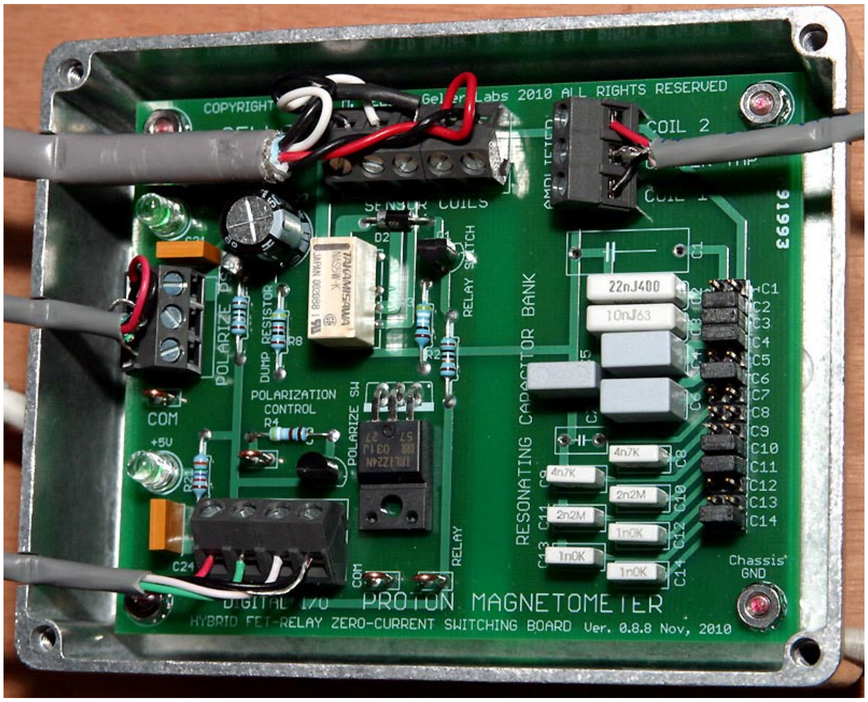
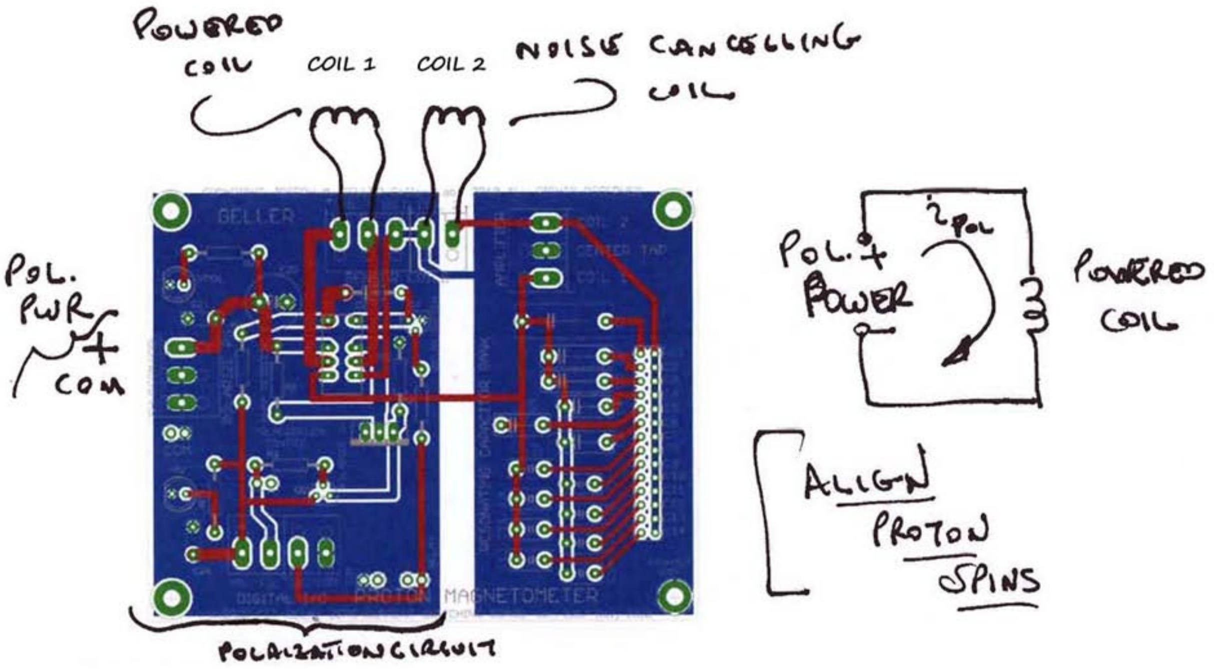
The switch control module provides many basic functions used by the FDM proton precession magnetometer. The SWCTRL board, in conjunction with digital outputs from the NI 6008 module, runs the FDM magnetometer measurement time line, the sequence of events that are used to generate the proton precession or free induction (FID) signal. Also, the SWCTRL board accepts as separate wired inputs, connections to each of the two coils of the counter-wound sensor coil pair. The board then automatically re-configures the two coils between the two operating modes, the polarization cycle and the measurement cycle.



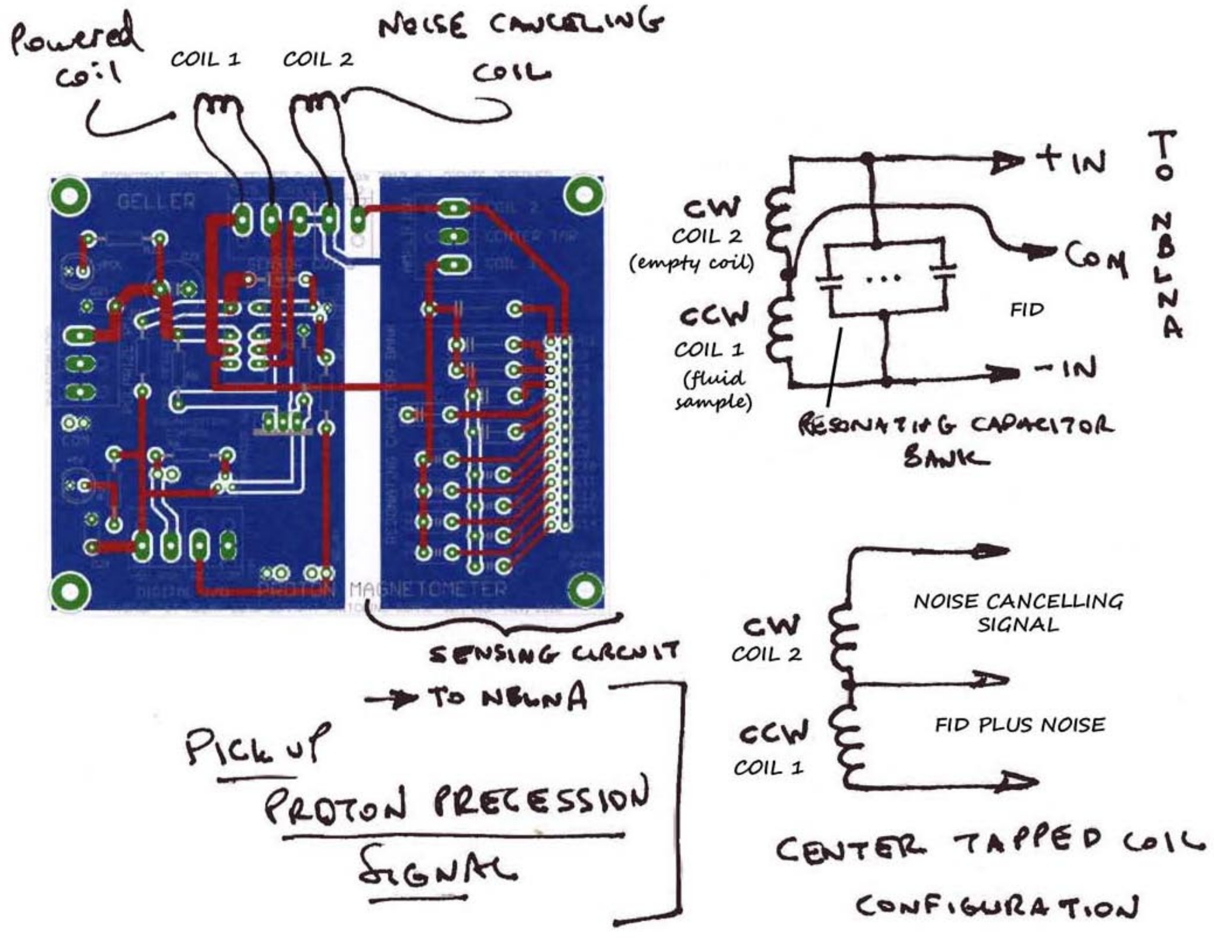
A very high quality small signal telecom relay was chosen for its ultra low capacitive coupling between the polarization contacts and the measurement contacts (around a pico Farad). Also, the relay has a rare earth magnet used not for latching, but to enhance contact closure speed and mechanical repeatability of the contact motion. However, one of the classic problems with relay usage in a proton precession magnetometer has been contact wear from arcing, particularly on contact opening. We solved this problem by adding a N-channel power FET to control the polarization current flow. Using this approach, the relay contacts never change state when there is polarization current flowing in the powered coil.

A time line run by the supervisory computer program and conveyed to the SWCTRL module by two digital outputs of the USB 6008 module (Relay and FET) first opens the relay (de-energizes the relay coil), and only after the contacts have settled in the open position (so the normally closed contacts of the DPDT relay are now closed), turns the FET on to power the powered coil. Note that for the polarization cycle, only the powered coil of the counter-wound coil pair (having the NMR fluid sample) is connected to the polarization circuit. As shown in the powered coil configuration diagram, no polarization current flows through the other un-powered (noise cancelling) coil during the polarization cycle.

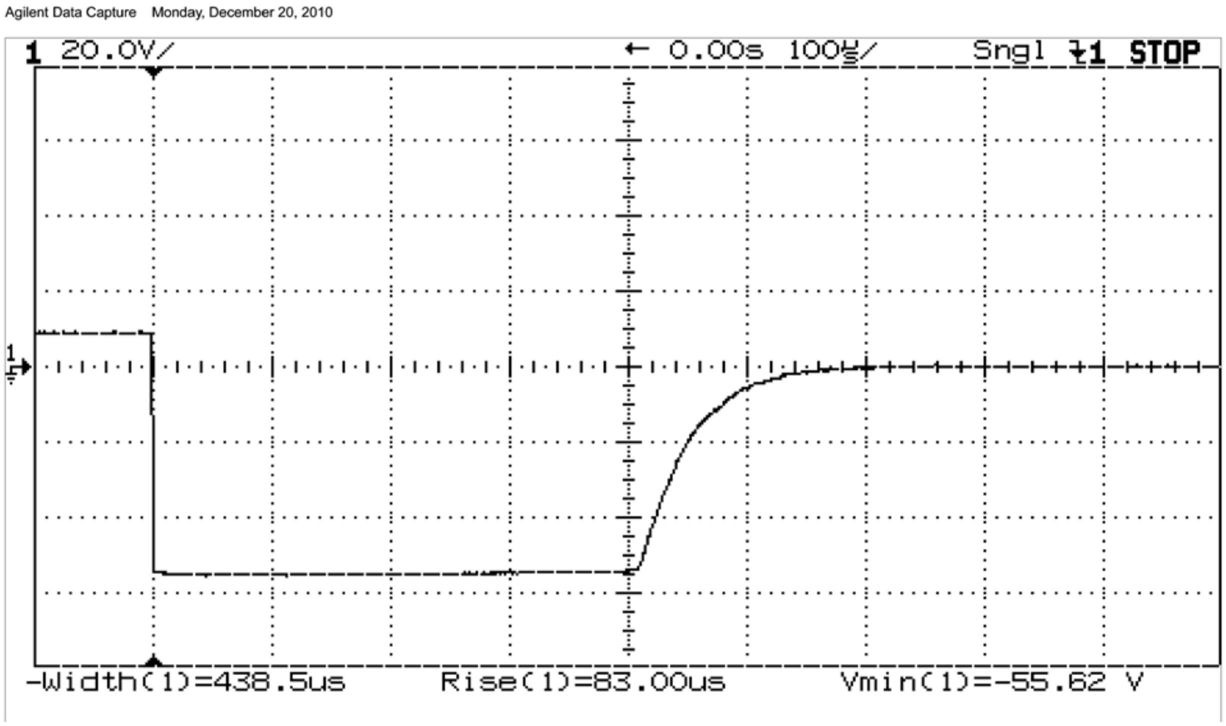


Following a desired polarization time (to align some percentage of the the proton spins in the NMR sample fluid), the current is turned off. For this type of Earth's field NMR (EFNMR) based proton precession magnetometer to function correctly, the current is turned off relatively quickly compared to the polarization time. With the sensor aligned normal to the Earth's magnetic field, the fast change in current sets the now aligned protons precessing at the Larmor frequency for the given ambient magnet field. The SWCTRL circuit provides the fast powered coil discharge in two steps. Initially, and for most of the duration of the discharge, once the FET is turned off, the coil voltage immediately reverses polarity and is allowed to rise to the FET reverse avalanche voltage. At this point, the FET essentially behaves like a zener diode and clamps the reverse voltage to the FET's rated avalanche voltage. Since the rate of change of current for a discharging inductor is directly proportional to the coil voltage during discharge, the fixed (clamped) powered coil voltage causes a mostly linear discharge curve of powered coil current versus time. Once the energy remaining in the powered coil has discharged past what can sustain the FET reverse avalanche voltage, the FET turns off. A fixed resistor which, only during the polarization cycle, is always across the powered coil, then takes over discharging the remaining energy in a classic L/R discharge.

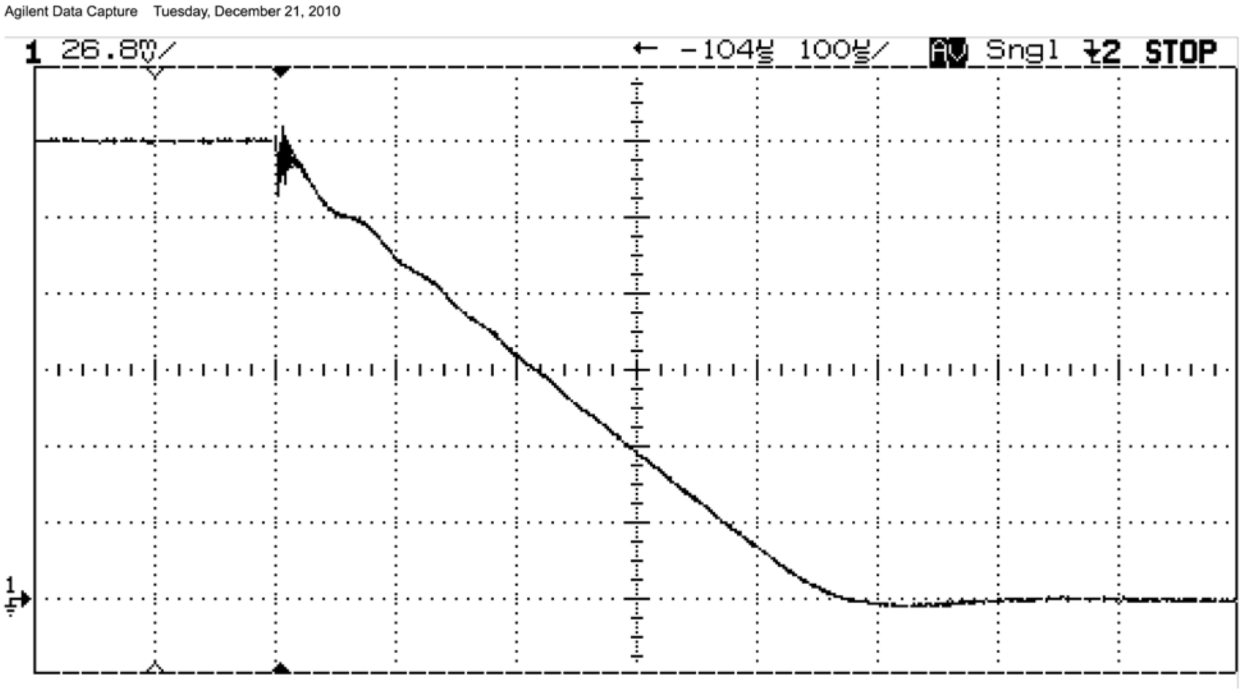
After the coil is completely discharged (zero powered coil current), the relay is closed (relay coil energized) and the normally opened contacts are now closed. In this measure mode, the two coils of the counter-wound pair are now configured a center-tapped coil having a resonating capacitor in parallel with the series combination of the two coils. Also, the combination of the center-tapped coil pair and the parallel resonating capacitor bank is simultaneously electrically coupled to the input of the narrow band low noise amplifier (the NBLNA module). In the picture of the SWCTRL PCB, it is easy to see the three wires of the center-tapped coil configuration between the polarization circuit side of the board and the analog measure side of the board. The large gap between the sections is to minimize capacitive coupling between the polarization circuitry which finds its common and ground reference through the USB 6008 module to the computer common (via the USB cable) and the analog side which is connected to the FDM magnetometer common (star) ground at the analog power supply common and ground terminals.



This operation of the relay where the relay is de-energized during the relatively low duty cycle of the polarization cycle is somewhat counter-intuitive. However, it turns out that far superior performance and precession (FID) signal repeatable relatively constant shot-to-shot amplitude is achieved by closing the relay contacts fast a reliably just prior to running the digitizer. The different performance (energize versus de-energize) is believed to be caused by the relay's internal rare earth magnet.

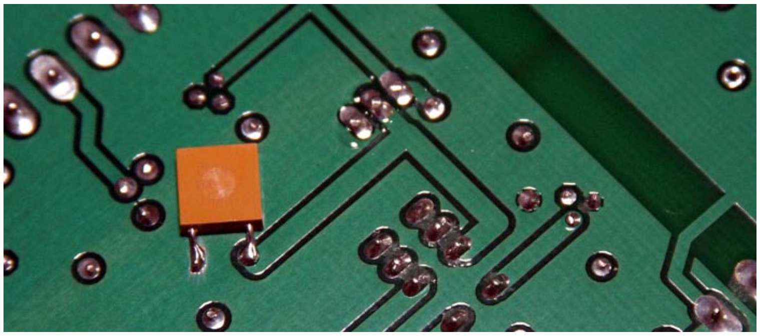


The oscilloscope display shows an example of a powered coil discharge at FET turn-off. The cable and powered coil voltage before trigger (about 9 V) is the voltage applied to the cable connected to the powered coil to cause a desired polarization current, here just over 1.5 A. When the FET is turned off (the trigger is shown by the small triangle in the lower left), the coil voltage immediately changes polarity and rises to the FET reverse avalanche voltage, here 55 V. The voltage remains clamped at the FET avalanche voltage so long as there is sufficient current flowing in the load to sustain a terminal voltage of 55 V. As can be seen in the oscillograph, after just over 400 micro seconds, there is no longer enough energy left to sustain the FET reverse avalanche mode. At this point, a secondary dump resistor takes over for the remaining portion of the classic L/R exponential discharge. The value of the secondary dump resistor should be set for about critical damping of the cable and self-resonance of the powered-coil, here above 10 kHz.



The oscillogram of powered coil current versus time shows the resulting linear ramp and final roll out from the L/R secondary dump resistor discharge. This current discharge oscillogram was based on a voltage measurement across a 0.1 ohm resistor temporarily placed in series with the "low side" lead of the powered coil cable wire. The oscilloscope was momentarily floated from AC mains ground so that the scope probe ground probe could be at a voltage different from chassis ground.

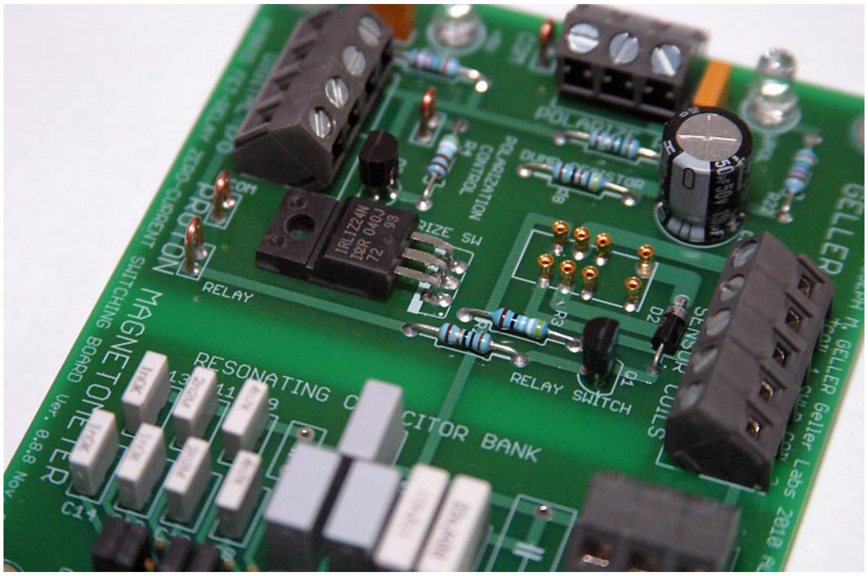
The initial current noise is due to another parasitic RLC circuit (over 100 kHz) and is mostly damped by a 0.1 uF capacitor from the FET drain to the SWCTRL PCB ground plane.



In later revisions of the SWCTRL board, this CK06 ceramic snubber capacitor will be normally mounted on the component side of the board.

The IRFLZ24N NMOS Power FET has an ultra low on resistance and does not even get warm to the touch during normal operation. Our use of the fully rated avalanche mode discharged about 22 milli

Joules, well below the maximum 70 mJ and below 2 A (absolute maximum current for the SWCTRL module), there is no concern about junction temperature rise in the reverse avalanche mode.



The TAKAMSAWA NAS5W-K (FUJISTA) is a surface mount device. However we found that by gently bending the relatively long SMD leads down, such as with a pair of small needle nose pliers, it fits nicely into MillMax gold pin jacks, our relay socket. We found that it is easiest to solder the pin jacks by first installing them on a relay and then holding them in place while soldering on the ground plane sides of the PCB. To achieve a slightly more robust construction, very small solder can be fed in from the top sides while *briefly* reheating each pin from the ground plane side.

RESONATING CAPACITOR BANK

The row of jumpers allows for selection of any desired total capacitance to achieve resonance with the powered coil at about an expected mean local Larmor frequency. One good approach is to begin with the expected local magnetic field value (F_{scalar}) as, for example, can be found from city or zip code using the online NOAA geomagnetic model[1]. Next, using the constant of 23.48720 nT/Hz[2] (derived from the Larmor constant), find your expected mean Larmor frequency by the equation:

$$f_{Larmor} = \frac{F_{scalar}}{23.4872\ \mathrm{nT/Hz}}$$

Next, determine the inductance of the series combination the counter-wound sensor coil pair[3] by either measurement with an impedance bridge, simple RLC circuit using a signal generator and an AC voltmeter, or by a modeled estimate[4]. From the expected Larmor frequency and the total coil inductance of the counter-wound coil pair (about twice the inductance of one of the coils), estimate what total resonating capacitance you need (the net sum value of the resonating capacitor bank when the jumpers are configured) by the equation:

$$C = \frac{1}{(2\pi f_{Larmor})^2 L}$$

For our 17.6 mH coils, we estimated C at about 138 nF for a center frequency of 2286 Hz, however our actual resonating C (because of mutual inductance between the two closely located side by side coils) was found to be about 125 nF.

It is only important that the resonating capacitor bank sum to at least the needed value (preferably at least slightly over, to allow for some optimization of the tuning). You can choose the value of individual capacitors in many ways. Some prefer binary related values, since the jumpers act like binary switches which add or remove each capacitor from the resonating capacitor bank (recall that capacitors add in parallel), others will use whatever values are readily available. It is probably good to use a few similarly valued very low standard values, such as 1 nF, 2.2 nF, and 4.7 nF to achieve easy fine tuning of the final selection for best resonance. Fine tuning can be accomplished by observing the precession waveform filtered envelope waveform as the values are varied shot to shot. The Fast Cycle mode can be used to expedite this process so you do not have to wait two minutes between measurements.

Work in progress … more to follow, including

checking system grounding and isolation

relay autopsy and relay life depending on applications (1,000s of hours for a geomagnetic observatory, probably less in very fast cycling field applications).

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[1] To estimate the magnetic field in your backyard, go to the NOAA National Geophysical Data Center web resource http://www.ngdc.noaa.gov/geomagmodels/IGRFWMM.jsp .

[2] IAGA Guide for Magnetic Measurements and Observatory Practice, J Jankowski and C Sucksdorff 1996, page 67 http://www.iugg.org/IAGA/iaga_pages/pdf/IAGA-Guide-Observatories.pdf .

[3] Recall that in the measurement mode, the counter-wound coil pair are presented to the NBLNA input as a center-tapped coil pair with the resonating capacitor bank in parallel. The total inductance is the sum of the two coils as modified by any mutual inductance by the close proximity of the two coils.

[4] For example, the Multi layer air core inductor calculator at http://www.circuits.dk/calculator_multi_layer_aircore.htm .