Noise reduction for SC pickups - with Telecaster and Stratocaster examples

Single coil (SC) pickups are much beloved. Humbucker tone can be great too, but it's different. There are lots of variations in pickup technologies out there, but the SC tone is a classic and a "must have" for me. Unfortunately, a penalty that comes with SC tone is hum and noise. If you're lucky, you don't notice or care or pay much attention to the noise and just play despite it. I'm not so lucky – the hum and noise really bugs me and I find myself switching to some kind of hum cancelling PU arrangement or another guitar. On a strat,reverse wound PUs more or less solve the problem although it would be nice to have true SC tone as a hum-free option. On a tele, the tone is all about SC neck and bridge PUs - and that's the point of this story. I just like the tele tone – the stock American Fender Tele guitar and pickups are great IMO. However, the hum is a killer. The stock tele has no RW PU option so you can't get rid of the noise. There are "noiseless" tele PUs, and I've tried some. The Deluxe Tele has the SCN pickups – which I like for their own sake and they are quiet, but they don't have the classic tele SC tone. I recently tried the Duncan "stacks", and they're also quiet and have a great tone all their own – but again, not a true Tele tone. Looking around, there are active PUs, and other "noiseless" options out there, but I can't afford to try all of them and I've come around to the fact that physics is the issue here, so there probably is no simple "replacement pickup" solution – at least I've not seen evidence of one yet.

What does a PU do and what causes the noise? The theory of how PUs work is pretty simple and covered in lots of books and websites. PU noise however is not so well explained and often less understood. There are two sources of noise with PUs. One is the electric field and this noise source is addressed by shielding. Again, there are lots of websites and articles about shielding. Ideally, a metal shield surrounds the guitar electronics, including the PUs, and is tied to the guitar cable ground. It's impractical to extend the shield over the PUs since that's where your hand is, so the best one can do is shield everything except the exposed tops of the PUs. Metal foil (copper or aluminum) works great for this and a great deal of noise reduction on a tele or strat is done with a day's effort at shielding. However, shielding doesn't block magnetic fields, which are the second source of noise. Magnetic fields are created by transformers (like an amp transformer) and power wiring in your walls, among other sources. The AC power grid creates a 60Hz (or 50Hz) mag field almost everywhere. A shield for mag fields is impractical for many reasons, chiefly because the PUs are exposed so you can play. The PUs create a signal from all sources of mag fields they are exposed to. Most of the field is created by the PU magnets and strings (that's how PUs work) but the 60Hz noise mag field adds to the signal.

The physics of coils and mag fields is understood and a working knowledge is easy to get from Wikipedia or a basic physics text. Faraday's equations state that a coil in a varying mag field will produce a voltage proportional to the number of turns in the coil and the area of the coil. These two factors are important to understand. Pickups have a small area within their coils and a large number of turns. These parameters work well to produce a strong string signal. The small area is also helpful in reducing the noise signal, but the large number of turns makes the coil sensitive to the noise mag field.

So, what can be done about the noise? A single coil pickup produces the sum of the string vibration signal ($signal_{SC}$) and the noise signal ($noise_{SC}$). A common approach is to produce a separate noise reduction signal ($noise_{nr}$) at the same level but out of phase with the noise from the SC pickup ($noise_{nr} = - noise_{SC}$). Wiring the two signals in series adds the SC and noise reduction signals together to get $signal_{SC} + noise_{SC} + noise_{nr} = signal_{SC}$. This assumes that the series connection has no detrimental impact on the SC signal. While this is easy to say and to write as an equation, it's not so simple to do in practice.

The humbucker is most common approach to noise reduction and it uses a second coil with reversed windings and magnet polarity. Both coils (call them SC and NR) pick up the same noise signals, but they are out of phase so they cancel, while their string vibration signals add. This is great for noise reduction – double the string signal and cancel the noise. However, now the string signal comes from two coils at two positions along the string and it just sounds different than a SC pickup by itself. Variations have been tried – stacked coils, alternating string magnets, etc. While these mostly do a great job of hum reduction, the second coil always impacts the tone. The output of the humbucker PU system is captured by this equation: $signal_{SC} + noise_{SC} + signal_{nr} + noise_{nr}$. Each coil creates both signal and noise but since the noise signals are out of phase, the output is $signal_{SC} + signal_{nr}$. Unfortunately, this does not sound like $signal_{SC}$ alone.

To get rid of the second coil's $signal_{nr}$ a "dummy coil" is often used for the NR pickup. This is a matched pickup coil that has no magnets and is often placed away from the strings so it only creates $noise_{nr}$. Because this NR coil is matched to the SC coil (small area and large number of turns) to produce the same noise signal, it also has a high resistance and inductance that impacts the $signal_{SC}$ tone when the coils are connected in series so the out of phase noise signals cancel. Ideally, we want a "benign" NR coil with low resistance and low inductance, however with the same noise sensitivity to cancel the SC coil noise. There are two options to undo the detrimental effects of the dummy coil. The first is to use an active system where the $noise_{nr}$ output of the dummy coil is added to the SC coil output in an electronic circuit. This keeps the SC signal out of the dummy coil so it has no detrimental impact, however, now you need batteries to power the circuit and you have an "active pickup" system.

The other option is to apply Faraday's equations to alter the dummy coil to more benign parameters and retain the passive series-connection method of summing the coil signals. Recall the number of turns and the area of a coil are proportional to the sensitivity of a coil to a mag field. So, rather than matching the SC coil area and turns, we can increase the coil area and reduce its number of turns and still get the same $noise_{nr}$ output. For example, increasing the area inside a coil by a factor of ten and decreasing the number of turns in the coil by a factor of ten produces the same noise-cancelling signal from the coil. Also, since area of a circle increases as the square of the radius, the length of wire in the large-area coil is less than what is needed in small area coil with the same noise sensitivity. In addition, since the larger coil has an air core, rather than the iron PU core, and there is less wire used, its inductance is reduced.

Let's summarize the impact of all this. Say a SC PU coil has N turns, A area, R resistance, and I inductance. If we want a dummy coil to match the noise level from our SC coil, Faraday's equations say we can get the same noise signal from a coil with a larger area and fewer turns. OK – that by itself doesn't seem like a big deal, but now look at the impacts of that bigger coil when we connect it in series with the SC PU to cancel noise. The big coil has far less turns and wire length than the SC coil so it's DC resistance is much lower. Also, the big coil has a lower inductance than the SC coil. Both of these mean the big coil is "benign" in terms of its impact on the SC signal when we connect these coils in series to cancel their noise signals. This is a big deal. By making a coil larger, we get the same noise cancellation benefits of a dummy coil, but less or none of the detrimental effects of adding high resistance and high inductance in series with the SC signal. A big coil cancels noise and passes the SC tone unaltered without the need for batteries or active circuits. It's a win-win and it seems too good to be true. Actually, it is true - physics works - and the details below describe my implementation and experience.

Telecaster and Stratocaster Mods

I've done this for two guitars now. First I did it for a Telecaster, as described below. I then did it for a G&L S-500 - which is essentially a Stratocaster. The S-500/Stratocaster modification was much easier than the Telecaster mod described below, and it involves no permanent or physical changes to the guitar. It is easy to do in a day and details can be found on the S-500 mod page.

Telecaster Mod

So, after convincing myself that this should work, I began to think about how to put a big coil into my Telecaster. Telecasters don't come with hidden compartments or cutouts for large coils. The tele has a good size pickguard however, and if I follow the edge I can hide over 20 inches of coil length under the pickguard. Putting a coil in the guitar back is also an option and maybe the better option since a 6" circle groove would easily fit, or a flat plastic disk mounted on the back would not detract severely from the guitar's appearance or playability. In the end, I opted to hide the coil under the pickguard. It makes the coil essentially invisible. I also wanted to try the S-1 switch system for series or parallel connection of the PUs in the center (both) selector position. The S-1 switching works really well on the Deluxe Tele, so I wanted to try it on the Standard PUs. This switching system adds some complexity to the coils, but the principle is the same and the coils work just as well with a standard Tele switch.

Before cutting up a perfectly good Telecaster, I built some coils and tested them with the real Tele pickups. To figure out what kind of coil I needed, I searched to find parameters for Telecaster pickups. I could not find exact specs, but I found some ballpark figures from various sources and used these to estimate my coil parameters.

My Fender American Standard Tele pickups (stock 2010)
Neck = 7.7k Bridge = 7.1k measured DC resistance of my pickup coils
Area of coil = average of measured coil size extent = 0.35" x 2.5" = 0.876 sq in

Telecaster (bridge pu) 42 guage wire Formvar insulation 8000 turns
Telecaster (neck pu) 43 guage wire Formvar insulation 8000 turns
from: http://home.provide.net/~cfh/pickups.html

Tele Bridge pickup has 9,850 turns of 42 gauge wire; DC resistance ~ 7.5 k-ohm
Tele neck pickup has 7,500 of 43 gauge wire; DC resistance of ~ 6.8 k-ohm
from: http://vintagevibeguitars.com/windows/sc_teleWin.html

Neck: 5.6K 2.1H AlNiCo5 Bridge: 7.4K 3.48H AlNiCo5
from: http://www.lollarguitars.com/mm5/merchant.mvc?Screen=technical-info

These numbers give me a general ballpark of coil area and number of turns. Using my measured pickup coil area estimate of 0.876 sq in, the noise sensitivity is proportional to area x turns = 0.876 x 8000 = 7000 (noise factor for a tele pickup). I can fit a coil with 20" length per-turn under the tele pickguard. In a circle shape that length produces a 20/pi = 6.36" diameter and pi x $(6.36/2)^2$ = pi x 10.1 = 31.8 sq inch coil area for a circle coil. After squashing the coil into an oval-ish shape to fit under the pickguard, I estimated ~28 sq in coil area for the final shape. (This turned out to a high estimate - it was more like 20 sq inches in the end)

To match the pickup noise sensitivity, I matched the noise factor = 7000 (turns x area). The big area coil = 28, so the number of turns needed is 7000/28 = 250 turns. I can get 250 turns on a coil from a 400 ft spool of wire (32 gauge) available for under $4 at Fry's.

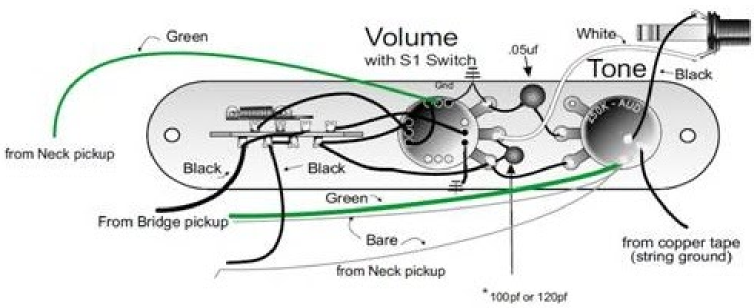
The 32 guage wire is thicker than it need be, but thicker is easier to work with and less prone to break. I'm not set up to do commercial-grade coil winding – I wound this coil by hand. Thicker wire also leads to less resistance in the coil, which is good. My final coil measures at 65 ohms. Lastly, thicker wire also reduces inductance of the final coil (see http://www.eeweb.com/toolbox/coil-inductance/). My final coil inductance is under 0.04 H (see calculations at bottom for how I estimate this)

So I now have a flexible coil with low resistance (good) and low inductance (also good) that has about the same noise sensitivity as my tele pickup. I need to fit this under the tele pickguard while preserving as much coil area as possible.

Winding the coil is not that hard. I used a round plastic container with a 20" circumference. Anything that size will do, but a few factors guided my choice. I wanted a flat edge on one side to wind the coil up against. I wanted a tapered surface to wind on so that the coil would slide off easily once I was done. I stuck a few pieces of foam tape along the coil path to create a ½ inch valley between the flat edge and the foam tape where the coils could collect without spilling off the form. Once the coil was wound, I removed the foam tape piece by piece, using some tape to bundle the freed-up section of the coil temporarily. Once all the foam tape was removed and the coil was taped, it was easily handled and ready for wrapping in spiral tubing. Spiral tubing is cheap and intended for wrapping wires together. A small 1/8 inch size is great for wrapping the coil since it hugs the coil strands tightly, protects the wire, and the whole coil assembly remains flexible. After wrapping, the coil wire bundle has a 0.2" cross section diameter.

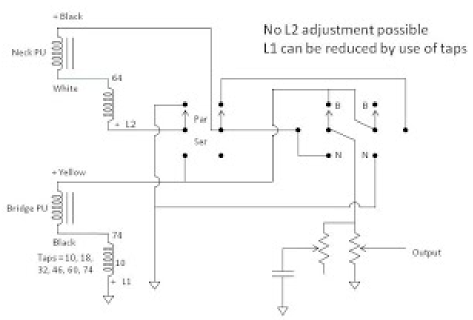
Since I want to use S-1 switching, two coils are needed – one for the neck PU and one for the bridge. I could have wound one double-long coil and added taps, but a single large coil seemed more difficult to make than two smaller ones. There is no difference electrically. The second coil was made the same way with 400 ft of 32 gauge wire, but in this case, I brought out taps every 50 turns. Also, I added another 100 turns of additional wire (350 turns total) since initial experiments with the first coil showed that the bridge PU had a higher noise level. It may have more turns or a slightly larger bobbin, I don't know, but I need more turns (or more area) to make up for that in the noise cancelling coil for the bridge PU. After wrapping, this coil has a 0.3" cross section diameter. So the groove that needs to be made in the Tele body has to be 0.3" wide and 0.5" deep to hold both coils. I'll add a bit to the depth (0.6") to make room for shielding foil and connecting wires.

Below is a diagram for standard S-1 switching for series-parallel connections of both pickups.



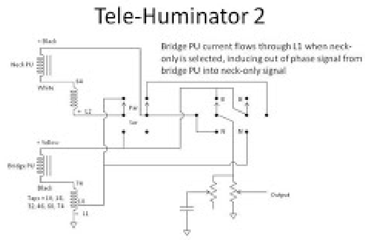
The next pages shows the evolution of the S-1 wiring with the coils. The version-1 figure shows how to simply add two "Huminator" coils (L1 and L2) to the standard S-1 wiring diagram. Note the S-1 switch (Par/Ser) and 3-way selector switch (B, B+N, N). The numbers on the L1 and L2 coils are the DC resistance for the taps used. L2 has only two ends (64 ohms), while L1 has multiple taps.

Tele-Huminator 1



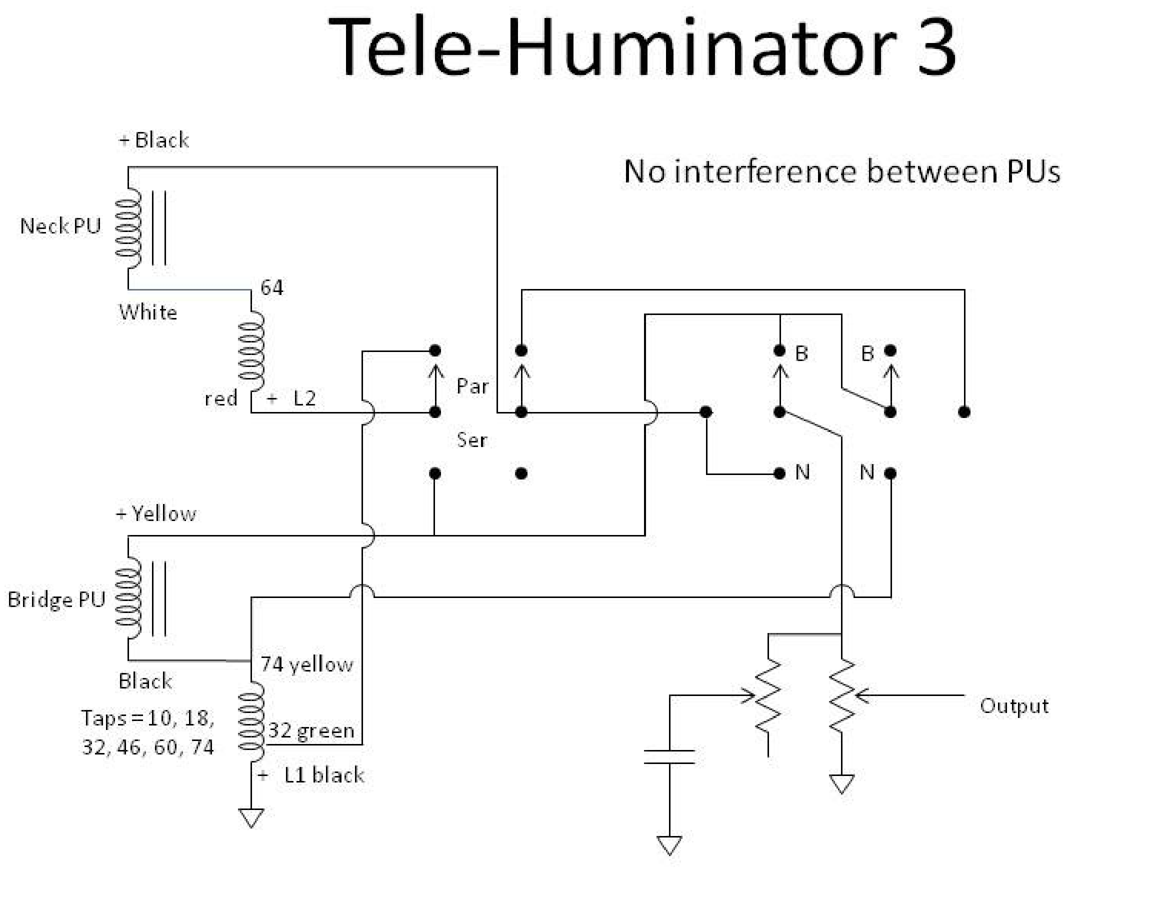
Fender S-1 wiring for series/parallel of both PUs with addition of hum rejection coils

Once the coils are "in body" of the guitar, I want to have some adjustment of the coils to select the optimal turns for minimizing hum. In fact, since the coil areas will be reduced by the "in-body" shape, it's likely that I'll need more turns, not fewer, so a scheme for using some L1 turns to adjust the neck PU hum rejection is shown in figure 2. When the neck PU is selected, a tap on L1 is added to L2 to allow an adjustable number of coils to be added to L2. The 10 ohm tap is shown in version-2 (below), but any tap could be used. This works except that there is some bridge PU current that will flow through the upper part of L2 and induce a small voltage (small but it's there) into the neck PU signal when the neck PU is selected. While this may not be a big deal, the whole point of this effort is to preserve the "pure SC tone" and the neck PU is most important to me. Fortunately there is a way around this problem as shown in version-3 of the circuit. Sometimes you can have your cake and eat it.



Use of a coil tap on L1 for matching neck PU hum-rejection once coils are "in body"

The third diagram (below) has all the features I need and it's the one I wired. Before I actually route the guitar body and commit to the mod I want to do some tests with the actual coils and PUs.



An L1 coil tap is used to match neck PU hum-rejection once coils are "in b

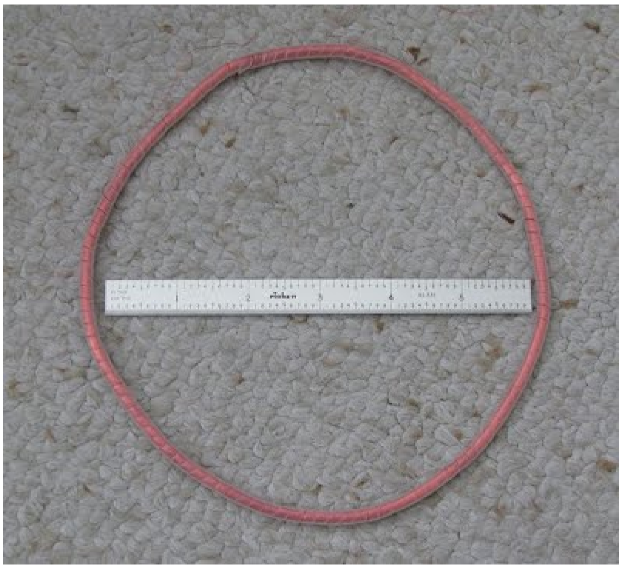
I tested each pickup separately after wiring it to its intended coils and observed the output on a scope. While I could see the noise cancelling effects, the scope gain was too low to give a real sense of how well it was working. So, I just connected the coils and PUs to an amp and cranked up the gain. I placed the pickups and dummy coils into a large metal cookie box and clipped a ground connection to the box to provide shielding. With the lid in place, the shield was pretty effective and I could hear 60Hz hum due to magnetic fields. Shorting out the dummy coil made for easy A/B testing with and without the dummy coil. After checking various coil taps and pickups, I concluded that the coils work pretty well. I got great noise reduction with the neck pickup using the fixed coil and the 10 ohm tapped coil, as shown in wiring version-2. However, the coil used for the bridge PU was a bit under-wound. Although the noise reduction was substantial, I probably need another 100-200 turns to optimally cancel the hum of the bridge PU. Since I had pretty good results with the coils I had, and I was convinced by the experiments that the cancellation works without side effects, I decided to do the guitar mod and deal with coil optimizations later.

The pictures below show the story better than I could describe it. The important point is that the mod was successful. The coils work great and the tele tone is unaltered as best I can tell. I don't have a stock tele to compare directly against, but I've played teles for years and this one sounds right to me – it just doesn't have noise anymore.

The neck PU is most quiet since that is what I optimized for. I picked the best tap to use once everything was mounted in the guitar – it turned out to be the 32 ohm tap. The tele neck PU is quieter now than a strat in hum-bucking positions (1-2, 2-3). The bridge PU is much better than before, but not as quiet as the neck PU. The middle position is about mid-way between the two PUs in terms of noise. In all positions it's a huge improvement - a dramatic day/night difference. I now play this tele without any awareness of noise. The noise levels are below what matters to me – and I'm pretty sensitive to noise – especially in recordings. If I ever optimize it I'll add a small additional coil to the top of L1, the bridge PU dummy coil. There is plenty of room in the groove and now it's just a matter of removing the pickguard when I'm changing strings. None of the other wiring has to change. The cost of the coil system was about $10 in wire. Don't ask about my time-cost, but I did the whole thing in about three days of effort spread out over two weeks. I enjoyed the challenge and its really rewarding to see and hear the successful outcome of an idea based on fundamental physics of coils… of course it's also just fun to play this guitar now.

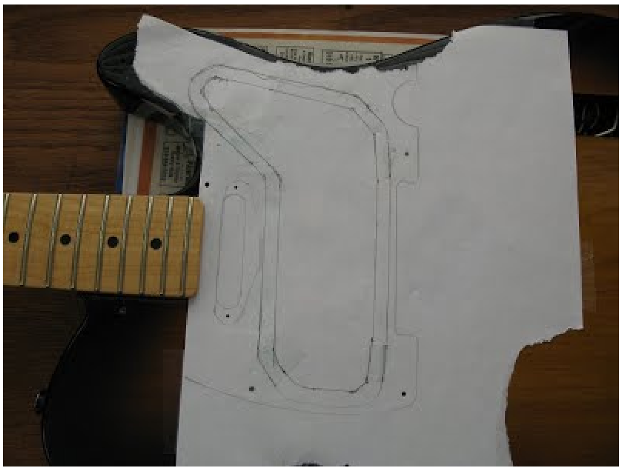
Both coils were wound on a plastic container with 20" circumference

L1 coil with taps after removal from the plastic form and just held by tape



L2 coil after wrapping in spiral tubing is about 6 inches in diameter

The stripped telecaster before the coil slot is cut with a router

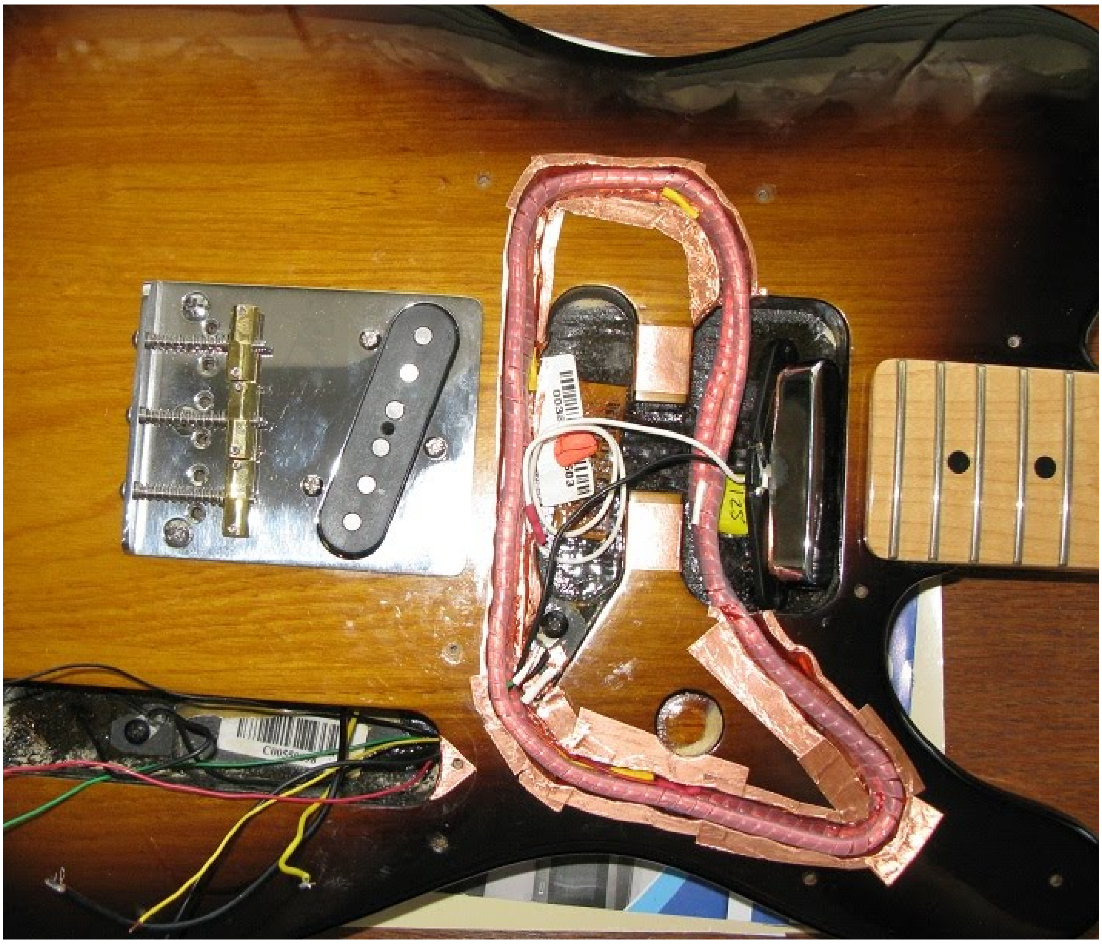


A paper sketch of the pickguard shape and coil groove shape taped to the guitar to guide me in routing

This was the hard part - routing the channel shape that was drawn on the paper. The channel is .3" wide and .6" deep and carefully routed to stay under the pickguard and clear the neck pickup. The channel length has to match the coil length precisely. The tele body wood is hard!

Copper foil is applied to shield the entire channel and any exposed parts of the guitar cavities. Some foil extends to the top surface to make contact with the pickguard shield (below). Fender uses conductive paint to shield the stock cavities. All the cavity shields are wired together to a common ground in the control cavity where the PU signal ground and the output jack ground are also connected together.

The backside of the pickguard is also shielded. I used spray adhesive and aluminum foil.



The PUs and coils are put in place for final tuning of the coil taps for the final coil shape
Wires from the coils and the PUs are visible extending into the control cavity

The pickguard is put in place after the neck PU is attached to it. The rest of the control cavity wiring is done. Note the S-1 switch on the volume control.

Finally... after the strings are on and the bridge is tuned up... its ready to play. It looks like nothing ever happened but it sounds better than ever.

Given how well this works, I'm wishing that guitar makers would add a groove for dummy coils, even if they don't add the coils. The Tele body has a third center-pickup spot routed out, even though it only comes with two pickups. Why not a nice coil slot along the inner edge of the pickguard? Makes me wonder if they put much effort into big dummy coils or whether they just don't care to reduce pickup noise.

It turns out that all good ideas have been thought of before. There is a patent on the "big coil" idea (US 7,259,318 B2), which I discovered after I did this. Good luck to the inventor - it's a great solution to an old and persistent problem. I wish I had thought of it years ago.

NOTE – I'm not connected to the inventor or selling anything and I'm not making any claims about the patent, his product, or its applicability.
It is interesting that the idea has been around for some years and it seems to work really well, but the most common SC guitars keep getting made without dummy coils or provisions for them.

A question on the FDP forum got me to work out the final coil spec and comment about the Suhr plate. The Suhr plate has similar area to my coil, but is made to be thin, so it means the coil wire is likely thinner than the wire in my coils and that will raise its dc resistance and inductance. I don't know anything more about it so I can't compare my results to theirs. If anyone has a plate and can measure it's DC resistance, I'd like to hear from you.

I measured my coils at 64 and 74 ohms. Their low resistance is due to the thick (relatively) gauge wire I used. Doing the physics (http://www.66pacific.com/calculators/coil_calc.aspx) calculation for inductance of a multilayer, multirow coil, my coils have ~15-38 millihenries of inductance. (I used 5" diameter, 0.3" length and depth, 250-400 turns for the calculations.) So comparing my coil resistance and inductance to the pickups (~7k ohms and ~4 Henries) --- I'm at ~1% of the PU specs on resistance and inductance. That's probably within the tolerance of winding of the PU. I consider I% parameter change pretty small. That is in line with what my ears tell me - I can't hear any difference in the tone.

I'll speculate that by optimizing the coil channel and coil construction for commercial production, the coil impact could be reduced another 50% to 0.5% of PU specs, making "truly noiseless" SC guitars possible and inexpensive.

As for worst case conditions... If I'm near an amp, the mag field becomes non-uniform so I still get a slight buzz (although much less than before). If I'm relatively far from a transformer (8-10 feet) the field is pretty uniform and the cancellation works great.

I also get excellent hum cancelling for the strat-style guitar - without the difficulty of altering the guitar body - details are here.

Results are everything. I have a video clip that shows me switching the tele PUs while I record audio straight from the guitar into a UA-25 USB interface. This is the raw guitar signal into the high-impedance input and right into the computer - no amps or mics are involved. I think the compression on my web-cam record software makes this less than ideal for critical evaluation, but it's all I can do right now. I'll get set up to do an A-B comparison at some point, but I'll have to wire in a switch to bypass the coil and that may take me some time. This does show that the noise level is pretty low. If you crank your audio you'll hear slight hum and noise level changes as I switch between PUs. You'll also get a sense of how low the noise is relative to the decaying notes. Tele volume and tone are set at max.

Coil tone impact test: As discussed in a Fender Forum post, it's hard to believe that there is little of no impact on the PU tone once you add the cancelling coil. IMO, this belief comes from people's experiences with dummy pickup coils and the Suhr coil - both of which are far from optimal for cancellation IMO. So, I've made a recording (uncompressed 16-bit mono) that compares the bridge tele pickup tone with and without the cancelling coil (L1). In this example, the tele bridge PU black wire is grounded with a switch to bypass the cancelling coil, or left connected to the cancelling coil. The volume and tone at max during the whole recording. As above, the guitar runs directly into the UA-25 without any amp. (There is no video for this since I want uncompressed audio, and I don't have a video recorder that records uncompressed audio).

The recording (link is here) has an initial sequence of quiet (no strings playing) with the coil being switched in and out. It starts with no coil (NC), then with coil (C), then NC, then C. Each segment is a few seconds long and you can pretty clearly hear the difference, although the cancellation is not perfect. (Recall, I optimized for the neck PU, not the bridge.)

Then I play a simple trill three times (10 and 12 fret). Between sets of trills I mute the strings and switch the coil in/out and play the trills again. The first trills are with the coil (C), then I play them without the coil (NC), then C, then NC, then C. With the strings muted between trill sets, you can clearly hear the coil switched in and out. In addition, I think you'll agree, there is no audible difference between the trills played with the coil (C) or without the coil (NC). Of course there is some variation in trill tone due to fingering and picking since its impossible for me to be perfectly consistent each time I play it, but it's not correlated with coil settings.

This is as close to an A-B test as I can do and I hope it dispels the myth that hum cancelling coils *always" impact PU tone. Note also that I used the tele bridge PU for my test. It has the brightest tone of most any PU and therefore the most sensitive to coil resistance or inductance. I think you'll agree, the cancelling coil does not change the tone at all.

Subpages (1): S-500 Hum Cancellation