Understanding H1's O3 B Electronics Compensation Systematic Error

J. Kissel for the Calibration Group

Outline

Two Parts, each quite long. *sigh*

PART I: The ETMX UIM Driver, from Nov 27 to Dec 03 2019

1. Why do you care about the UIM?
2. Review where we were before we started
3. Review of the Circuit
4. The Measurement
5. Other models of the circuit
6. The Fit and Each Coil Result
7. Converting fit results in to systematic error in A_{UIM}
8. Converting sys error in A_{UIM} to sys error in R and Conclusions

PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

1. Review of the Circuit
2. Fit Results for each channel
3. Converting fit results in to systematic error in C
4. Converting sys error in C to sys error in R

But -- your time is valuable

This is 126 page slide show. Here are the answers, in case you don’t have time to be educated as to how I came to each conclusion, with the confusing details and the lessons learned that got me to it. I hope at least some folks read it.

PART I: The ETMX UIM Driver, from Nov 27 to Dec 03 2019

- **Executive summary:** non-Jeff’s everywhere whom guessed the answer ahead of time are vindicated in that **the UIM electronics error** -- either from differences in compensation between states, or poor compensation in general – **doesn’t substantially contribute to the response function systematic error. (See slide 70 for quantitative answer)**
- We may safely proceed with O3B chunk 1 uncertainty budget development without including this systematic error.
  - Note that this would have *not* been “covered” by the GPR even it it were non-negligible.

PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

- **Executive summary:** While I can predict the systematic error from the configuration switch, **it also doesn’t substantially contribute to the response function systematic error (see slide 124 for quantitative answer)**.
- We can probably proceed with O3B chunk 2 uncertainty development without including this systematic error.
- We need to remeasure and recompensate the OMC Whitening Chassis.
- We need to find out what happened on / around 2020-03-23 instead.
- We need to use different measurements we have to make the best guess for the systematic error…

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from Nov 27 to Dec 03 2019

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PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

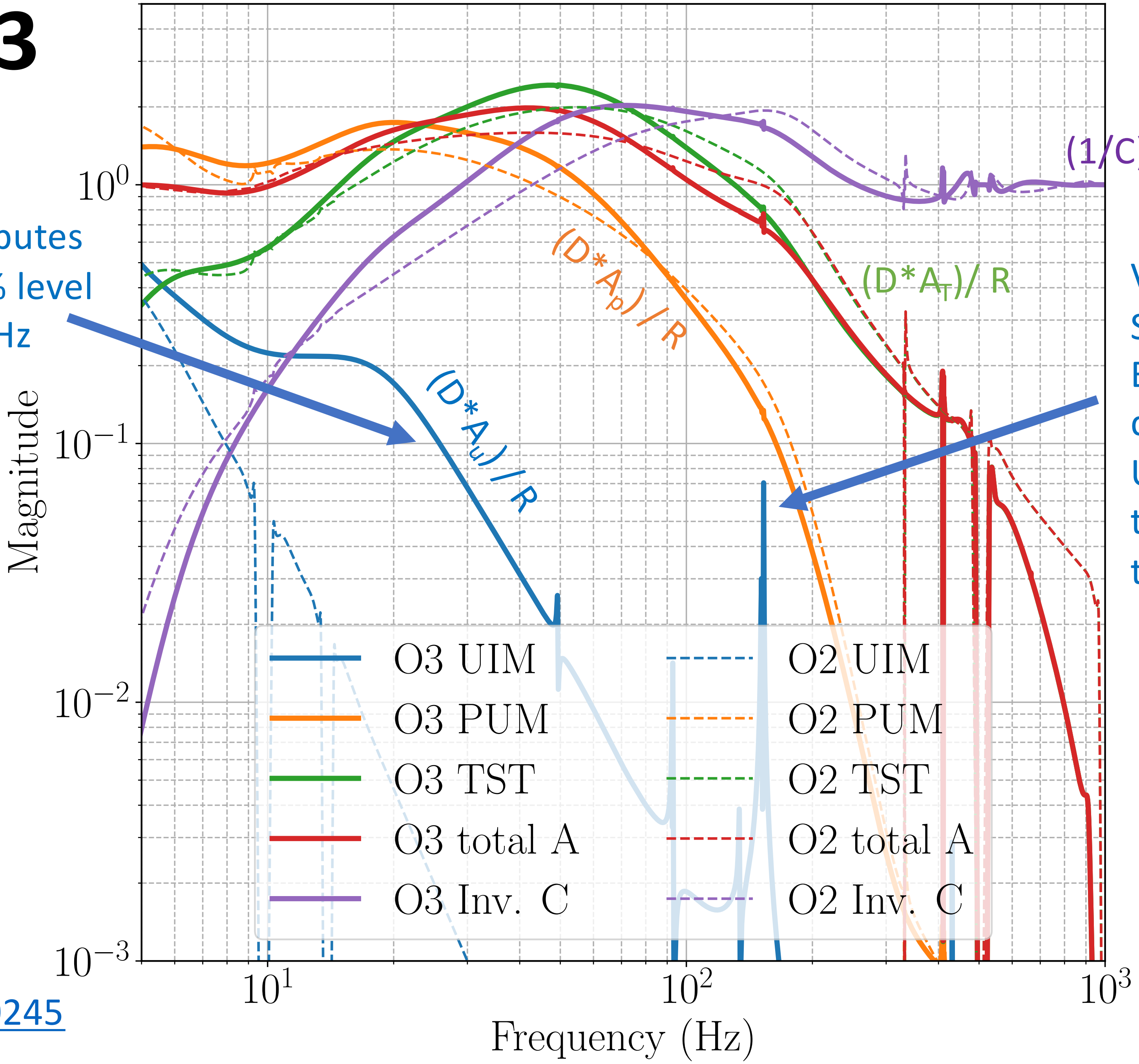
I.1 Why do you care about the UIM?

- The UIM always gets pushed to ”low priority” because “we should be rolling off its authority fast enough that it doesn’t matter in the detection band.”
- That means: we ignore it, assuming anything we do above 10 Hz to the UIM doesn’t matter, and don’t stress about the consequences when we change something until it’s too late.
- We’ve already identified one systematic error in the UIM that has bit us ‘cause we ignored it: the nasty bending response of the UIM Blade + Non-magnetic Blade Dampers.
- This amplifies the contribution of the UIM to the response function at 150 Hz, making *all* UIM systematic error important, right in the bucket. (This is true only for H1, which doesn’t roll off their UIM fast enough. L1 should be safe.)
- **But also: this is the era of the 1%. Even when we fix the UIM contribution by rolling it off faster, this study emphasizes that we must question everything and *confirm* *quantitatively* that something is “negligible.”**
- **This didactic presentation is good practice, and by presenting in great detail, I aim to train the next generation, lest the art of understanding analog electronics analysis dies.**

I.1 Why do you care about the UIM?

H1 O3

UIM Contributes at the ~10% level out to ~25 Hz



Vertical Blade Spring Twisting / Bending in L direction causes UIM contribution to spike back in to play at 150 Hz

Figure 4 from P1900245

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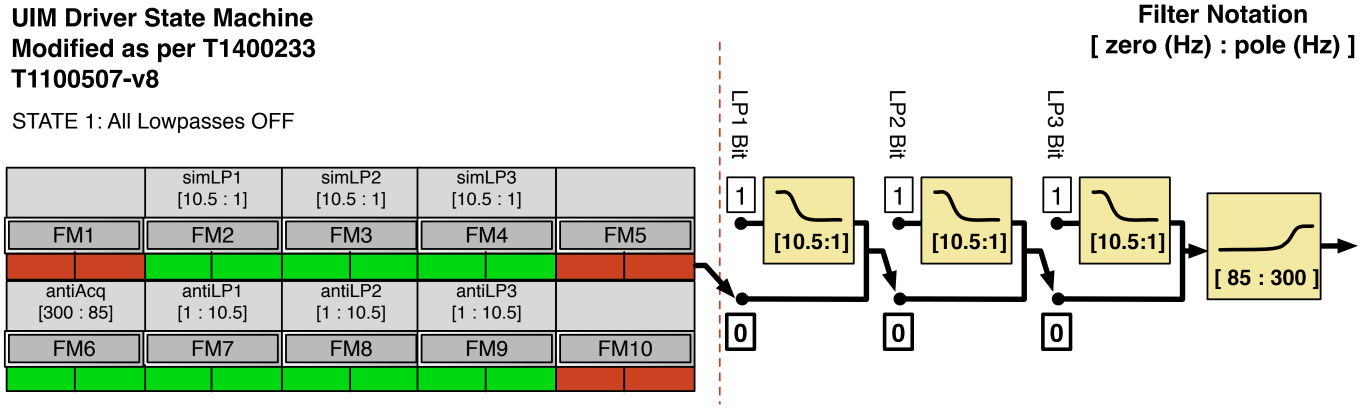
PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

I.2 Review of where we were before starting



- During O1 and O2, we were using all ETMY stages for the DARM actuators, the UIM included.
- We updated the low-pass compensation filters on ETMY based on fit to measurements [LHO:21283], but we only used the "DTT measurements with the coil driver monitor circuits" technique, which are insensitive to the 85:300 zero:pole pair which results from the output impedance network [LHO:21142], and we ran out of time (remember GW150914?), so we didn't update the antiAcq filter.
- We ran in ETMY, UIM, State 1 for all of O1 and O2, so the updates didn't actually matter (Sorry Darkhan!).
- In Jan 2019, 4 months before O3, we made the switch to using all ETMX stages for the DARM actuator.
- The UIM electronics were fully measured in analog on Feb 03 2019 (yes, a Sunday!), by Rich Abbott and Jeff Kissel. Rich was unconvinced that we needed the differential driver full setup as described in D1900027, so we did some sort of single-ended, direct via clip-leads measurement [LHO:46927] (this becomes important later).
- Lilli tried to fit the State 1 data, but they didn't make any sense to us at the time [LHO:47195].
- We did take the DTT data on Feb 07 2019 to update the low pass compensation, but never got to processing it.
- Because of confusion about the results in the State 1 measurements, and because the UIM was low priority, we just chose not to update anything: [LHO:47167]. (Remember ER14 and how there was systematic error everywhere [LHO:47378] ?)
- Flash-forward to Nov 27 2019, we got suspicious of DAC quantization noise [LHO:53376], and switched the ETMX UIM driver to State 2 [LHO:53528], forgetting the terrible state of the compensation, and assuming "the UIM doesn't matter."
- Only 6 days later on Dec 03 2019 (and thus in between regular calibration sweeps), we reverted back to State 1 [LHO:53652].
- **The switch happened between two regular actuator sweeps (taken on 2019-11-11 and 2019-12-04), so there for we must model what the systematic error with the measurements we have (namely, the Feb 03 2019 data) for this 6 day period, in which -- of course – there lies GW191129.**

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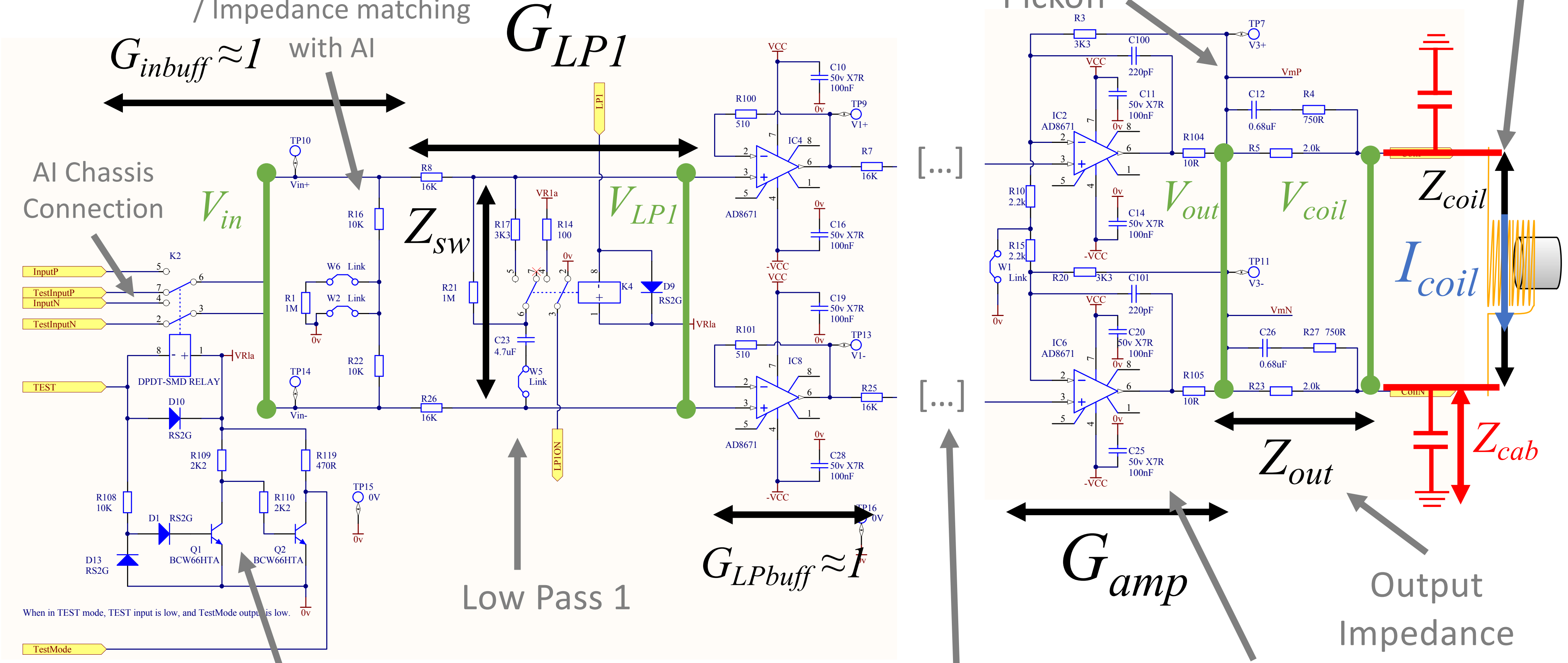
PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

I.3 Review of the Circuit: Forest through the Trees

To understand the 2019-02-03 data, we need to understand the circuit and the measurement.

Let's start with the circuit: D070481, specifically, the UIMCircuit_v5.pdf

It looks intimidating, so I'll start with the parts, and break it down to the parts that are important to our story.



Input buffering / Impedance matching with AI

AI Chassis Connection

test/coil enable switch circuit

Low Pass 1

Identical Low Passes 2 and 3 not shown

Voltage Monitor Circuit Pickoff

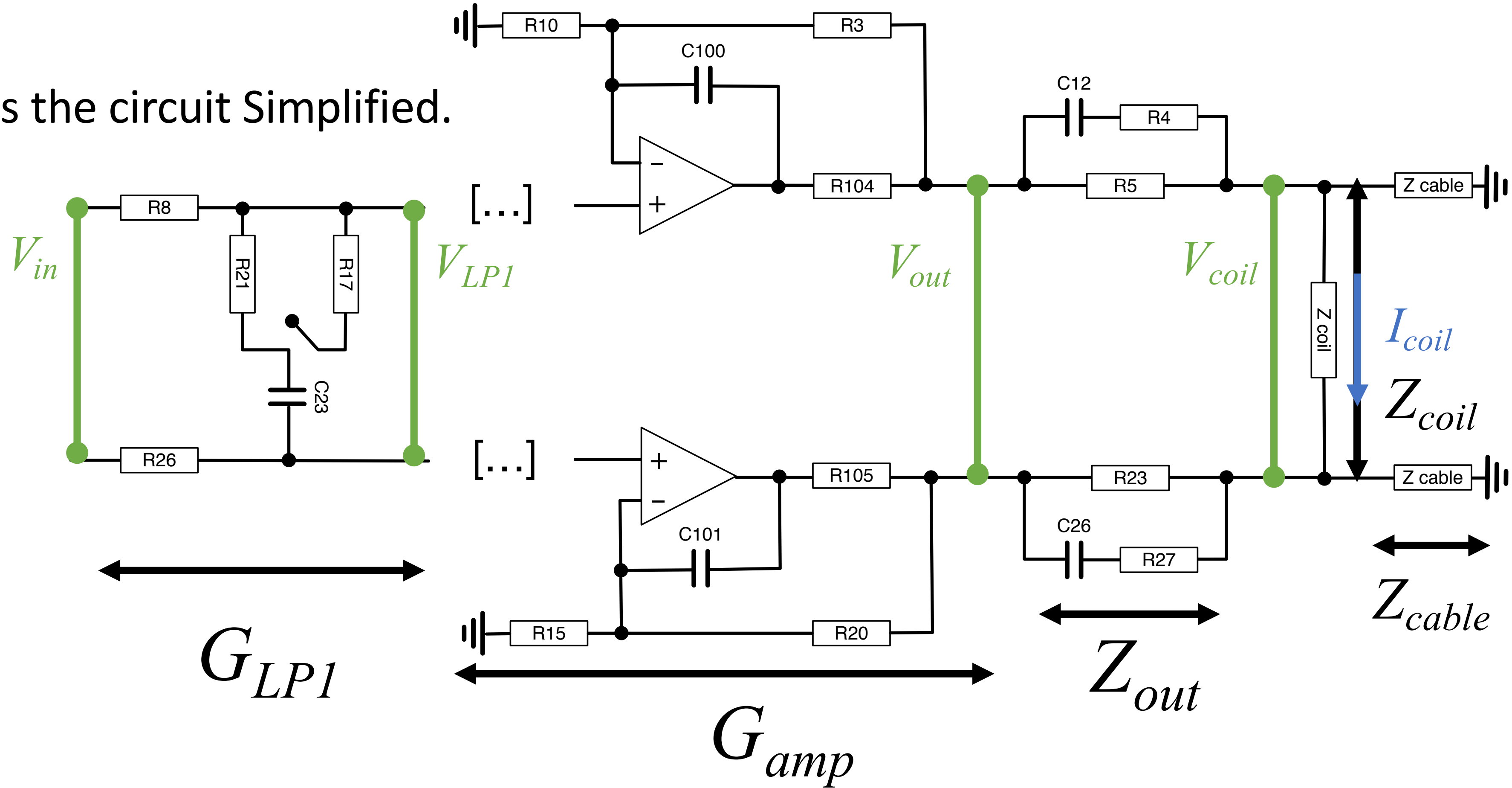
The BOSEM Coil Connected across P and N legs

Output Current Driver

Output Impedance Network

I.3 Review of the Circuit: Simplified, Differential

Here’s the circuit Simplified.



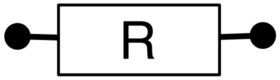
- All parts of the circuit that have gain, but no frequency dependence, we just ignore. We’ll scale the gain of all models to the measurement in the end. We’re looking for poles and zeros
- The low pass, the output impedance network, and the coil will define the ”important” poles and zeros (below 1 kHz). (I wonder if the output current amplifier is important later)
- In the end, the “transfer function” we want the *transconductance* of the driver / coil system: I_{coil} / V_{in}

I.3 Review of the Circuit: Trust the Basics

Here's a friendly reminder of the tools in the circuit analysis toolbox:

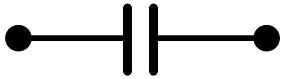
Converting to Impedance:

$$Z_R = R$$

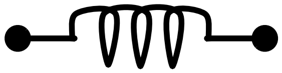


$$Z_C = 1/i\omega C$$

$$(\omega = 2\pi f)$$

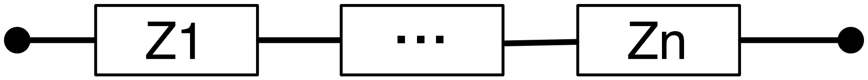


$$Z_L = i\omega L$$



Series Impedance:

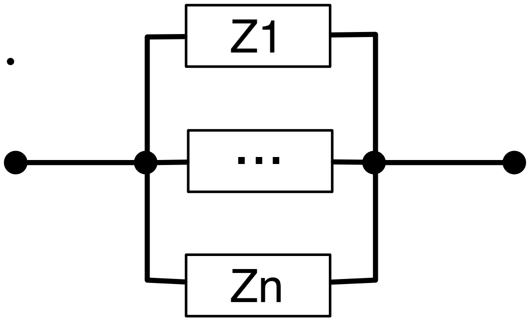
$$Z_{tot}^S = Z_1 + Z_2 + \ldots$$



Parallel Impedance:

$$\frac{1}{Z_{tot}^P} = \frac{1}{Z_1} + \frac{1}{Z_2} + \ldots$$

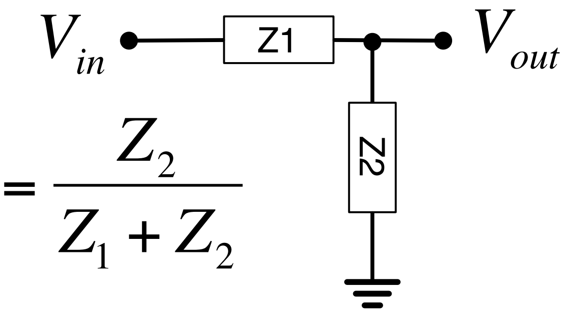
$$Z_{tot}^{P(2)} = \frac{Z_1 Z_2}{Z_1 + Z_2}$$



Ohm's Law:

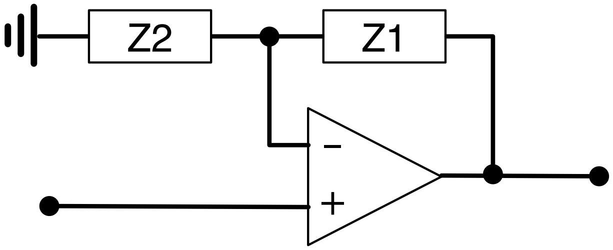
$$V = I Z$$

Voltage Divider:



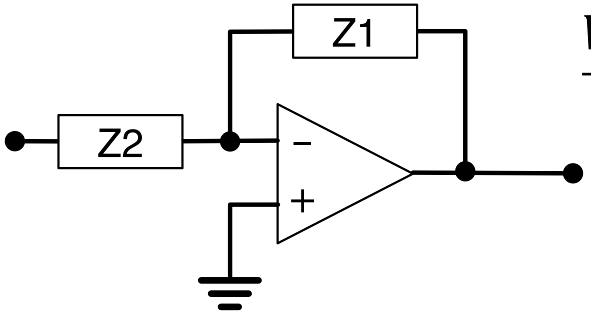
$$\frac{V_{out}}{V_{in}} = \frac{Z_2}{Z_1 + Z_2}$$

Non-inverting Op-Amp



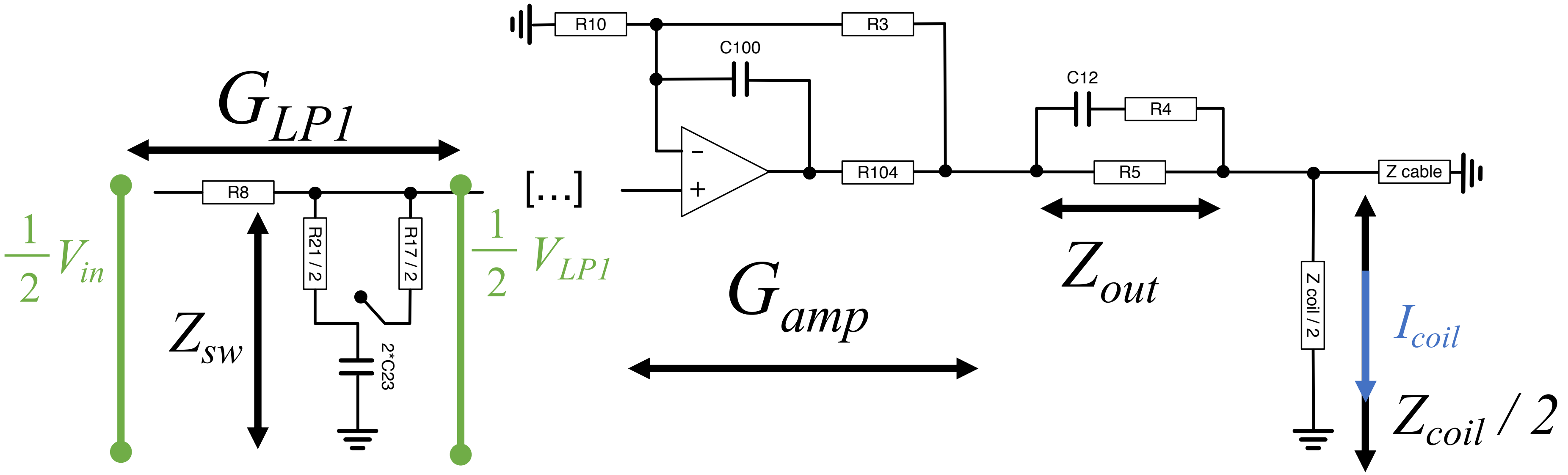
$$\frac{V_{out}}{V_{in}} = 1 + \left(\frac{Z_1}{Z_2}\right)$$

Inverting Op-Amp



$$\frac{V_{out}}{V_{in}} = -\left(\frac{Z_1}{Z_2}\right)$$

I.3 Review of the Circuit: Simplified, Single-Ended



- **One trick for differential circuit analysis:** consider only one leg, and divide everything that “crosses between legs” by two -- voltage, impedance, etc, -- and reference everything to ground (0V). The transfer functions are the same, and the analysis is equivalent.

$$Z_{sw}^{Open}(\omega) = \frac{1}{2}\left(R_{21} + \frac{1}{i\omega C_{23}}\right)$$

$$Z_{sw}^{Closed}(\omega) = \frac{1}{2}\left(\left[\frac{R_{17}R_{21}}{R_{17}+R_{21}}\right] + \frac{1}{i\omega C_{23}}\right)$$

$$\frac{(1/2)\,V_{LP1}}{(1/2)\,V_{in}} = \frac{V_{LP1}}{V_{in}} = G_{LP1} = \frac{Z_{sw}}{R_8 + Z_{sw}}$$

With the switch closed, that means,

$$G_{LP1}\Big|_{closed} = \frac{\frac{1}{2}\left(\left[\frac{R_{17}R_{21}}{R_{17}+R_{21}}\right] + \frac{1}{i\omega C_{23}}\right)}{R_8 + \frac{1}{2}\left(\left[\frac{R_{17}R_{21}}{R_{17}+R_{21}}\right] + \frac{1}{i\omega C_{23}}\right)}$$

which is enough to plot the transfer function, but we can re-arrange to show the analytic computation of the poles and zeros of this TF…

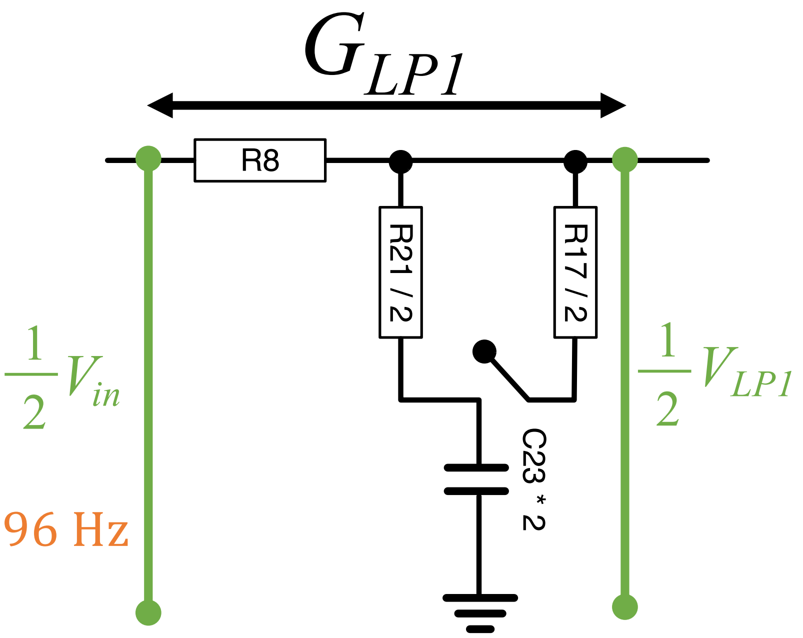
I.3 Review of the Circuit: The Low Pass

$$G_{LP1}\Big|_{closed} = \frac{\left(1 + i\omega\left[\frac{R_{17}R_{21}}{R_{17}+R_{21}}\right]C_{23}\right)}{\left(1 + i\omega\left(R_8 + \frac{1}{2}\left[\frac{R_{17}R_{21}}{R_{17}+R_{21}}\right]\right)(2C_{23})\right)}$$

That means

$$f_z^{LP1}\Big|_{closed} = 1/\left(2\pi\left[\frac{R_{17}R_{21}}{R_{17}+R_{21}}\right]C_{23}\right) = 10.2953 \text{ Hz}$$

$$f_p^{LP1}\Big|_{closed} = 1/\left(2\pi\left[R_8 + \frac{1}{2}\frac{R_{17}R_{21}}{R_{17}+R_{21}}\right](2C_{23})\right) = 0.9596 \text{ Hz}$$



Consistent with the expected low pass z:p = (10.5 : 1.0) Hz.

With the switch open, Rpara reduces to R17, leaving,

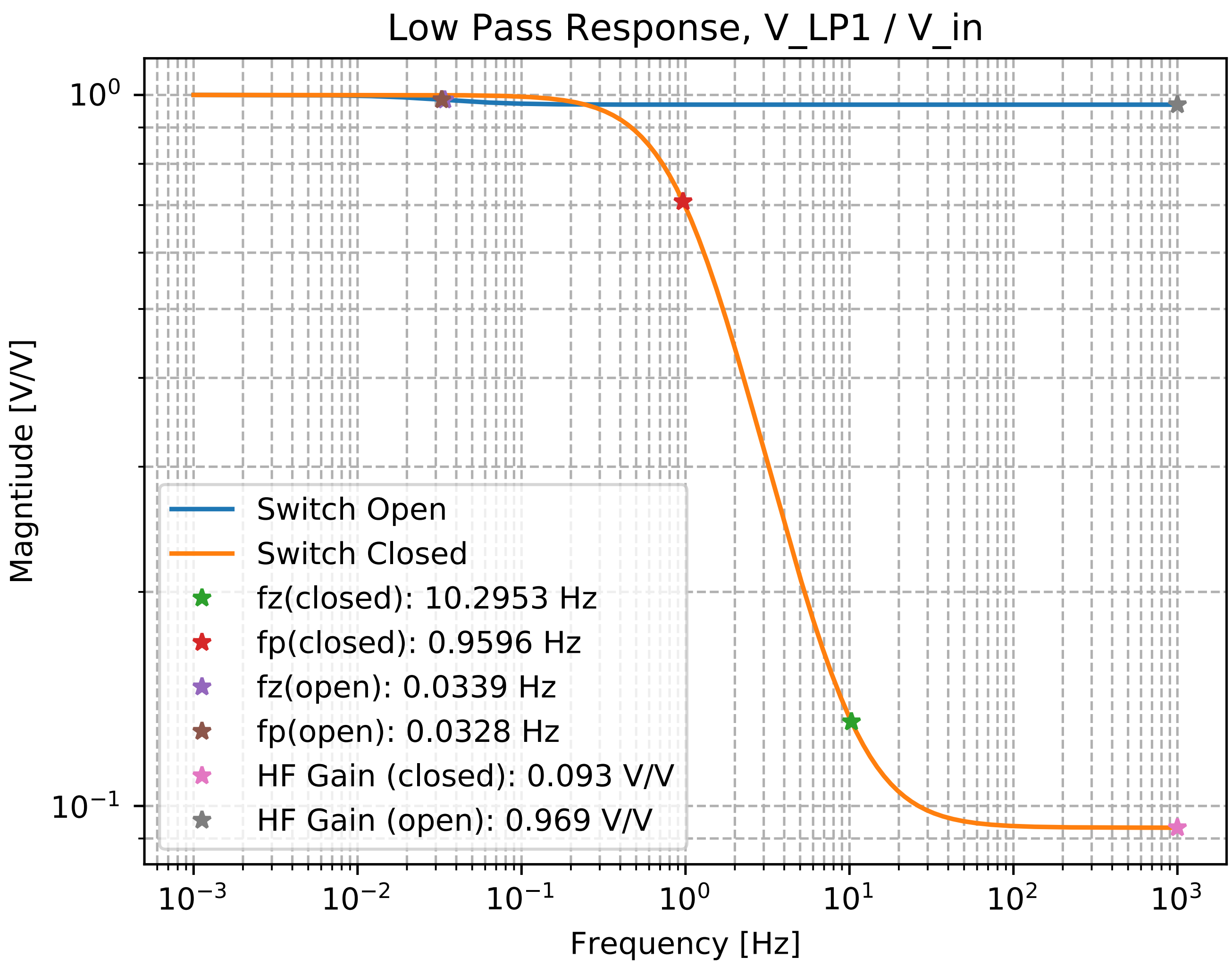
$$G_{LP1}\Big|_{open} = \frac{1 + i\omega R_{21}C_{23}}{1 + i\omega\left(R_8 + \frac{1}{2}R_{21}\right)(2C_{23})}$$

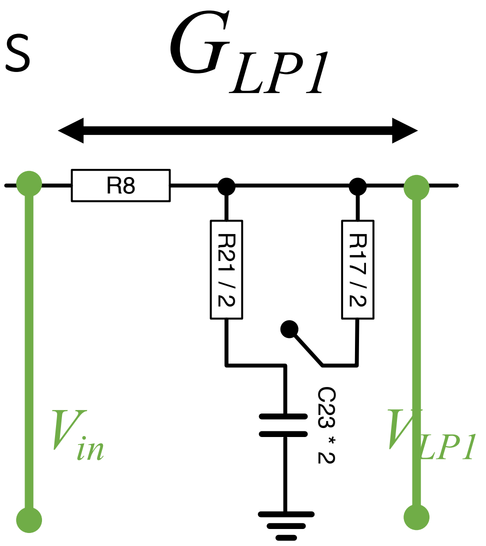
$$f_z^{LP1}\Big|_{open} = 1/(2\pi R_{21}C_{23}) = 0.0339 \text{ Hz}$$

$$f_p^{LP1}\Big|_{closed} = 1/\left(2\pi\left[R_8 + \frac{1}{2}R_{21}\right](2C_{23})\right) = 0.0328 \text{ Hz}$$

R8 = 16e3 # Ohms
R17 = 3.3e3 # Ohms
R21 = 1e6 # Ohms
C23 = 4.7e-6 # Farads

I.3 Review of the Circuit: The Low Pass





Another analysis trick: the suppression of the low pass (i.e. the asymptotic gain at high frequency) is the ratio of f_p / f_z

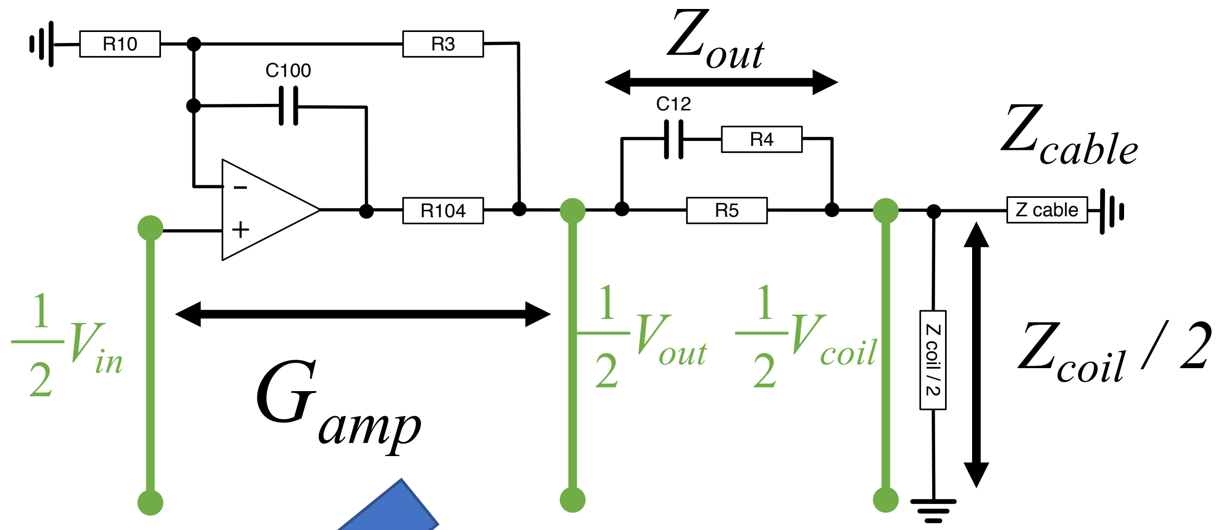
Also, with the switch open, the pole and zero nearly cancel.

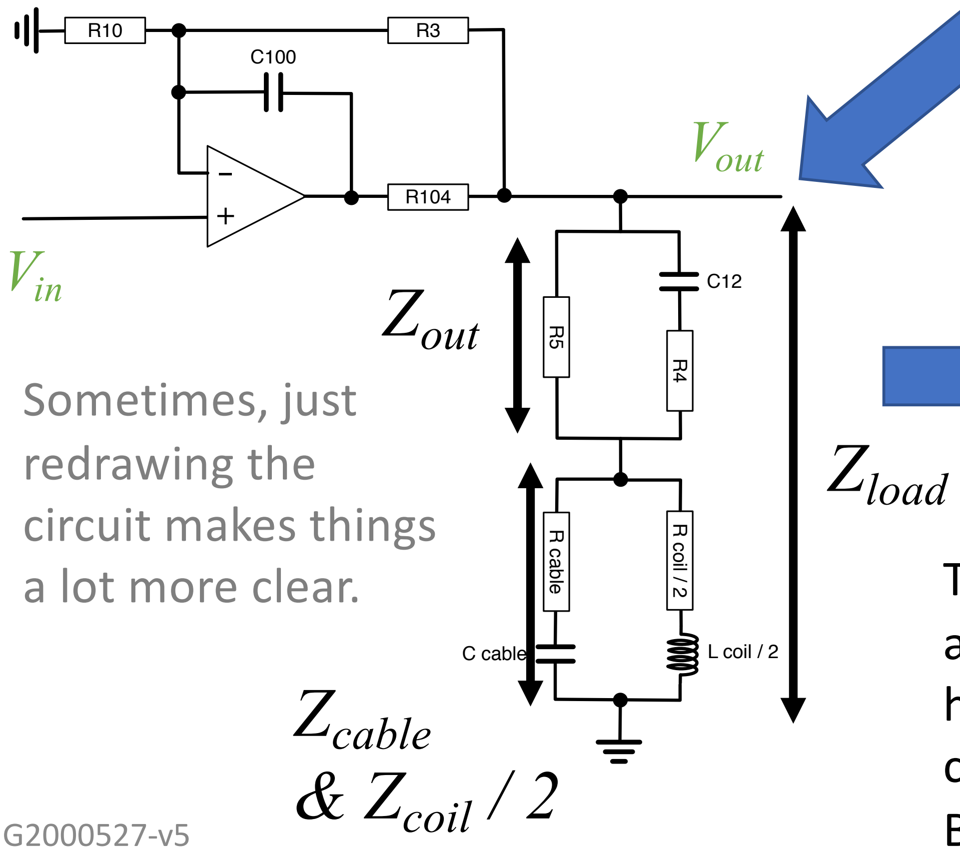
- When the switch is open, each LP stage – above 0.1 Hz – has gain of 0.969 V/V ≈ 1 V/V.
- Where we're concerned – above 1 Hz – we can treat this as "just" a part of the overall gain to be measured later, and uninteresting in terms of the frequency response
- **Thus: For State 1 (with no low passes on, all switches open), we can ignore the response of all three low passes.**

I.3 Review of the Circuit: The Output

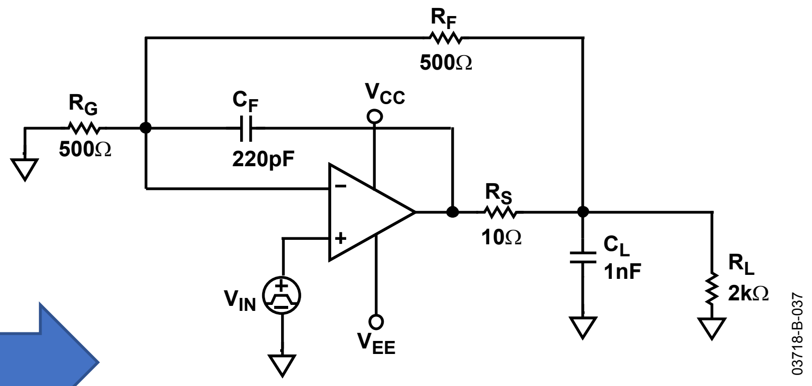
On to the response of the amplifier gain and impedance network.

These are important for State 1.





Sometimes, just redrawing the circuit makes things a lot more clear.

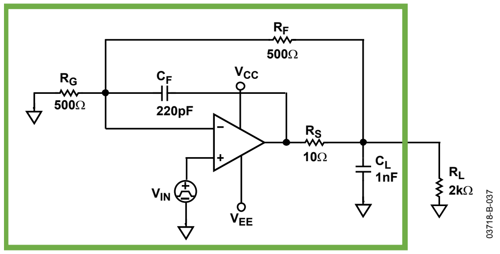


From the AD8671 Data Sheet!

This complicated network can be treated as "just" a non-inverting amplifier, with capacitive load, that has been "in-loop compensated." More in-loop compensation here.

But, with a "duct tape and bubble gum" story …

I.3 Review of the Circuit:

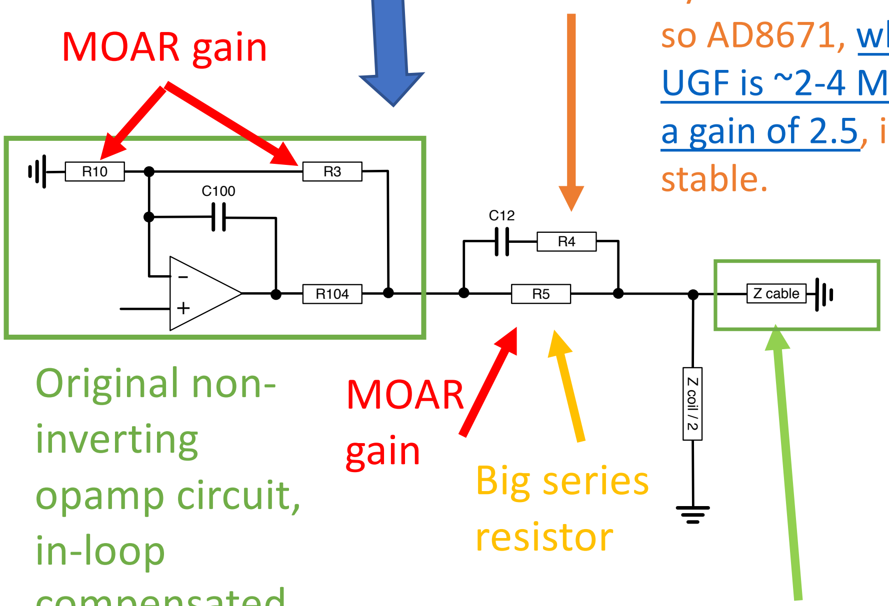


R_S = R104 = 10 # Ohm
R_F = R3 = 3.3e3 # Ohm
R_G = R10 = 2.2e3 # Ohm
C_F = C100 = 0.22e-9 # Farad
C_L = C_{cable} = 1.0e-9 # Farad
R4 = 750.0 # Ohm
"R_L" = R5 = 2.0e3 # Ohm
C12 = 0.68e-6 # Farad

RC bypass

$Im\{\frac{1}{i\omega C_{12}}\} \ll \frac{R_4 R_5}{(R_4+R_5)}$ by 1 kHz and above, so AD8671, whose UGF is ~2-4 MHz with a gain of 2.5, is quite stable.

MOAR gain



Original non-inverting opamp circuit, in-loop compensated with R104

MOAR gain

Big series resistor

Original cable load that motivated the in-loop compensation design

- Use the AD8671, it's a nice, low noise op amp.
- "OK, I'll use the data-sheet-recommended configuration, because the cable run will be pretty long – probably 3 nF of parasitic capacitance. Same component values should be fine."
- Right, but be conscious of the current noise, so make sure R_L stays big (the BOSEM, Z_{coil} , should be connected after it), and DAC noise from upstream.
- "OK, cool, a big series resistor *in the driver circuit*, prior to the cable load with R5 = 4k and increase R_F/R_G from 1 to 0.33."
- Mmm... but that reduces the actuator range. Can you give me more gain?
- "Sure –let's put in an RC bypass around R_L to amplify the range at 100 Hz."
- That reduces the protection against current noise, but should still be OK. And also... sorry... we still need more range.
- "OK, dropping R_5 to 2k, and bumping R_F/R_G up to 0.5."
- **But wait... the circuit isn't really ever capacitively loaded any more... so the this design doesn't make sense with this silly R_S that makes the circuit confusing to analyze!**

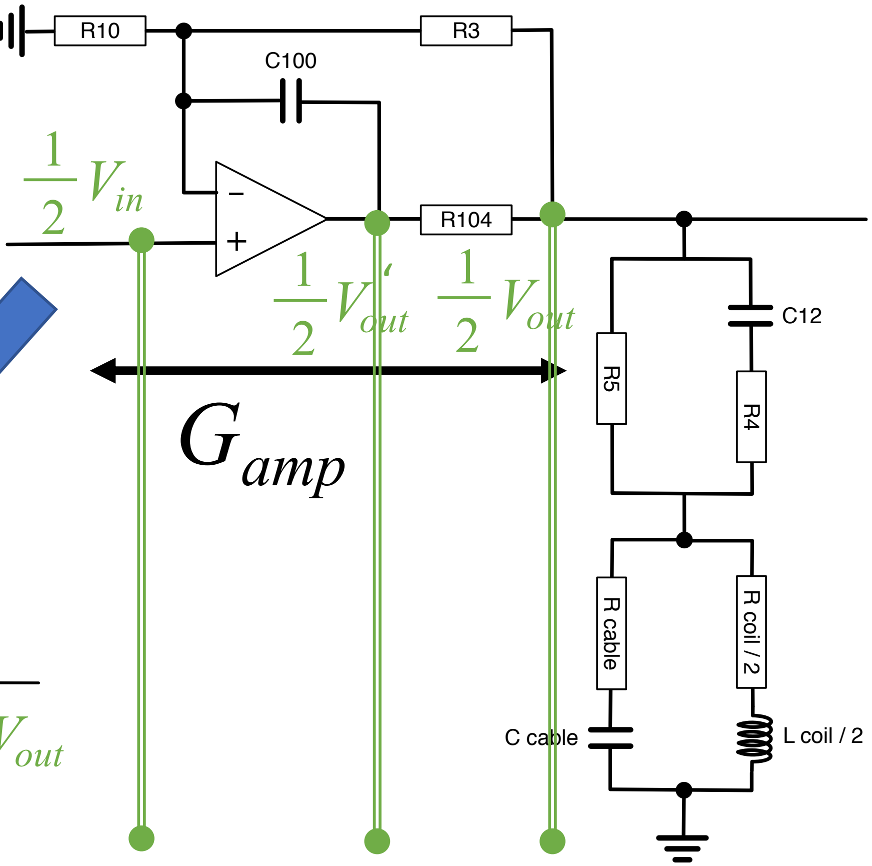
I.3 Review of the Circuit: Op-Amp = Just a Gain

So can we just ignore R_S = R104 = 10 Ohms?

```
R3 = 3.3e3        # Ohm
R10 = 2.2e3       # Ohm
R104 = 10         # Ohm
C100 = 220e-12  # Farad
```

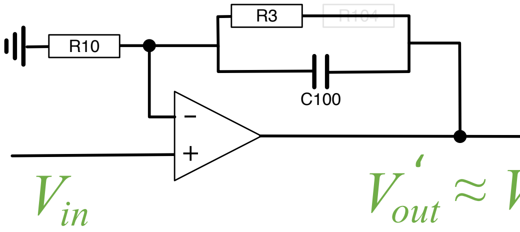
$$\frac{V_{out}}{V'_{out}} = \frac{R_3}{R_3 + R_{104}} = 0.997$$

YES. R10 is just a tiny voltage drop between Vout and Vout'.



Now, "just" a non-inverting amplifier.

What's the pole frequency?



$$Z_{RC} \approx \frac{R_3(1/i\omega C_{100})}{R_3 + 1/i\omega C_{100}} = R_3 \frac{1}{(1 + i\omega R_3 C_{100})}$$

$$G_{amp} \approx \frac{V_{out}}{V_{in}} = 1 + \left(\frac{Z_{RC}}{R_{10}}\right) = 1 + \frac{R_3}{R_{10}}\left(\frac{1}{1 + i\omega R_3 C_{100}}\right)$$

$$G_{amp}\Big|_{DC} = 1 + \frac{R_3}{R_{10}} = 2.5$$

$$f_p^{RC} = 1/(2\pi R_3 C_{100}) = 219.2\ kHz$$

219 kHz is sufficiently high frequency that we can ignore this pole too.

So, YES, ignore R104 *and* C100.
G_{amp} for us is just 2.5.
This won't be a part of the State 1 response either

I.3 Review of the Circuit: Output Zs: Rs, Ls, and Cs

Let’s look at the load impedance.
We’ll find out here’s from were *all* the response from State 1 comes.

$$Z_{out} = \frac{R_5(R_4 + 1/i\omega C_{12})}{R_5 + (R_4 + 1/i\omega C_{12})} = R_5\left(\frac{1 + i\omega R_4 C_{12}}{1 + i\omega (R_4 + R_5) C_{12}}\right)$$

$$f_z^{out} = 1/(2\pi R_4 C_{12}) = 312.069\ Hz$$
$$f_p^{out} = 1/(2\pi(R_4+R_5)C_{12}) = 85.110\ Hz$$

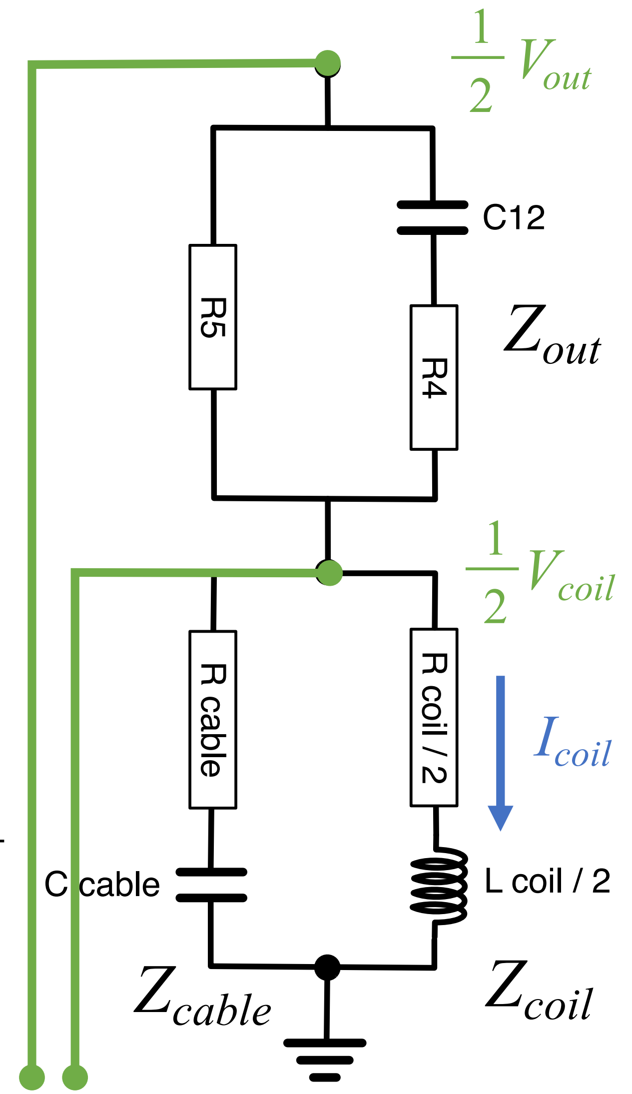
$$Z_{coil} = \frac{1}{2}(R_{coil} + i\omega L_{coil}) = \frac{R_{coil}}{2}(1 + i\omega(L_{coil}/R_{coil}))$$

$$f_z^{coil} = 1/(2\pi L_{coil}/R_{coil}) = 571.085\ Hz$$

$$Z_{RLC} = Z_{coil} \parallel Z_{cable}$$

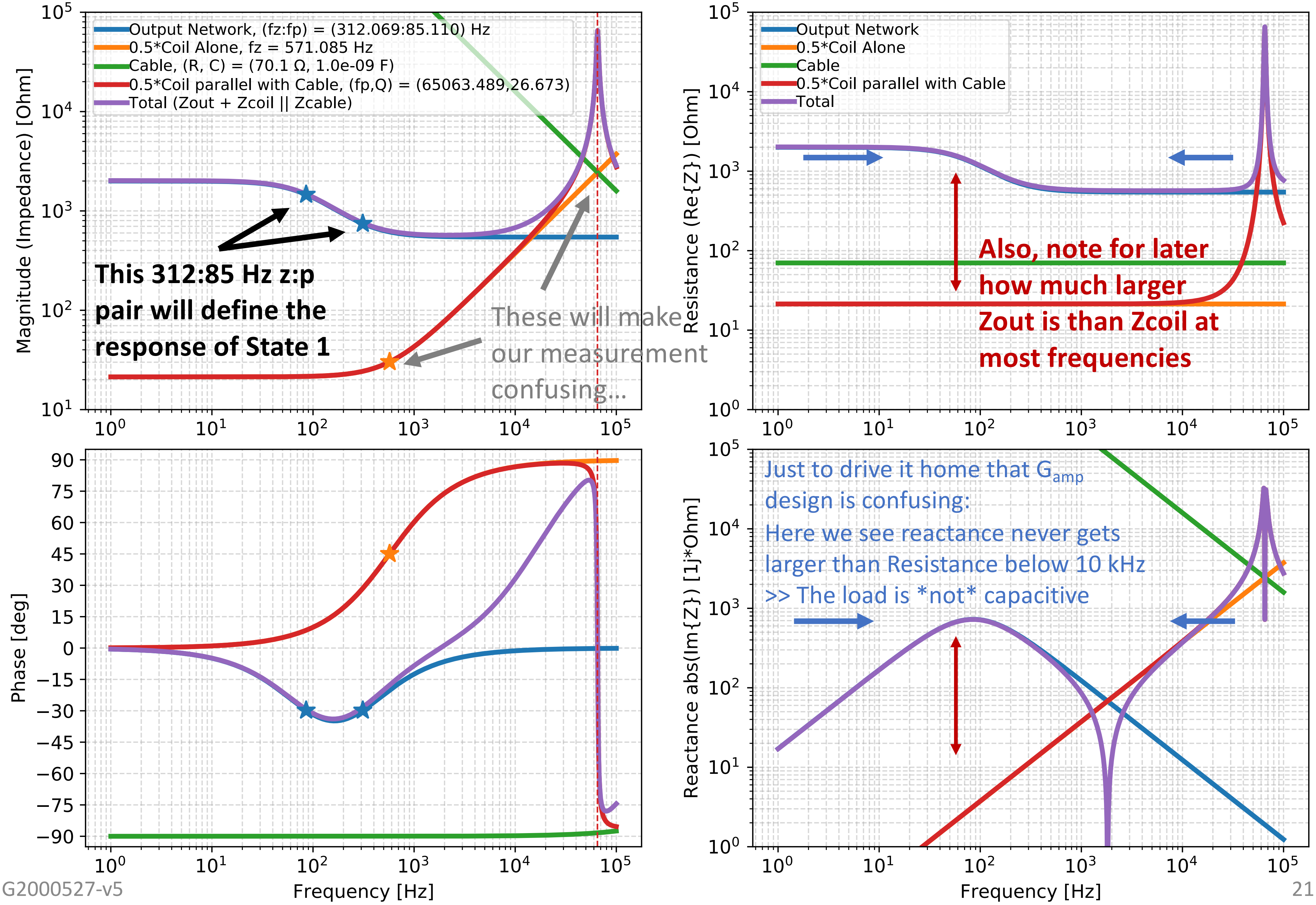
$$= \frac{1}{2}R_{coil}\frac{(1 + i\omega[L_{coil}/R_{coil}])(1 + i\omega R_{cable}C_{cable})}{(1 + i\omega(2R_{cable} + R_{coil})C_{cable} - (1/2)\omega^2 L_{coil}C_{cable})}$$

$$f_z^{coil} = 1/(2\pi L_{coil}/R_{coil}) = 571.085\ Hz$$
$$f_z^{cable} = 1/(2\pi R_{cable}C_{cable}) = 2.27\ MHz$$



$$f_p^{coil||cable} = 1/(2\pi)\sqrt{\frac{1}{(1/2)L_{coil}C_{cable}} - \left(\frac{2R_{cable} + R_{coil}}{(1/2)L_{coil}}\right)^2} = 65.063\ kHz$$

I.3 Review of the Circuit: Z total: poles and zeros



This 312:85 Hz z:p pair will define the response of State 1

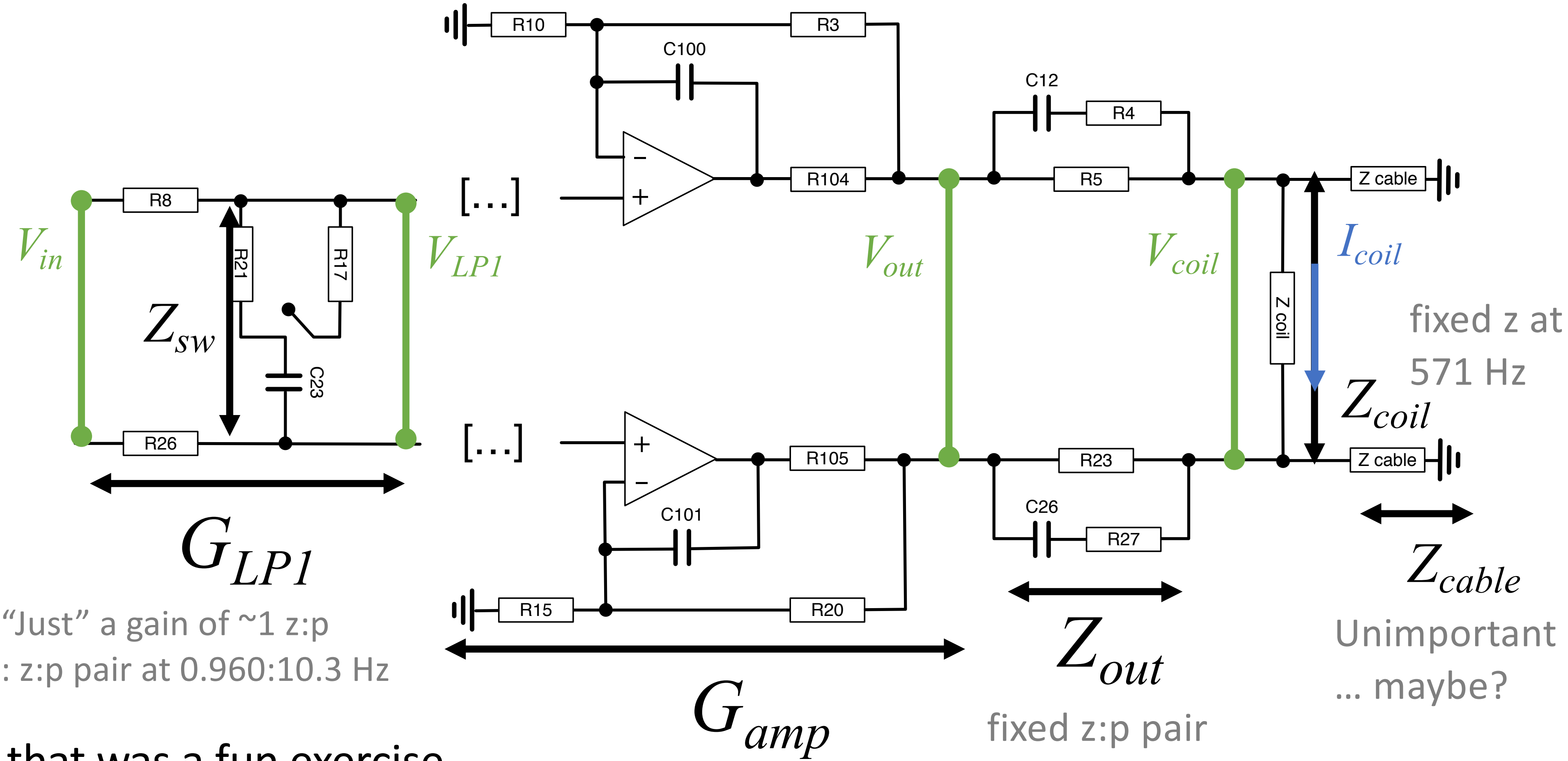
These will make our measurement confusing...

Also, note for later how much larger Zout is than Zcoil at most frequencies

Just to drive it home that G_{amp} design is confusing:
Here we see reactance never gets larger than Resistance below 10 kHz
>> The load is *not* capacitive

I.3 Review of the Circuit: OK, Let’s Review

OK, now that we know what kind of response to expect from everything, we can head back to the differential picture and summarize.



Open: “Just” a gain of ~1 z:p
Closed: z:p pair at 0.960:10.3 Hz

fixed z at 571 Hz

Unimportant … maybe?

fixed z:p pair at 312:85 Hz

“Just” a gain of 2.5.

Well, that was a fun exercise.
But what do we really want?

The response of the current created across the coil, *I_{coil}* to V_{in}.
So let’s talk about how to measure it.

Outline

Two Parts, each quite long. *sigh*

PART I: The ETMX UIM Driver, from Nov 27 to Dec 03 2019

1. Why do you care about the UIM?
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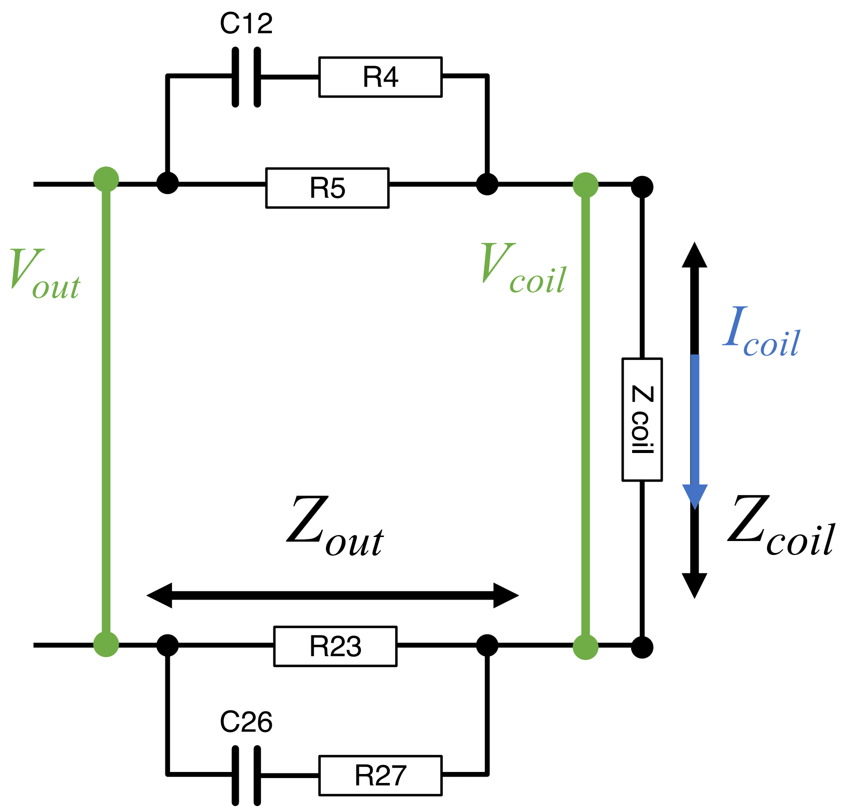
PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

I.4 The Measurement: Coil Current/Vout



We calculated that whatever the values of Rcable and Ccable are, they're not going to matter until several 10s of kHz. So let's make it easy to think about.

In **State 1**, we already know, Vout/Vin is "just a gain" at ~2.5. So the current, held fixed by the G_{amp} opamps, will just obey Ohms Law as it heads out to the coil and back across the differential connection to the coil:

$$V_{out} = I_{coil}\, Z_{total} = I_{coil}(2Z_{out} + Z_{coil})$$

$$\frac{I_{coil}}{V_{out}} = \frac{1}{(2Z_{out} + Z_{coil})}$$

And, we know for State 1, that means,

$$\left.\frac{I_{coil}}{V_{in}}\right|_{State\ 1} \approx \frac{2.5}{(2Z_{out} + Z_{coil})}$$

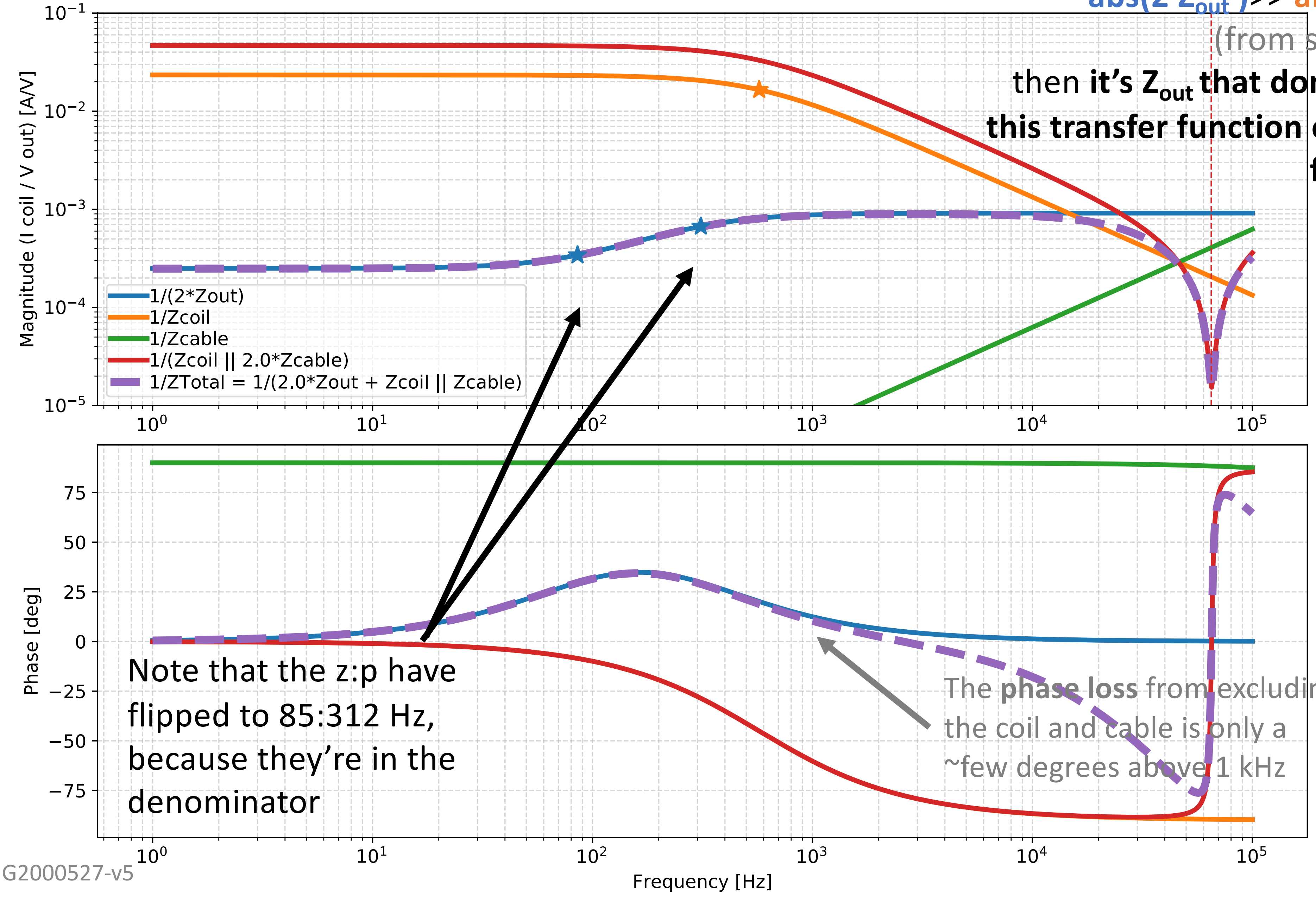
So let's look at that response, with our basic analytic model.

I.4 The Measurement: Coil Current / Vout

$$I_{coil}/V_{out} = 1/(2Z_{out} + Z_{coil})$$

Ah – OK, since **abs(2 Z_{out})**>> **abs(Z_{coil})** (from slide 17)

then **it's Z_{out} that dominates this transfer function** out to a **few kHz**



Note that the z:p have flipped to 85:312 Hz, because they're in the denominator

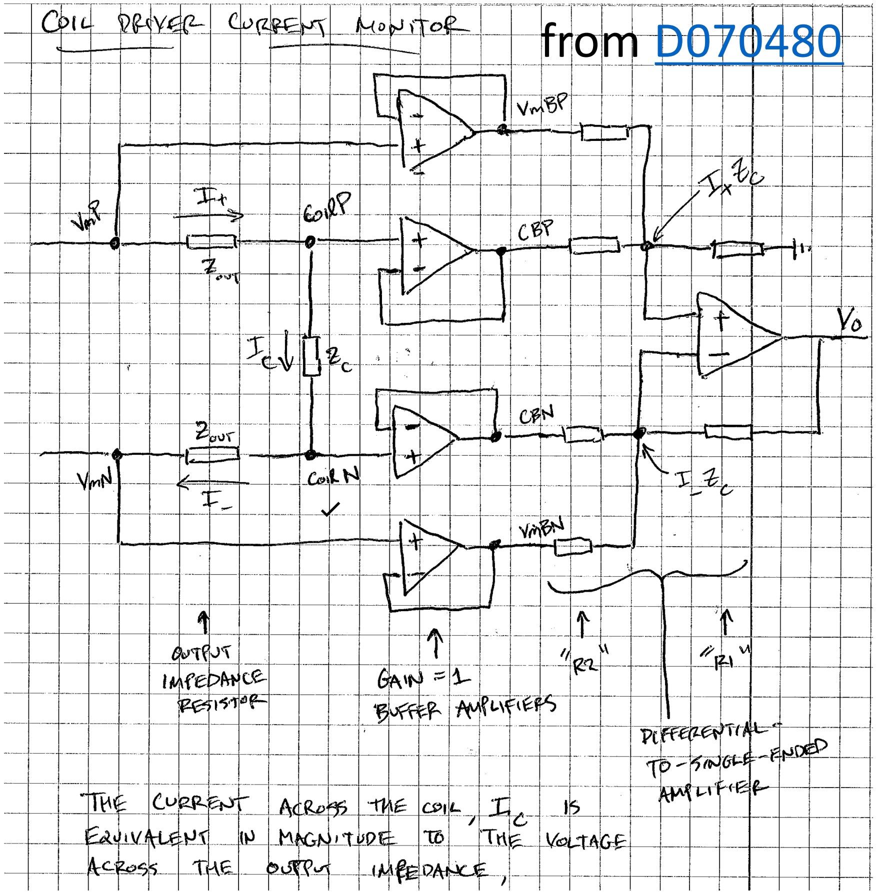
The **phase loss** from excluding the coil and cable is only a ~few degrees above 1 kHz

I.4 The Measurement: Fast Current Monitor?

Why do we have to physically measure the transfer function in analog? Why not use the fast current monitor?

- **The answer does include the output impedance network for this driver** (contrary to popular belief, started by 2014 Jeff)
- BUT -- the fast current monitor board itself may contribute some frequency dependence, and there's an AA chassis between the analog IMON signal and where it's read in by the DAQ. **These responses will confuse fitting routines and/or your interpretation of the results.**
- It works well for *ratios* of measurements, namely to get poles and zeros from things that *change* between states (i.e. the low pass filters), but it does not help you characterize State 1.
- We typically operate in state 1, and at least the AA chassis has appreciable response in frequency bands of interest to us, so …

- Analog measurement it is.



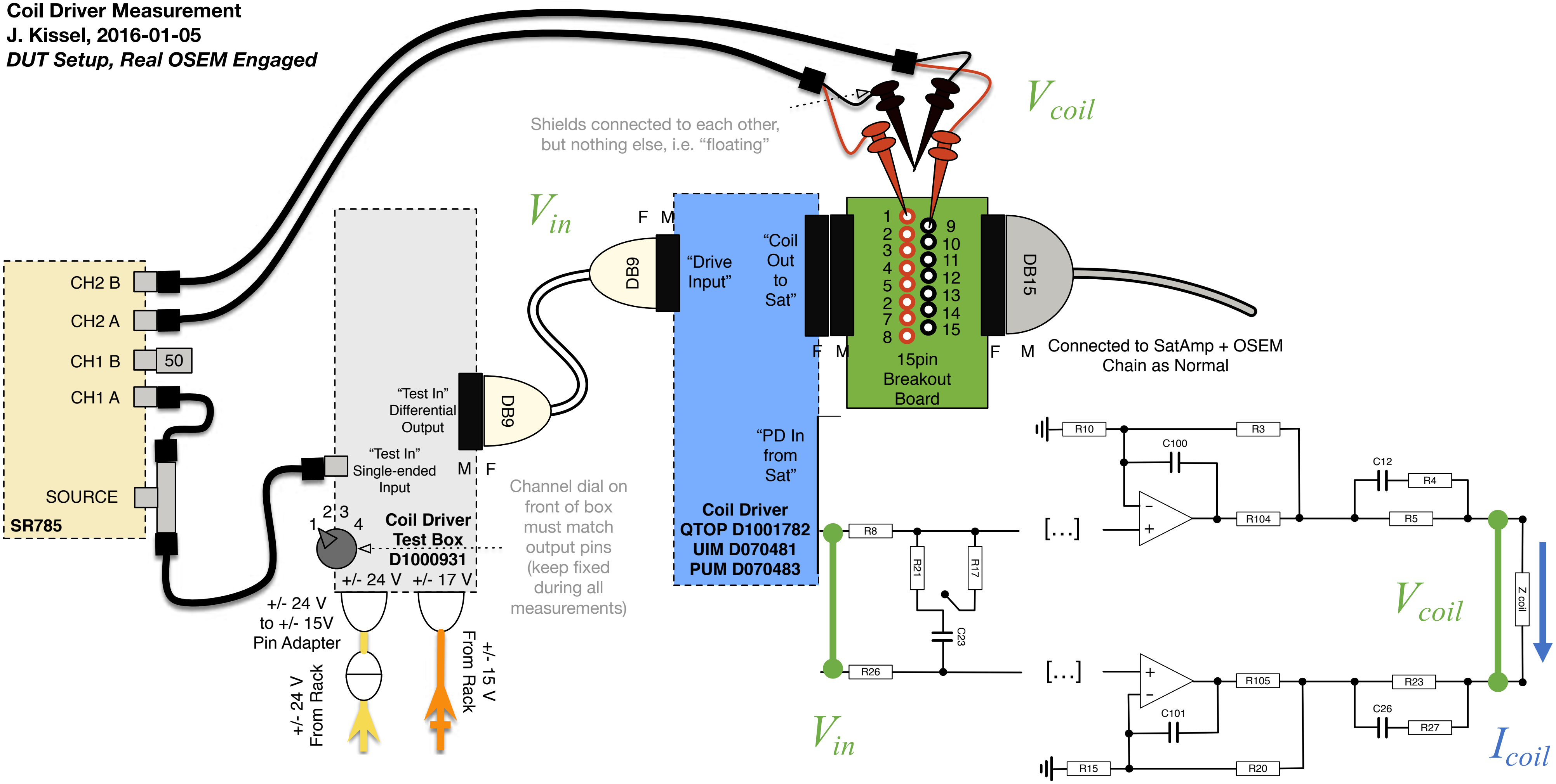
from D070480

THE CURRENT ACROSS THE COIL, I_c, IS EQUIVALENT IN MAGNITUDE TO THE VOLTAGE ACROSS THE OUTPUT IMPEDANCE,

$$\frac{V_o}{I_c} = 2 Z_{out} \frac{R_1}{R_2}$$

I.4 The Measurement: Should / Would / Could…

OK Great! Gung-ho Jeff will go out there, he'll take some clip leads, a differential driver, and breakout boards, to measure at the output of the driver – but leaving output connected to the OSEM as normal, "because you need the current to go across the output legs" – the op-amps need to be loaded with *something,* so might as well make it "as accurate as possible."



I.4 The Measurement: Facepalm!

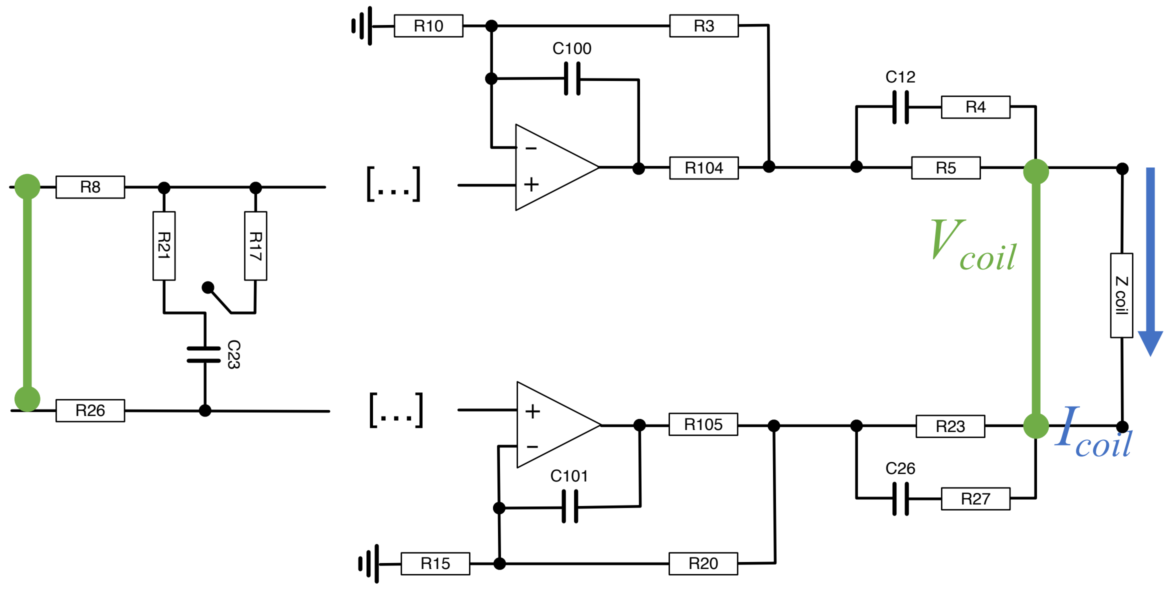
But wait – if you've left the coil connect "as normal" then you're not going to measure…

$$\left.\frac{I_{coil}}{V_{in}}\right|_1 \approx \frac{2.5}{(2Z_{out}+Z_{coil})}$$

But instead…

$$V_{coil} = I_{coil} Z_{coil}$$

$$\left.\frac{V_{coil}}{V_{in}}\right|_1 \approx \frac{2.5\,Z_{coil}}{(2Z_{out}+Z_{coil})}$$



$$f_z^{coil} = 1/(2\pi L_{coil}/R_{coil}) = 571.085\ Hz$$

$$f_p^{out} = 1/(2\pi R_4 C_{12}) = 312.069\ Hz$$

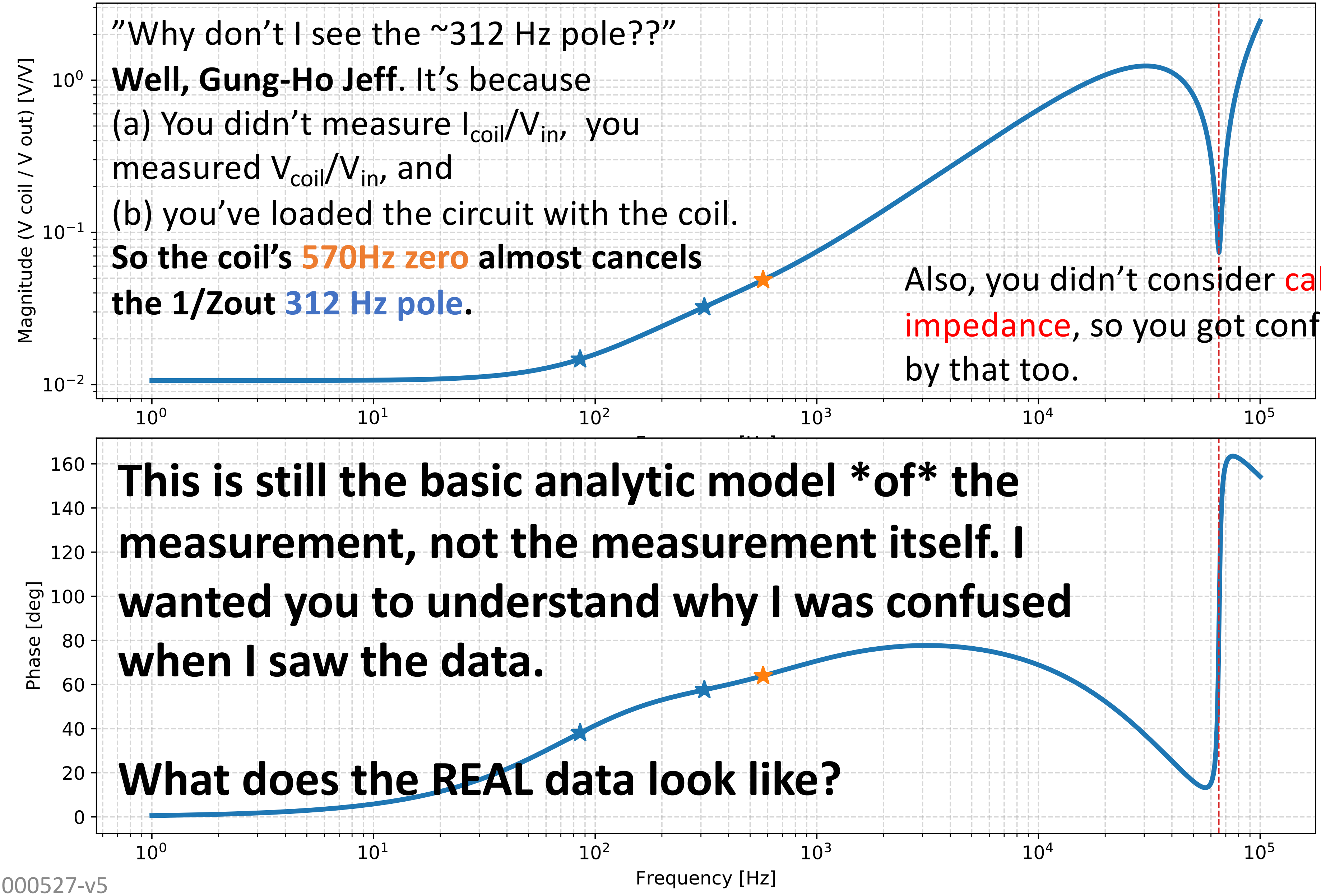
$$f_z^{out} = 1/(2\pi (R_4+R_5) C_{12}) = 85.110\ Hz$$

flipped because Zout is in the denominator

Which means you're going to be confused for months – YEARS – by your results, until you write this presentation!

I.4 The Measurement: “missing” pole, *really* solved.

$$V_{coil}/V_{in} \approx Z_{coil}/(2Z_{out} + Z_{coil})$$



”Why don’t I see the ~312 Hz pole??”

Well, Gung-Ho Jeff. It’s because

(a) You didn’t measure I_{coil}/V_{in}, you measured V_{coil}/V_{in}, and

(b) you’ve loaded the circuit with the coil.

So the coil’s 570Hz zero almost cancels the 1/Zout 312 Hz pole.

Also, you didn’t consider cable impedance, so you got confused by that too.

This is still the basic analytic model *of* the measurement, not the measurement itself. I wanted you to understand why I was confused when I saw the data.

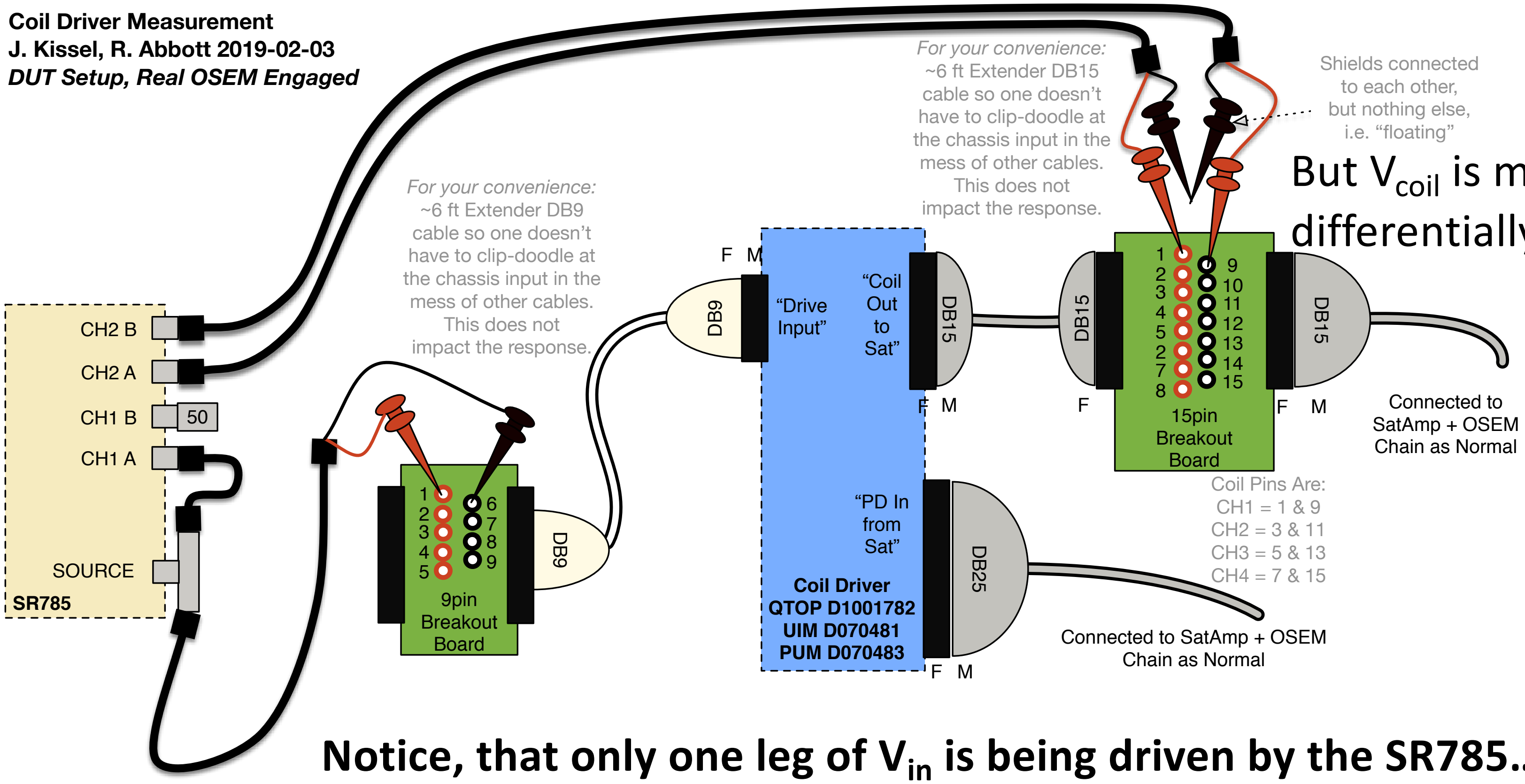
What does the REAL data look like?

I.4 The Measurement: What we really did…

But wait … it gets worse. To quote [LHO:46927]:

"This time (unlike the 2016 attempt; with measurement as shown on the last slide, as in [LHO:24725]) we tried to cut corners by only driving the coil drivers with single-ended input directly from the SR785 -- so we can avoid having to characterize the details of the differential driver box that has been used previously. This failed, causing (what we believe to be saturations) of the coil driver electronics and wonky unphysical*** transfer functions."

The joys of that Sunday measurement you think will work to save you time…



Coil Driver Measurement
J. Kissel, R. Abbott 2019-02-03
DUT Setup, Real OSEM Engaged

For your convenience: ~6 ft Extender DB9 cable so one doesn't have to clip-doodle at the chassis input in the mess of other cables. This does not impact the response.

For your convenience: ~6 ft Extender DB15 cable so one doesn't have to clip-doodle at the chassis input in the mess of other cables. This does not impact the response.

Shields connected to each other, but nothing else, i.e. "floating"

Connected to SatAmp + OSEM Chain as Normal

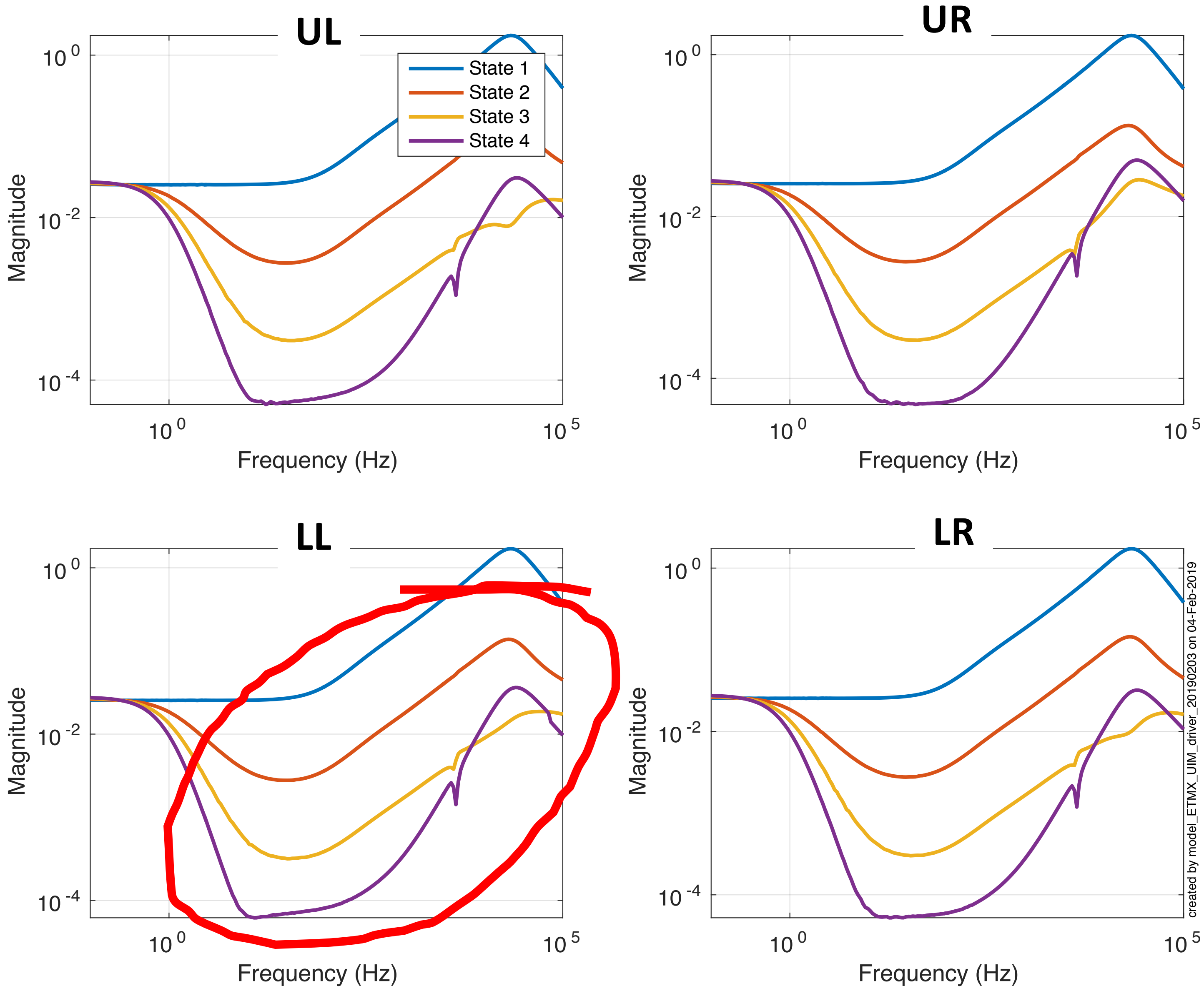
Coil Pins Are:
CH1 = 1 & 9
CH2 = 3 & 11
CH3 = 5 & 13
CH4 = 7 & 15

Connected to SatAmp + OSEM Chain as Normal

But V_{coil} is measured differentially…

Notice, that only one leg of V_{in} is being driven by the SR785…

I.4 The Measurement: *** wonky, unphysical TFs



Evan plotted the results 2019-02-03 results the next day (see [LHO:46773]).

Evan apologizes for the lack of tick marks.

Sure, it looks like there's "there's no 300 Hz pole," but we now understand that.

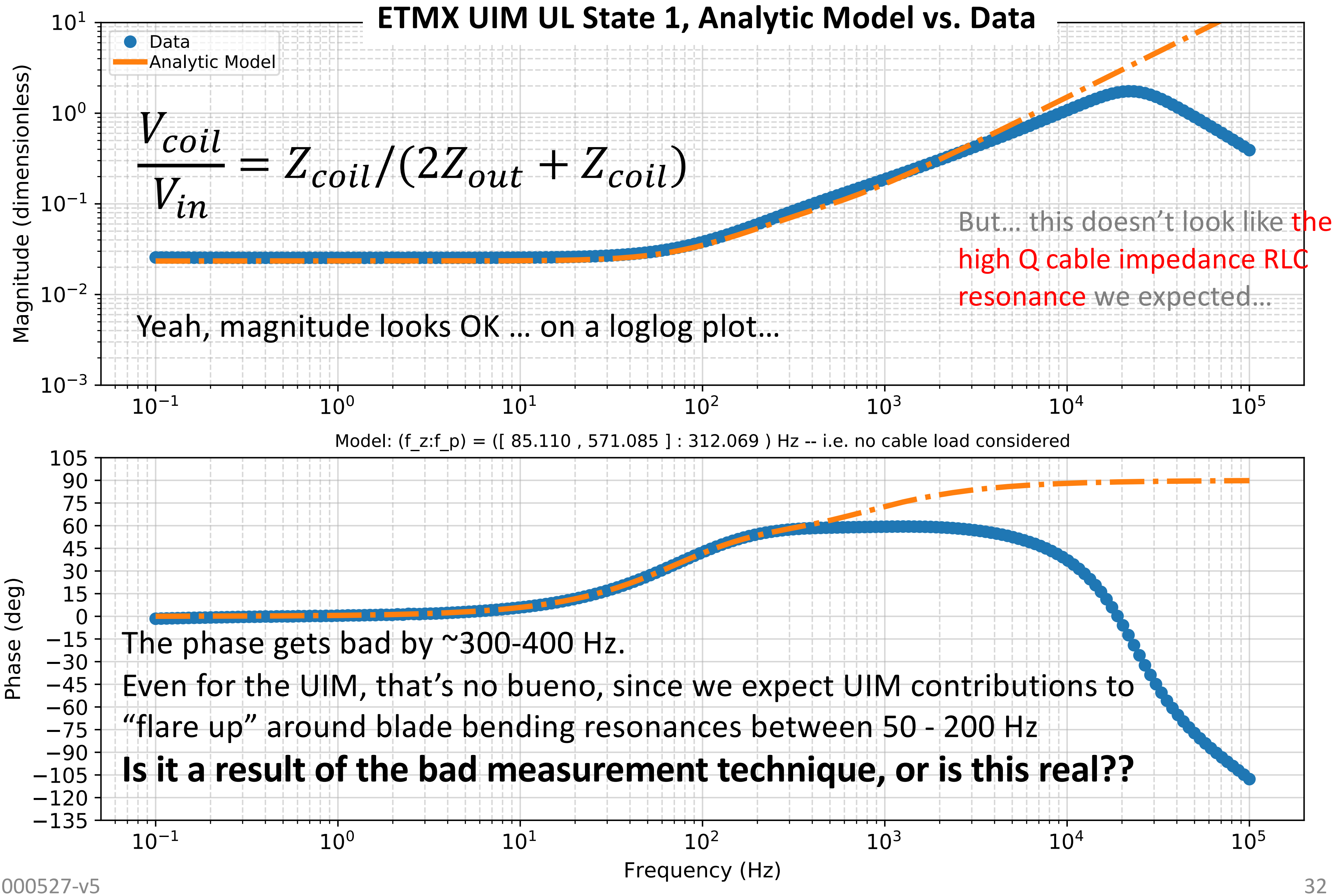
Further, it looks like, for at least State 2, the z:p = 10.5:0.95 Hz low pass shows up, good…

But look at how the magnitude gets distorted at (let's say 500 Hz) and above in States 3 and 4…

^/trunk/Common/Electronics/H1/Data/SUSElectronics/ETMX/UIM/2019-02-03/2019-02-03_UIMdriver_measurementnotes.txt

But … this is the data we have. Maybe we can salvage the data for States 1 and 2?

I.4 The Measurement: Finally, The Data.



$$\frac{V_{coil}}{V_{in}} = Z_{coil}/(2Z_{out} + Z_{coil})$$

Yeah, magnitude looks OK … on a loglog plot…

But… this doesn't look like the high Q cable impedance RLC resonance we expected…

The phase gets bad by ~300-400 Hz.

Even for the UIM, that's no bueno, since we expect UIM contributions to "flare up" around blade bending resonances between 50 - 200 Hz

Is it a result of the bad measurement technique, or is this real??

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PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

I.5 Other Models of the Circuit

- **What if we use a more sophisticated model? Can we predict this deviation?** There are lots of more sophisticated modelling tools for circuits out there, LISO, Spice, Altium, etc.

- Chris Wipf put together a LISO model of the UIM circuit in the Noise Budget SVN,
  - https://svn.ligo.caltech.edu/svn/aligonoisebudget/trunk/Dev/SusElectronics/LISO/QUAD/UIM
  - Note that, unfortunately, the LISO models Chris ran didn't export poles and zeros, we so don't have them (we'll find later that re-running to get them won't be worth it)

- It will be instructive to show that model too, especially because
  - More models = more understanding
  - More poles and zeros will appear from the fit than we predict from the analytic model,
  - The LISO model doesn't make approximations for clarity, and
  - The parameters of the cable and coil load are (apparently) quite uncertain

But, also, let's just fit the data.

Outline

Two Parts, each quite long. *sigh*

PART I: The ETMX UIM Driver, from Nov 27 to Dec 03 2019

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This parts a four-sub-part doooosey

PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

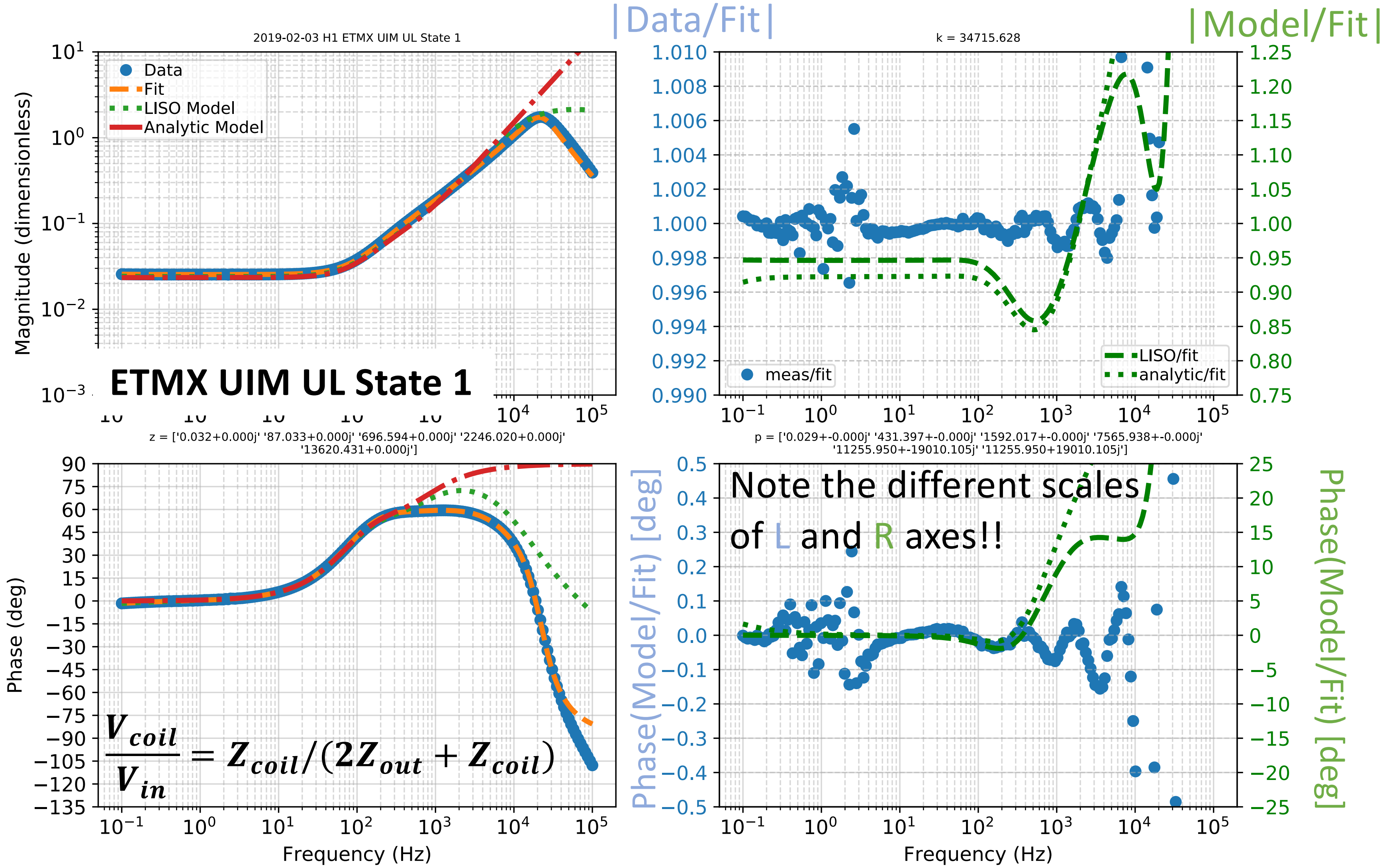
I.6.1 The Fit: IIR Rational is Awesome

- Most transfer function software is unruly: if you don’t understand what your data is, or the quality of the data, you’re going to have a tough time tailoring the tool to suit your needs, and/or understanding the results.
- A 2016 call to action, G1601173, inspired Lee McCuller to develop IIRrationalv2. I’ve found it to work excellently, with minimal input.
- The script to run the fit lives here:
- `^/trunk/Common/Electronics/H1/Scripts/fit_ETMX_UIM_driver_20190203_IIRrational_20200401.py`
- Here’s my environment that I used to get it to work (determined using `^/trunk/Common/Misc/Scripts/versioncheck.py` the output of which is quoted here):

```
This is Python version:
3.7.4 (default, Aug 13 2019, 15:17:50)
[Clang 4.0.1 (tags/RELEASE_401/final)]

If you import the following packages, you
will get the versions listed below:
    matplotlib.__version__ = 3.1.1
    numpy.__version__ = 1.17.2
    scipy.__version__ = 1.3.1
    sklearn.__version__ = 0.21.3
    gwpy.__version__ = 1.0.1
    nds2.__version__ = 0.16.5
    IIRrational.__version__ = 2.0.11
    h5py.__version__ = 2.9.0
    emcee.__version__ = 3.0.2
    corner.__version__ = 2.0.1
```

I.6.1 The Fit Results Per Coil: Intro to Plot



|Data/Fit|

|Model/Fit|

ETMX UIM UL State 1

$$\frac{V_{coil}}{V_{in}} = Z_{coil}/(2Z_{out} + Z_{coil})$$

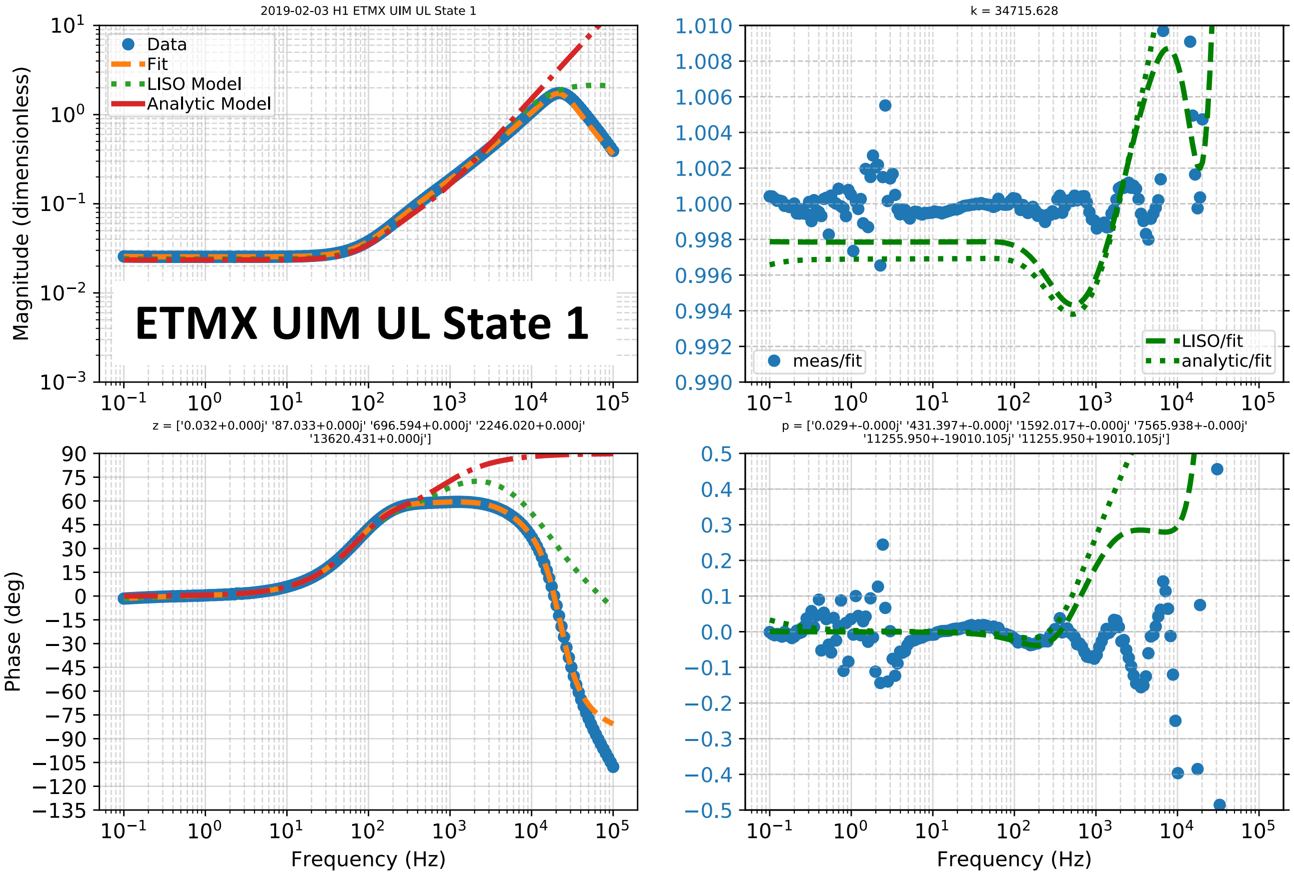
Note the different scales of L and R axes!!

- The **basic analytic model** is as bad as we know from slide 27 (residual shown in dotted green)
- The **LISO model** seems to miss the basic RC and Coil pole and zero frequencies, resulting in magnitude error of ~15% by 300 Hz, and also bad in phase (residual, in dashed green, is 10 deg by 1 kHz).
- The **IIRrational fit** is excellent, all the way out to 10 kHz. But … let's look at all the poles and zeros it returns …

I.6.1 Fit per Coil: State 1 Results Interpretation

Again, understand the fit results is an important part of the game:

- Do zeros and poles make sense?
- Are there more than you expect?
- Are results consistent across several coils?
- Can we ignore any?



Take UL for example:

$$\frac{\boldsymbol{V_{coil}}}{\boldsymbol{V_{in}}} = \boldsymbol{Z_{coil}/(2Z_{out} + Z_{coil})}$$

Circuit Feature Assignment	UL Fit Zeros	UL Fit Poles
Coil Impedance	**696.5942 Hz** 🟡	
RC Network	**87.0329 Hz** 🟢	**431.3965 Hz** 🟡
SW Closed LP	**0.0325 Hz** 🟢	**0.0293 Hz** 🟢
?????	**2246.0201 Hz** 🔴	**1592.0174** 🔴
Cable impedance?		**pair(22092.54 Hz, 59.37 deg)** 🟡

🟢 f_z or f_p , or combo is right about where we expect. Or the fz:fp is close enough to "canceling" to ignore

🟡 f_z or f_p is probably from feature X, but is pretty far off from expected, or maybe high frequency enough to not matter

🔴 **WUT**

I.6.1 Fit per Coil: State 1 Results Summary

Circuit Feature Assignment	UL Fit Zeros	UL Fit Poles
Coil Impedance	696.5942 Hz 🟡	
RC Network	87.0329 Hz 🟢	431.3965 Hz 🟡
SW Closed LP	0.0325 Hz 🟢	0.0293 Hz 🟢
????	2246.0201 Hz 🔴	1592.0174 🔴
Cable impedance?		pair(22092.54 Hz, 59.37 deg) 🟡

Circuit Feature Assignment	UR Fit Zeros	UR Fit Poles
Coil Impedance	671.7041 Hz 🟡	
RC Network	85.9533 Hz 🟢	422.2943 Hz 🟡
SW Closed LP	No fit? 🟡	No fit? 🟡
????	2337.1901 Hz 🔴	5132.4934 Hz 🔴
????	pair(12262.2781 Hz, 15.218 deg) pair(12822.8952 Hz, 21.5666) 🔴	pair(11037.6219 Hz, 61.3485 deg) 🔴
????	19443.5355 🔴	
Cable impedance? 🟡		pair(21731.503 Hz, 73.7415 deg) 🟡

$$f_z^{coil} = 1/(2\pi L_{coil}/R_{coil}) = 571.085\ Hz$$

$$f_p^{out} = 1/(2\pi R_4 C_{12}) = 312.069\ Hz$$

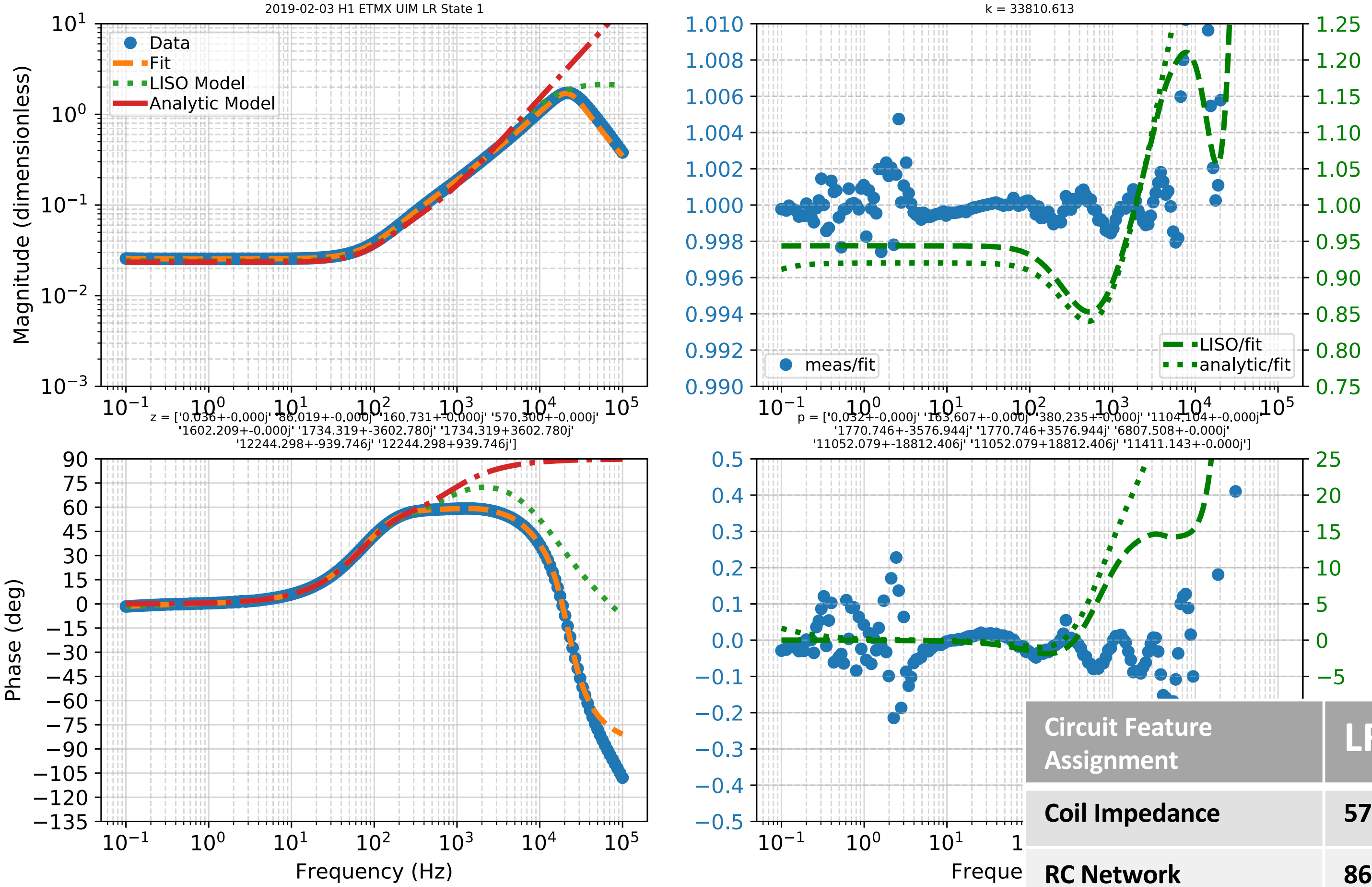
$$f_z^{out} = 1/(2\pi (R_4+R_5) C_{12}) = 85.110\ Hz$$

Circuit Feature Assignment	LL Fit Zeros	LL Fit Poles
Coil Impedance	699.0254 Hz 🟡	
RC Network	86.5228 Hz 🟢	427.0135 Hz 🟡
SW Closed LP	No fit? 🟡	No fit? 🟡
????	2315.2727, 5247.6252 Hz 🔴	1623.5029, pair(5943.6595, 10.6624 deg) 🔴
Cable impedance?		pair(21390.090 Hz, 58.138 deg) 🟡

$$f_p^{coil||cable} = 65.063\ kHz$$

Circuit Feature Assignment	LR Fit Zeros	LR Fit Poles
Coil Impedance	570.3 Hz 🟢	
RC Network	86.019 Hz 🟢	380.235 Hz 🟢
SW Closed LP	0.036 Hz 🟢	0.032 Hz 🟢
????	160.731 Hz 🔴	1104.104 Hz 🔴
Nearly canceling	pair(3998.485 Hz, 64.2946 deg) 🟢	pair(3991.249Hz, 63.6625 deg) 🟢
????	pair(12280.307 Hz, 4.400 deg) 🔴	6807.508, 11411.143 🔴
Cable impedance?		pair(21818.686 Hz, 59.566 deg) 🟡

I.6.1 Fit per Coil: State 1 Results LR



Circuit Feature Assignment	LR Fit Zeros	LR Fit Poles
Coil Impedance	**570.3 Hz** 🟢	
RC Network	**86.019 Hz** 🟢	**380.235 Hz** 🟢
SW Closed LP	**0.036 Hz** 🟢	**0.032 Hz** 🟢
???	**160.731 Hz** 🔴	**1104.104 Hz** 🔴
Nearly canceling	**pair(3998.485 Hz, 64.2946 deg)** 🟢	**pair(3991.249Hz, 63.6625 deg)** 🟢
???	**pair(12280.307 Hz, 4.400 deg)** 🔴	**6807.508, 11411.143** 🔴
Cable impedance?		**pair(21818.686 Hz, 59.566 deg)** 🟡

Just to show that the data, the fit, or the fit residuals for the LR "poster child" don't look any different, but the fit has poles and zeros right where we expect, AND some ones that we don't expect at all.

I.6.1 The Fit per Coil: State 1 Results Discussion

- Why is LR the poster child, with f_z:f_p = (86, 570: 380) Hz, where the other three are consistently f_z:f_p = (86, 690: 430)?
  - Let's assume that, for whatever reason, the three coils – though not as expected, are fit at real values. 430 vs. 380 Hz means R4, C12 values are in question, and 690 vs. 570 Hz means R_{coil} or L_{coil} are in question.
  - Let's assume we know the resistances well at (R4, R_{coil}) = (750,42.7) Ohm. That means (C12,L_{coil}) are actually ~(0.49e-6 F, 9.8 mH) instead of the drawing/cannon values of (0.68e-6 F, 11.9 mH).
  - Plausible…

- What are all of these mid- kHz poles and zeros? Can we get by with ignoring the fit results above 1 kHz?
  - Is this a manifestation of the bad measurement / saturation?

- Why is the cable impedance so low in frequency and so low in Q?
  - Is *this* a manifestation of the bad measurement / saturation?

I.6.1 The Fit per Coil: What’s next?

You feel I’m in the weeds. I know. *I* feel I’m in the weeds. How can we come back up for air? Look at some more weeds.

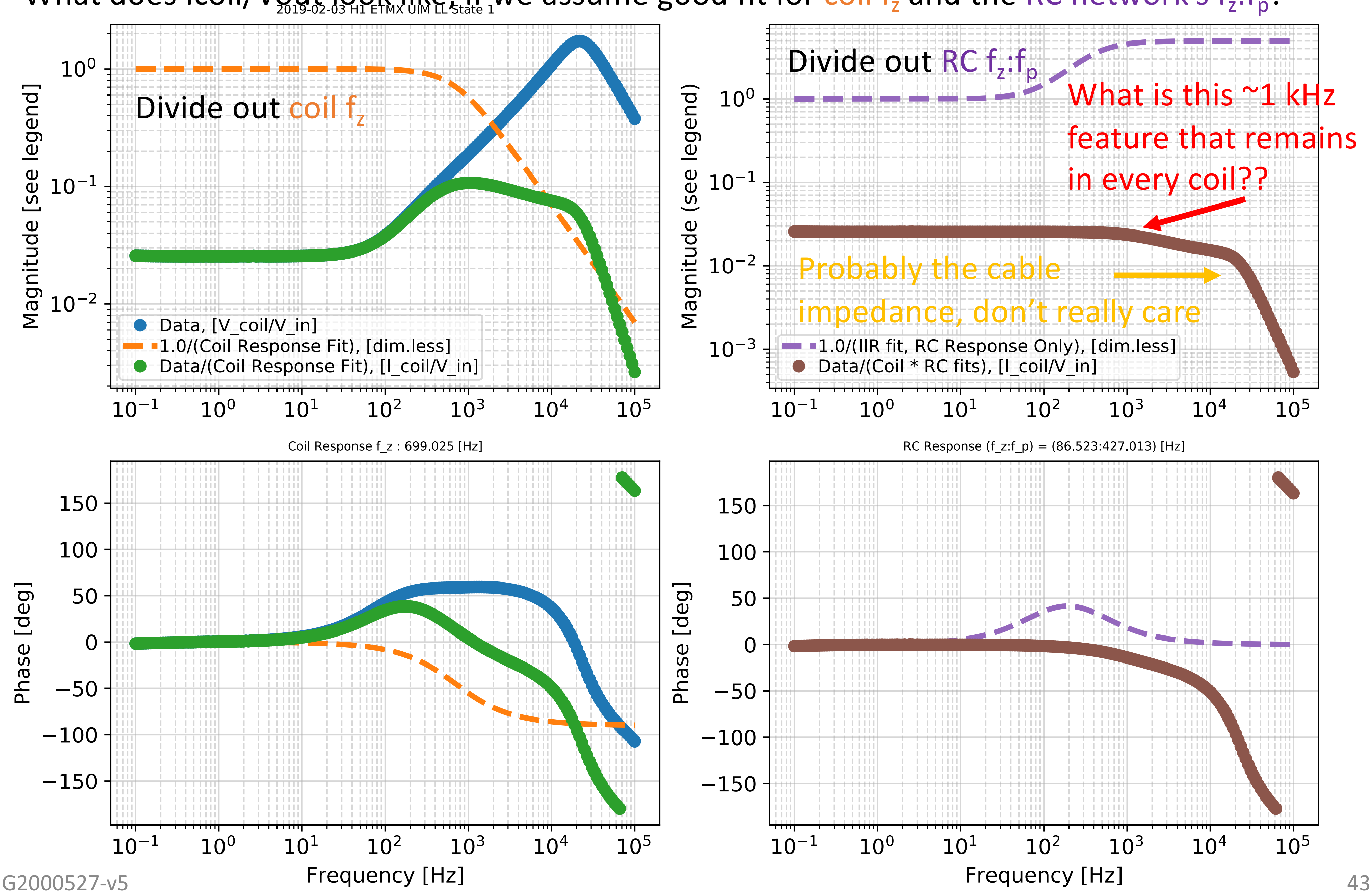
2. We can blindly assume that the fit is perfect for all coils. If so, we’d use the value of the coil f_z, divide it out of the V_{coil} / V_{in} data, and look at the I_{coil} / V_{in} transfer function. Does it make sense? Should we bother (re)fitting *that* data?

3. Look at the ratio of State 2 to State 1. Is getting the low pass f_z:f_p pair from that is as easy as we expect?

4. Look (and fit) at state 2 by itself. Does the data match the State 1 fit * (State 2 / State 1) fit?

I.6.2 Fit per Coil: State 1 I_{coil} / V_{out}, taking out "knowns"

What does Icoil/Vout look like, if we assume good fit for coil f_z and the RC network's f_z:f_p?



2019-02-03 H1 ETMX UIM LL State 1

Divide out coil f_z

Divide out RC f_z:f_p

What is this ~1 kHz feature that remains in every coil??

Probably the cable impedance, don't really care

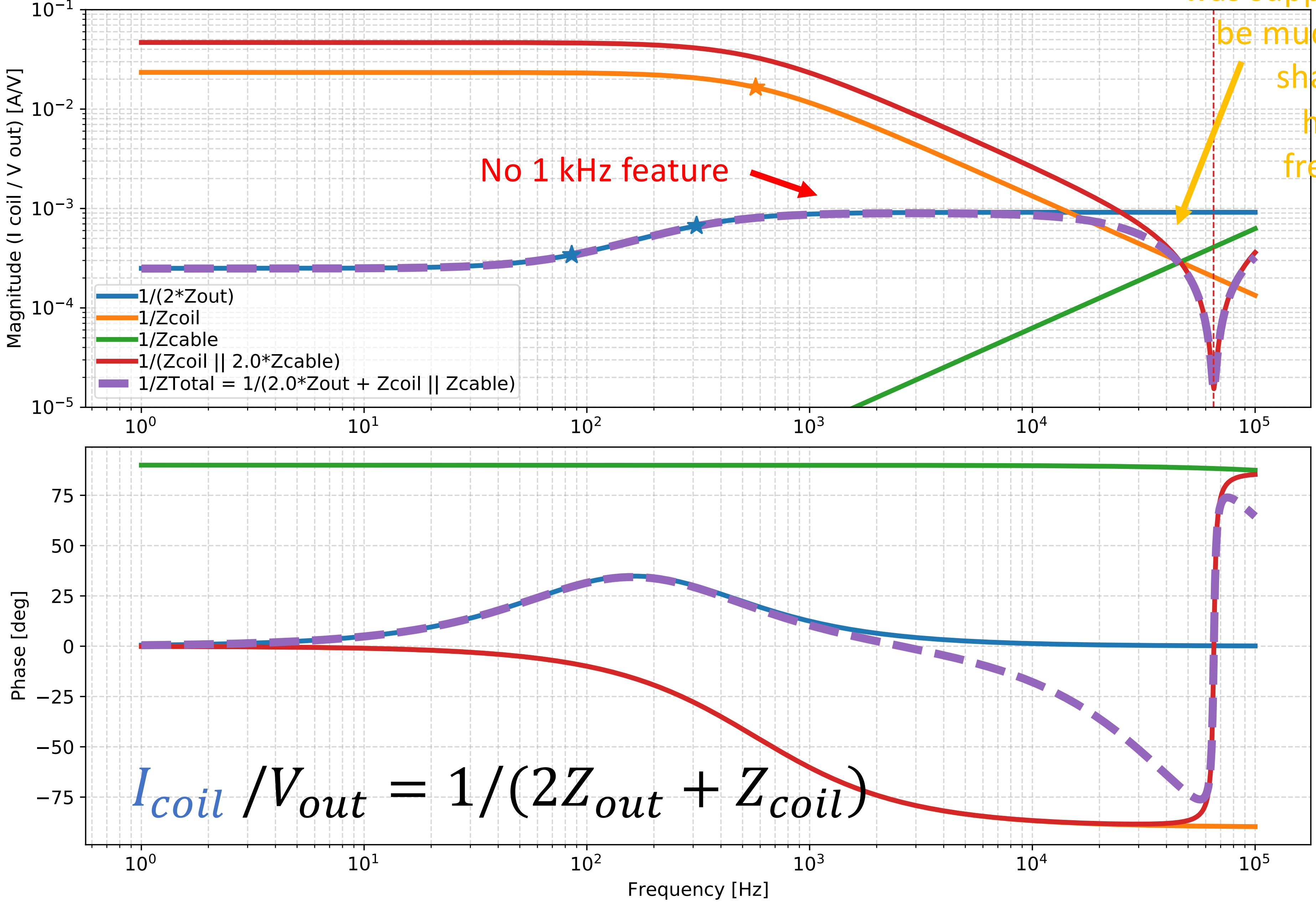
Coil Response f_z : 699.025 [Hz]

RC Response (f_z:f_p) = (86.523:427.013) [Hz]

I.6.2 Fit per Coil: State 1 remember our expectations?

Green Solid on previous slide should look like **Purple dashed** here

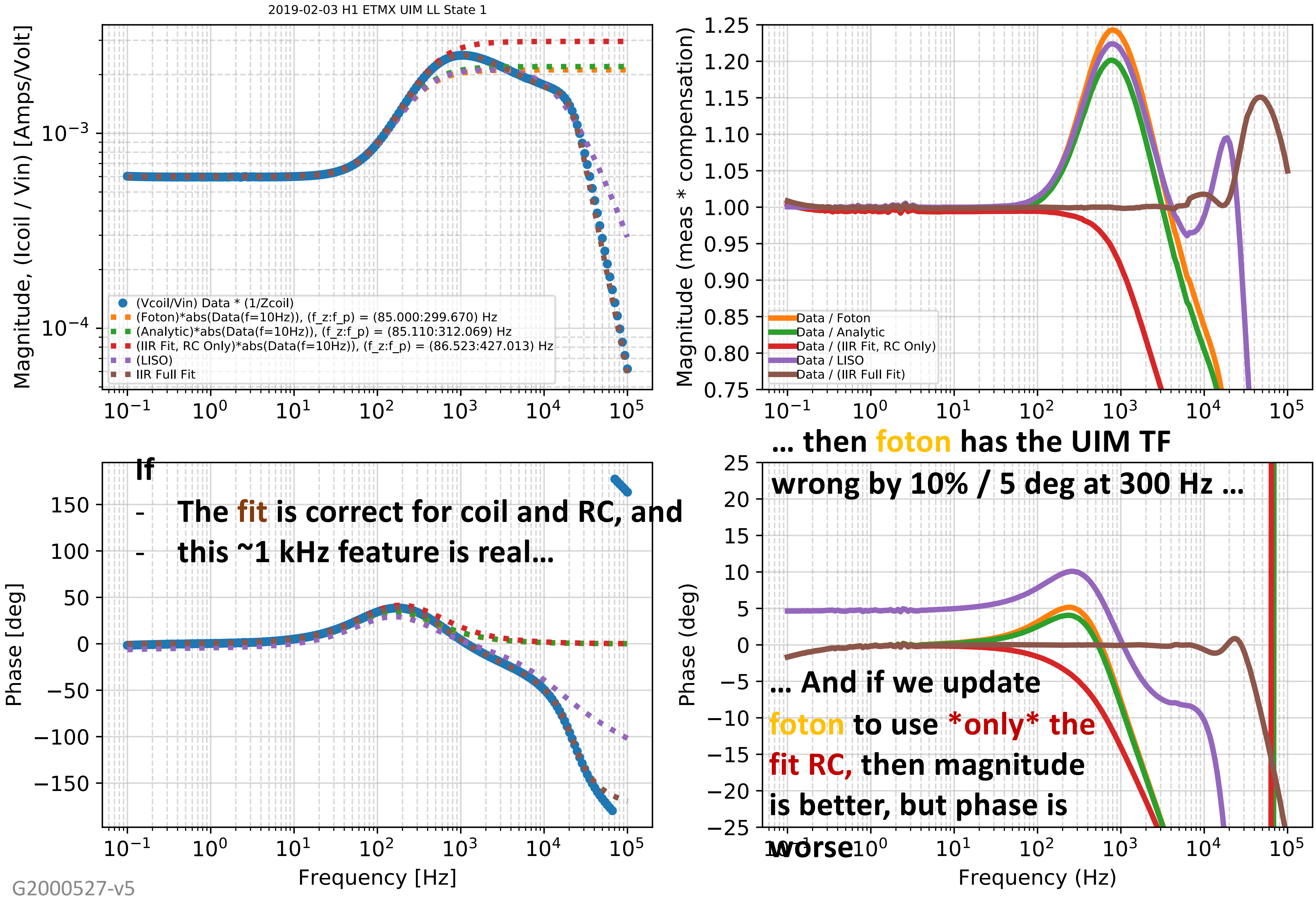
Coil Impedance was supposed to be much more sharp, and higher in frequency



No 1 kHz feature

$$I_{coil}/V_{out} = 1/(2Z_{out} + Z_{coil})$$

I.6.2 Fit per Coil: State 1 How bad would it be?



If

- **The fit is correct for coil and RC, and**
- **this ~1 kHz feature is real…**

… then foton has the UIM TF wrong by 10% / 5 deg at 300 Hz …

… And if we update foton to use *only* the fit RC, then magnitude is better, but phase is worse

I.6.1 The Fit per Coil: What’s next?

You feel I’m in the weeds. I know. *I* feel I’m in the weeds. How can we come back up for air? Look at some more weeds.

2. We can blindly assume that the fit is perfect for all coils. If so, we’d use the value of the coil f_z, divide it out of the V_{coil} / V_{in} data, and look at the I_{coil} / V_{in} transfer function. Does it make sense? Should we bother (re)fitting *that* data?

   Conclude: There’s really something weird with this data, manifesting at 1-2 kHz

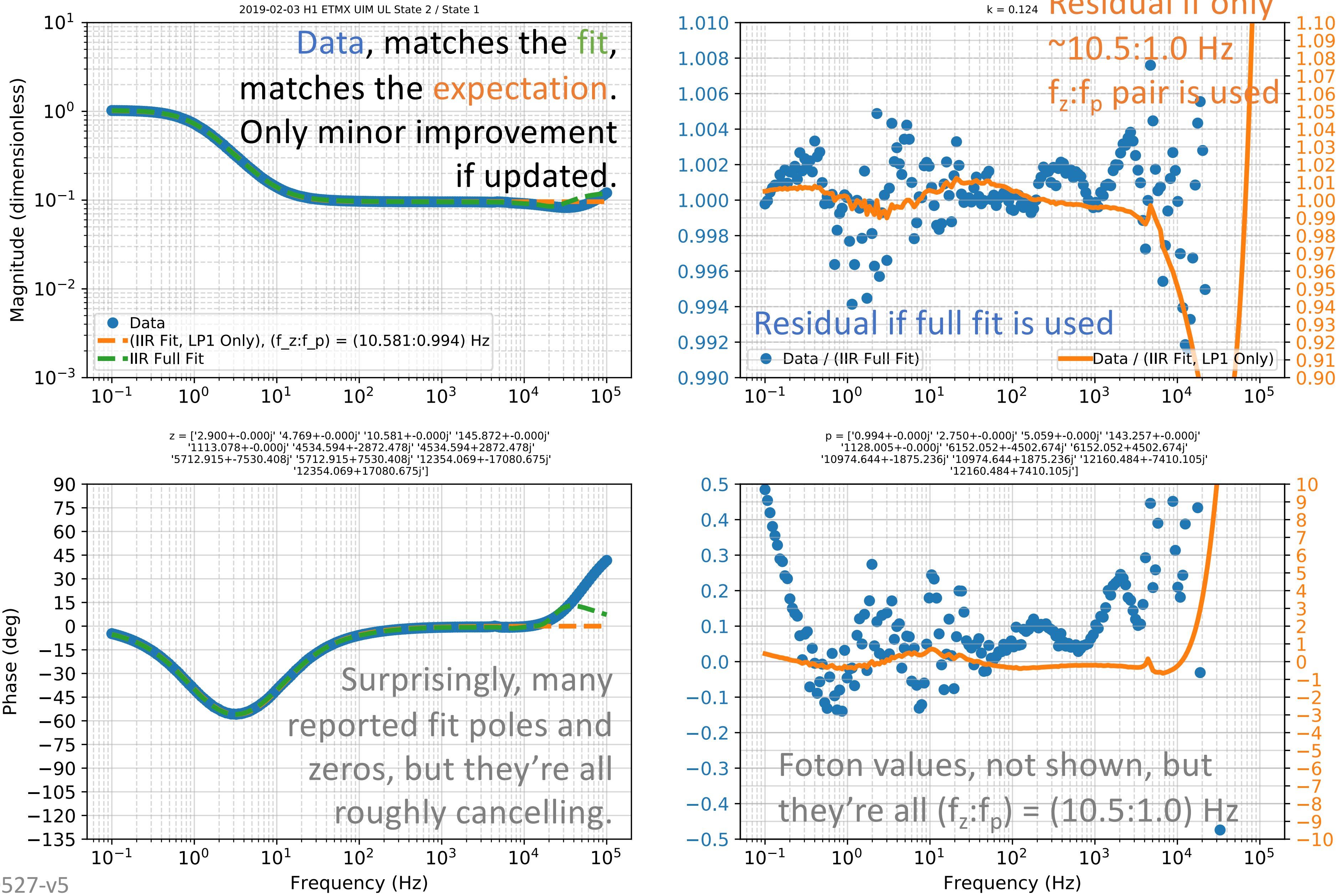
3. Look at the ratio of State 2 to State 1. Is getting the low pass f_z:f_p pair from that is as easy as we expect?

4. Look (and fit) at state 2 by itself. Does the data match the State 1 fit * (State 2 / State 1) fit?

I.6.3 Fit per Coil: State 2/State 1: the LP1 zs and ps

OK. Need some air. Does the analog data we have make any sense? It does.

Look at the ratio between state 2 and state 1.



Data, matches the fit, matches the expectation. Only minor improvement if updated.

Residual if only ~10.5:1.0 Hz f_z:f_p pair is used

Residual if full fit is used

Surprisingly, many reported fit poles and zeros, but they're all roughly cancelling.

Foton values, not shown, but they're all (f_z:f_p) = (10.5:1.0) Hz

I.6.3 Fit per Coil: State 2/State 1: Results Summary

UL	Fit Zeros	Fit Poles
Nearly cancelling	2.89952 Hz 🟢	2.75042 Hz 🟢
Nearly canceling	4.76888 Hz 🟢	5.05923 Hz 🟢
SW Closed LP	**10.5814 Hz** 🟢	**0.99443 Hz** 🟢
Nearly canceling	145.8720 Hz 🟢	143.2566 Hz 🟢
Nearly canceling	1113.0777 Hz 🟢	1128.0047 Hz 🟢
????	Pair(5367.8369 Hz 32.3526 deg) 🟡	Pair(7623.7668 Hz 36.2003 deg) 🟡
????	Pair(9452.2185 Hz, 52.8143 deg) 🟡	Pair(11133.7022 Hz, 9.6965 deg) 🟡
????	Pair(21080.1439 Hz 54.1226 deg 🟡	Pair(14240.3312 Hz 31.3564 deg) 🟡

UR	Fit Zeros	Fit Poles
SW Closed LP	**10.3314 Hz** 🟢	**0.98556 Hz** 🟢
Nearly canceling	52.4826 Hz 🟢	51.6746 Hz 🟢
Nearly canceling	344.4865 Hz 🟢	341.47236 Hz 🟢
Nearly canceling	2137.9732 Hz 🟢	2163.3018 Hz 🟢
????	3211.9846 Hz 🔴	5833.4346 Hz 🔴
????	pair(4802.2480 Hz. 32.800 deg) 🟡	4409.4475 Hz, 5019.2094 Hz 🟡
????	pair(11329.7897 Hz. 52.0737 deg 🟡	Pair(14962.1253 Hz. 39.2143 deg 🟡
????	pair(24347.3447 Hz 57.547 deg 🟡	15509.4456 Hz, 17175.5778 Hz 🟡

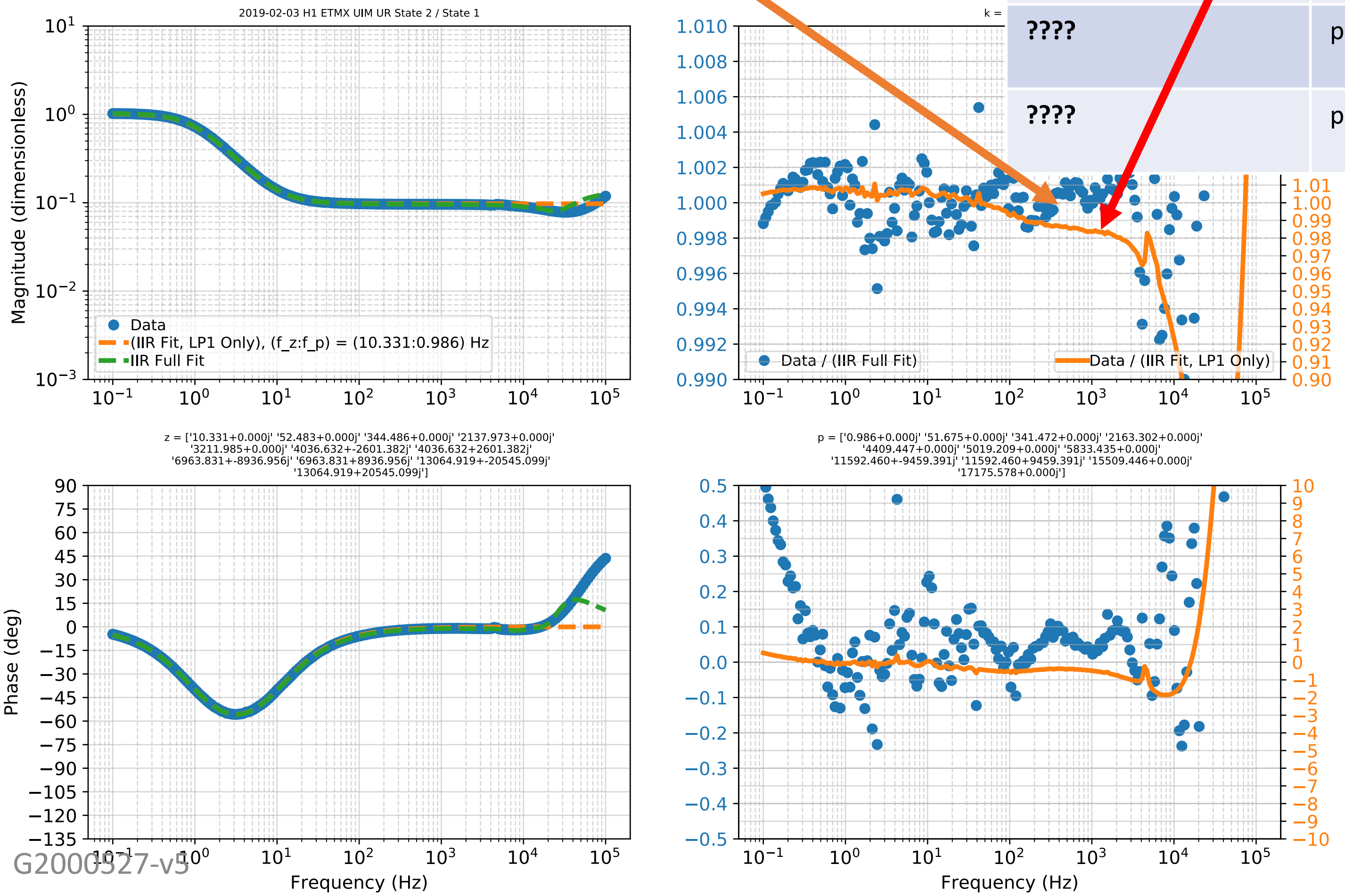
LL	Fit Zeros	Fit Poles
SW Closed LP	**10.3830 Hz** 🟢	**0.9820 Hz** 🟢
Nearly canceling	61.3351 Hz 🟢	60.2293 Hz 🟢
Nearly canceling	282.9903 Hz 🟢	291.4153 Hz 🟢
Nearly canceling	Pair(643.6467 Hz 11.4552 deg) 🟢	630.7973 Hz, 654.7394 Hz 🟢
????	Pair(5512.6344 Hz 39.6531 deg) 🟡	Pair(6718.1860 Hz 65.2573 deg) 🟡
????	Pair(7085.8327 Hz 66.5343 deg) 🟡	10061.4559 Hz, 10891.6712 Hz 🟡
Nearly canceling	Pair(13638.8270 Hz. 63.1878 deg) 🟢	Pair(13419.9763 Hz. 26.1267 deg) 🟢
????	Pair(24657.6748 Hz 61.7029 deg 🟡	Pair(15566.9234 Hz 55.0929 deg) 🟡

LR	Fit Zeros	Fit Poles
Nearly cancelling	0.05932 Hz 🟢	0.06045 Hz 🟢
SW Closed LP	**10.4728 Hz** 🟢	**0.98792 Hz** 🟢
Nearly canceling	93.0036 Hz 🟢	91.4280 Hz 🟢
Nearly canceling	1522.7636 Hz 🟢	1579.1637 Hz 🟢
????	Pair(4255.9612 Hz, 29.7771 deg) Pair(8332.2720 Hz 54.3682 deg) 🟡	5443.8019 Hz, 8077.0312 Hz, Pair(11032.6047 Hz 39.2195 deg) 🟡
Nearly canceling	Pair(13237.5898 Hz, 61.0969 deg) 🟢	Pair(13752.7035 Hz, 39.9270 deg) 🟢
????	Pair(25155.6858 Hz, 59.6633 deg) 🟡	Pair(13801.8767 Hz, 29.9008 deg) 🟡

I.6.3 Fit per Coil: State 2 / State 1 Oddball -- UR

Only UR is of concern with the residual of "if we ignore everything but the fit fz:fp that closely matches the expected low pass frequencies" exceeding 1% in magnitude above 100 Hz…

UR	Zeros		Poles	
SW Closed LP	**10.3314 Hz**	🟢	**0.98556 Hz**	🟢
Nearly canceling	52.4826 Hz	🟢	51.6746 Hz	🟢
Nearly canceling	344.4865 Hz	🟢	341.47236 Hz	🟢
Nearly canceling	2137.9732 Hz	🟢	2163.3018 Hz	🟢
????	3211.9846 Hz	🔴	5833.4346 Hz	🔴
????	pair(4802.2480 Hz, 32.800 deg)	🟡	4409.4475 Hz, 5019.2094 Hz	🟡
????	pair(11329.7897 Hz, 52.0737 deg	🟡	Pair(14962.1253 Hz, 39.2143 deg	🟡
????	pair(24347.3447 Hz. 57.547 deg	🟡	15509.4456 Hz, 17175.5778 Hz	🟡



But … as you'll see (and what is often said with details of these studies): we've got bigger fish to fry…

I.6.1 The Fit per Coil: What’s next?

You feel I’m in the weeds. I know. *I* feel I’m in the weeds. How can we come back up for air? Look at some more weeds.

2. We can blindly assume that the fit is perfect for all coils. If so, we’d use the value of the coil f_z, divide it out of the V_{coil} / V_{in} data, and look at the I_{coil} / V_{in} transfer function. Does it make sense? Should we bother (re)fitting *that* data?

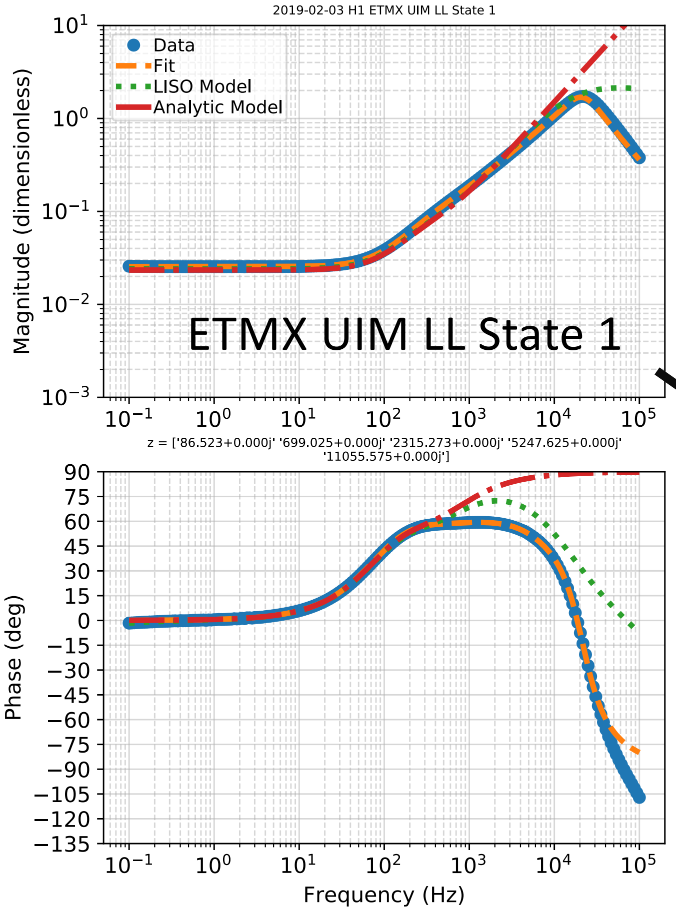
   Conclusion: There’s really something weird with this data, manifesting at 1-2 kHz

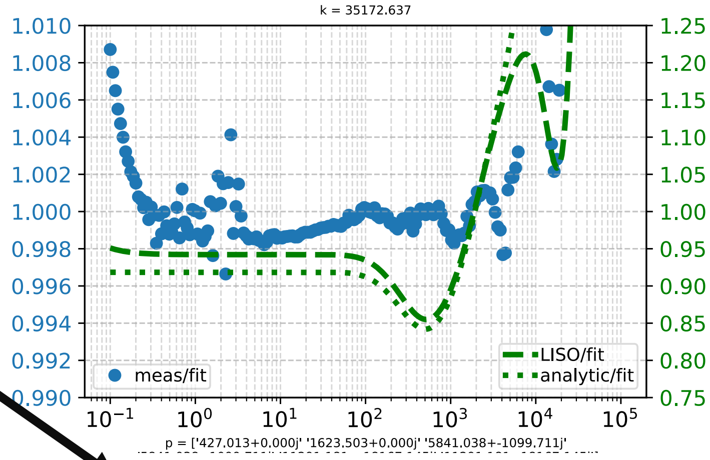
3. Look at the ratio of State 2 to State 1. Is getting the low pass f_z:f_p pair from that is as easy as we expect?

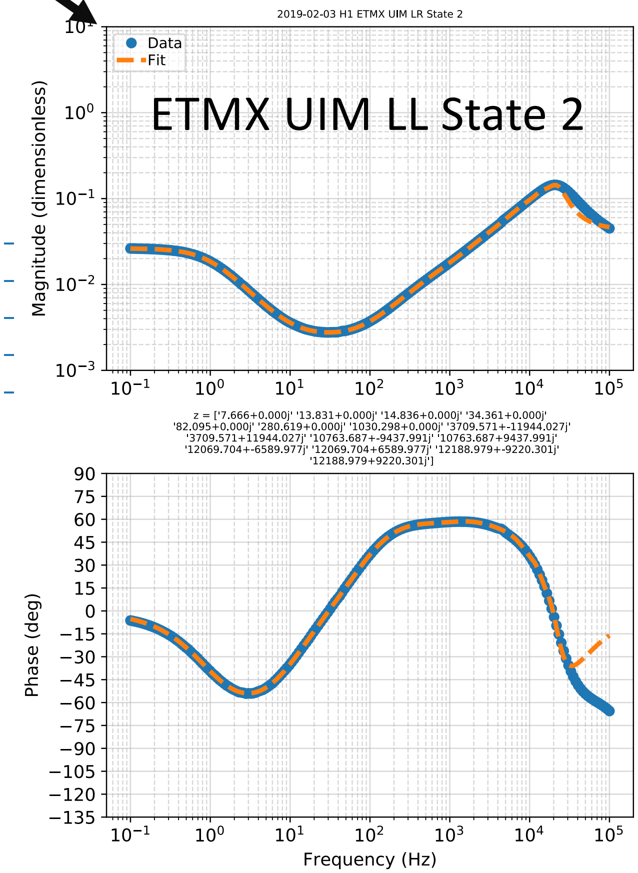
   Conclusion: Yes, we can safely extract the fit low pass f_z:f_p pair.

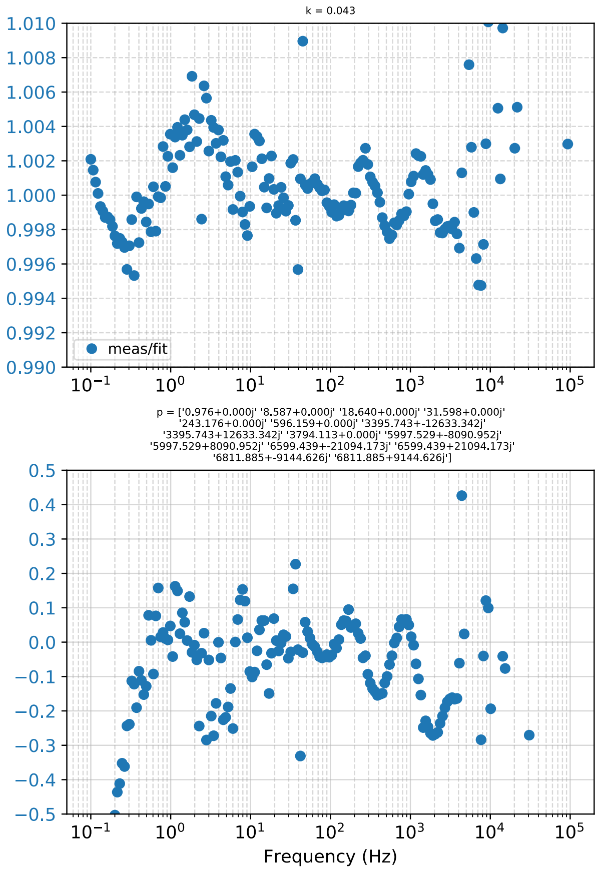
4. Look (and fit) at state 2 by itself. Does the data match the State 1 fit * (State 2 / State 1) fit?

I.6.4 Fit per Coil: State 2 vs State (1) and (2/1) Fits



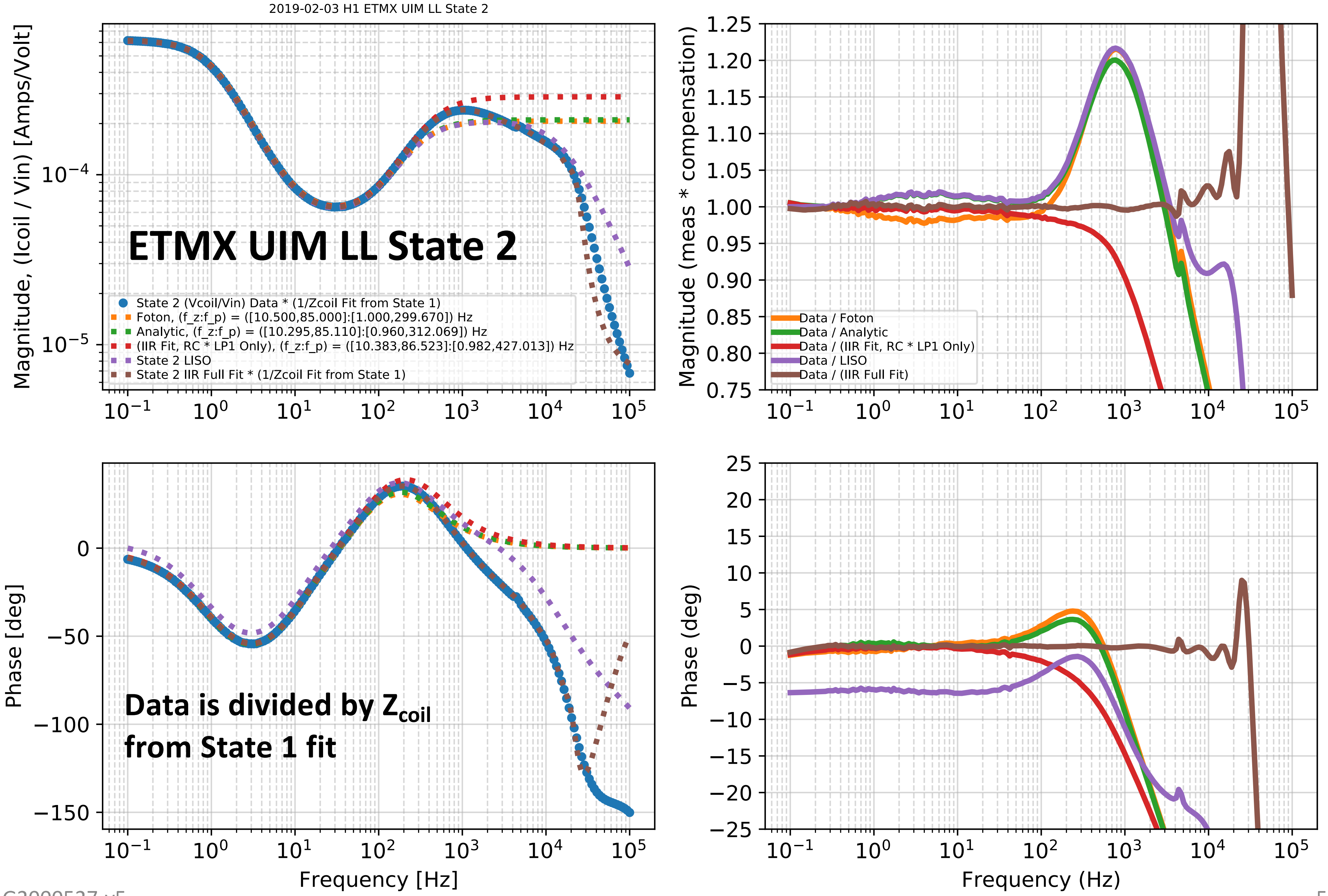






Since the ratio behaved so much like expected, State 2 by itself is probably going to look like the product of the State 1 results and the State2/State1, **and it does.**

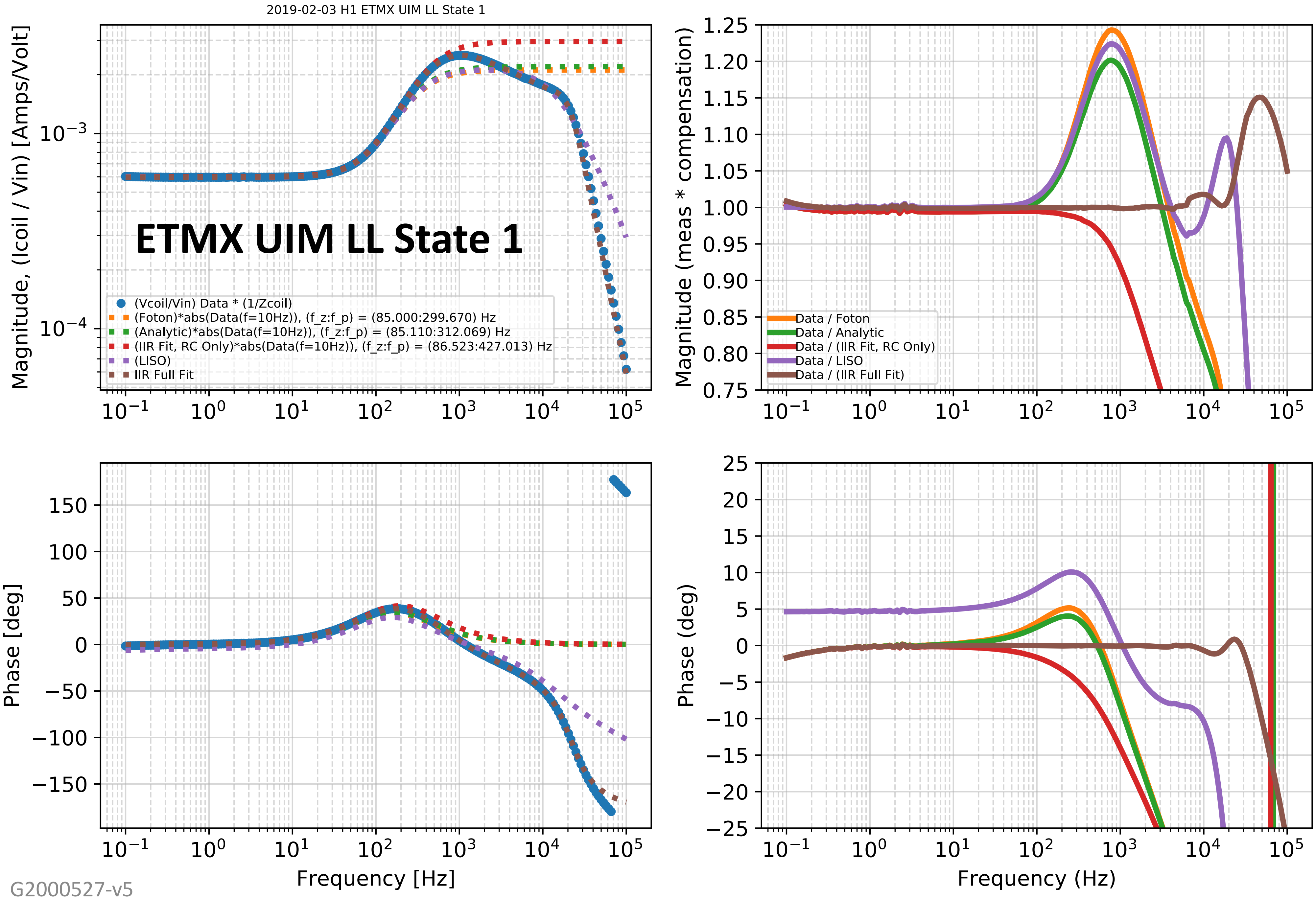
I.6.4 Fit per Coil: State 2 I_{coil} / V_{in} Residuals



ETMX UIM LL State 2

Data is divided by Z_{coil} from State 1 fit

I.6.4 Fit per Coil: Remember State 1…



I.6.4 Fit per Coil: Fit answer Comparison: UL and LL

State 1 fit and State 2/1 fit results

Circuit Feature Assignment	UL Fit Zeros	UL Fit Poles
Coil Impedance	**696.5942 Hz** 🟡	
RC Network	**87.0329 Hz** 🟢	**431.3965 Hz** 🟡
SW Closed LP	**10.5814 Hz** 🟢	**0.99443 Hz** 🟢
?????	2246.0201 Hz 🔴	1592.0174 🔴
Cable impedance?		pair(22092.54 Hz, 59.37 deg) 🟡

Hrmm… State 2 fit f_z:f_p numbers are pretty different from State 1 fit and State 2/1 fit, except for LP1 values

Circuit Feature Assignment	LL Fit Zeros	LL Fit Poles
Coil Impedance	**699.0254 Hz** 🟡	
RC Network	**86.5228 Hz** 🟢	**427.0135 Hz** 🟡
SW Closed LP	**10.3830 Hz** 🟡	**0.9820 Hz** 🟡
?????	2315.2727, 5247.6252 Hz	1623.5029, pair(5943.6595, 10.6624 deg)
Cable impedance?		pair(21390.090 Hz, 58.138 deg) 🟡

State 2 fit results

Circuit Feature Assignment	UL Fit Zeros	UL Fit Poles
Nearly canceling	0.028847 Hz 🟢	0.026747 Hz 🟢
Coil Impedance	**842.2736 Hz** 🟡	
RC Network	**89.2645 Hz** 🟢	**472.0885 Hz** 🟡
SW Closed LP	**10.3110 Hz** 🟢	**0.97697 Hz** 🟢
?????	4401.5227 Hz 🔴	2798.8233 Hz 🔴
Cable impedance?		pair(21118.6667 Hz, 42.1804 deg) 🟡

Circuit Feature Assignment	LL Fit Zeros	LL Fit Poles
Nearly canceling	0.37481 🟢	0.36443 🟢
Nearly canceling	6.43273 🟢	6.36145 🟢
Nearly canceling	183.9139 🟡	200.7849 🟡
Coil Impedance	**549.8213** 🟢	
RC Network	**89.9268** 🟢	**346.3705** 🟢
SW Closed LP	**10.2956** 🟢	**0.9999998** 🟢
????	1632.2068 🔴	1177.1166 Hz, 🔴
????	pair(15713.5244 Hz, 42.2756 deg) 15762.0667 Hz 🔴	3750.3363 Hz, pair(7843.1654 Hz, 52.3709 deg), 🔴
Cable impedance?	pair(20052.8982Hz, 26.0454 deg) 🔴 21877.4091 Hz, 22594.0678 Hz	pair(13919.8163 Hz, 69.7893 deg) 🔴 pair(22669.5375 Hz, 77.5484 deg)

I.6.4 Fit per Coil: Fit answer Comparison: UR and LR

Circuit Feature Assignment	UR Fit Zeros	UR Fit Poles
Nearly canceling	40.5700 Hz 🟢	39.1471 Hz 🟢
Nearly canceling	112.8337 Hz 🟢	101.2331 Hz 🟢
Coil Impedance	**767.4099 Hz** 🟡	
RC Network	**77.2791 Hz** 🟡	**455.1022 Hz** 🟡
SW Closed LP	**10.2308 Hz** 🟢	**0.97447** 🟢
?????	pair(5414.0903 Hz, 57.7074 deg) pair(8543.0235 Hz, 31.6995 deg) pair(12415.6958 Hz, 20.2785 deg) 🔴	2200.0659 Hz pair(4588.0341 Hz, 51.4882 deg) pair(6168.5520 Hz, 63.2901 deg) 🔴
Nearly canceling	pair(11209.1738 Hz, 2.010 deg) 🟢	pair(11298.7088 Hz, 65.2882 deg) 🟢
Cable impedance?		pair(21411.5152 Hz, 71.3476 deg) 🟡

Circuit Feature Assignment	LR Fit Zeros	LR Fit Poles
Coil Impedance	**280.6193 Hz** 🔴	
RC Network	**82.0951**	**243.1757 Hz** 🔴
SW Closed LP	**13.8309** 🟡	**0.97606 Hz,** 🔴
Nearly canceling	7.66634 Hz 🟡	8.58653 Hz 🟡
Nearly canceling	34.3607 Hz, 🟡	31.5980 Hz 🟡
?????	14.8359 Hz 1030.2985 pair(12506.8258 Hz, 72.7462 deg) pair(13751.5651 Hz, 28.6342 deg) pair(14315.4683 Hz, 41.2455 deg) 🔴	18.6402 Hz 596.1594 3794.1125 Hz pair(13081.7578 Hz, 74.9549 deg) pair(10071.4374 Hz, 53.4518 deg) pair(11402.8925 Hz, 🔴

Circuit Feature Assignment	UR Fit Zeros	UR Fit Poles
Coil Impedance	**671.7041 Hz** 🟡	
RC Network	**85.9533 Hz** 🟢	**422.2943 Hz** 🟡
SW Closed LP	**10.3314 Hz** 🟢	**0.98556 Hz** 🟢
????	2337.1901 Hz pair(12262.2781 Hz, 15.218 deg) pair(12822.8952 Hz, 21.5666) 🔴	5132.4934 Hz pair(11037.6219 Hz, 61.3485 deg) 🔴
????	19443.5355 🔴	
Cable impedance?		pair(21731.503 Hz, 73.7415 deg) 🟡

Circuit Feature Assignment	LR Fit Zeros	LR Fit Poles
Coil Impedance	**570.3 Hz** 🟢	
RC Network	**86.019 Hz** 🟢	**380.235 Hz** 🟢
SW Closed LP	**10.4728 Hz** 🟢	**0.98792 Hz** 🟢
????	160.731 Hz 🔴	1104.104 Hz 🔴
Nearly canceling	pair(3998.485 Hz, 64.2946 deg) 🟢	pair(3991.249Hz, 63.6625 deg) 🟢
????	pair(12280.307 Hz, 4.400 deg) 🔴	6807.508, 11411.143 🔴
Cable impedance?		pair(21818.686 Hz, 59.566 deg) 🟡

I.6.1 The Fit per Coil: What’s next?

You feel I’m in the weeds. I know. *I* feel I’m in the weeds. How can we come back up for air? Look at some more weeds.

1. We can blindly assume that the fit is perfect for all coils. If so, we’d use the value of the coil f_z, divide it out of the V_{coil} / V_{in} data, and look at the I_{coil} / V_{in} transfer function. Does it make sense? Should we bother (re)fitting *that* data?

   Conclusion: **There’s really something weird with this data, manifesting at 1-2 kHz**

2. Look at the ratio of State 2 to State 1. Is getting the low pass f_z:f_p pair from that is as easy as we expect?

   Conclusion: Yes, we can safely extract the fit low pass f_z:f_p pair.

3. Look (and fit) at state 2 by itself. Does the data match the State 1 fit * (State 2 / State 1) fit?

   Conclusions: **Sort of.** The residuals have same mysterious 1-2 KHz features from State 1, **but the poles and zeros are astoundingly different, some more like expected, some just wrong, with no general trends as each coil is different.**

I.6 Fit per Coil: Grand Conclusions

- We definitely, definitely, definitely need to get good measurements.
  - We should always drive the drivers, and measure the response differentially.

- Unfortunately, we can’t assume each coil channel is going to be even roughly the same, and we may get conflicting answers between what should be the same answers when switching between states.
  - e.g. State 2 / State 1 for for LP1 is not the same as State 2 alone
  - So we should be prepare to the “two clocks” situation, where don’t know which to choose.

- Make the data going in to the fitter as simple as possible, when it makes physical sense to do so.
  - Never, ever, ever take measurements with the coil as a part of the measurement. Just put a no-capacitance, 40 Ohm dummy OSEM “across the back” of the driver as the “coil” “load” impedance.
  - That also means that we can’t use the FAST_I_MONs measurements either -- not because “they don’t measure the output network” -- but because they include the coil impedance which drastically confuses the even the best fitting routines
  - We should perform the same analytical analysis on PUM driver vs. the AOSEM to confirm Zcoil << Zout…. another day.

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Two Parts, each quite long. *sigh*

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PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

I.7 Converting Individual Coil Fit Results in to Systematic Error in A_{UIM}

- Let's assume we understood and we're happy with everything from section I.6.
  - **Remember: we're not, but let's move on anyways, because this is the data we have.**

- The individual coil results must be used retroactively to predict what error was caused in the *total* longitudinal actuation strength in the UIM.

You can think of it like this:

$$A_U = E2O * \begin{pmatrix} F_{UL} \\ F_{LL} \\ \hline F_{UR} \\ F_{LR} \end{pmatrix} * \mathrm{DAC} * \ \mathrm{AI} \ * \begin{pmatrix} CD_{UL} \\ CD_{LL} \\ \hline CD_{UR} \\ CD_{LR} \end{pmatrix} * M * S_U$$

I.7 Fit per Coil >> Error in $\mathrm{A}_{\mathrm{UIM}}$: Reality

Or like this:

$$F_{ii}(f) = E2O_{ii} * D_{ii}\,(f) * DAC_{ii} * \; AI_{ii} \; * TC_{ii} * CD_{ii}\,(f) * M_{ii}$$

$$A_{UIM} = S_U(f) * \sum_{ii} F_{ii}$$

where $ii = UL, LL, UR, LR$, and for each coil chain, the actuation strength of each driver/coil/magnet chain, $\boldsymbol{F_{ii}}$, has the following components:

- $\boldsymbol{E2O}$ is the Euler 2 OSEM matrix (exactly 0.25 for each coil),
- $\boldsymbol{D(f)}$ is the normalized digital compensation “COILOUTF” filter for each coil,
- $\boldsymbol{DAC}$, $\boldsymbol{AI}$, and $\boldsymbol{TC}$ are the digital-to-analog converter gain, anti-aliasing filter, and DC transconductance of the coil driver respectively
- $\boldsymbol{CD(f)}$ is the normalized coil driver response,
- $\boldsymbol{M}$ is the magnet strength, and
- $\boldsymbol{S_U}$ is the UIM longitudinal force to TST displacement transfer function response

Ideally, $D_{ii}(f)$ would be the perfect inverse of $CD_{ii}(f)$ for every coil, they would cancel to a unity transfer function and we can exclude it from any model.

That’s what we’ve done for the UIM in the calibration group’s DARM loop model.

However, the frequency dependent systematic error in $\mathrm{A}_{\mathrm{UIM}}$ arises when $D_{ii}(f)$ doesn’t perfectly invert $CD_{ii}(f)$, and the fact that the frequency dependent error from each stage is *summed* means that error is not easily intuitable from the individual chain error.

I.7 Fit per Coil >> Error in A_{UIM}: Model

$$F_{ii}(f) = E2O_{ii} * D_{ii}\,(f) * DAC_{ii} * \ AI_{ii}(f)\ * TC_{ii} * C_{ii}\,(f) * M_{ii}$$

$$A_{UIM} = S_U(f) * \sum_{ii} F_{ii}$$

So we need to construct a model with these terms explicitly included.

Let's take the above, and assume everything in between $\boldsymbol{D_{ii}}$ and $\boldsymbol{C_{ii}}$ for each chain (namely DAC_{ii}, $AI_{ii}(f)$, and TC_{ii}) is only a common gain to all four chains. This is an OK assumption because

- we take some effort (eg LHO:42740) to "balance" the gain of each path to minimize length to angle coupling.
- the AI filter response, $AI(f)$, which is a 16kHz elliptic lowpass, in general doesn't start to deviate from "just a gain" until several kHz, and each channel would only have a small difference at that. Including the measured differences is an exercise for some other day.

$$F_{ii}(f) = E2O * DAC * AI(f) * TC * M * D_{ii}(f)\ * C_{ii}\,(f)$$

$$A_{UIM} = S_U(f) * E2O * DAC * AI(f) * TC * M * \sum_{ii} D_{ii}\,(f)\ * C_{ii}\,(f)$$

Under this assumption, the systematic error, η_{UIM}, can be computed using only what we already have!

$$\eta_{UIM} = \frac{A_{UIM}^{(\text{“no” } sys.\,error)}}{A_{UIM}^{(w/\,sys.\,error)}} = \frac{A_{UIM}^{(well-compensated)}}{A_{UIM}^{(poorly-compensated)}} = \sum_{ii} \frac{\left[C_{ii}^{fit}\right]^{-1} C_{ii}^{meas}}{\left[C_{ii}^{foton}\right]^{-1} C_{ii}^{meas}} = \sum_{ii} \frac{C_{ii}^{foton}}{C_{ii}^{fit}}$$

I.7 Fit per Coil >> Error in A_{UIM}: Model

- But wait! Remember the whole reason we got in to this game was to find out what error was caused by *switching* from State 1 to State 2,

- So we should also compute

$$\frac{\eta_{UIM}|_2}{\eta_{UIM}|_1} = \frac{\Sigma_{ii}\left(C_{ii}^{foton}/C_{ii}^{fit}\right)\Big|_2}{\Sigma_{ii}\left(C_{ii}^{foton}/C_{ii}^{fit}\right)\Big|_1}$$

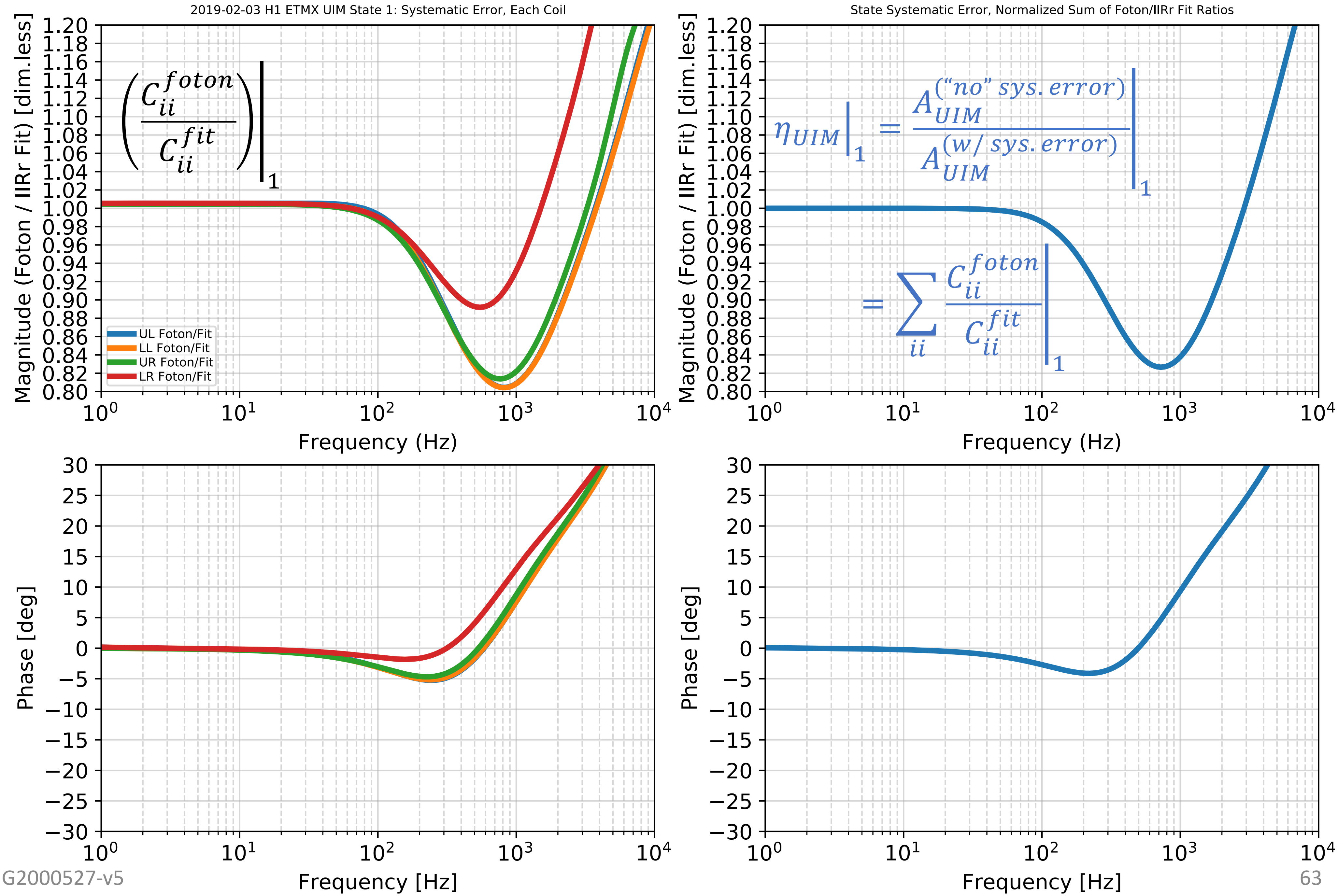
such that we'll know, not only the systematic error under "normal" operation (i.e. in state 1), but also during this Nov 27 – Dec 03 2019 time period.

$$A_{UIM}^{(\text{“}no\text{”}\ sys.error)}(most\ times) = \eta_{UIM}|_1 A_{UIM}(20200113\ Model)$$

$$A_{UIM}^{(\text{“}no\text{”}\ sys.error)}(Nov\ 27 - Dec) = \eta_{UIM}\Big|_2 A_{UIM}(Nov\ 27 - Dec\ 03)$$

$$= \eta_{UIM}|_1 \left(\frac{\eta_{UIM}|_2}{\eta_{UIM}|_1}\right) A_{UIM}(20200113\ Model)$$

I.7 Fit per Coil >> Error in A_{UIM}: State 1 Results

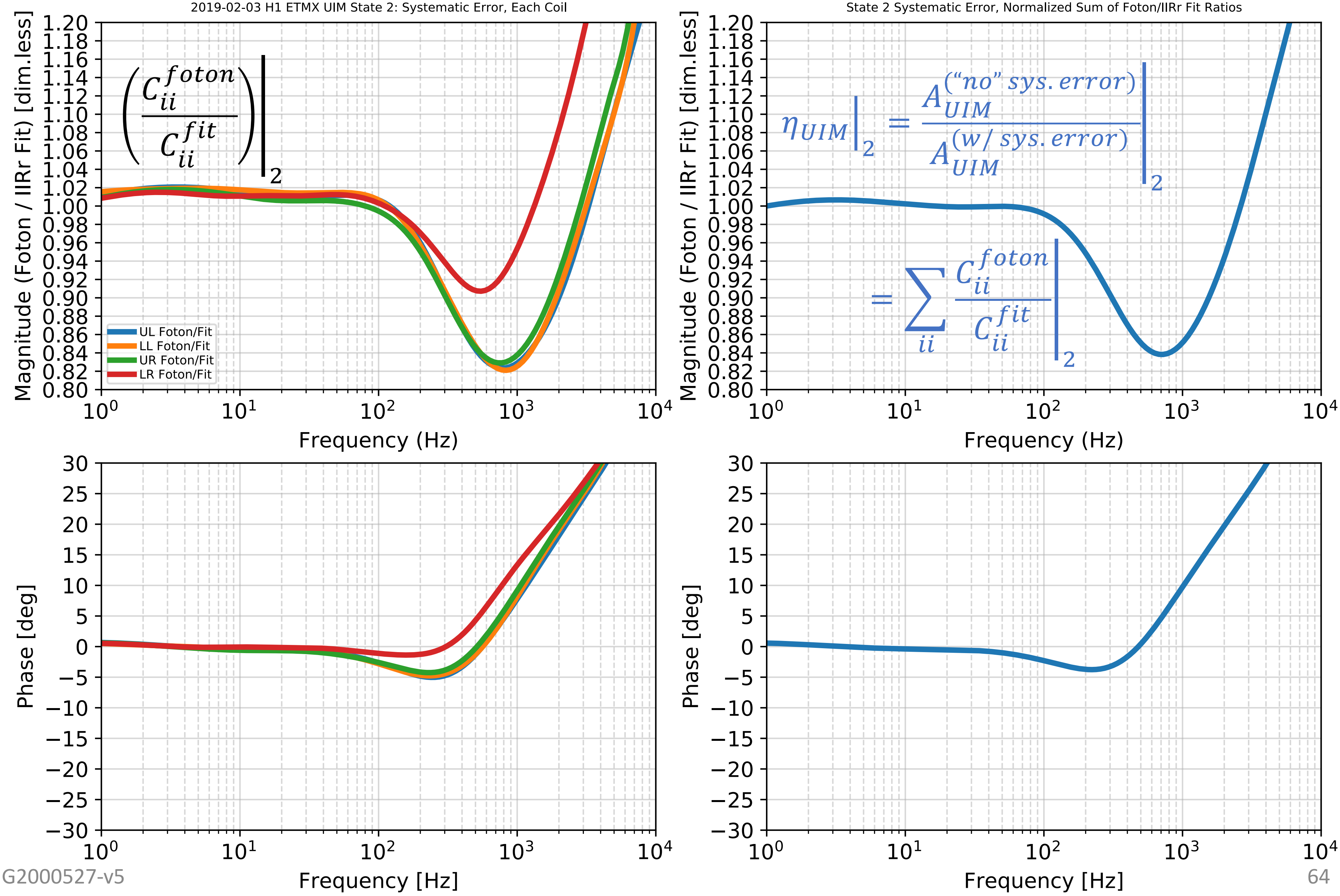


$$\left.\left(\frac{C_{ii}^{foton}}{C_{ii}^{fit}}\right)\right|_1$$

$$\eta_{UIM}\Big|_1 = \left.\frac{A_{UIM}^{(\text{“no” sys. error})}}{A_{UIM}^{(w/\,sys.\,error)}}\right|_1$$

$$= \left.\sum_{ii} \frac{C_{ii}^{foton}}{C_{ii}^{fit}}\right|_1$$

I.7 Fit per Coil >> Error in A_{UIM}: State 2 Results

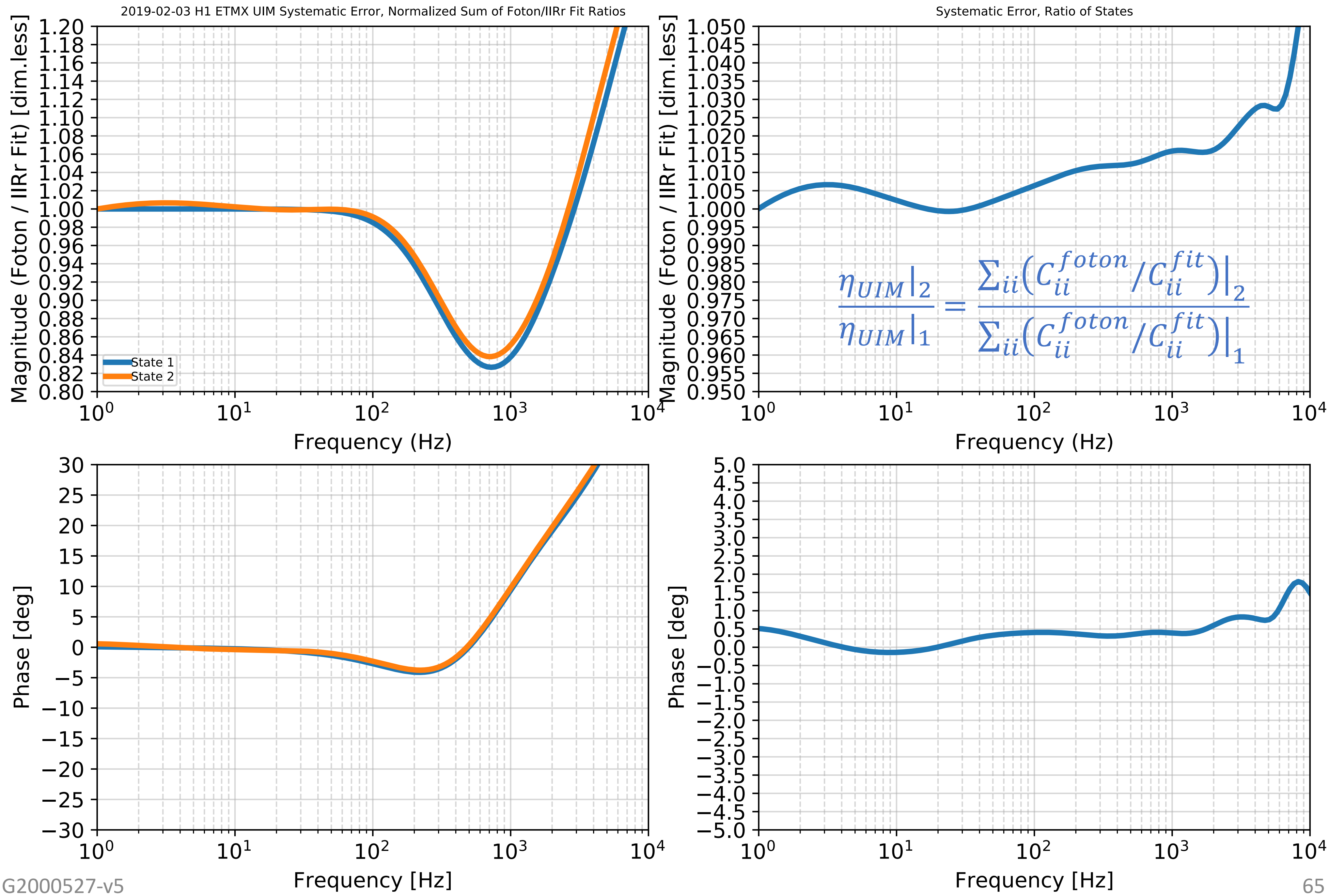


$$\left.\left(\frac{C_{ii}^{foton}}{C_{ii}^{fit}}\right)\right|_2$$

$$\eta_{UIM}\Big|_2 = \left.\frac{A_{UIM}^{(\text{“no” } sys.error)}}{A_{UIM}^{(w/\, sys.error)}}\right|_2$$

$$= \left.\sum_{ii} \frac{C_{ii}^{foton}}{C_{ii}^{fit}}\right|_2$$

I.7 Fit per Coil >> Error in A_{UIM}: Results Compared



$$\frac{\eta_{UIM}|_2}{\eta_{UIM}|_1} = \frac{\Sigma_{ii}\left(C_{ii}^{foton}/C_{ii}^{fit}\right)\big|_2}{\Sigma_{ii}\left(C_{ii}^{foton}/C_{ii}^{fit}\right)\big|_1}$$

I.7 Fit per Coil >> Error in A_{UIM}: Discussion

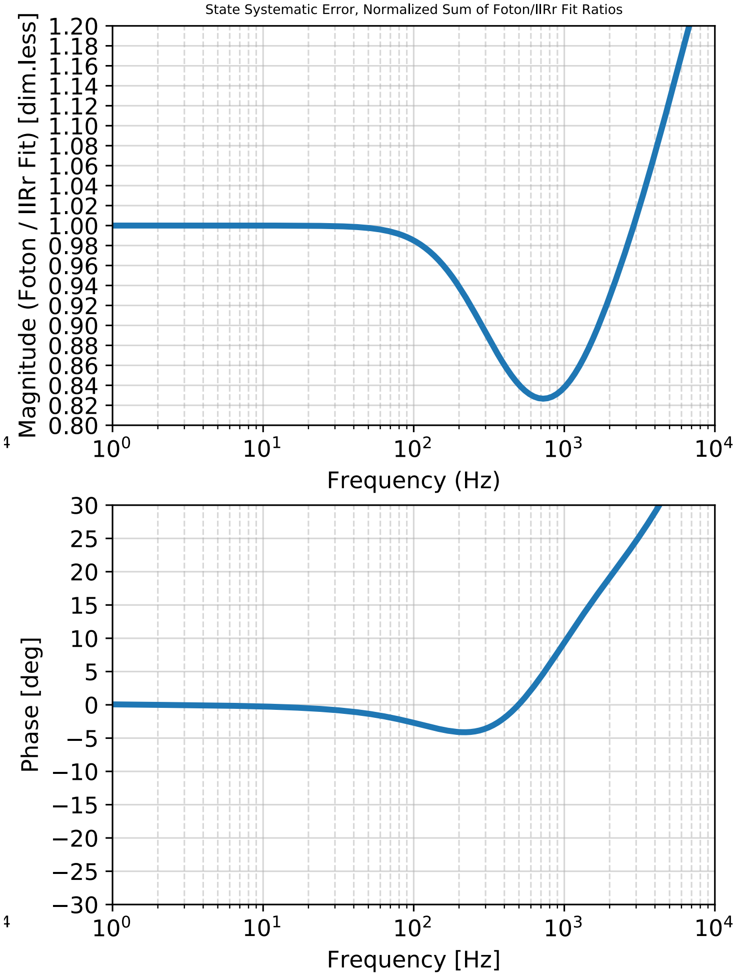
- Huh! So – it looks like the error in State 1 compensation is really of much more concern that the switch between State 1 and State 2 for a short time period.

- That’s pretty much it. At least all of this careful study was worth it for some reason.

- On to showing how this manifests in the response function!

- **But also – do remember that this is based on fits of data that doesn’t make sense. So hold these truths to be full of salt grains until we get a better measurement.**

$$\eta_{UIM}\Big|_1 = \frac{A_{UIM}^{(\text{“no” } sys.error)}}{A_{UIM}^{(w/\ sys.error)}}\Bigg|_1$$

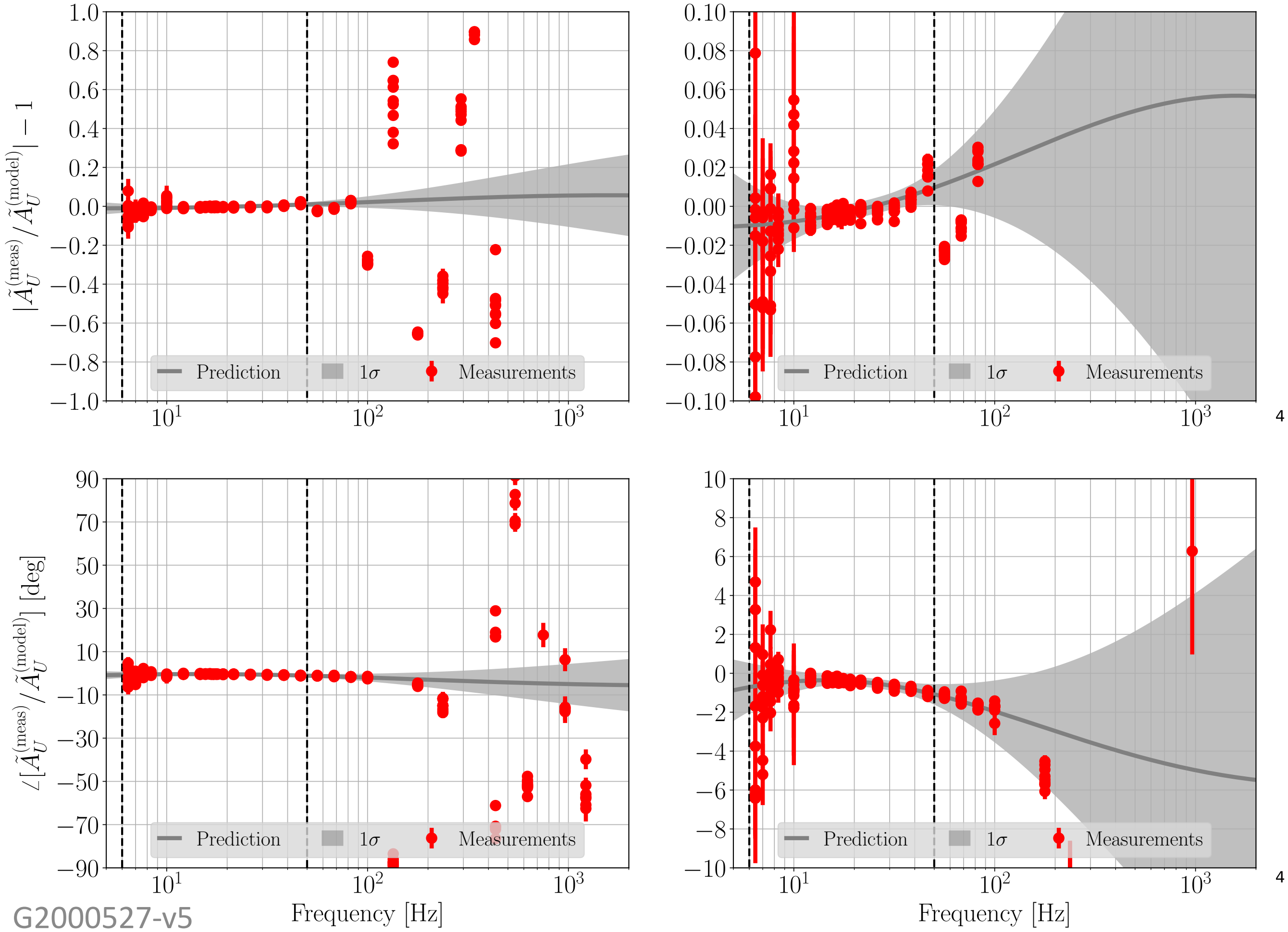


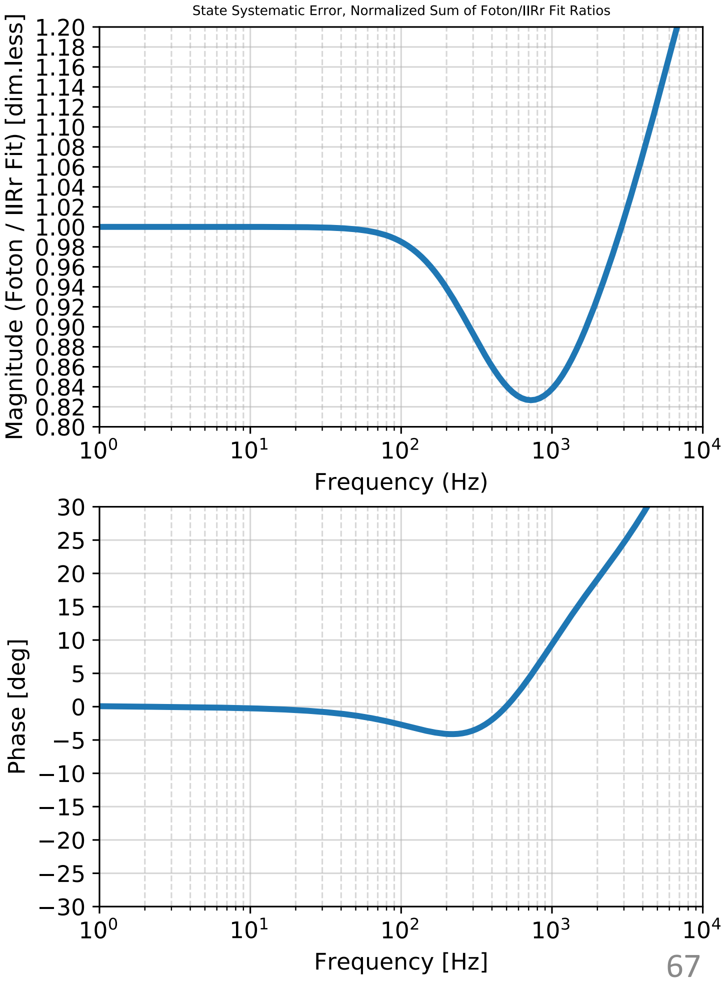
I.7 Sys. Err in A_{UIM} Recap

But, **if we believe the measurement**, is this error big w.r.t. other errors in the UIM?

Yeah – it kinda is!

Namely – the blade spring bending nonsense completely fools the GPR above 50 Hz. So this kind of smoothly varying function just would not be found in / “accounted for with” the GPR. So, we’re stuck having to model it all and estimate the impact on the Response Function systematic error.





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PART II: The OMC Whitening Chassis, from Mar 16 to 27 2020

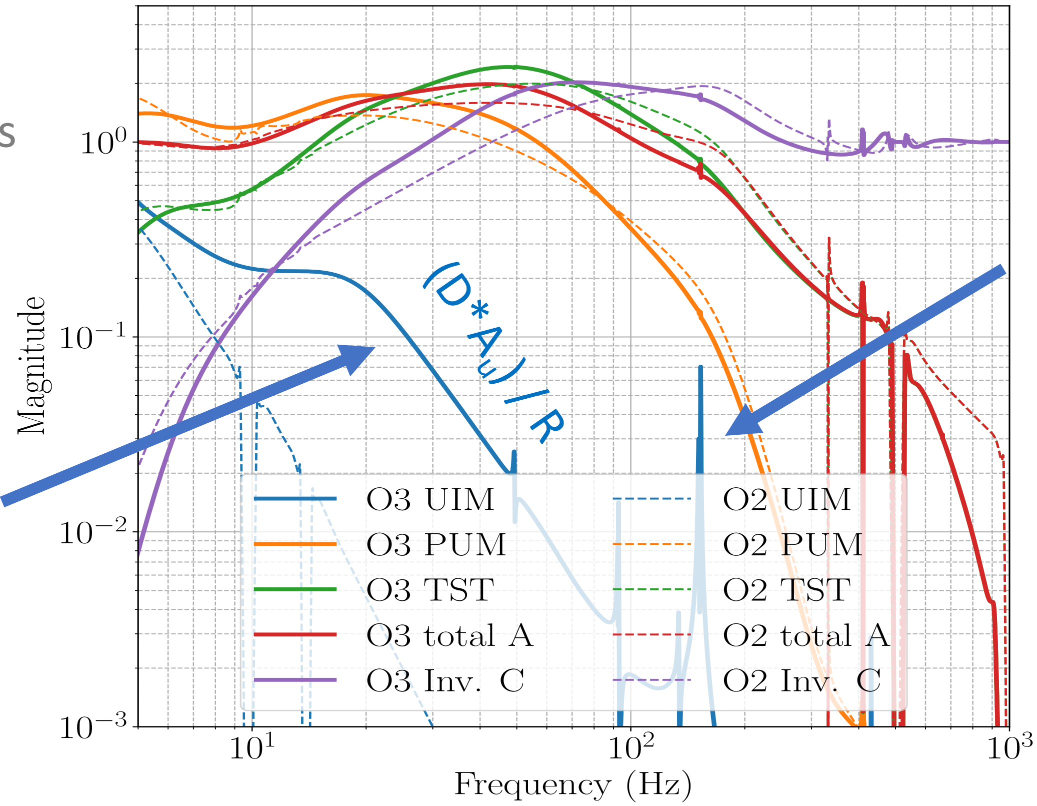
I.8 Converting Sys. Err in A_{UIM} to that in R

- Hey! We wrote a paper on this! Check out Eq. 11 in P1900245:

$$\tilde{\eta}_{R;A_i} = \frac{1}{R^{(\text{model})}}\left[\frac{1}{C^{(\text{model})}} + \left(\tilde{\eta}_{A_i}\tilde{A}_i^{(\text{model})} + \sum_{j\neq i}\tilde{A}_j^{(\text{model})}\right)\tilde{D}\right]$$

H1 O3

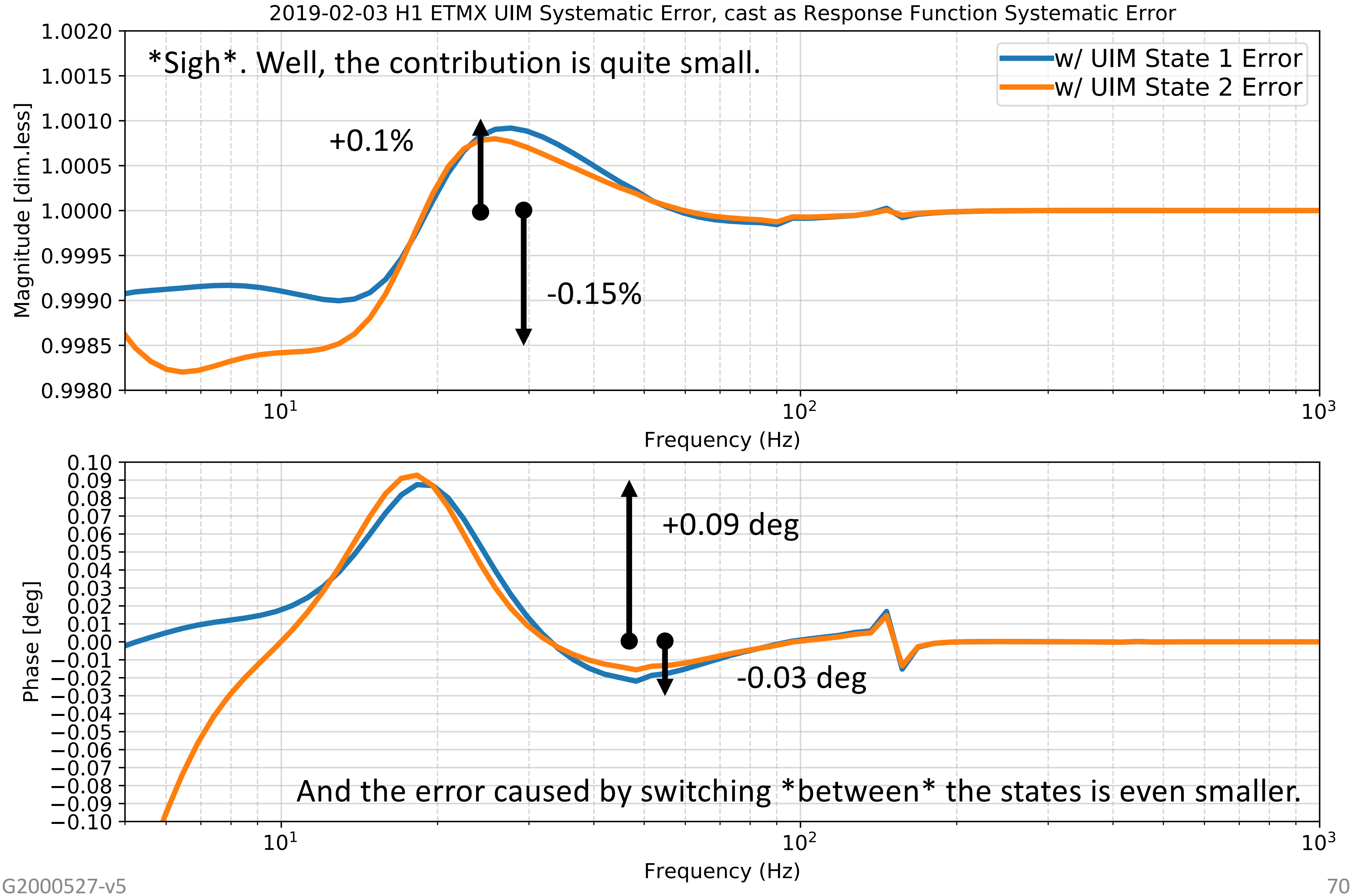
Error contributions to the response function recapped from Slide 6



UIM Contributes at the ~10% level out to ~25 Hz

Vertical Blade Spring Twisting / Bending in L direction causes UIM contribution to spike back in to play at 150 Hz

I.8 Sys. Error R as a result of A_{UIM} Error



2019-02-03 H1 ETMX UIM Systematic Error, cast as Response Function Systematic Error

Sigh. Well, the contribution is quite small.

+0.1%

-0.15%

+0.09 deg

-0.03 deg

And the error caused by switching *between* the states is even smaller.

I.8 UIM Electronics Error Conclusions

- **The executive summary:** non-Jeff’s everywhere whom guessed the answer ahead of time are vindicated in that the UIM electronics error -- either from differences in compensation between states, or poor compensation in general – doesn’t substantially contribute to the response function systematic error.

- We may safely proceed with O3B chunk 1 uncertainty budget development without including this systematic error.
  - Note that this would have *not* been “covered” by the GPR even it it were non-negligible.

- BUT: we’ve now learned many valuable lessons about:
  - How to take the right measurement of a coil driver
  - How to make sense of a fit to data using rough analytic expectations from converting a circuit diagram in to a collective transfer function
  - How bad the compensation is for the UIM driver response
  - How to propagate electronics errors to the response function