OMC DCPD Whitening Chassis Design Update

Oct 2022

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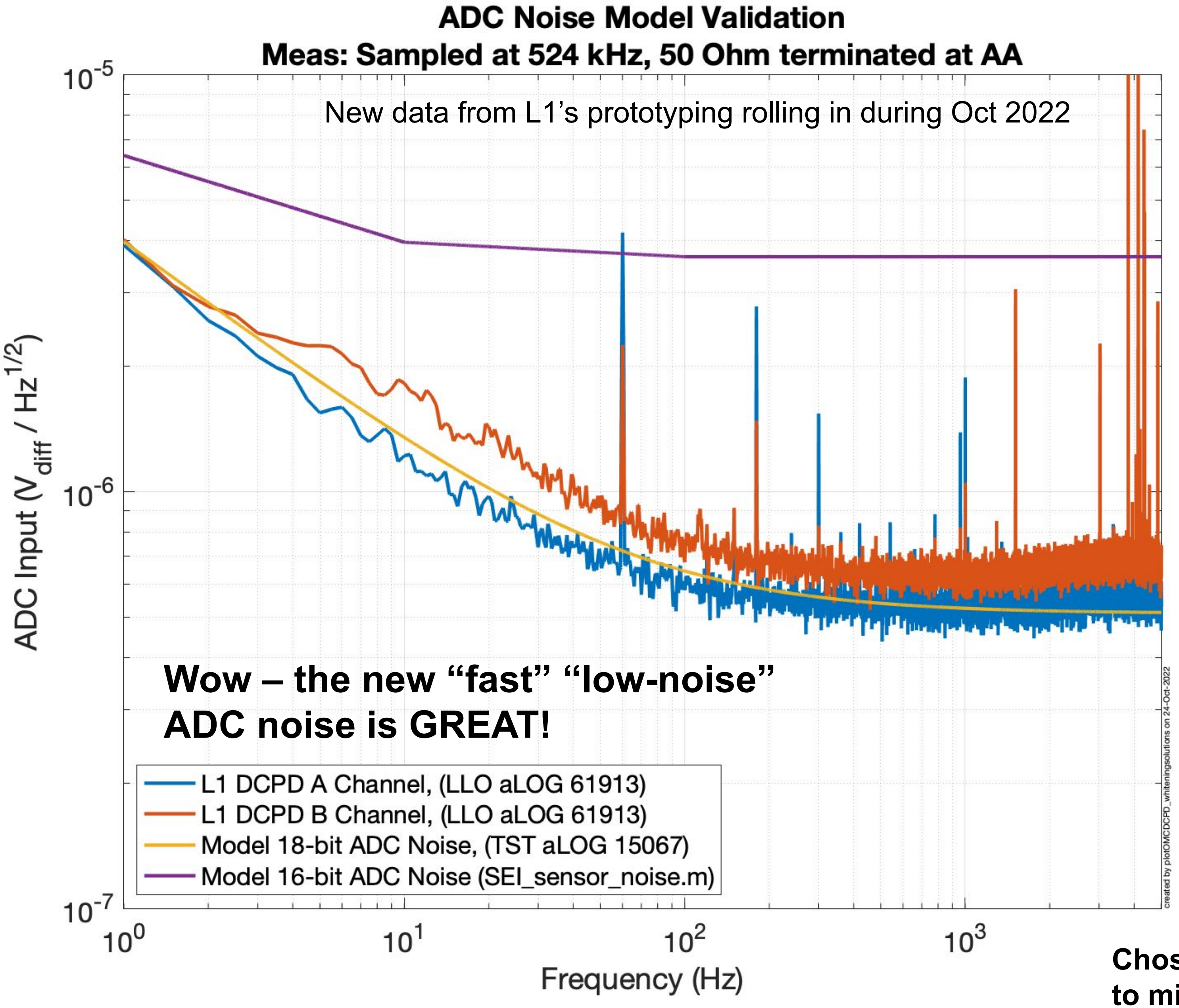
G2201909



New data from L1's prototyping rolling in during Oct 2022

Wow – the new "fast" "low-noise" ADC noise is GREAT!

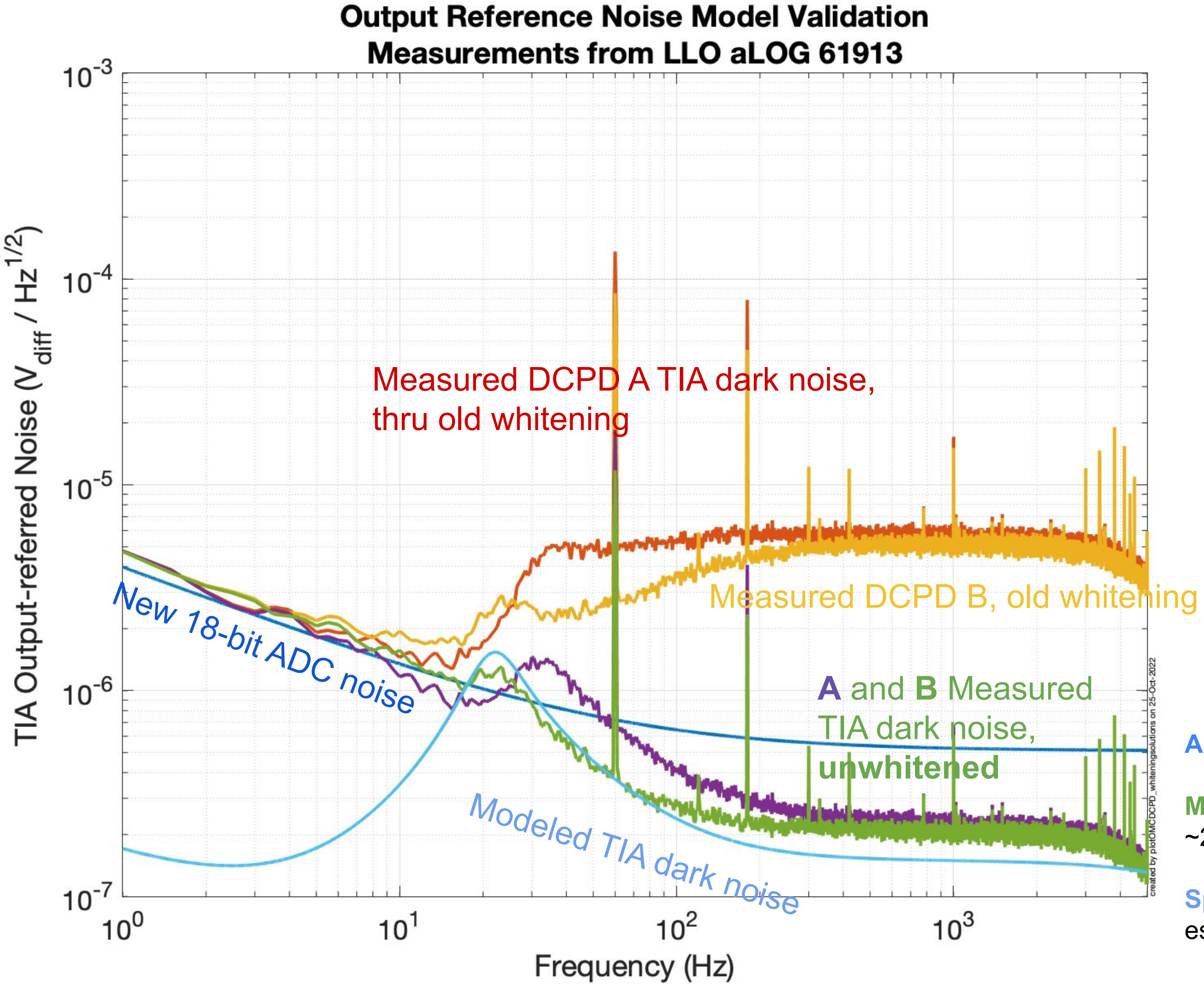
Old ADC
~4 uV/rtHz

New ADC
~500 nV/rtHz

Chose 18-bit ADC model to mimic the noise from TST:15067, which is similar to DCPD A channel

LLO aLOG 61330

TST aLOG 15067



ADC noise is ~500 nV/rtHz,

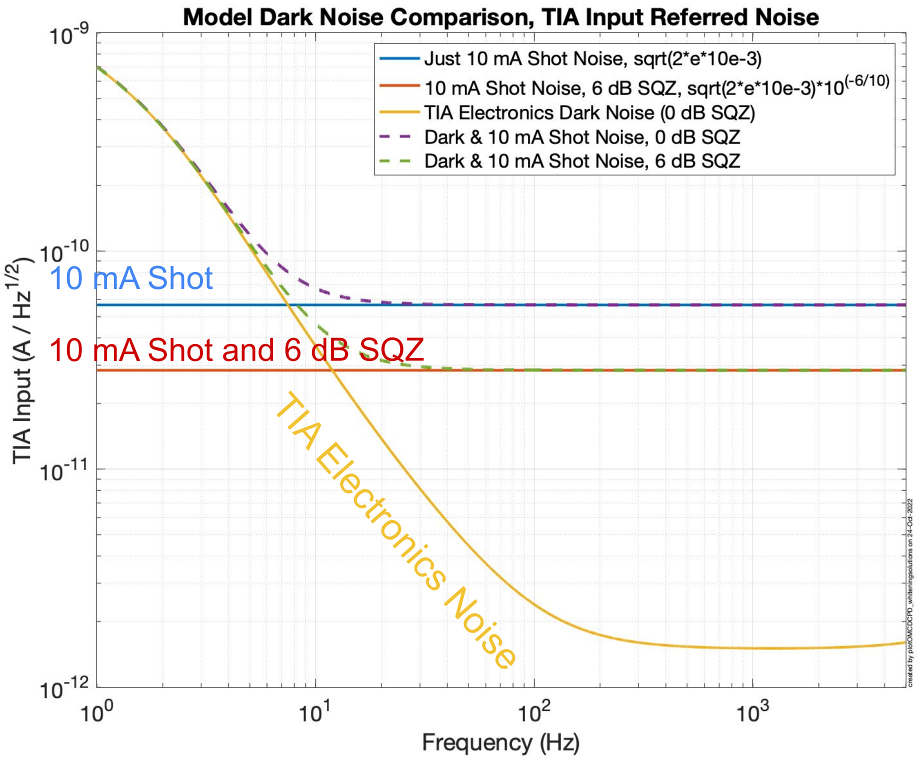
Measured new TIA dark noise is ~200 nV/rtHz

Spice model TIA dark noise estimates ~150 nV/rtHz

Spice model agrees with measured data for TIA output referred electronics self noise, aka “dark” noise.

Some whitening is needed. Measured noise is higher that model, so whitening solution that works for the model should work for measured.

Design Goal: Don’t spoil “the” signal-to-noise ratio!

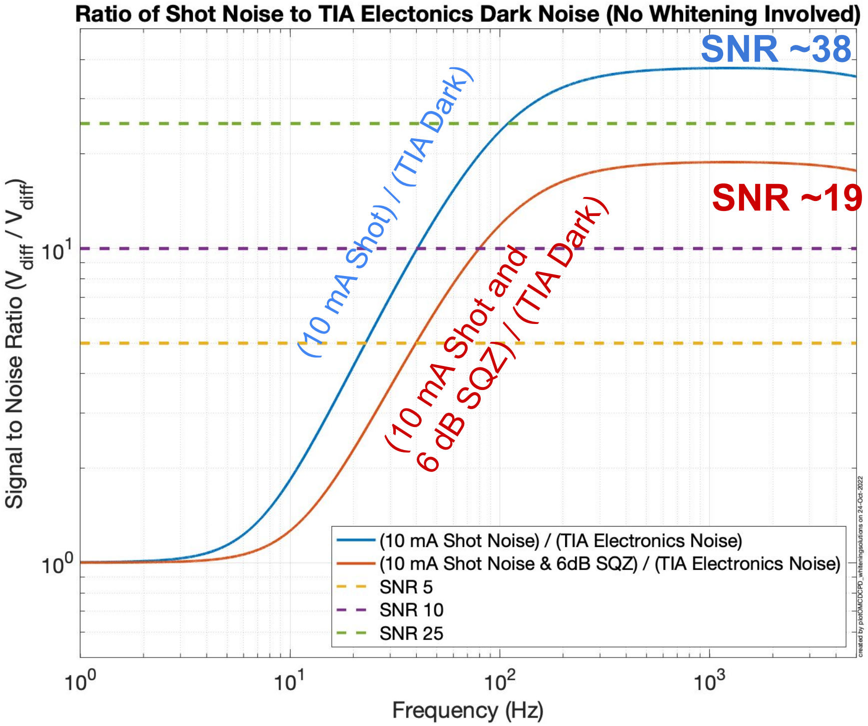


So – what is the “**signal to noise**” ratio we’re trying to preserve?

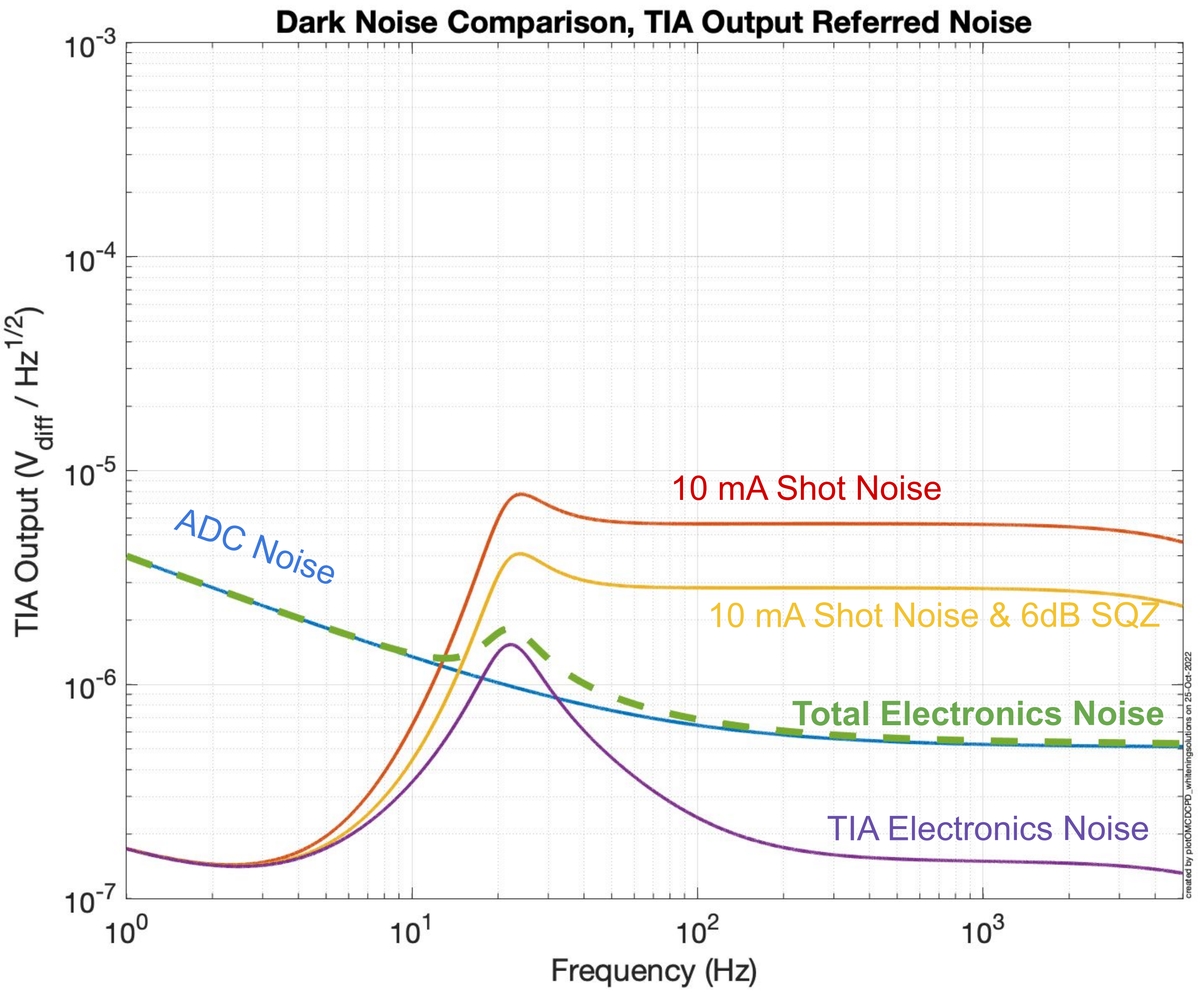
“10 mA worth of Shot Noise” = sqrt(2 e [10e-3 mA]) = 5.6e-11 [A/rtHz]

Use spice model to estimate the *input* referred **electronics noise**, in A/rtHz.

“Dark” electronics noise is the same regardless of input, but “signal” will be different between squeezing and no squeezing.



No model is perfect, and getting this right to the factor of 2 level is hard. We carry around the “6 dB SQZ” curves also representative of the TIA electronics noise, or ADC noise being larger than models, also degrading the SNR.



Back to **TIA output-referred voltage noise** metric.

We assume **spice model TIA dark noise** is representative.

Add two examples of **shot noises** to demonstrate the "signal" part of SNR.

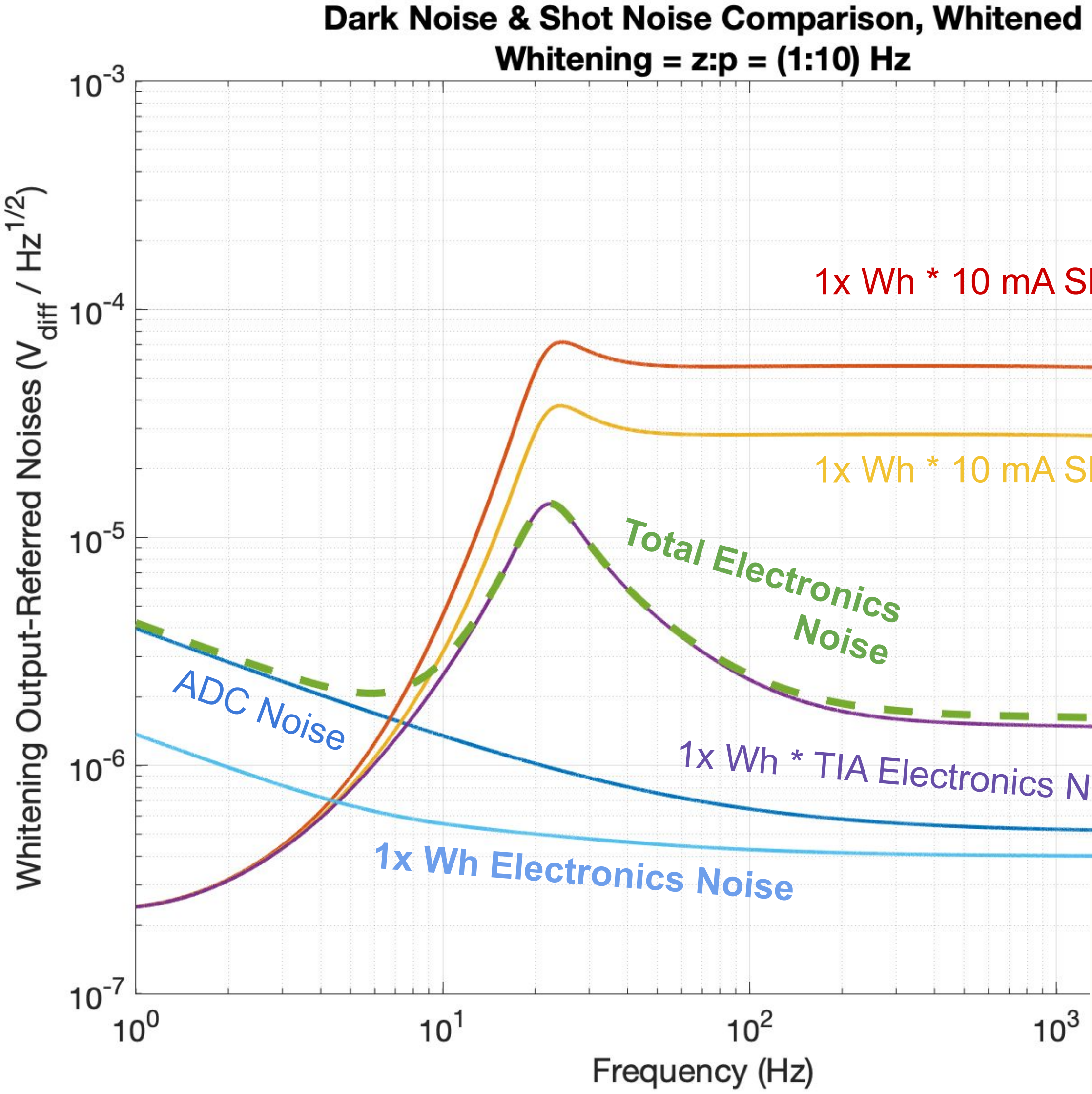
Add **total electronics noise** for the "noise" part of SNR.

If **no whitening as shown here**, then **ADC noise** dominates the **total electronics noise**

(No whitening was incorrectly suggested in G2201909-v1)

We don't want this (no whitening gain).

Must have *some* whitening gain to surpass ADC noise.

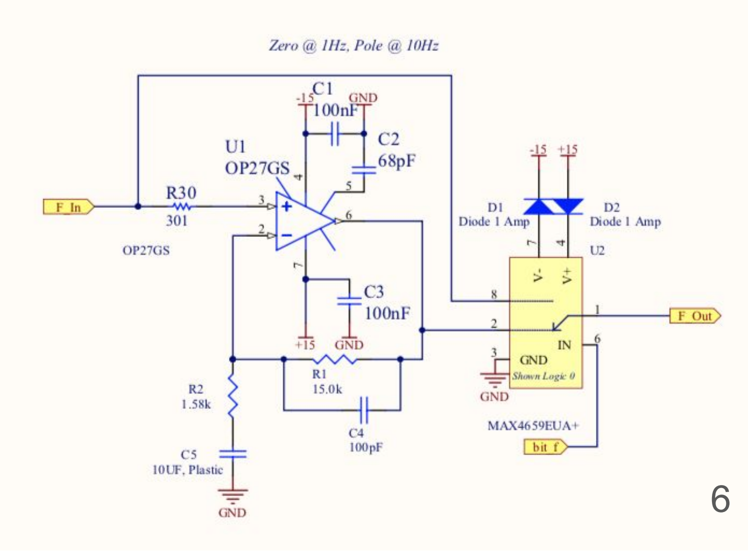


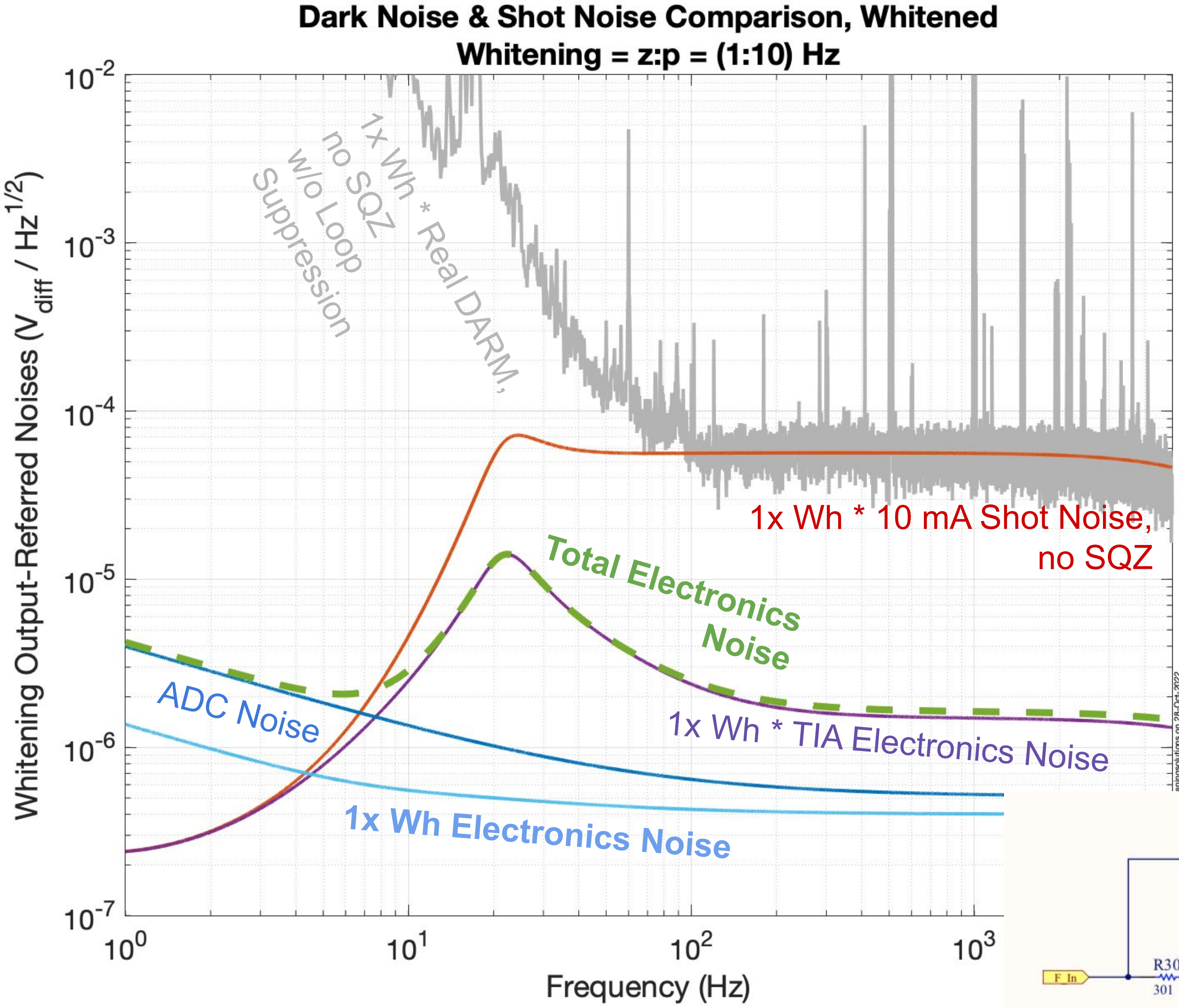
“Just use what we had in O3.”

If we apply the “battle-tested” design of a single z:p = 1:10 Hz filter that’s used in the majority of ISC whitening chassis (D1001530 page 4),

Then **1x Wh * TIA electronics noise** is above **ADC noise**, and **ADC noise** is only a small contributor to the **total electronics noise**.

This will do nicely.
How about our SNR metric?





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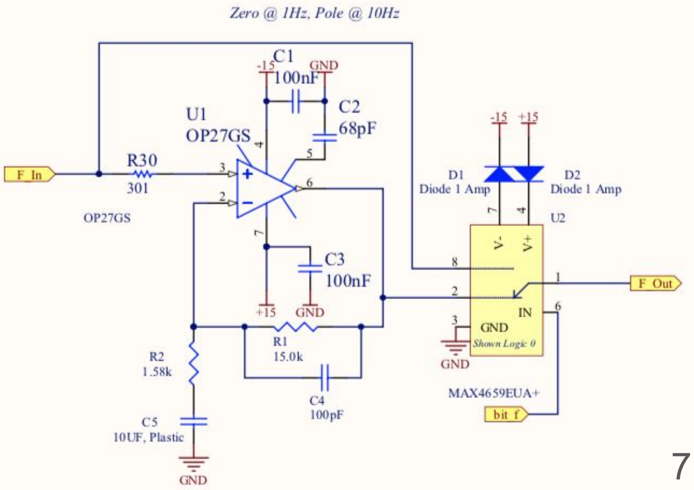

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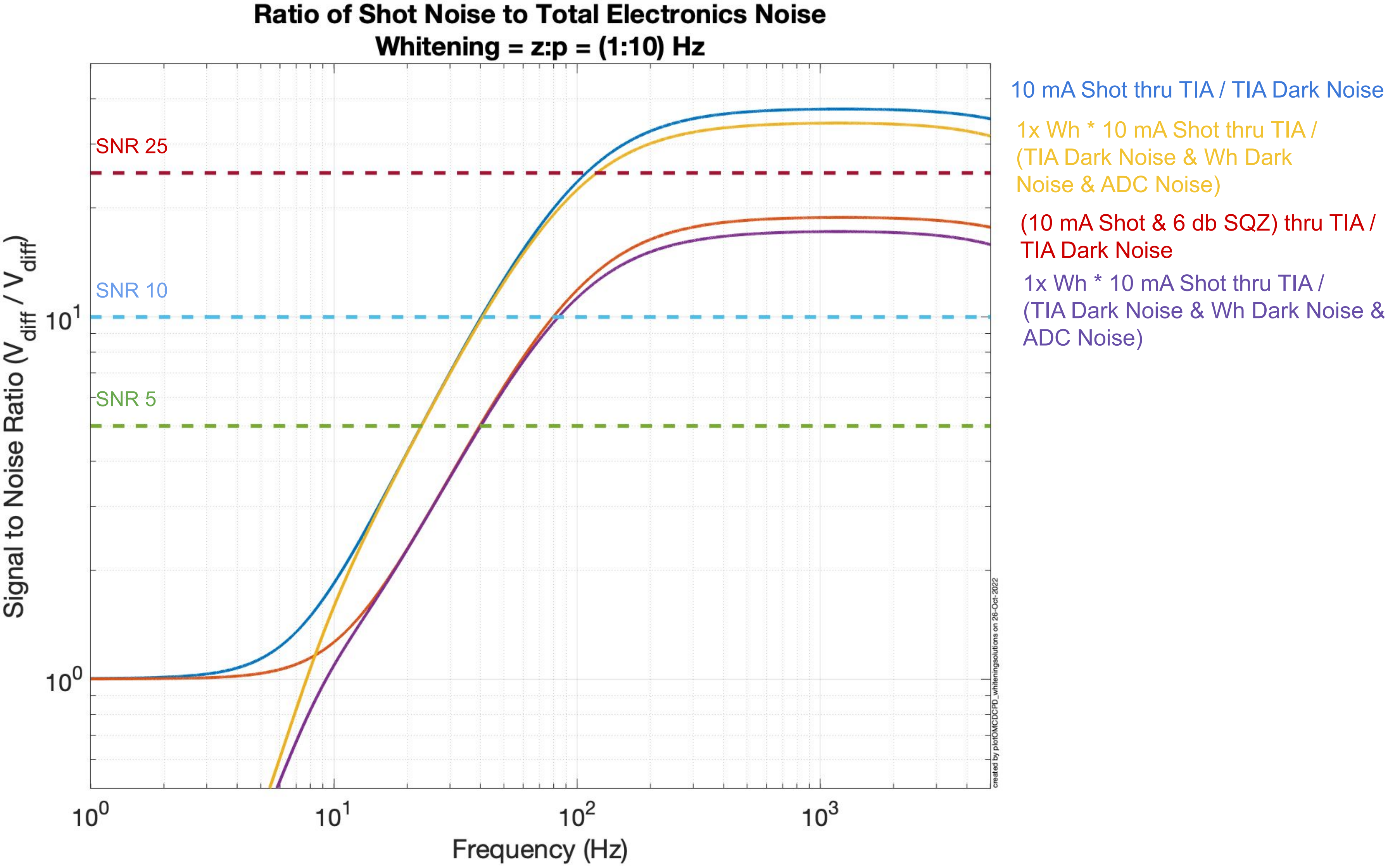


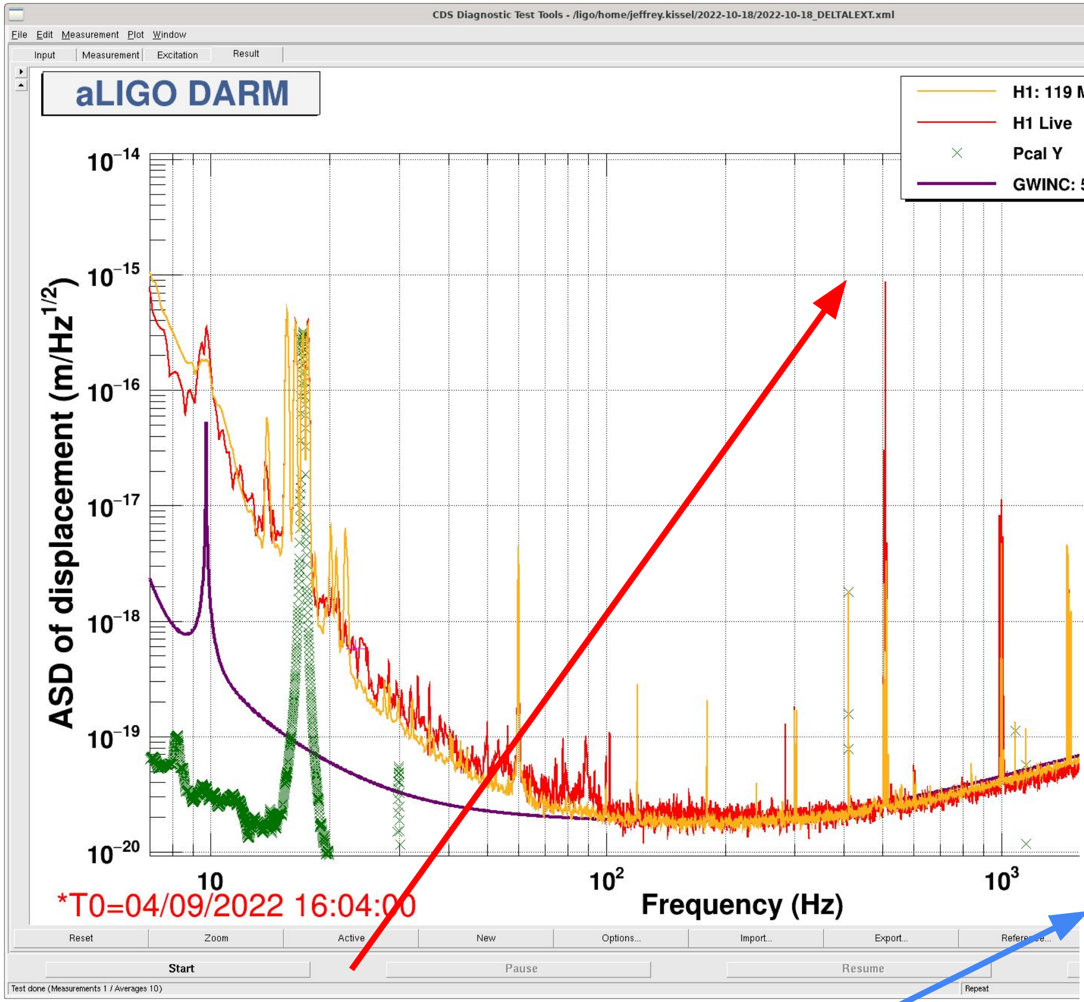
Ratio of Shot Noise to Total Electronics Noise
Whitening = z:p = (1:10) Hz

With 1x stage of (1:10) whitening, the ADC noise

- Reduces (10 mA) SNR at 1 kHz from **~38** to **~34**
- Reduces (10 mA & 6dB SQZ) SNR at 1 kHz from **~19** to **~17**

1x (1:10) whitening is enough that ADC Noise does not dominate electronics noise,
Only slightly impacts SNR.
As long as this SNR doesn't go below 10, then it's acceptable.

Saturation and Violin Modes

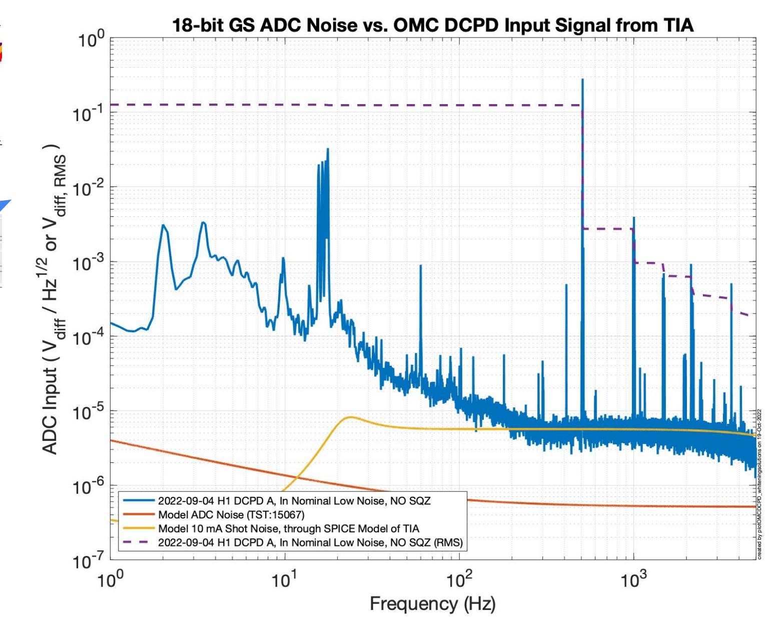


Connecting the dots of how this "**representative**" ASD chosen from 2022-09-04, corresponds to what we typically see.

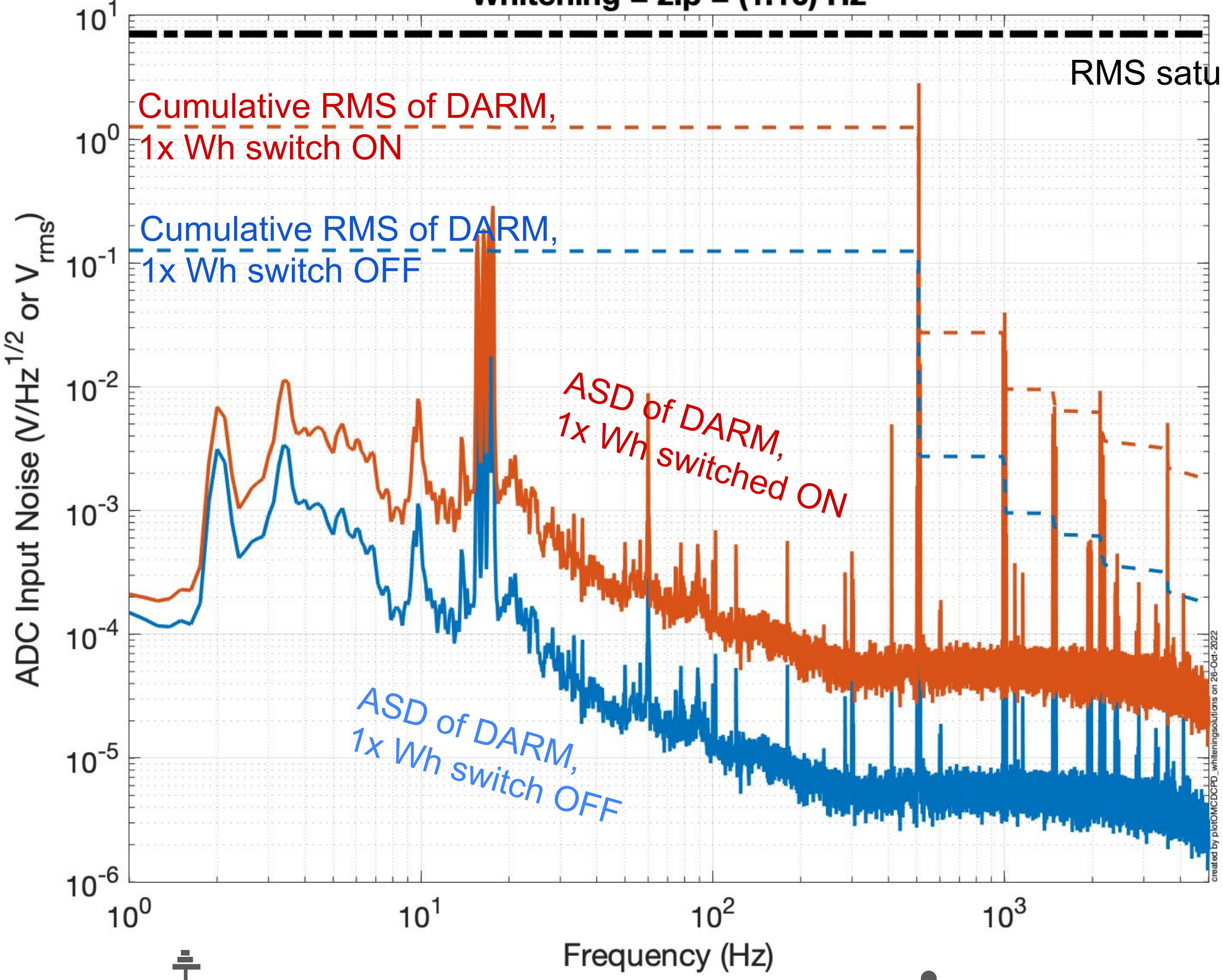
RED DELTAL EXT trace is the data that I've grabbed as the representative trace.

YELLOW trace shows typical "good" O3 times, where the violins are several orders of magnitude lower.

When 500 Hz violins are around **~1e-15 [m / rtHz] in DARM**, the **current** on DCPDs have peak voltage of 0.16 [V_rms] = **~0.2 [V_{peak}]** out of the TIA.

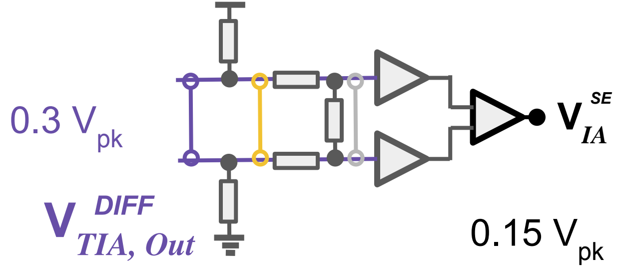


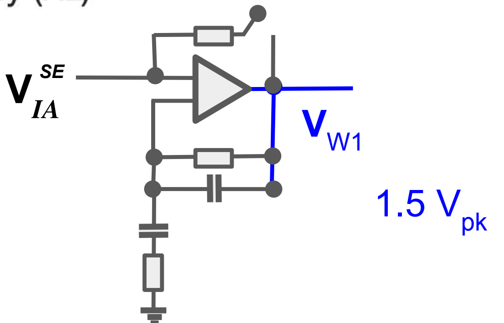
Signal Chain Saturation Check
Whitening = z:p = (1:10) Hz

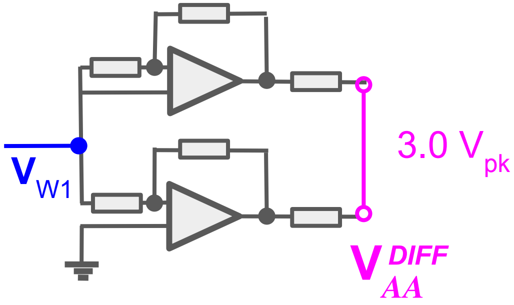


With violin modes at whitening input this level, ~0.3 V_{pk},

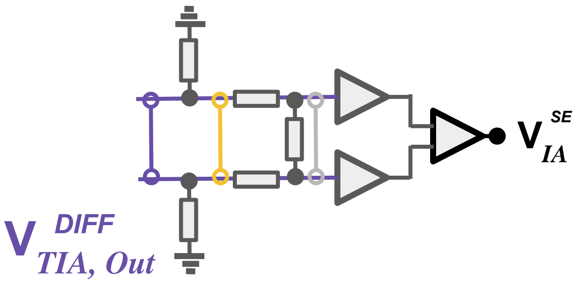
no stage of the whitening saturates, nor will the ADC (comes in as 3.0 V_{pk}).







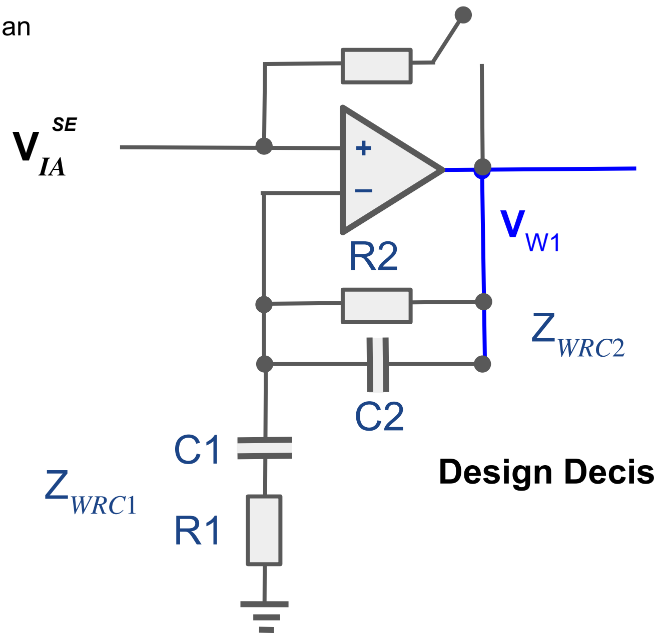
Design Intent



Same differential receiver, but with updated slew-rate limiting pole at ~44.21 kHz, rather than at ~11 kHz

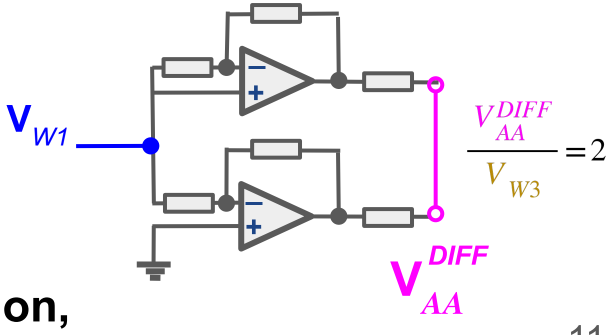
Design Decision 1:
1x “Standard” stage of Switchable Whitening filter

- Default state is whitening ON (as it was in O3.)
- z:p = 1:10 Hz



Design Decision 2: No DC gain (switchable or not)

Design Decision 3: (carried over from -v1) NO extra 10 kHz Poles in any of these stages. Plenty of 10 kHz poles from TIA and ~44.21 kHz pole from slew-rate limiting filter.



Same differential amplifier

In short: nominal operation has whitening on, with a gain of 10x

Timeline

It’s the week of Oct 24 - Nov 4.

Dean says he can have the design finished within ~1-2 weeks of us saying “go for production. Nov 7 - Nov 11 (Maybe another quick review then with all the Altium products finished?)

Can have the chassis back from shops and assembled in 2-3 weeks from that. Nov 14 - Nov 25.

So, delivery on site is plausible the week of Nov 28 2022.

Jeff / Joe now have experience and understanding of what’s coming, and the user interface is a lot more clear, so could measure and compensate the week of Dec 5 - Dec 9.

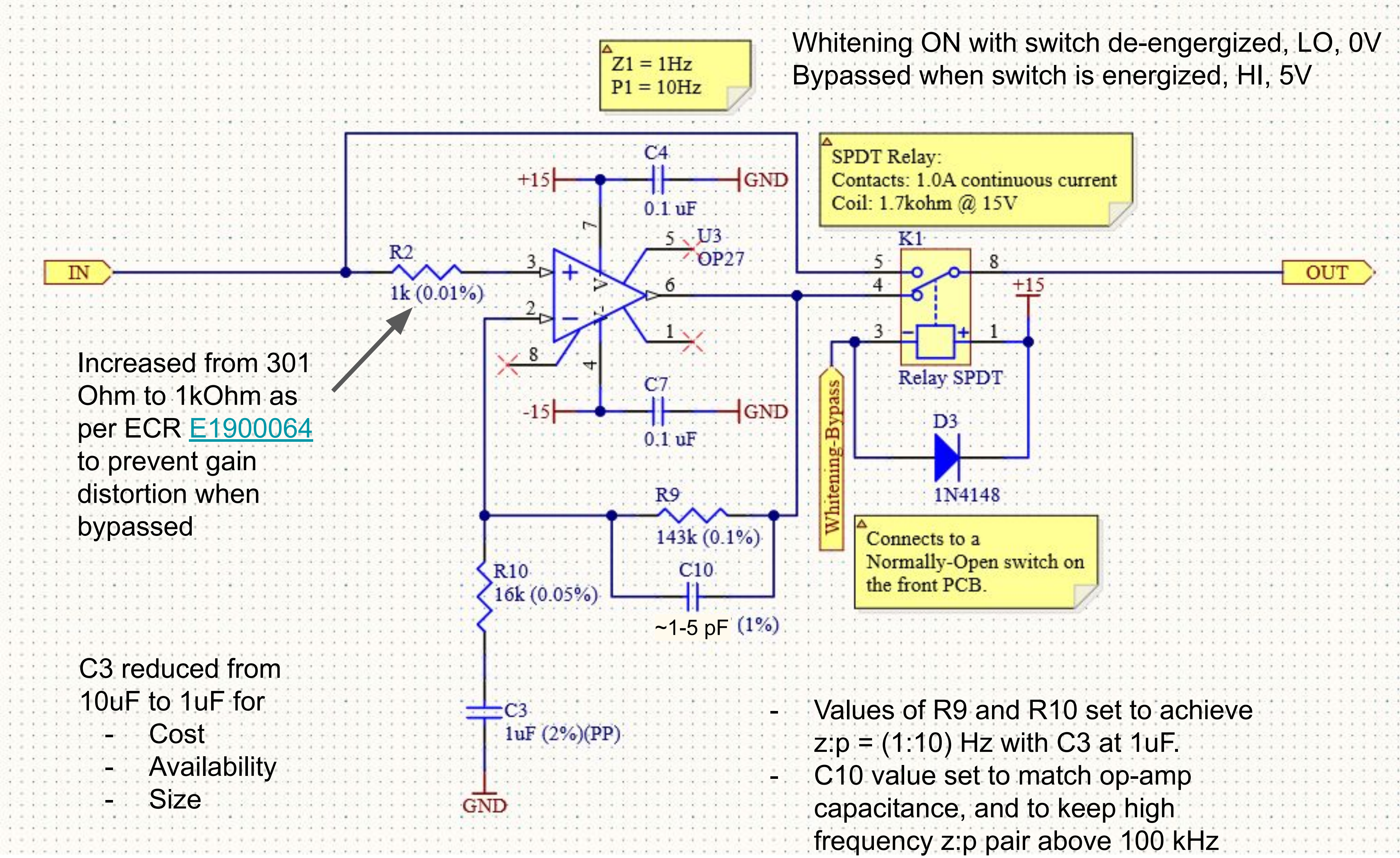
Great! Let’s get this in before O4!

But … not useful unless both sites have functional low-noise 18-bit ADCs in place. Open question: how does this jive with the timeline for

- Getting a low-noise 18-bit ADC running at LHO?
- Moving this low-noise 18-bit ADC to another segregated IO chassis?

OTHER UPDATES AND DESIGN CHOICE AIDES

Whitening ON with switch de-engergized, LO, 0V
Bypassed when switch is energized, HI, 5V

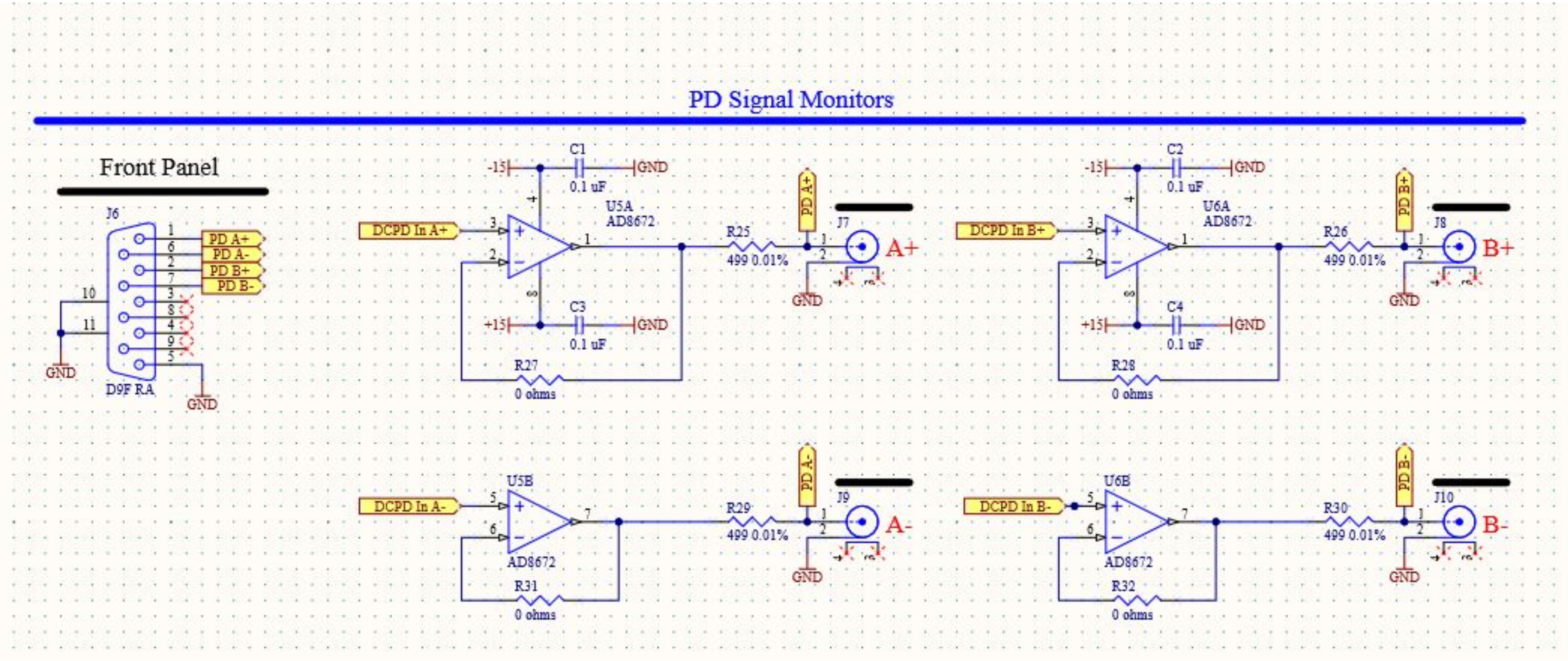


Increased from 301 Ohm to 1kOhm as per ECR E1900064 to prevent gain distortion when bypassed

C3 reduced from 10uF to 1uF for
- Cost
- Availability
- Size

- Values of R9 and R10 set to achieve z:p = (1:10) Hz with C3 at 1uF.
- C10 value set to match op-amp capacitance, and to keep high frequency z:p pair above 100 kHz

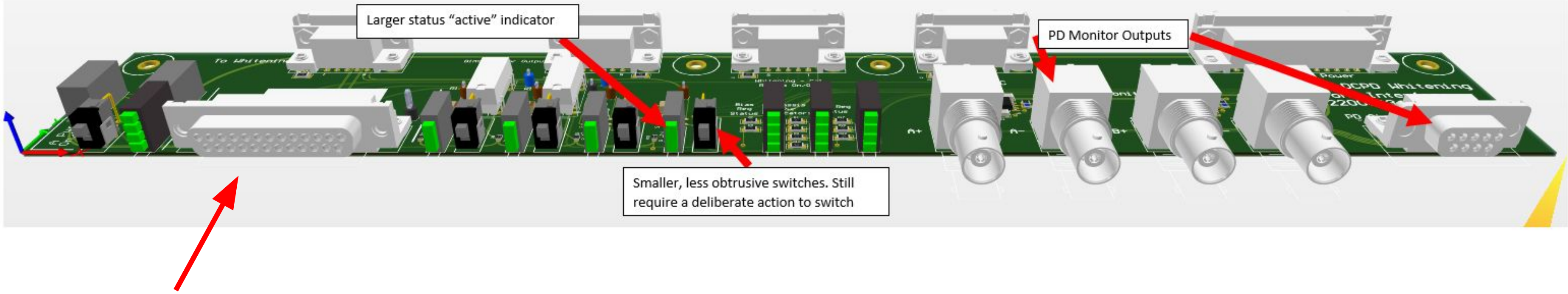
PD Signal Readouts – Front-Panel User Interface



DB9 Differential Output
For use with SR785
Accessory Box
(picked off from buffered
output just before BNC)

Each leg exposed to BNC for
quick/diagnostic checks with
Oscilloscope

PD Signal Readouts – Front-Panel User Interface



Larger status “active” indicator

PD Monitor Outputs

Smaller, less obtrusive switches. Still require a deliberate action to switch

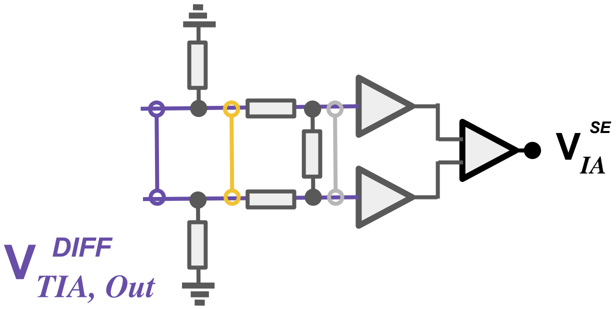
DB25 from / to in-vac TIA preamp

What if we read out with several ADC channels?

Out of the scope of this design change, but in case it comes up:
An idea bantered about – because the 18-bit low noise ADC has 32 differential channels available, and we want to segregate the OMC DCPD signals in their own card on their own chassis – why not make copies of the whitening chassis' DCPD voltage output and feed them into multiple channels, then digitally take the average to improve against the ADC noise further?

- 32 available channels on new LN ADC.
- 4 DCPDs, 2 chans per DPCD GW readout and Bias Mon
    - Map 1 DCPD GW readout into 4 ADCs channel.
- 16 + 4 = 20 channels total – plenty enough channels.
- Split the output of the differential receiver into four paths, right out to the DB connector…
- Any need to change the whitening filter design topology (to improve self noise) if we do that? **No.**
    - For copies of 20 nV/rtHz noise vs. TIA self noise vs. sqrt(2)*(AA+ADC) noise…
    - Gut feeling is "no" but if we're serious about this, we should run the numbers.
- Would we need a new and improved "low noise" AA chassis for this? **No.**
    - Spec for AA chassis has their self noise between 75 to 100e-9 V/rtHz.
    - Typical test results have them come in at 30-50 nV/rtHz
    - Still well below ~400 nV/rtHz of the 18-bit ADC channel.

Quick note about the slew-rate limiting pole frequency



Previous A+ whitening design had slew-rate limiting filter at

For the LT1125 op amps used.

LT1125 have a slew rate limit of 4.5 [V/us]. For A = 10 V sinusoidal signal at frequency w = 2*pi*f, then the frequency where we hit this limit is at

```
            V = A sin(w t)
      dV / dt = A w cos(wt)
4.5e6 [V/s] = 10 [V] w cos(wt)
    2 * pi * f = 4.5e6 [V/s] / 10 [V]
             f = 4.5e6 / (2*pi*10) [Hz]
             f = 71.6e3 [Hz]
```

f_p = 71.6 [kHz]

We don’t want to hit this limit, so we’ve chosen component values (R=1kOhm, C=1800pf) such that the RC filter – with the C connecting across the two legs, so C_{eff} = 2C – has a pole at

f_p = 1/(2*pi*1e3*(2*1800e-12)) = 44.2 kHz

Quick Note about Whitening the Bias Monitor

Summary: elected to go without extra whitening for the bias monitor beyond what's in the TIA.

Design criteria: bias noise current to be a factor of 100x below shot noise current (a factor of ten below the factor of ten limit on electronics). Want a *monitor* to be able to detect that level of bias noise.

Assume bias voltage couples in via capacitance of PD, C_{pd} = 300 pF.

10 mA photocurrent = sqrt(2 e I) = 5.6e-11 A/rtHz

Want to sense 1/10th of shot noise = 5.6e-12 A/rtHz

1/(iwC_{pd}) * A = 1/(2*pi*(1 kHz)*300e-12 [F]) * 5.6e-12 [A/rtHz] = ~ 3e-06 V/rtHz noise

Bias monitor in the preamp has a gain of ~20x at in the sensitive LIGO band (DC gain is 2).

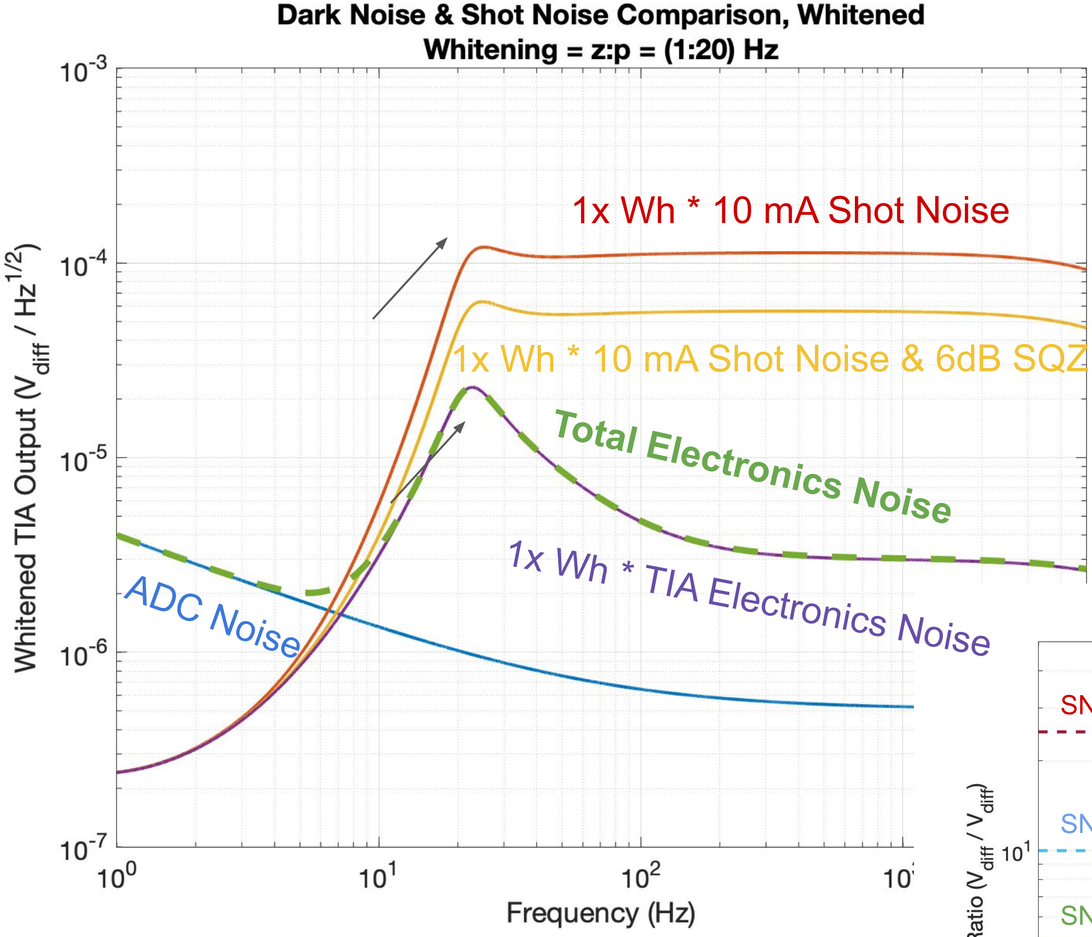
So that's = ~ 6e-05 V/rtHz noise, well above 500 nV/rtHz ADC noise.

Other Filter Design Options

- While playing around with whitening we say that a single stage 1:10 Hz whitening filter does still leave some ADC noise in play, reducing the 1 kHz SNR a bit. So we ask a few questions:
- What about a z:p = 1:20 Hz filter? A z:p = 1:25 Hz? When does the ADC noise *stop* limiting the total electronics noise?
- Also, in those various design scenarios, how much more gain can we tolerate before the system saturates under when violin modes are bad?

These next few slides show plots to show the exploration, but in the end, anything more that the single stage of 1:10 Hz filtering is deemed too much gain (w.r.t. the 10 V limit), and the improvement in SNR is not worth it.

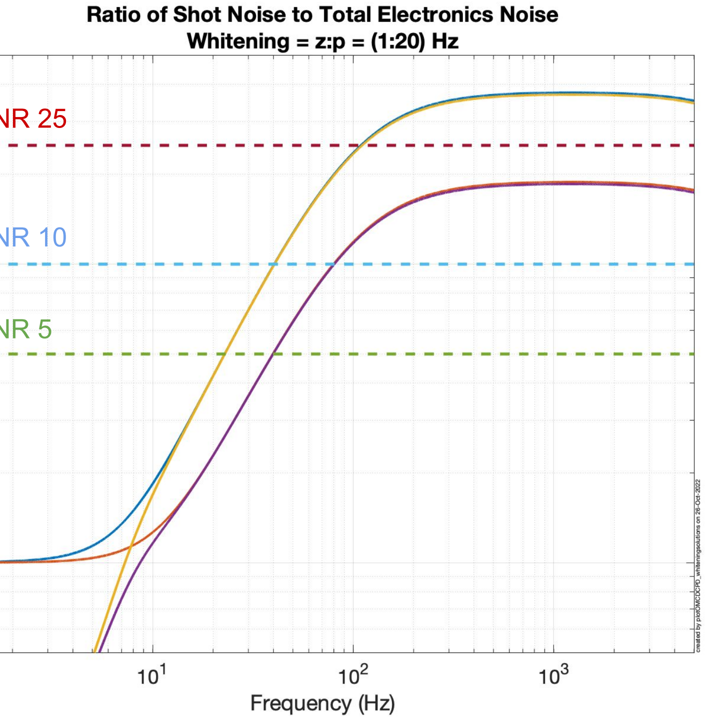
How about 1x stage of 1:20 Hz?



1x stage of (1:20) asymptotes to an extra factor of 2x gain above ~20 Hz for a total gain of 20.

Quite similar to existing A+ design gain of 25x.

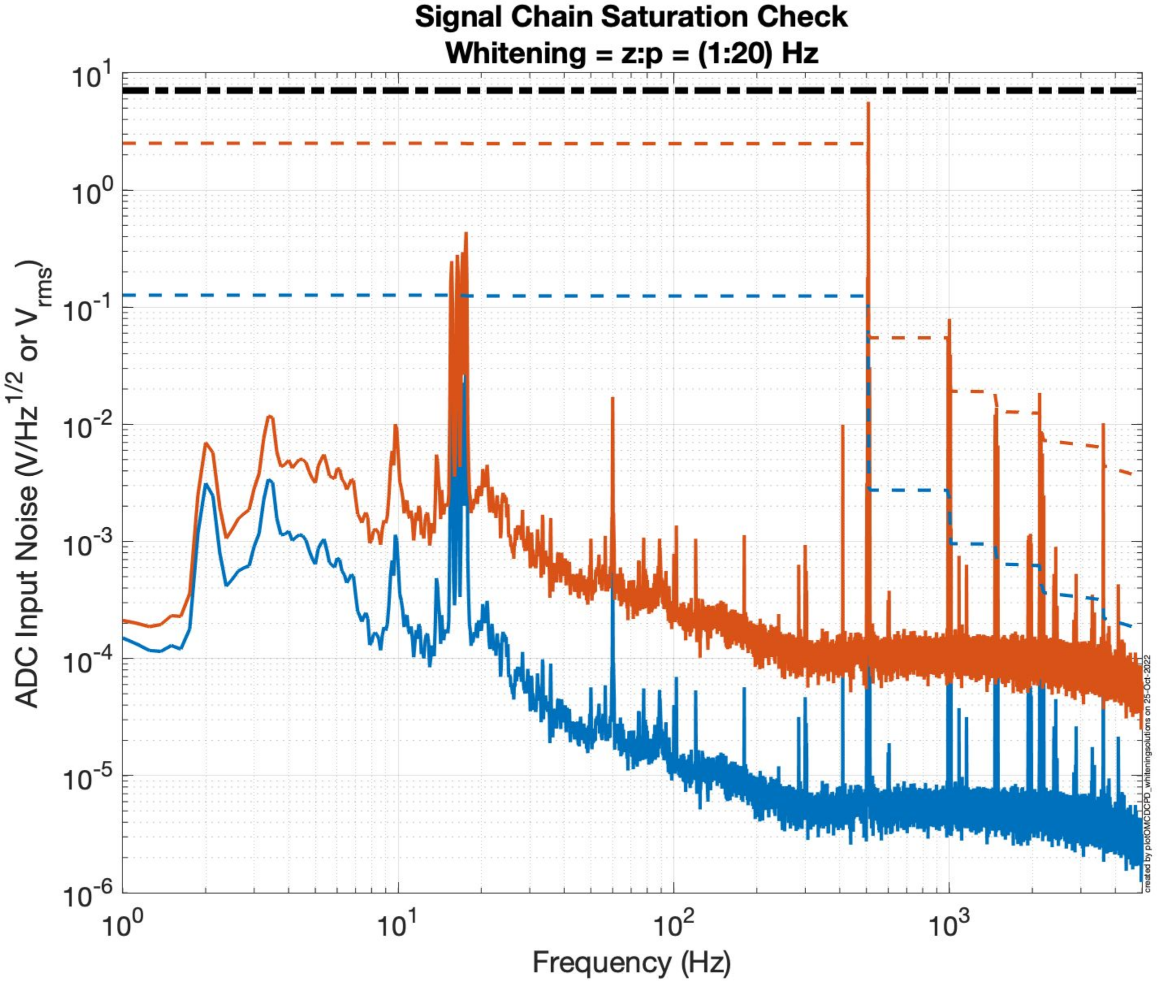
Ensures that **ADC noise** does not contribute at all to **Total electronics noise**.



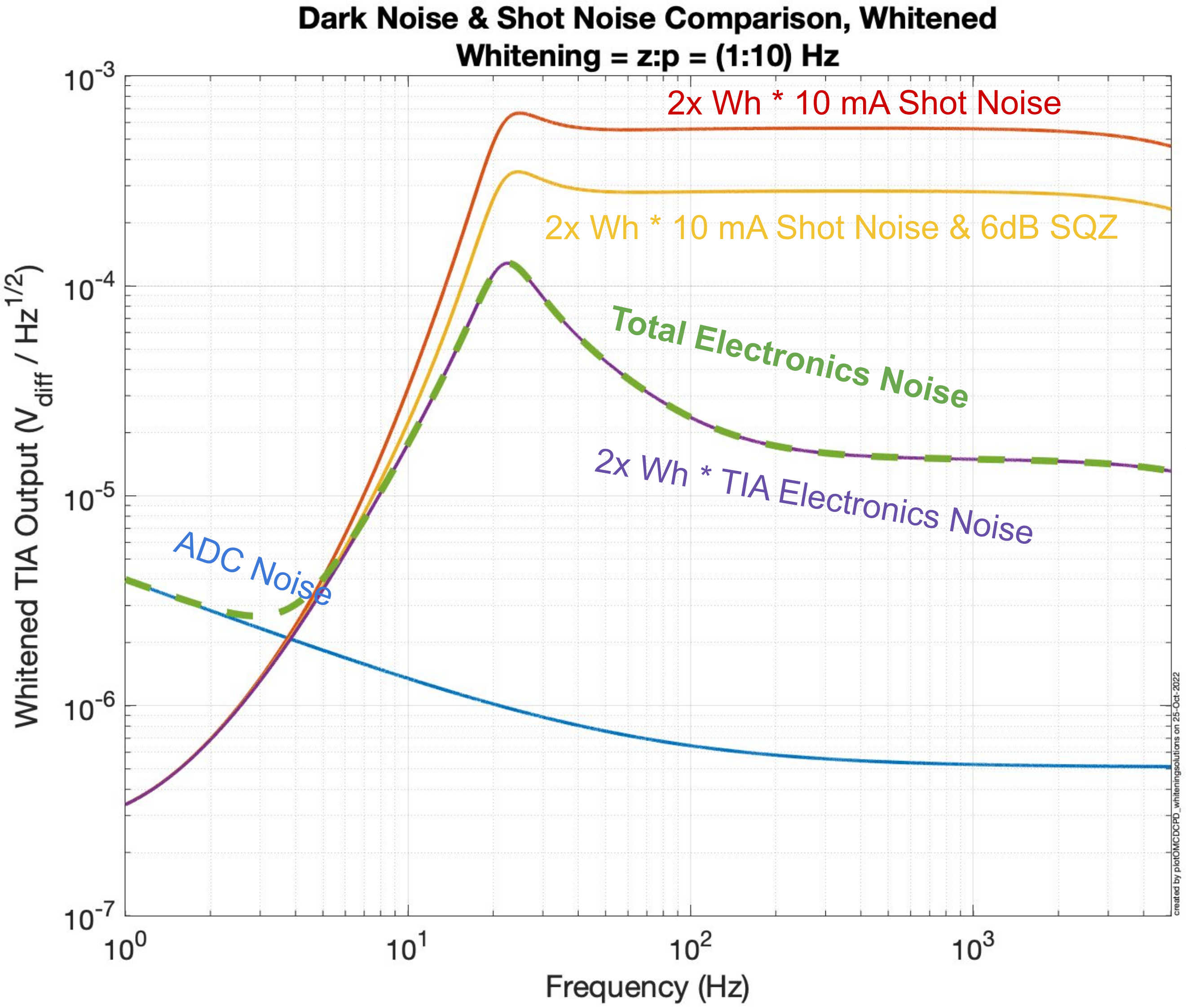
With 1x stage of whitening, ADC noise

- Reduces (10 mA) SNR at 1 kHz from **37.52** to **36.95**
- Reduces (10 mA & 6dB SQZ) SNR at 1 kHz from **18.82** to **18.54**

How about 1x stage of 1:20 Hz?



1x stage of (1:20) would not saturate with this example state of violin modes.



Two stages of z:p = 1:10 Hz is likely **too much** voltage gain for too little noise improvement gain.

Noise Improvement:
ADC noise goes from “small” to “negligible” contribution to **total electronics noise.**

The next two slides show that under certain conditions, 2x whitening saturates the signal chain.

Design Intent – Redone / Corrected from -v1

G2201909-v1 design approach was all wrong.

- The **corrected design goal** is now: **preserve "signal-to-noise" ratio** between
  - Shot noise, through the transimpedance amplifier as the "signal" and
  - "Dark" electronics self-noise of the transimpedance amplifier as the "noise"

  Cast both noises as "output referred" noises, at the output of the transimpedance amplifier (TIA).

- Mission: create a whitening filter than brings the TIA dark noise, n_{TIA}, well above the new better ADC noise, n_{ADC}.
  - The ADC noise improvement asymptotes to about a factor of ~7x improvement. So, we should expect to need about that much less gain.
  - Former A+ whitening filter design had a gain choice between 25x or 50x in the ~1 kHz region, so we should expect to need *some* whitening, but not a lot.
  - Gain of 25x is currently OK, but need ability to switch it off.

- Whitening filter design must have self-noise, n_{WH}, sufficiently small to not "spoil" the dark noise from the TIA n_{TIA}.
  - -v1 Showed the SNR between shot-noise and ADC noise. It's not that the signal-to-noise ratio between the ADC "noise" and shot-noise-through-the preamp "signal" "does not matter," it was just **the wrong metric**. We want

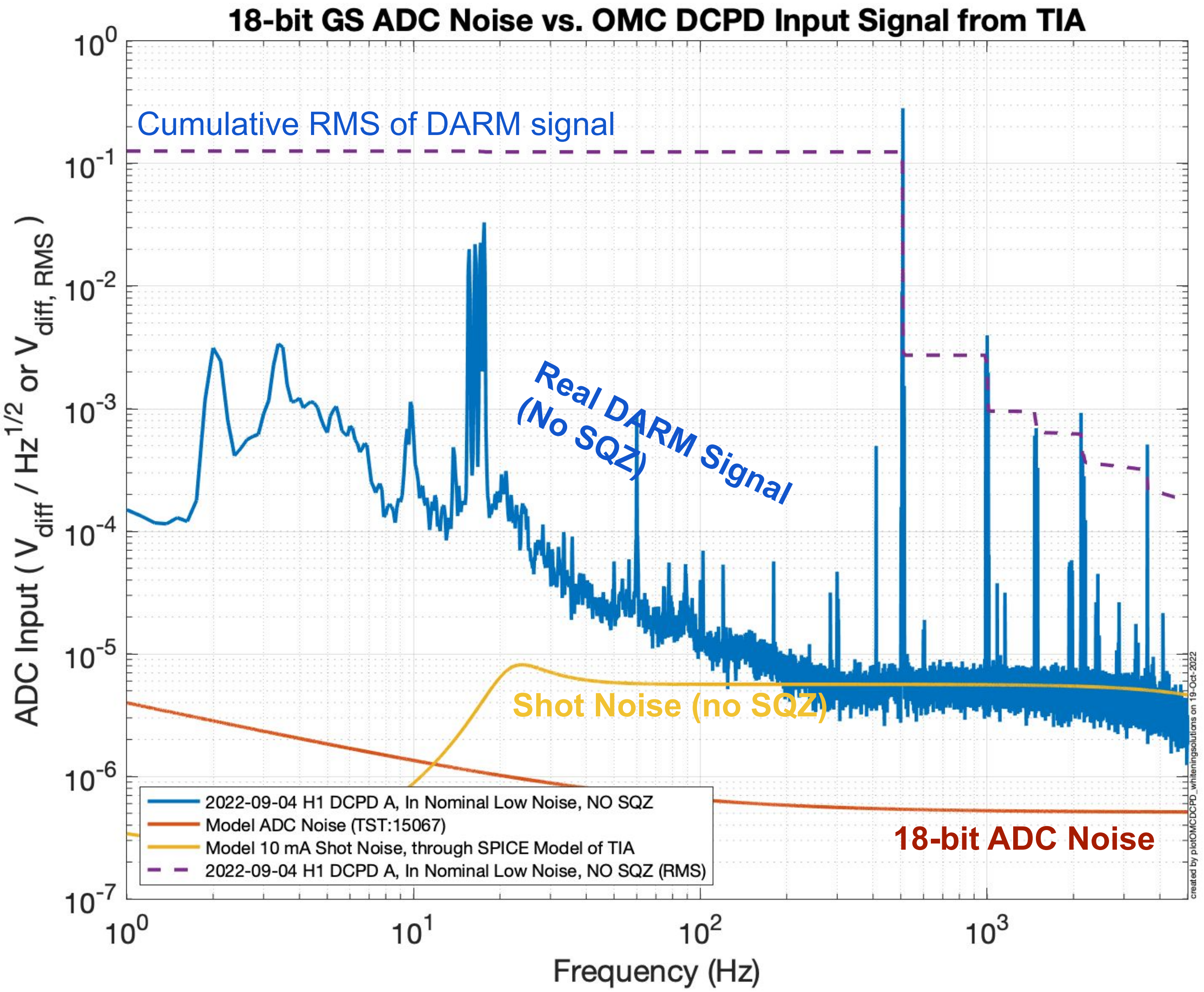
    $$n_{TIA} > \mathrm{sqrt}(n_{WH}^2 + n_{ADC}^2),$$

    such that it remains true that

    $$n_{shot} >> \mathrm{sqrt}(n_{TIA}^2+n_{WH}^2+n_{ADC}^2)$$

- Re: saturations – every electronics component from the TIA to the ADC has +/- 15 V range. That means if the ADC is saturating, then it's likely that the TIA is also saturating. Thus, there's no point in putting any low-passing in the signal chain below a gain of 1.0 V/V.
  - The -v1 design suggested **low-passing below a gain of 1.0, and that was wrong**.
  - It also suggested putting a whitening filter up-stream of the low-passing. That also doesn't make sense, because it the whitening stage is saturating, then **sending a saturated signal into the low-pass won't work**.

Whitening for below 20 Hz? No.



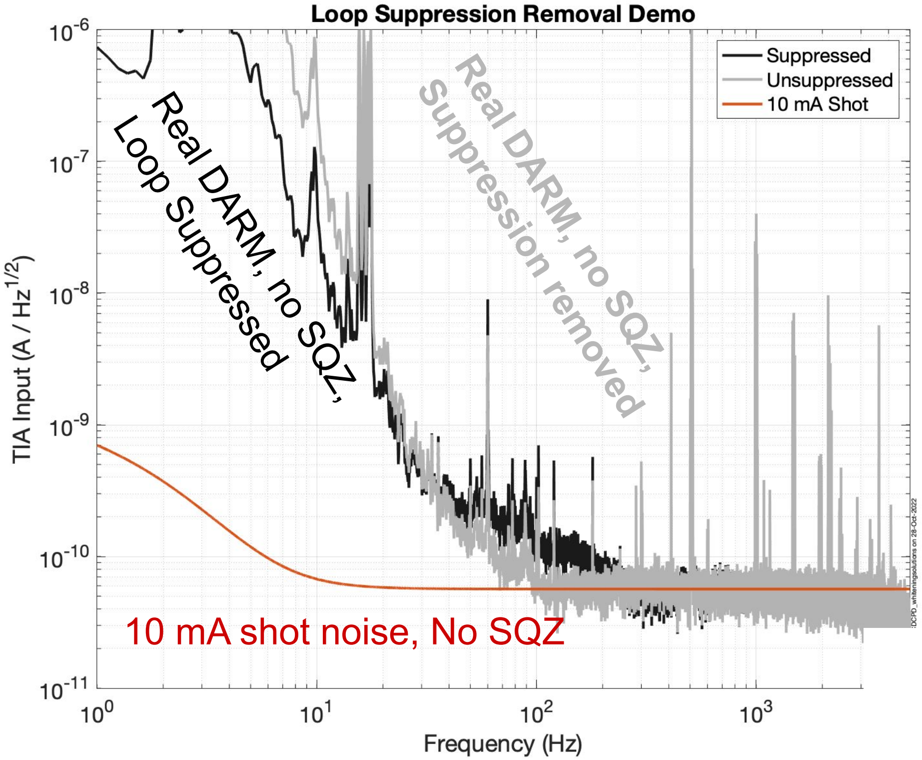
What's the **blue trace**?

Real DARM signal (no SQZ). Quick and dirty recent imperfect data from LHO but good enough for this.

Took a "**representative**" ASD of the H1 DCPDs via front-end [mA / rtHz], during nominal low-noise,and multiplied it by the TIA transfer function.
Random day of H1 data, (2022-09-04 16:04:00 UTC), with

- **No Squeezing**
- OK **violin Modes**, with 500 Hz peak heights at ~1e-15 m/rtHz (bad days are 1e-14 m/rtHz)
- **DARM loop suppression *not* taken out** (if I did "do it right" low-frequency ASD would only get louder, increasing the SNR)

Below ~100 Hz, signal dominates shot noise and remains large w.r.t to new 18-bit ADC noise. No need to any low-frequency whitening.



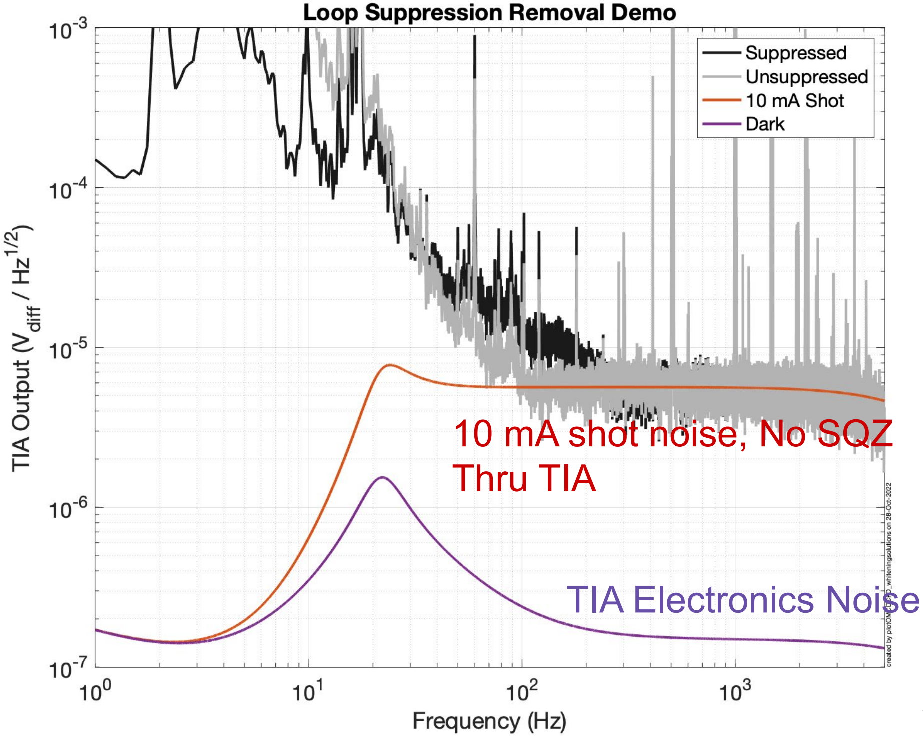
What does the current on the PDs look like if I *do* take out the loop suppression?

As expected, the unsuppressed curren is only larger w.r.t. the electronics noise.

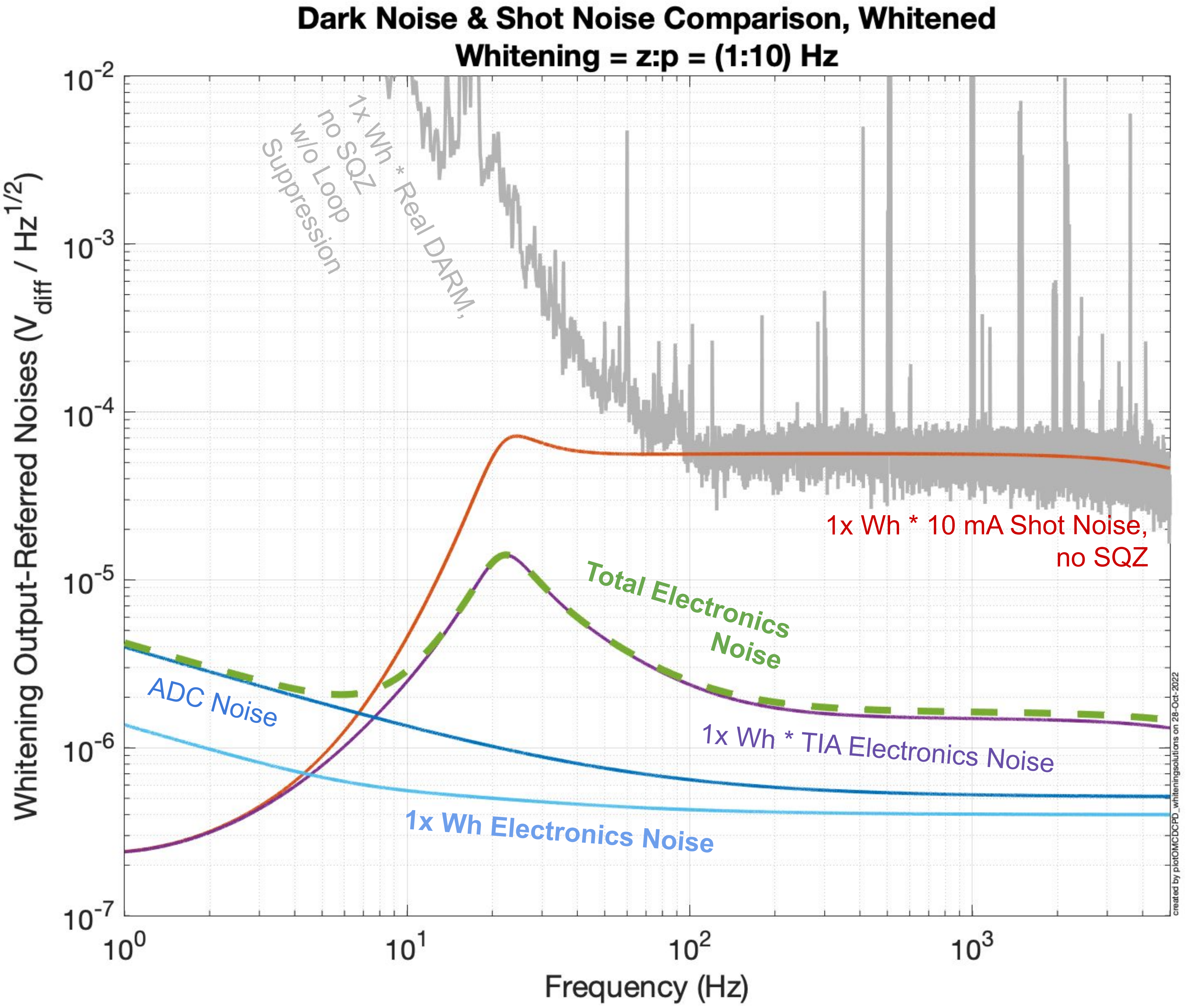
For comparison between

- unsuppressed, real DARM, thru TIA and 1x (1:10) Wh
- Unsuppressed, 10 mA shot, thru TIA and 1x (1:10) Wh
- TIA electronics noise thru 1x stage of (1:10) Hz Wh
- Electronics noise from 1x stage of (1:10) Wh itself
- ADC noise,

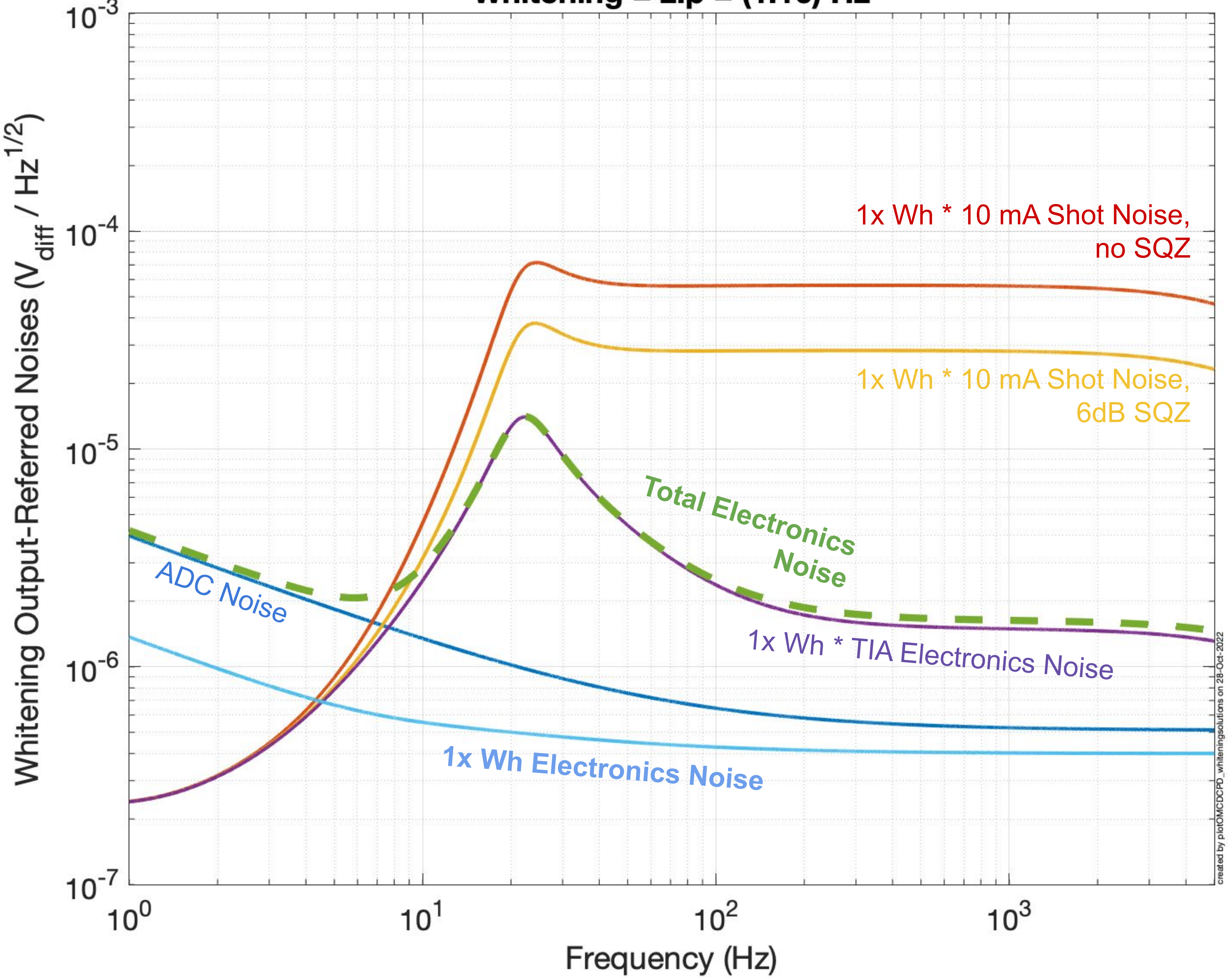
See slide 6.



Final Answer Plots Again (pages 6, 7 and 8), but with no messaging


Dark Noise & Shot Noise Comparison, Whitened
Whitening = z:p = (1:10) Hz
Whitening Output-Referred Noises (V_{diff} / $Hz^{1/2}$)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1x Wh * Real DARM,
no SQZ
w/o Loop
Suppression
1x Wh * 10 mA Shot Noise,
no SQZ
Total Electronics
Noise
ADC Noise
1x Wh * TIA Electronics Noise
1x Wh Electronics Noise
created by plotOMCDCPD_whiteningsolutions on 28-Oct-2022
10^0
10^1
10^2
10^3
Frequency (Hz)

Dark Noise & Shot Noise Comparison, Whitened
Whitening = z:p = (1:10) Hz



Ratio of Shot Noise to Total Electronics Noise
Whitening = z:p = (1:10) Hz