# On the reported TDCF change when the OMC Whitening Electronics Chassis Configuration Changed

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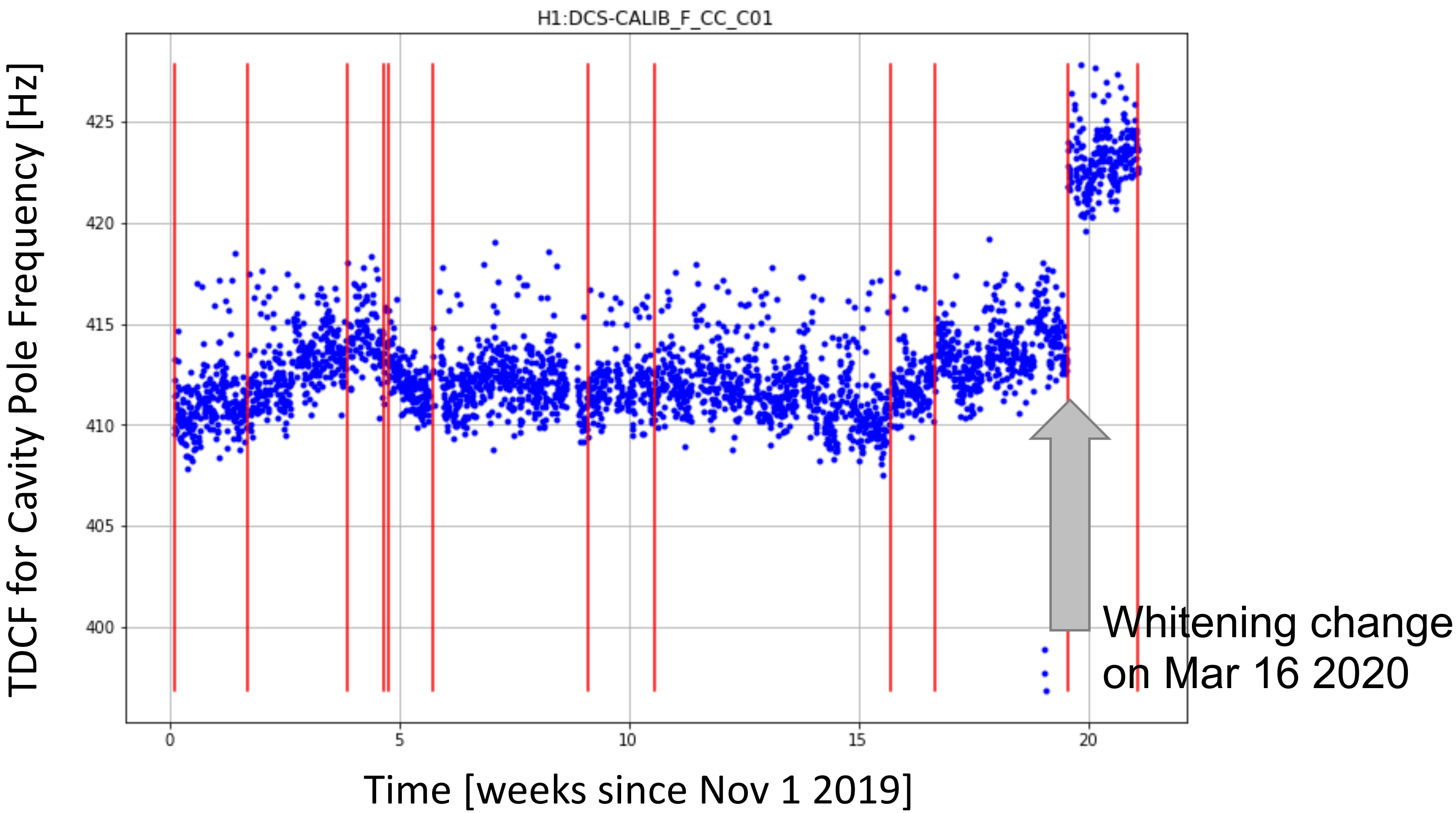
# What're we going to do tonight, Brain?

Trying to solve yet another mystery of O3B Chunk 2…

- As a part of the O3B Chunk 2 review, G2001206, Alan asks "why did the reported cavity pole change when the OMC Whitening Chassis Configuration changed?"

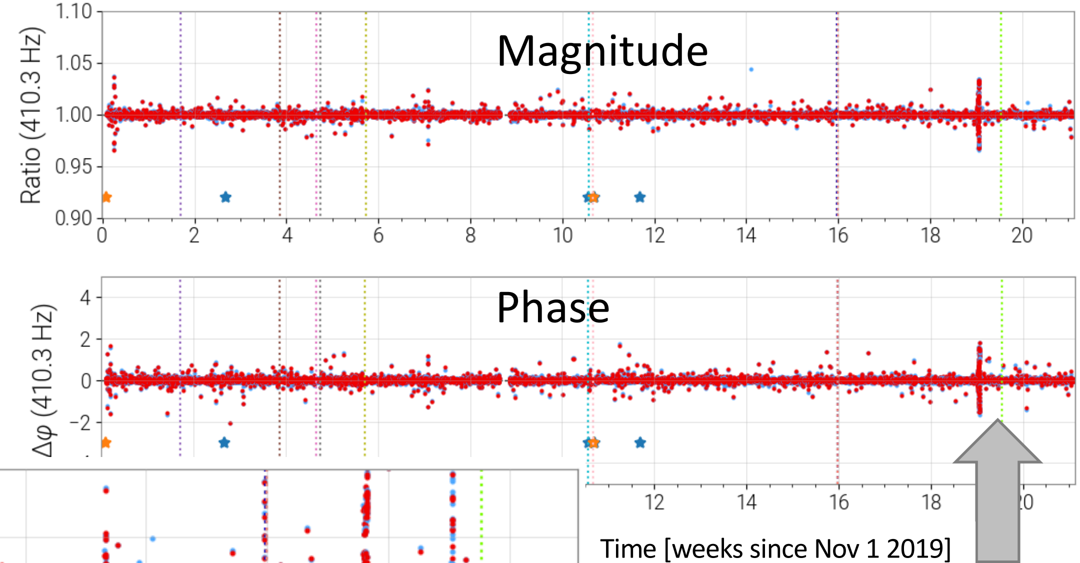
From Alan's Sanity Checks, calCheck_plots.html

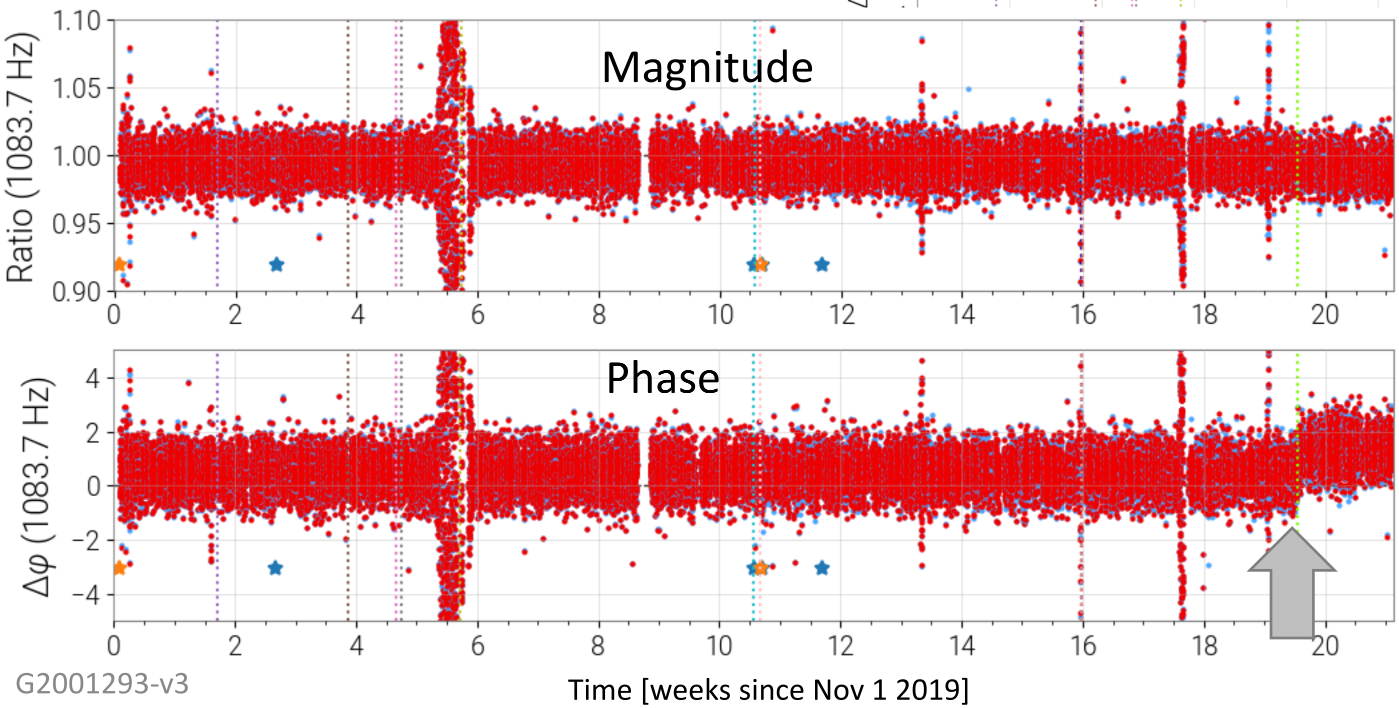


# First, let’s check the DCS / PCAL Trend

- If the cavity pole really changed, and the DCS model is now wrong, then we should see an impact in both the 410 Hz and 1083 Hz lines after the change.

[O3B C01 Cummary Pages]



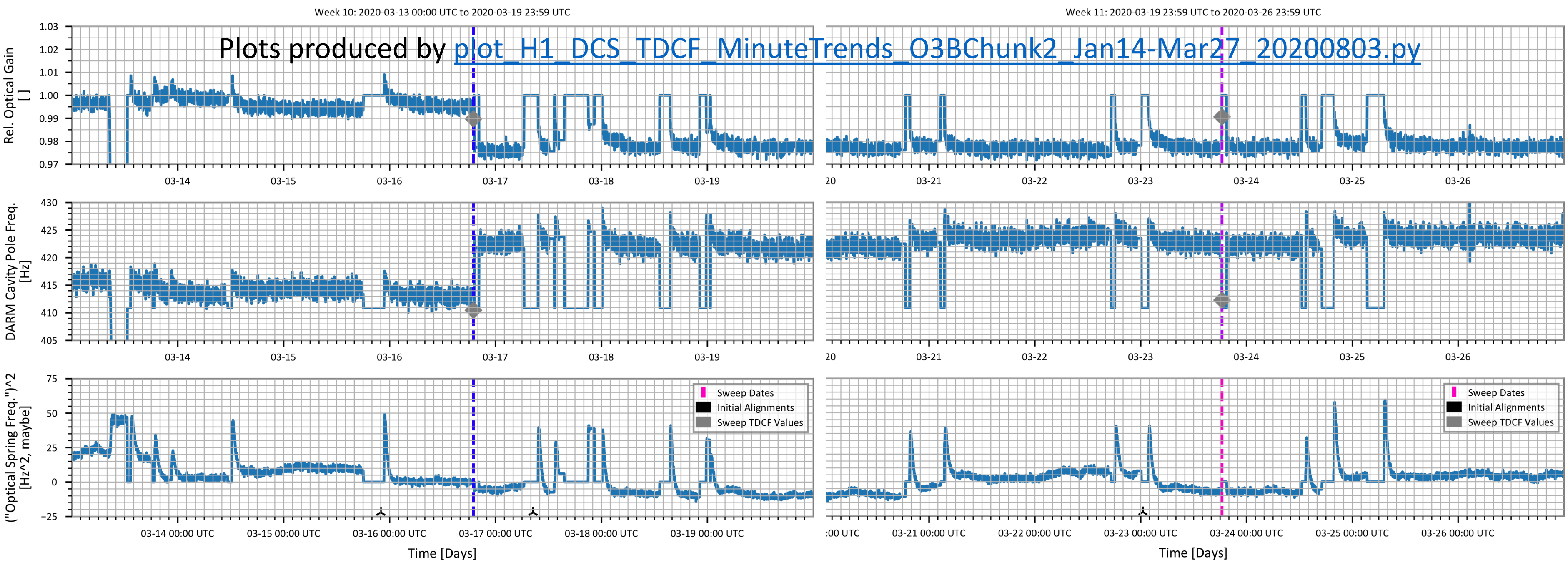




OK, maybe there’s something here.
A ~1 deg change…

# What do the TDCFs Report?

- Zooming in on the last two weeks of the Run, I show
  - the actual minute trends of the sensing function TDCF channels from the DCS frames, and
  - the MCMC fit values for the two sensing function sweeps

Plots produced by plot_H1_DCS_TDCF_MinuteTrends_O3BChunk2_Jan14-Mar27_20200803.py

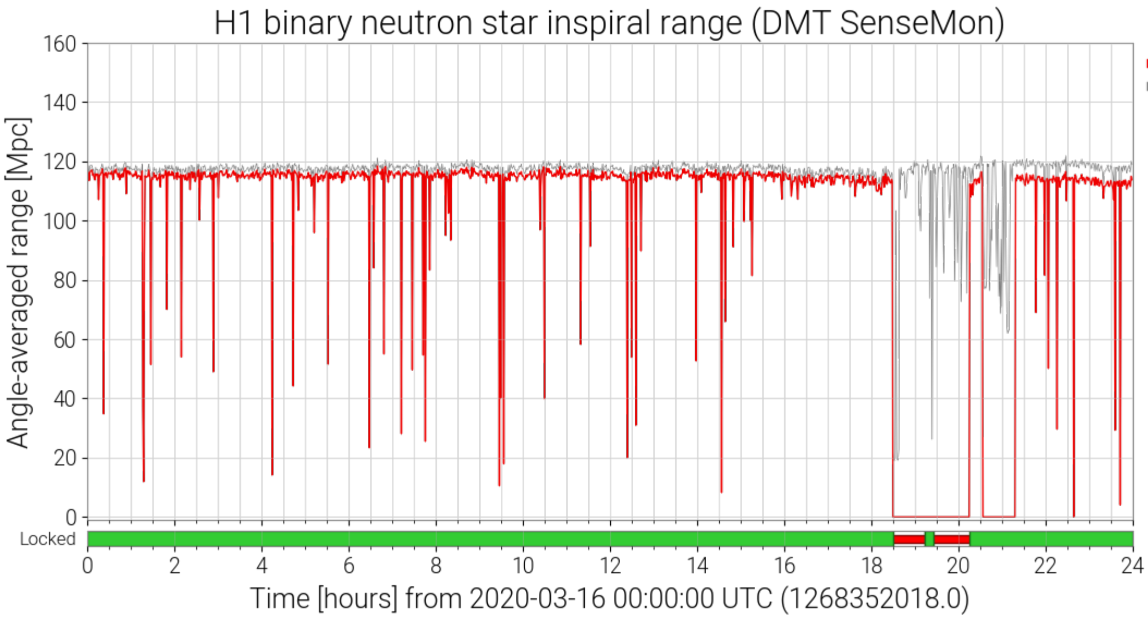



From calibration lines, $\kappa_C$ reports a 3% drop, and $f_{cc}$ reports a ~10 Hz increase, **but it doesn't agree with the sweep values, which report no change.**

| Date | $\kappa_C$ from MCMC | $f_{cc}$ (Hz) from MCMC |
|---|---|---|
| 2020-03-02 | 0.995955 | 413.984 |
| 2020-03-09 | 1.002442 | 413.387 |
| 2020-03-16 | 0.989786 | 410.457 |
| 2020-03-23 | 0.990593 | 412.271 |

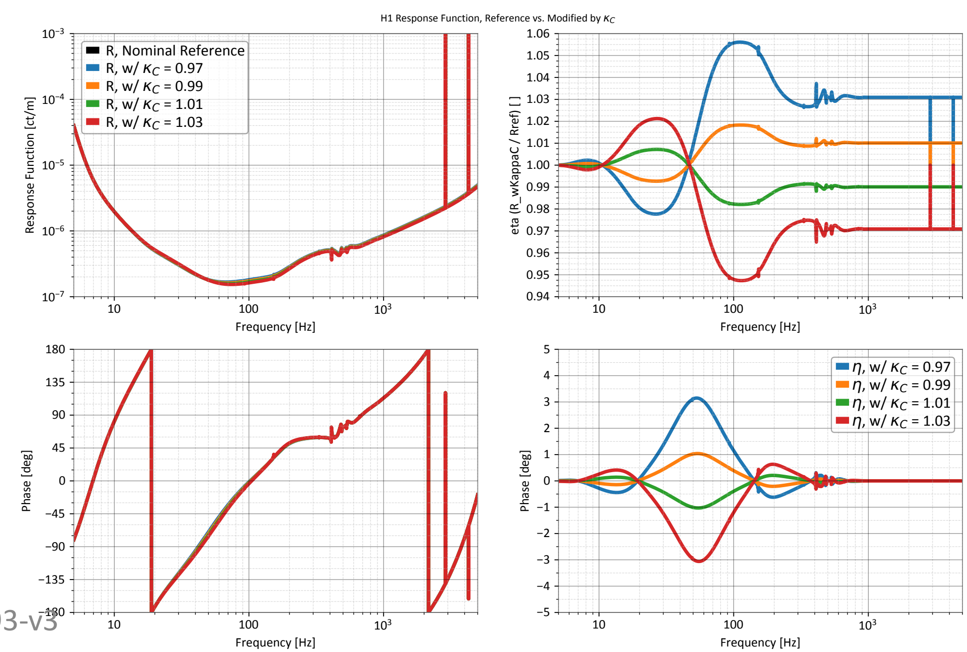
# Note, the Range Dropped…

… probably because of the arguably errant -3% $\kappa_C$ change:




~120 Mpc

~116 Mpc




$$\frac{\Delta L_{after}}{\Delta L_{before}} = \frac{R_{after}}{R_{before}} \equiv \eta_R$$

$$= \frac{\dfrac{1+\kappa_C ADC}{\kappa_C C}}{\dfrac{1+ADC}{C}}$$

$$= \frac{1+\kappa_C ADC}{\kappa_C(1+ADC)}$$

$$\eta_R = \frac{1}{(1+ADC)}\left[\frac{1}{\kappa_C} + ADC\right]$$

$$\eta_R \propto \frac{1}{\kappa_C} \; (when\ ADC \ll 1)$$

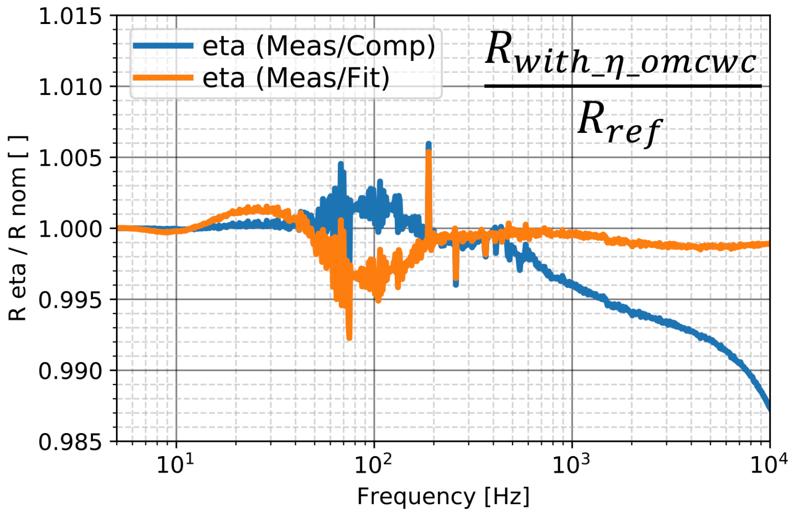
$$Range \propto \int \frac{f^{-\frac{7}{3}}}{\Delta L^2(f)} df$$

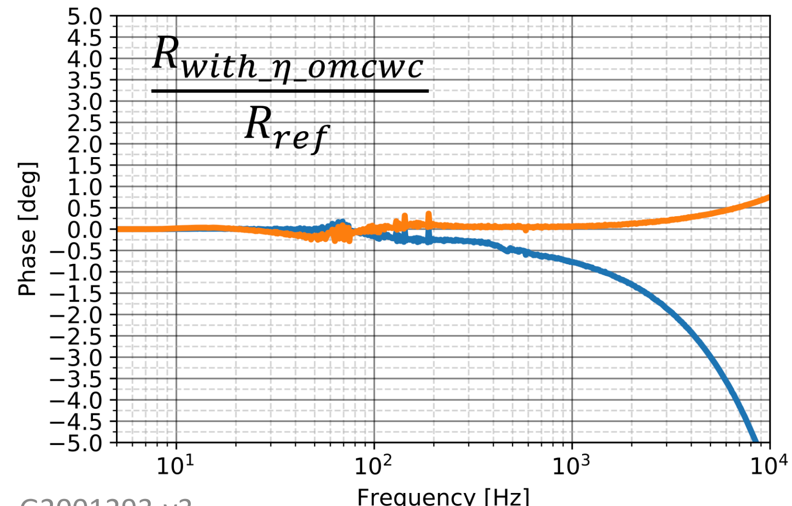
$$Range_{after} = \int \frac{f^{-\frac{7}{3}}}{\eta_R^2(f)\Delta L_{before}^2(f)} df$$

$$Range_{after} \propto \kappa_C^2 \; (when\ ADC \ll 1)$$

# But let’s get back to f_cc

- What happens when the response function changes at calibration line frequency?




From G2000527, Part II, slide 117, when we switch configurations from one whitening stages to one, the response function incurred the **blue** error.

Focus on ~410 Hz. We see a magnitude change of 0.001%, but a phase change of 0.5 deg.

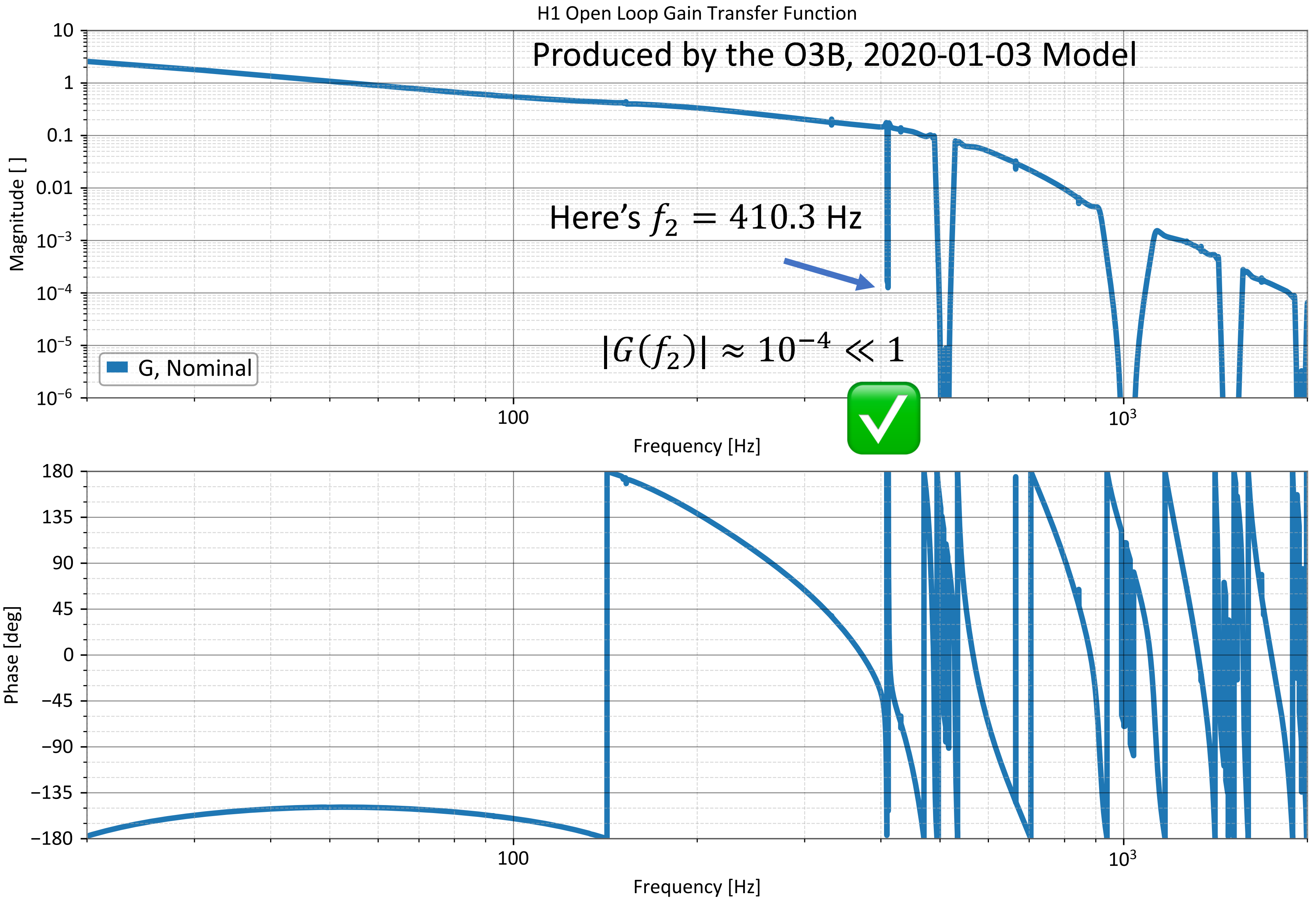
If the response phase changes by 0.5 degrees, then following the math of T1700106 (eq. 15) the value of

$$C(f_2,t) = \left(1 + G(f_2,t)\right)\frac{d_{err}(f_2,t)}{x_{PCAL}(f_2,t)} \approx \frac{d_{err}(f_2,t)}{x_{PCAL}(f_2,t)}$$

where we demand $G(f_2,t)$ with a notch filter, and thus

$$S_C(f_2,t) \equiv \frac{C(f_2,t)}{C_{res}} \approx \left(\frac{\kappa_C(t)}{1 + i\, {f_2}/{f_{cc}(t)}}\right)$$

# Just in case you need proof $G(f_2) \ll 1$



# OK, so let's reconcile some math

If the measured transfer function

$$\left(\frac{d_{err}(f_2,t)}{x_{PCAL}(f_2,t)}\right) = \frac{1}{R(f_2,t)} \approx C(f_2,t) \qquad (1)$$

and

$$S_C(f_2,t) \equiv \frac{C(f_2,t)}{C_{res}} \qquad (2)$$

then we know we're measuring

$$\left(\frac{d_{err}(f_2,t)}{x_{PCAL}(f_2,t)}\right)\frac{1}{C_{res}} = S_C(f_2,t) \equiv \frac{\kappa_C(t)}{1 + i\, {f_2}\big/{f_{cc}(t)}} \qquad (3)$$

and that means with the measured response function drops in phase, $S_C(f_2,t)$ phase goes up.

How does that translate to the estimate of $f_{cc}$?

Well, again from T1700106 (but now eq. 22) ,

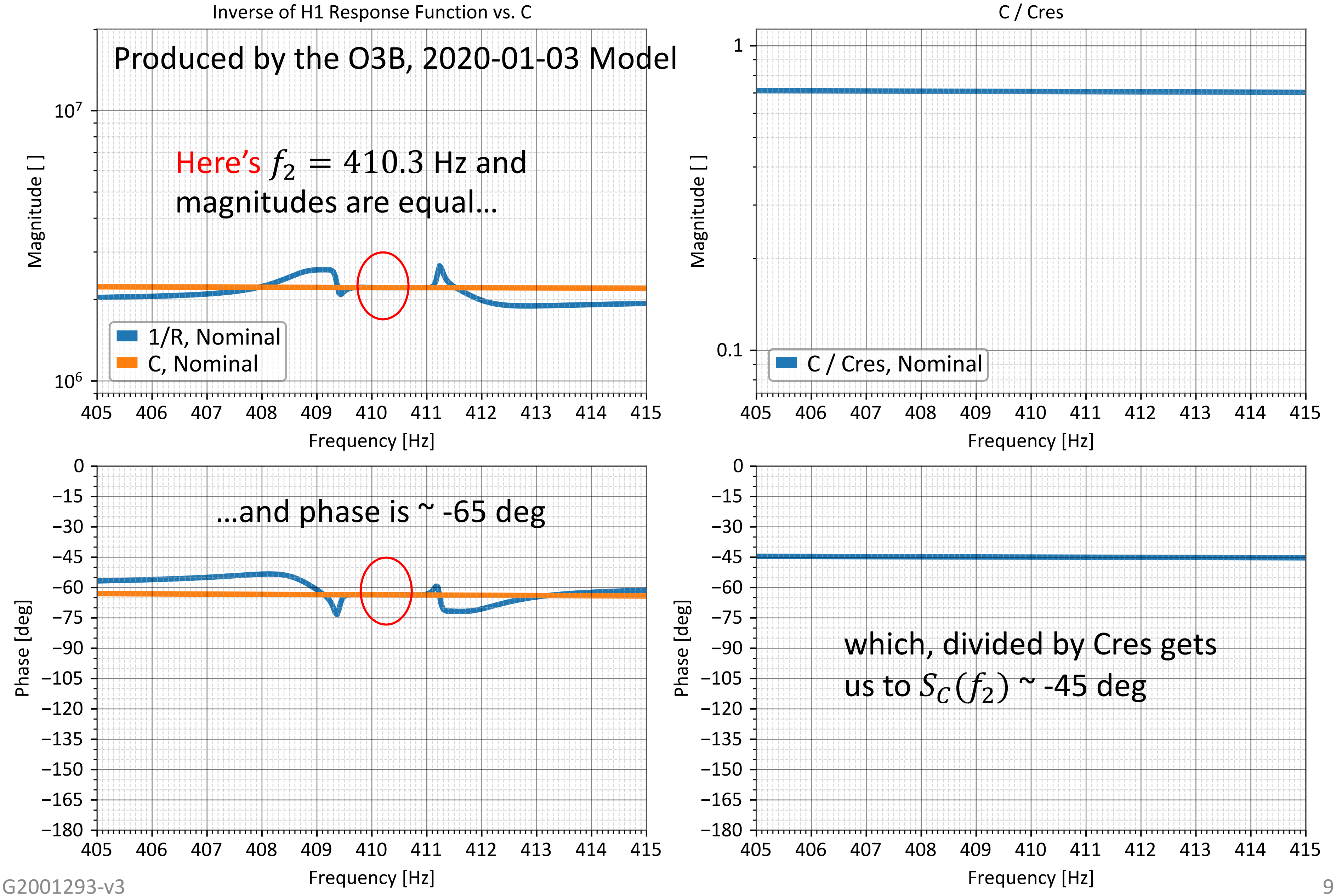
$$f_{cc} = -f_2 \frac{\Re e\big(S_C(f_2,t)\big)}{\Im m\big(S_C(f_2,t)\big)} = -f_2 \frac{|S_C(f_2,t)| \cos\left(\phi_{S_C}(f_2)\right)}{|S_C(f_2,t)| \sin\left(\phi_{S_C}(f_2)\right)} = -f_2 \frac{\cos\left(\phi_{S_C}(f_2)\right)}{\sin\left(\phi_{S_C}(f_2)\right)} \qquad (4)$$

which means

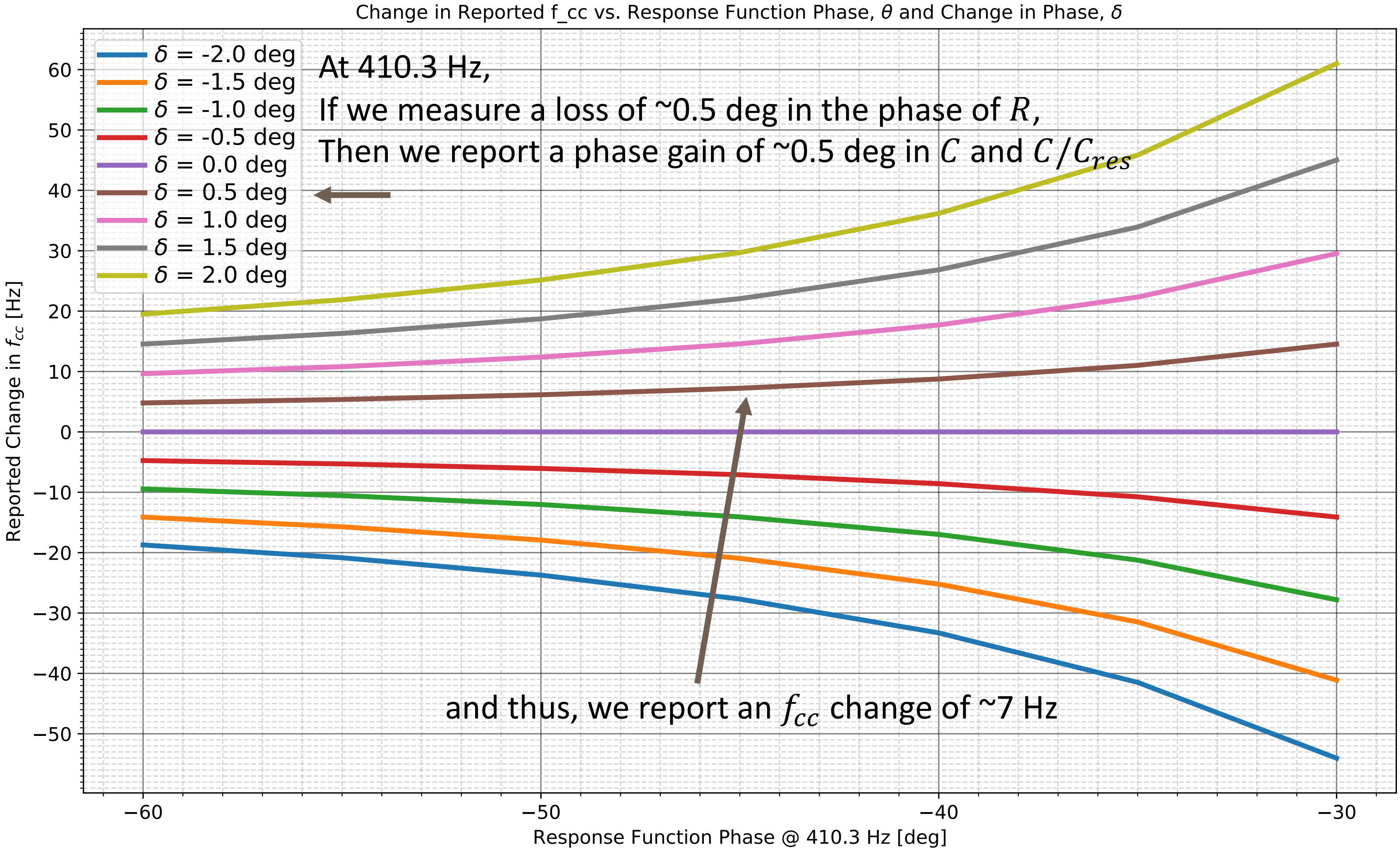
$$\Delta f_{cc} = f_{cc}^{After} - f_{cc}^{Before} = -f_2 \left[\frac{\cos\big(\phi_{S_C}(f_2) + \delta\big)}{\sin\big(\phi_{S_C}(f_2) + \delta\big)} - \frac{\cos\left(\phi_{S_C}(f_2)\right)}{\sin\left(\phi_{S_C}(f_2)\right)}\right] \qquad (5)$$

where $\delta$ is the measured phase change in $S_C(f_2,t)$.

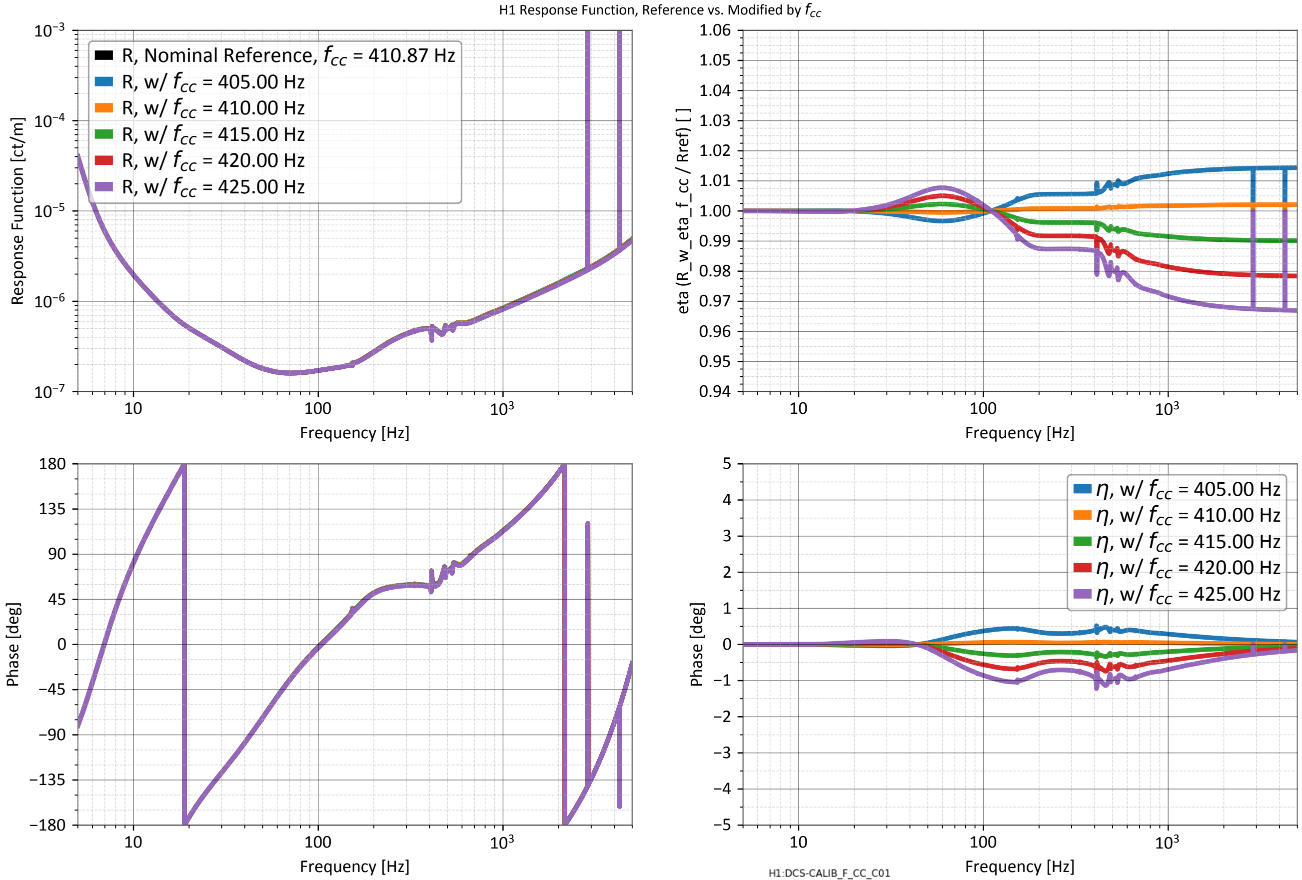
# In case you need proof $1/R = C$ at 410.3 Hz,



# Which gets us here.



# How does a change f_cc impact R?




$$\frac{\Delta L_{after}}{\Delta L_{before}} = \frac{R_{after}}{R_{before}} \equiv \eta_R$$

$$\eta_{f_{cc}} = \frac{(1 + if/f_{cc}^{ref})}{[1 + if/f_{cc}]}$$

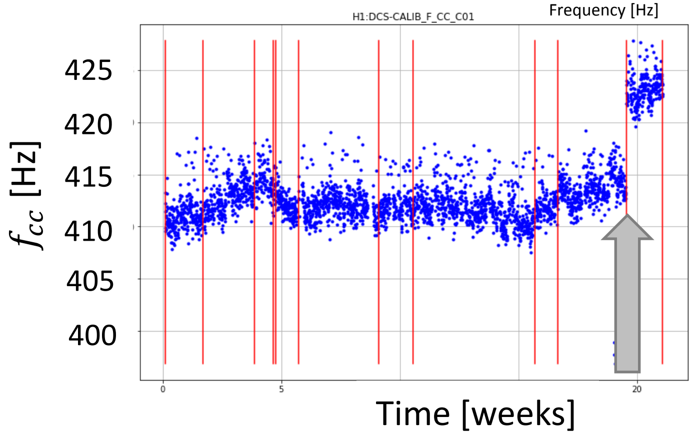
$$= \frac{\frac{1 + \eta_{f_{cc}} ADC}{\eta_{f_{cc}} C}}{\frac{1 + ADC}{C}}$$

$$= \frac{1 + \eta_{f_{cc}} ADC}{\eta_{f_{cc}}(1 + ADC)}$$

$$\eta_R = \frac{1}{(1 + ADC)}\left[\frac{1}{\eta_{f_{cc}}} + ADC\right]$$

$$\eta_R \propto \frac{1}{\eta_{f_{cc}}} \ (when\ ADC \ll 1)$$

Given that $f^{-7/3}$ weighting, the range drop was probably the $\kappa_C$ change

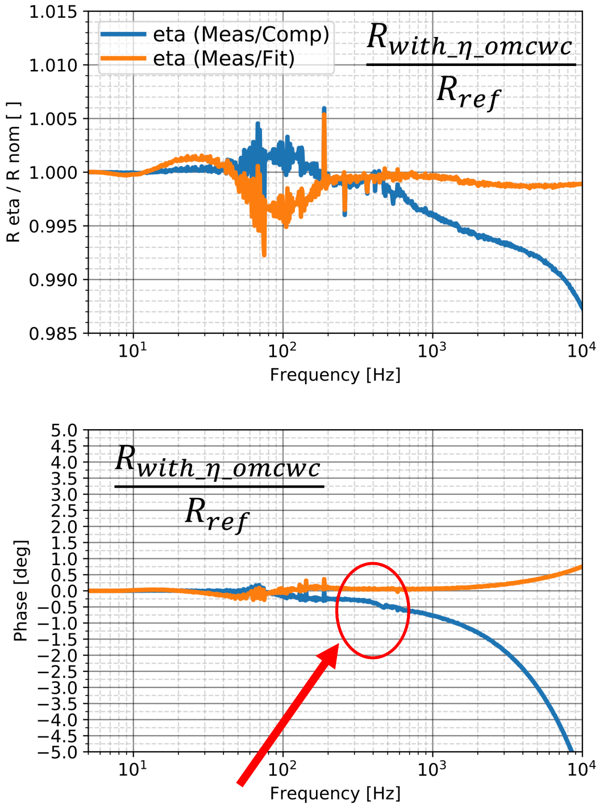



$$Range \propto \int \frac{f^{-\frac{7}{3}}}{\Delta L^2(f)} df$$

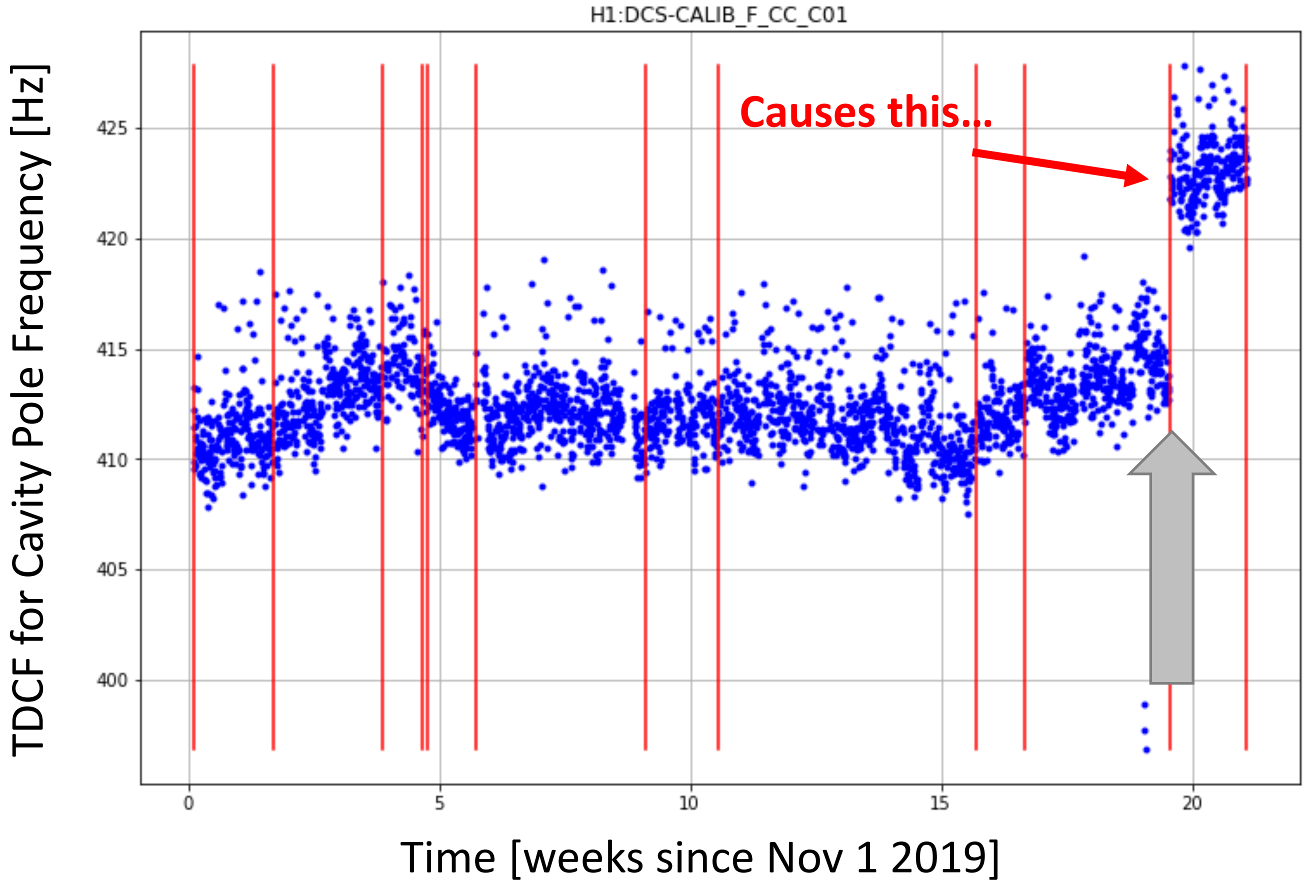
$$Range_{after} = \int \frac{f^{-\frac{7}{3}}}{\eta_R^2(f) \Delta L_{before}^2(f)} df$$

$$Range_{after} \propto \eta_{f_{cc}}^2 \ (when\ ADC \ll 1)$$

# Which is what I think happened here.




**This...**




Here we see a shift of ~415 to ~423 Hz, which is a change of 8 Hz.

Is this bad?

Do I think we need to do anything about it?

# (Ha! Math. Pff.) (But … Math?) (Oh wait – Maaaaath.✅)

On previous slides, we naively showed the impact of $\kappa_C$ and $f_{cc}$ independently had on the response function.

$$\eta_{f_{cc}} = \frac{(1 + if/f_{cc}^{ref})}{(1 + if/f_{cc})}$$

$$R_{after} = \frac{1 + \eta_{f_{cc}} ADC}{\eta_{f_{cc}} C}$$

$$\eta_R^{f_{cc}} = \frac{1 + \eta_{f_{cc}} ADC}{\eta_{f_{cc}}(1 + ADC)}$$

$$R_{after} = \frac{1 + \kappa_C ADC}{\kappa_C C}$$

$$\eta_R^{f_{cc}} = \frac{1 + \kappa_C ADC}{\kappa_C(1 + ADC)}$$

And in previous version of this talk, I naively thought "$\eta_R$"s should all be multiplicative, so if $\kappa_C$ and $f_{cc}$ both change, I should just be able to multiply them together,

$$\eta_R^{naive} = \eta_R^{f_{cc}}\, \eta_R^{f_{cc}}$$ (Ha! Math. Pff.)

But it turns out that's wrong. Why? Because of the dang "1 + blah" in the numerator of $R$, and that the modification is happening to $C$ not $R$.

$$R_{after} = \frac{1 + \kappa_C \eta_{f_{cc}} ADC}{\kappa_C \eta_{f_{cc}} C}$$

$$\eta_R^{better?} = \frac{1 + \kappa_C \eta_{f_{cc}} ADC}{\kappa_C \eta_{f_{cc}}(1 + ADC)} \neq \frac{1 + \eta_{f_{cc}} ADC}{\eta_{f_{cc}}(1 + ADC)} * \frac{1 + \kappa_C ADC}{\kappa_C(1 + ADC)}$$ (But … Math?)

# (Ha! Math. Pff.) (But … Math?) (Oh wait – Maaaaath.✅)

But even *this*,

$$\eta_R^{better?} = \frac{1 + \kappa_C \eta_{f_{cc}} ADC}{\kappa_C \eta_{f_{cc}} (1 + ADC)} \qquad \eta_{f_{cc}} = \frac{(1 + if/f_{cc}^{ref})}{(1 + if/f_{cc})}$$

is *still* not what's happening for our problem. In our problem, we've *already applied* an *incorrect* $\kappa'_C$ and $f'_{cc}$ to $C$ create h(t). We want to backout that incorrect $\kappa'_C$ and $f'_{cc}$, and apply a *correct* $\kappa_C$ and $f_{cc}$. Thus, we need to divide out the applied incorrect $\kappa'_C$ and $f'_{cc}$, and multiply in the correct $\kappa_C$ and $f_{cc}$, i.e.

$$R_{ref} = \frac{1+ADC}{C}$$

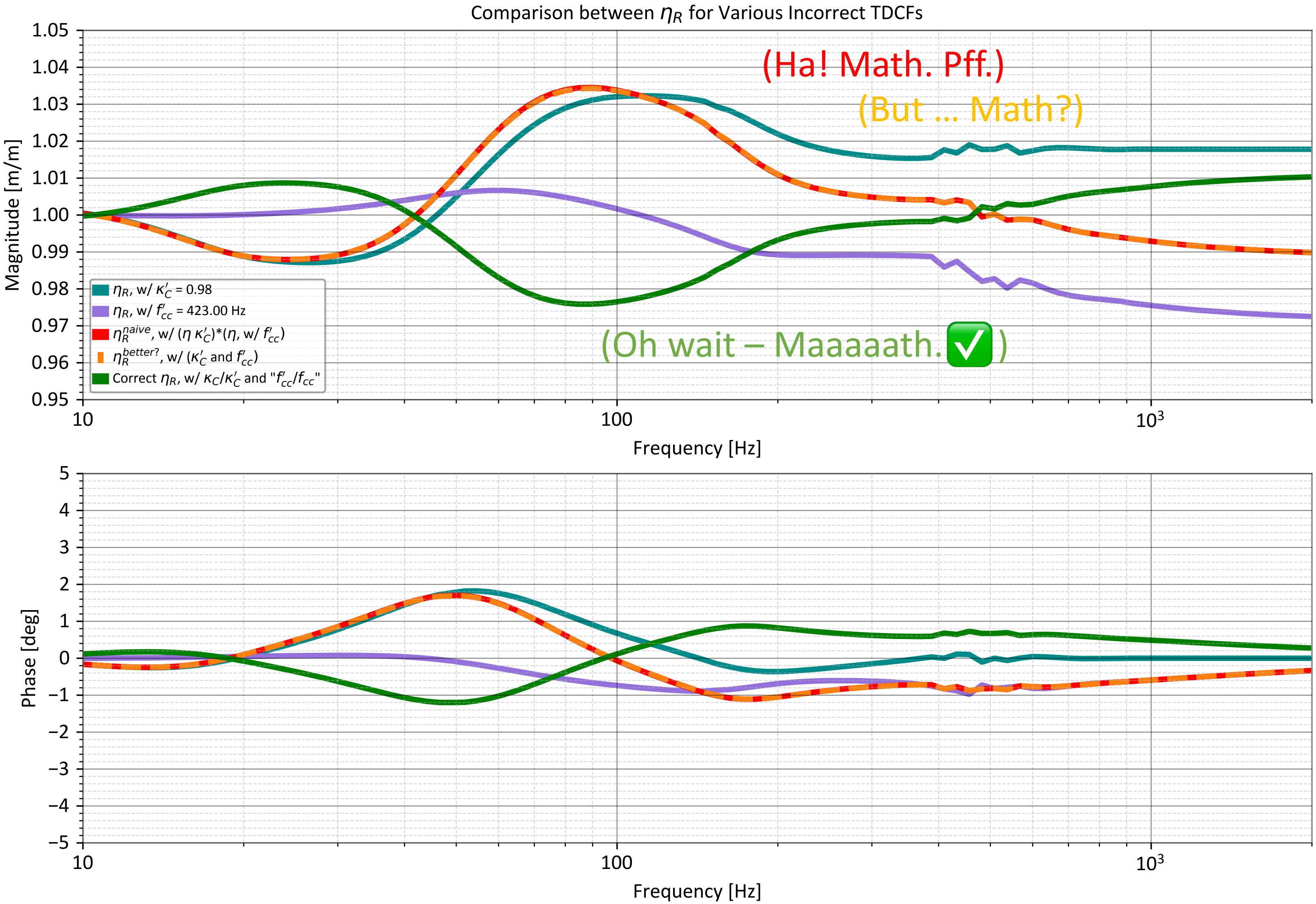
$$R_{incorrect} = \frac{1+\kappa'_C \frac{(1+if/f_{cc}^{ref})}{(1+if/f'_{cc})} ADC}{\kappa'_C \frac{(1+if/f_{cc}^{ref})}{(1+if/f'_{cc})} C}$$

$$R_{correct} = \frac{1+\frac{\kappa_C}{\kappa'_C}\frac{(1+if/f'_{cc})}{(1+if/f_{cc})} \kappa'_C \frac{(1+if/f_{cc}^{ref})}{(1+if/f'_{cc})} ADC}{\frac{\kappa_C}{\kappa'_C}\frac{(1+if/f'_{cc})}{(1+if/f_{cc})} \kappa'_C \frac{(1+if/f_{cc}^{ref})}{(1+if/f'_{cc})} C}$$

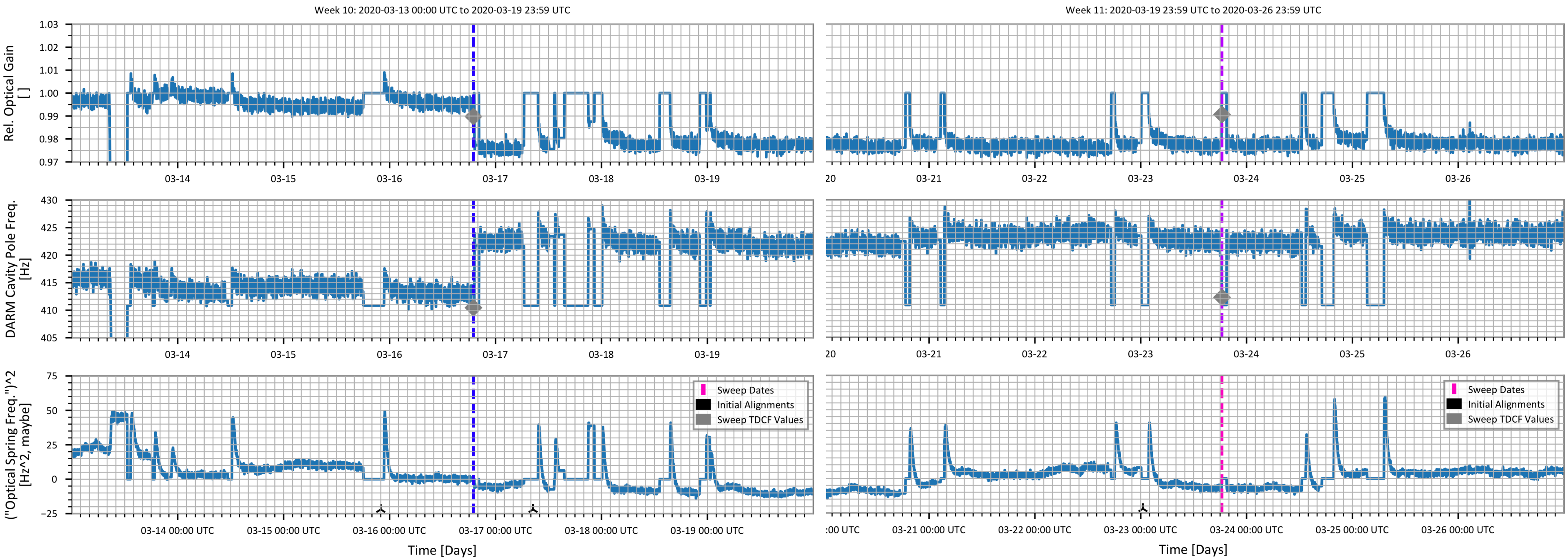
(Oh wait – Maaaaath.✅)

$$\eta_R^{TDCFs} \equiv \frac{R_{correct}}{R_{incorrect}} = \frac{1+\frac{\kappa_C}{\kappa'_C}\frac{(1+if/f'_{cc})}{(1+if/f_{cc})} \kappa'_C \frac{(1+if/f_{cc}^{ref})}{(1+if/f'_{cc})} ADC}{1+\kappa'_C \frac{(1+if/f_{cc}^{ref})}{(1+if/f'_{cc})} ADC} \frac{1}{\frac{\kappa_C (1+if/f'_{cc})}{\kappa'_C (1+if/f_{cc})}} = \frac{\left[\frac{1}{\kappa_C}\frac{(1+if/f_{cc})}{(1+if/f_{cc}^{ref})} + ADC\right]}{\left[\frac{1}{\kappa'_C}\frac{(1+if/f'_{cc})}{(1+if/f_{cc}^{ref})} + ADC\right]}$$

# Comparison between Naïve, Better? and Correct versions of $\eta_R$



# OK, so what values of $\kappa_C'$, $f_{cc}'$, $\kappa_C$, and $f_{cc}$?



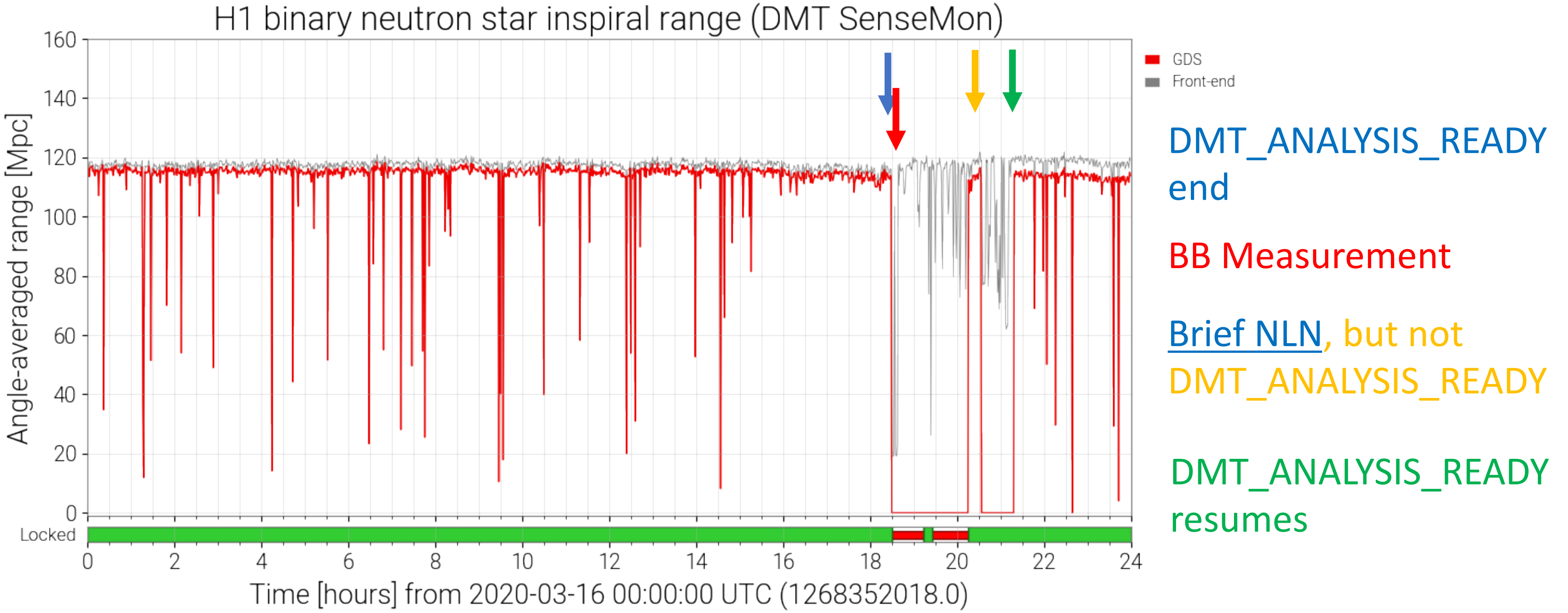

```
meas_kappaC = 0.995
meas_kappaCprime = 0.9825
meas_fcc = 413
meas_fccprime = 423
```

These are the numbers I gathered with an eye-ball average of the above trend plots we saw on slide 4.

- The prime values taken *after* the whitening change.
- The presumed correct values taken *before* the whitening change.

# And just one more thing…

Before we verify our predicted systematic error budget,
Let’s review what before vs. after broadband injection data is available (slide from G2000527)

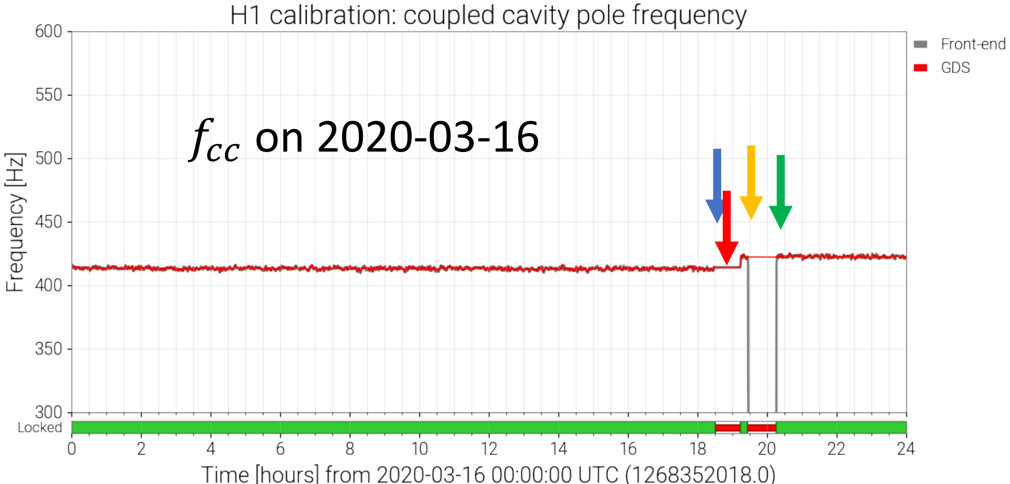


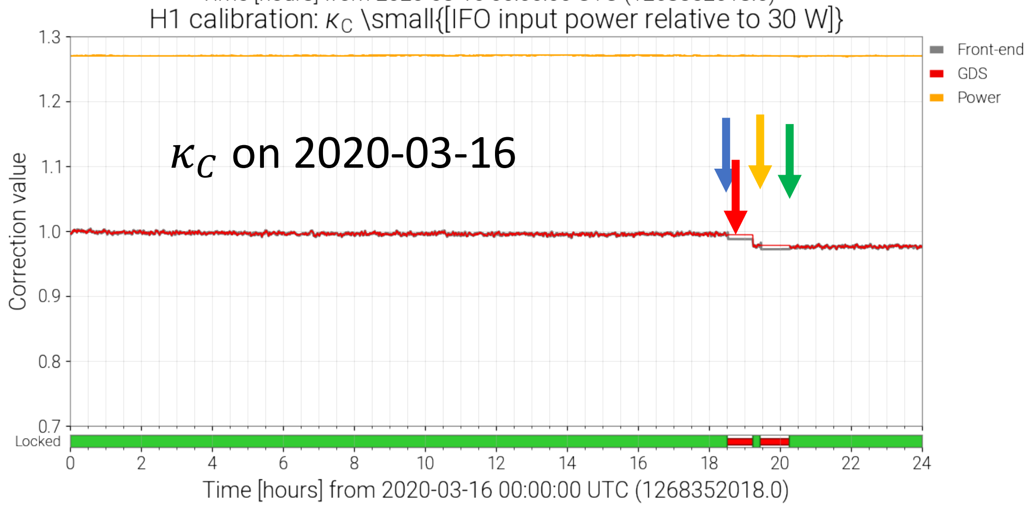

Detector was locked and happy for ~19 hours. Went out of OBS_READY at Mar 16 2020 18:29:59 UTC, switched whitening config, and measured broadband 30 seconds afterword.

- Pre
  - 2020-03-02_H1_PCALY2DARMTF_BB_3min.xml: 2020-03-02 19:00:32 UTC
  - 2020-03-09_H1_PCALY2DARMTF_BB_3min.xml: 2020-03-09 18:00:33 UTC
- Post
  - 2020-03-16_H1_PCALY2DARMTF_BB_3min.xml: 2020-03-16 18:30:31 UTC
  - 2020-03-23_H1_PCALY2DARMTF_BB_3min.xml: 2020-03-23 18:01:20 UTC

# And just one more thing.

But remember, that once we go out of observation ready mode and turn off the calibration lines, there're no TDCFs being measured. So, Aaron processes the BB injections with the DCS TDCFs from the observation ready stretch *right before* the BB injection.



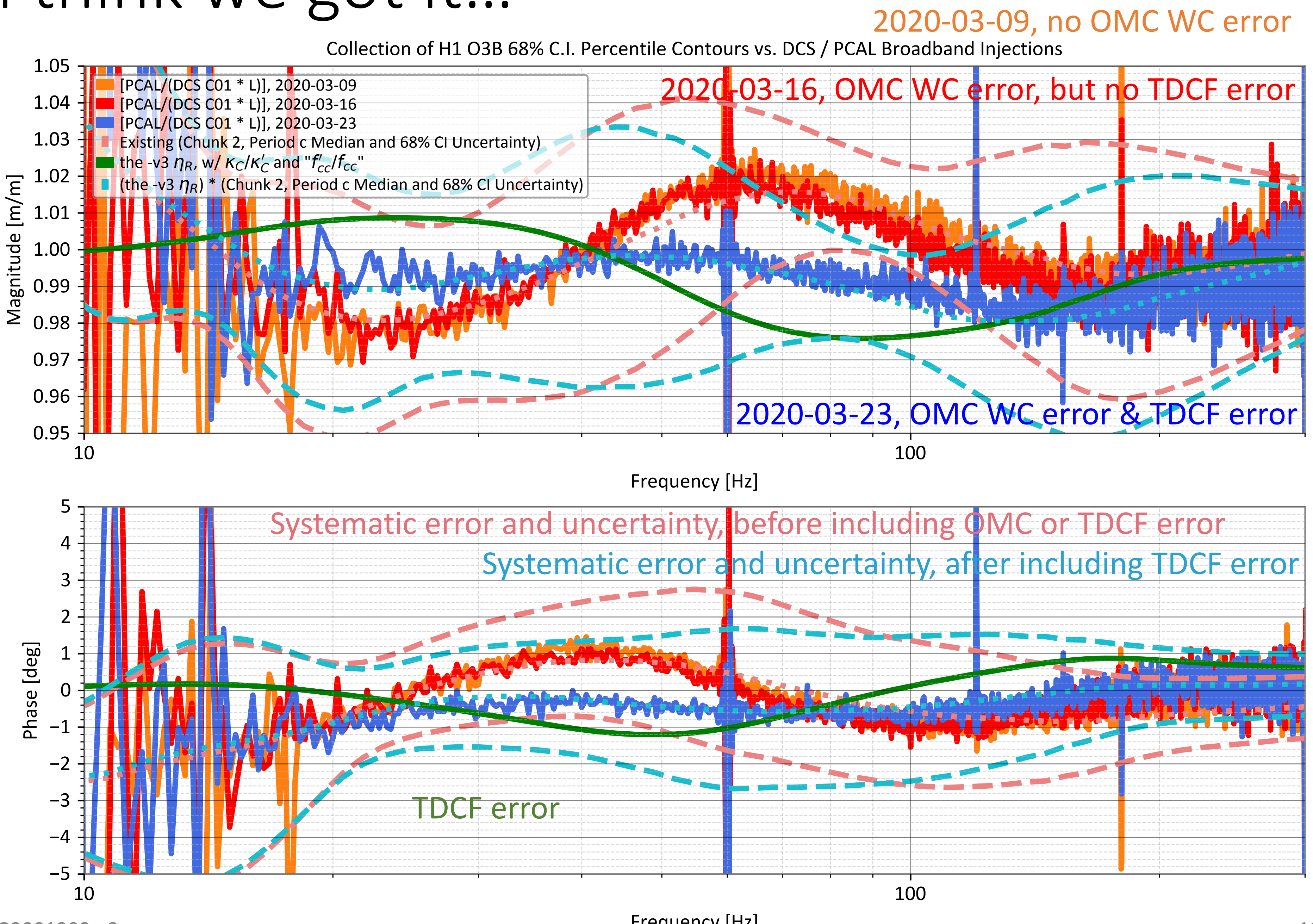

Why do I bring it up?

Because that means 2020-03-16 BB injection has the (small) whitening chassis error, but it does *not* have the error from the TDCFs

**This is why the 2020-03-23 BB injection looks so different from the 2020-03-16 injection.**

The 2020-03-23 measurement shows *both* the (small) whitening chassis error AND the error from applying incorrect TDCFS.

# I think we got it...



# In conclusion!

- From G2000527, we definitely need to update the OMC whitening filter compensation.
- Also from G2000527, we have an estimate of what $\eta_R^{OMCWC}$ should be (blue trace on slide 6 of this presentation).
- Now, we also have $\eta_R^{TDCFs}$ that is needed to correct for the collateral damage caused by the application of incorrectly estimated change in $\kappa_C'$ and $f_{cc}'$ that were a result of $\eta_R^{OMCWC}$
- We've verified that after $\eta_R^{TDCFs}$ (alone) are applied to the Chunk 2, Period c systematic error and uncertainty budget, the prediction agrees with the measured systematic error.
- For completeness, however, we will apply both the (negligible) $\eta_R^{OMCWC}$ and the (more impactful) $\eta_R^{TDCFs}$ to the Chunk 2, Period c systematic error and uncertainty budget.
    - (where the application of $\eta_R^{OMCWC}$ will mostly just account for the small amount of error above 1 kHz)