Editing the O3 Pcal paper incorporating all the comments/suggestions

We have listed the comments from all in a chronological order. The green text are the comments/suggestions we received. The black text is our response to the comments/suggestions.

Lilli (4/26/2020)

1. It might be helpful to provide a brief summary of the paper structure in introduction.

I think this could be added. We need to decide where. We need to make it easier for the reader to understand all these Greek letters too (Vlad's comment).

Added to the end of the Introduction section.

2. Page 5 - When optical loss \eta is defined, the value is estimated to be 1%-1.5%, which is not consistent with eq (4). I guess in eq (4), it is (1+\eta)?

This was a mistake and the wording of the sentence has been changed to address it. The sentence now reads. 'While the reflectivity of the ETM is greater than 0.9999, the anti-reflection coated vacuum windows and a number of relay mirrors located inside the vacuum envelope reduce the optical efficiency, η, between the transmitter and receiver modules to approximately 0.985 - 0.990, i.e. the overall optical loss is about 1.0 to 1.5 %.'

3. It seems that \rho_W and \rho_G are not defined, also in figure caption, different notations are used (\rho_WS and \rho_GS).

Changed to use only the former, not _GS and _WS. Defined the variables in text.

4. Some parameters have units, e.g., M, which are missing in the tables.

   Updated the tables to include units.

5. Maybe a sentence explaining the difference between Type A and Type B evaluations of uncertainties would be helpful.

   Included a footnote for this. Page 10.

Ethan (4/27/2020)

1. Affiliation be updated to "OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia"

   Affiliation updated.

2. The sentence "EP is supported by ARC CE170100004" be added to the acknowledgements section

   Acknowledgement added.

Vlad (4/27/2020)

1. Fig.2, UR and LR: "Relative variation" is not what I would use. I think it should say something like "Relative response discrepancy".

Changed to “Relative discrepancy”

2. Equations is Sec. 1.1 come from Sudarshan's thesis right? (reference 21 I think). There is no citations in this section.

It seems that you are referring to the equations that include the rotation effect. This equation, that includes rotation, was first written in our Pcal paper from 2009. It was (one of) Evan Goetz’s significant contributions to the Pcals as part of his dissertation work. See Eq. 9 in E. Goetz, et al., Precise Calibration of LIGO test mass actuators using photon radiation pressure, Classical Quantum Gravity, 26, 245011 (2009). Added citation in the line before equation 2.

3. Is the sigma value (0.99 10^-4) from Fig 3 used anywhere else? This is what I expect to be what describes WSH/GS reponsivity uncertainty.

   - I can't easily figure out what the comparable parameter is in the tables

No. Figure 3 is an example of what is possible using this setup. It is the result of 2800 measurements. Our typical measurement suite is only 100. Also, note that the data were “de-trended,” i.e. we removed a linear fit to the responsively vs. temperature plot.

It is the standard deviation of the suite of 2800 measurements. The value that describes the uncertainty in the WSH/GS responsivity, if just from this one suite of measurements, would be this sigma / sqrt (number of meas), i.e. the relative standard error on the mean. The standard errors on the means of the values in the measurement suites are the error bars in figures such as Fig. 5 (where the error bars are multiplied by 20 for visibility) in the paper.

These standard deviations don't appear in the tables, rather the U_rel, i.e. relative standard errors.

4. I am guessing Tables use a Type B (uniform) uncertainty for this? Surely this subplot illustrates a good case for replacing that uncertainty with a Type A, Gaussian uncertainty which should be better?

No. The statistical variation in the 100 samples from a typical responsivity ratio measurement inform the error bars in plots such as figure 5, lower panel. These error bars are ± standard error on the mean of the 100 measurements (typically). Note that the error bars in this plot have been expanded by a factor of 20 for visibility. We do use Type A for this kind of uncertainty estimate, see alpha_WG in Table 2.

5. Parameters in the many tables would be aided by saying what the parameter is.

- But this issue is fairly pervasive: Maybe better to have a table of parameters in the beginning of the paper, since there is just so many, but that might look clunky.

Agreed. We were running out of Greek letters, there are so many variables. We tried to introduce them methodically, saying in the text what each one is. But we may have missed one or two. We will look. We will also consider a table or appendix describing what the kinds of variables are: \rho, \alpha, \eta, \zeta, \xi, \gamma, \Chi, etc.

It is done.

6.The tables roll in so many parameters that contribute to each parameter in the table - perhaps that needs to be explained in the captions?

Decided to add an appendix with all the parameters and what they stand for.

7. I can't see why we'd use two sub-plots to show the same thing in Fig 5 - Surely just multiplying the uncertainties in the top plot and showing only that would suffice.

There are no uncertainties in the top plot, but maybe there should be. This seems to distract the reader. If the means in the top plot are weighted, then we should show the error bars (I think). Maybe multiply by 20 in that panel too. Sudarshan updating the plot.

The reason that we are showing both panels is to emphasize the step when the GS changed. We can consider removing this and just explaining in the text, but we thought showing this graphically, where one can see there is a very clear, and singular, step, of about 0.4% was helpful. We still feel this repetition is worth it given the value of emphasizing the step.

8. Section 3.1 (temperature section), and Fig 7: You are pointing out that each instrument seems to exhibit a different temperature gradient. I can't tell easily in the paper how impactful that is (variables are rolled into something else in table 3). Is the variability in the temperature dependences a big deal, or is this a super small contributing such that a factor that with 50% difference in temperature dependence slope is irrelevant compared to larger error sources?

Equations 12 and 13 give the equations for the factors in Table 3. Only two standards come into play - WS and GS, hence Figure 7. The temperature correction factors, required because of the dependencies seen in Figure 7 and because the NIST, Pcal lab, and end station temperatures different are +19 hop and -15 hop. So pretty significant contributions to uncertainty when our overall estimated uncertainty is 37 hop. However, in this case, the factors have opposite impacts, i.e. the product of the two is only 4 hop. But this would not necessarily be the case and we want to show the method for taking this kind of thing into account.

9. It's hard to tell there are two sub figures in Fig.8. Maybe add a pixel or two of white space between them.

Figure 8 is updated to incorporate it.

Jeff’s comments on v1, through section 2 (4/28/2020)

%%%%%%% Title: %%%%%%%

1.Huh! It doesn't mention "Photon Calibrator" or "via Photon Radiation Pressure" or anything like that.

We like this title, give that the scope is fiducial displacements in general.

%%%%%%% Abstract: %%%%%%%%%
2. Wasn't the PCAL from "the" PCAL paper already at a sub-percent accuracy?

Good point. Sentence change to start with “Developments in propatation …” and end with “... with improved accuracy,” rather than “...with sub-percent accuracy.”

3. "elements of the detector network" >> "elements" seems like not the right term for a part of a network, but ... could be OK.

Can’t think of a better word to use here. Is “component” better? Doesn’t seem so. Left it as is for now.

4. "Efforts within the national metrology institute community to...." >> save for later, see if there's actual content in the paper.

We’ll wait to hear the rest of your comments.

%%%%%%% Introduction: %%%%%%%%%
5. "...have detected gravitational waves with increasing frequency..." makes it sound like we're detecting less and less massive signals as time goes on. I know you mean the cadence of detection is increasing, but maybe a use a different word that the overloaded "frequency."

Updated sentence to begin with “As the rate of detections ….” and remove “frequency” from that sentence.

6. Perhaps in addition to citing lindblom, you also cite papers that are focused on limitations of calibration on parameter estimation of CBC detections,
[a] Vitale, Salvatore, et al. "Effect of calibration errors on Bayesian parameter estimation for gravitational wave signals from inspiral binary systems in the advanced detectors era." Physical Review D 85.6 (2012): 064034.
Or in short: Vitale S et al 2012 Phys. Rev. D 85 064034
<https://dcc.ligo.org/LIGO-P1100141>
[b] Abbott, Benjamin P., et al. "GW150914: First results from the search for binary black hole coalescence with Advanced LIGO." Physical Review D 93.12 (2016): 122003.
<https://dcc.ligo.org/LIGO-P1500269>
(we cite both of these papers in the O3A calibration systematic error paper when we try to make a similar statement.)

Thank you. We knew this was a weakness in the introduction. Citations added.

7. At the tail end of the second paragraph, it might be useful to discuss the "state of the art" in terms of interferometer calibration, since you mention that Lindblom suggests 0.5% accuracy is

needed, and resolving Hubble Constant tension needs 1% or better. Perhaps only one sentence is needed,
Something like "The detector network systematic error and uncertainty is complex-valued and frequency dependent, but in the ballpark of 5% / 3 deg, and limited its fundamental reference in the most sensitive frequency bands [c,d,e]."

We have addressed this in the summary and conclusions section, at the end.

[c] the LIGO O3A calibration paper
for now,
https://dcc.ligo.org/LIGO-P1900245,
but should have an arXiv number by the end of the week
[d] the VIRGO O3 paper,
@article{O3VirgoCalB:2019,
author = "Virgo Collaboration",
title = "{Virgo actuator and sensing calibration for O3 , Virgo h(t) reconstruction and uncertainties}",
journal = "In preparation",

8. The introduction seems to "dive right in" with out the traditional summary of the paper.

Lilli also suggested this. I (Rick) don't think this "traditional" summary, is very nice. But we are planning to add a couple of sentences at the end of the introduction section.

Roadmap paragraph added at the end of Introduction section.

9. Also, no citation of previous Pcal papers?
For example, before Equation (1), (or after), you can introduce that the LIGO Pcals have a periscope that ensures theta is the *only* angle you need to consider, because the PCAL is transmitted to and reflected from the test mass in the XY plane of the detector -- and cite the Pcal paper just prior to this one.
I see you wait until a tiny footnote to cite the iLIGO era PCAL paper…

We have now cited: the RSI paper (first introduciton of Pcals), the 2012 Pcal paper (footnote regarding two beams together with Hild local deformation paper). Also, Virgo Pcal paper, Kagra Pcal (and Ncal) paper and GEO 600 Pcal papers.

Don't think we need a reference for the angle of incidence.

Sudarshan will take care of this.
10. I really like figures 1 and 2!!
Figure 1 is a great concatenation of two diagrams, and I'm so very happy to see S(w) so clearly shown and in detail in Figure 2. Well done!

Thanks. We have the creator of the "subway" map as our graphic consultant.

11. Why quote the units of R(w) when comparing against 1/(Iw^2)? You didn't when you compared S(w) to 1/(Mw^2)?

Added the units to S(w).

12. You're quoting that both S(w) and R(w) have a minus sign in the text before equation 2 (I think because of the "above its fundamental resonance frequency, the force-to-displacement transfer function falls to 180 deg"). But equation 2 subs in for S(w) and R(w) without including that minus sign in the approximate version.
I don't have a preference for including or excluding the minus sign, but these two should be consistent.

This was an oversight. Added the minus sign to equation 2 and subsequent relevant equations.

13. It seems like equation 3 is redundant with the approximate version of equation (2), given the only difference is pulling the M out of the brackets. And one can do that without needing to know the details discussed in between about not knowing \vec{a}.

It is true, we could avoid equation 3 by pulling the 1/ M outside the bracket in the the second line in equation 2. We have done this to emphasize that, at least for now, we don't know the details of the rotation (don't know the Pcal beam offset), so treat it as an uncertainty.

14. Speaking of \vec{a} (and if you decide to keep this detail in the intro, instead of saving it for section 3.2), don't we also not know \vec{b}? I'm confused as to why this makes a difference in how Eq. (2) is re-written.

We do know vec{b} from the dither measurements. But we don't know the magnitude or sign of vec{a}. Equation 3 is written as [1 + uncertainty]. Can't do this with [1/M + uncertainty].

%%%%%%% Methodology: %%%%%%%%

::: 2.1 :::::
15. Here, you're starting to use the overloaded word "calibrated" and "calibrating" as a verb on what to do to a power sensor, but don't really define it until a paragraph later, and in that definition you use Figure 1. I would either define it or swap it out with a process description and I prefer ending up using a different word that "to calibrate" but if you do, then use that word to indicate that specific process, and *only* that process, throughout the paper.
My guess, is that you mean "the process of interpreting the voltage that comes out of the transimpedance amplifier as something physical, by multiplying that voltage by a ct/V number [as you'll describe later], a W/V number [transferred from what you originally get from NIST, as in Figure 1, which you later call "responsivity"], and then N/W [as described in Eq 1, and later call "Force coefficients"], and then N/m [as described in Eq 2 or 3 by S(w) + R(w)(a.b)]."
A clear sentence (likely more clear than my suggestion) on this would be helpful.

Lots of subtle issues co-mingled here. First, we are exclusively using "factors" rather than "coefficients" in response to a comment from John Lehman. Second, we do purposely say "calibration" for what we do to the WSs and the Rx detectors. Then, we do purposely, in places,

use calibration for what we do when we apply the displacement calibration factors to the Rx detector outputs.

So I think we are okay here.

16. you're quoting 0.9999 as the reflectivity of the ETM. I'd clarify whether that's power or amplitude reflectivity (unless you think it's obvious in context). Just the extra word, "While the *power* reflectivity of the ETM" or "While the amplitude reflectivity of the ETM"

Added “power” for clarification.

17. Discussion of the relay mirrors, the vacuum system... all of this could use the citation to the aLIGO PCAL paper…

Added citation to RS paper after “envelope.”

18. The motivation for preferring for the RX module is muddled. Rather than improve it with more technical details, would you consider just removing this sentence? The rest of this section (and most of the paper, really) is agnostic and describes both Rx and Tx with equal footing.

We have concrete reasons for preferring Rx over Tx. Rx and Tx are not on equal footing in the paper or in reality. We have minimized the role of the Tx detector in the paper and focused on the Rx detector. We think this is balanced the way we want it now.

Rick to reword sentence.

19. In equation (6), you're introducing that d's and F have frequency dependence. Do they? If so, motivate with a descriptive sentence.

These vary with time. They can be transposed into the frequency domain, in which they can and do have frequency dependence.
Equation 6 (now equation 5) follows from equation 1, intentionally written in the frequency domain.

20. Maybe it's discussed later, but you don't mention the digital signal processing of the d's at all. The AA filters at least are important to account for, and it may be worth mentioning that the transimpedance amps are frequency independent out to "ww" frequency.
But maybe you're trying to restrict the discussion here to the "simple parts" of the frequency region, i.e. ~20 Hz to ~1 kHz where the process is all frequency independent?
Dunno
>> I'll check back in on this later.

Seems an unnecessary complication for this paper. It is discussed in the RSI Pcal paper. Not something we want to focus on in this paper.

21. Equation (8) switches to (f) to indicate "as a function of frequency," but up until now, it's been (w). Why the switch?

We are considering sticking with omega throughout the paper. We don't really capitalize on the simplicity of factors being easily defined and identified at 1 Hz, then falling as 1/f^2 in this paper anyway. We switched to \omega exclusively and think it simplifies the equations. Thank you for the suggestion.

22. The parenthetical call out of units are good. However, it starts to get messy with the displacement coefficients before Eq. (9). Maybe switch to a more standard convention of units, e.g. what NIST does,
<https://physics.nist.gov/cuu/Units/checklist.html>
<https://physics.nist.gov/cuu/pdf/sp811.pdf>

We (think we) are following these guidelines, but we need to remain vigilant.

23. Right after equation (9), "The Pcal systems at both end station [...]" >> "The Pcal systems at both end stations [...]"

Fixed.

23a. Interesting introduction of the comparison between X and Y.... I know you must, but the discussion and definition seem a bit rushed. I don't have a better suggestion!

We have elaborated and clarified (we think).

:::: 2.2 :::::
24. Big picture: I think think this section might be better if the content were re-ordered in the following:
- Description of what it means to transfer the responsivity from the GS to the WS and then to the end station.
Then, focus on the GS / WS transfer
- Description of the basics of the GS/WS transfer setup up, and mention that the set up is motivated by canceling out the beam splitter ratio
- Discussion of all systematic error at once (laser speckle, lab temperature, etc.)
- Then, presentation of the results.
Then, focus on the WS / RX or TX transfer measurement
Then, focus on how all standards are combined, and the systematic error that can creep in there (differing ADC gains, the temperature difference between labs)

We decided to do methodology first in section 2, then measurements and results in section 3. We could reconsider, but it would mean dragging the reader through all the results before explaining how all the factors and coefficients fit together. We think we prefer the way we have it now. Let's see after we implement some other suggestions and clarifying changes.

25. The mention of what type of PD all the sensors are is a bit distracting, and you're bouncing around between describing the GS/WS setup, and talking about the systematic errors within it. The above re-order would have a nice logic flow.

We have eliminated some of the technical details in order not to distract the reader. We refer to the RSI paper for details.

26. Seems like this discussion of transferring the GS W/V number should come much sooner... see comment at the top of 2.1…

Need to try to understand this more clearly.

27. The description of the transfer standards and the Rx PDs seem to exclude the Tx PD, but then there's no description of the Tx PD. Add a sentence?
("Maybe this is why you said the Rx module is preferred?" the reader is left guessing...)

The Tx PDs are not really relevant. We could say what they are (2" integrating spheres), maybe in a footnote if we think the readers will really be interested in these.

28. Second sentence of second paragraph, "LHO" is not defined anywhere.

It is defined in the first paragraph of section 2.2

29. Let me know if you need to make all the technical notes you reference Public (if they're not already).

Thank you for your help with this. We will check one last time before submitting.

30. The transmitter module hasn't been described yet in this paper. A citation to the aLIGO paper or a redescription is needed before discussion here. Alternatively, you can just dump the fact that it's a spare Tx module, and just refer to it as "an independent, intensity stabilized laser"

Citation to RSI Pcal paper added.

31. The cartoon in Figure 3 doesn't show two beams coming out of the transmitter module, it just shows a laser. Is one beam dumped?

Cartoon in Fig 3 is a cartoon. Doesn't even show the Tx module. It is intended to show the process of taking two beams downstream of a BS. We have noted that the BS is inside the Tx module elsewhere in the paper.

32. "Point by point division of the recorded voltages [...]" you've not described if the record is digital or analog, what method is used for recording, anything. I'm also not sure what "point-by-point" means here in this context.

How they are recorded is not relevant here, we think. They are digital, of course. Are you thinking of magnetic tape or something like that? By point-by-point, we mean that we divide the first (of five) points in one time series with the first point in the other time series, then to on to the second points, etc. This rather than taking the mean of each time series and dividing those.

Point-by-point replaced with “simultaneous.”

The next paragraph *seems* to describe the process you actually do, so maybe jut dump this? It's still worth describing the readout system (unless you prefer to defer to T2000182, which is also fine -- as long as it's described in there)
I see that you describe the digital voltmeter readout later in the *end station* calibration paragraph... (see above comments about re-ordering the section).

Not sure what to do here.

33. Do the *integrating spheres* exhibit laser speckle? Or are you just mentioning that they're sensitive to it?

Laser speckle is caused by the scattering of coherent light inside the sphere. So in that sense the spheres and the light cause it.

34. "*the* digital acquisition system" -- *I* know you mean the LIGO DAQ, but the reader's don't at this point, since you haven't mentioned the DAQ in section 2.1, nor anything in the GS/WS setup discussion. Two good citations for the LIGO DAQ, when you need 'em is.
<https://dcc.ligo.org/LIGO-P2000107>
<https://dcc.ligo.org/LIGO-P1100052>

Let’s add a citation when we discuss the WS using the ADC of the DAQ at the end station.

Added citation for the first reference suggested above.

4/29/20 Shivaraj’s comments

1 Introduction:
(i) The statement about detection by Lindblom could be modified/softened. This is a old paper, now that we have many confirmed detections these numbers have to checked with observations. For example, in O3A calibration paper we quote max magnitude uncertainties to be 6-7 % for some epochs while in the current Pcal paper we say, according to Lindbolm, the accuracy should be 5% for detections. However we have confirmed detections in O3. The 5% cannot be a blanket requirement for detection (for example, even if the absolute accuracy is off by 50% we could still make detection, only our distance estimate will be bad).
The necessity of 0.5% for parameter estimation is fine to quote. This is close to what we claim for correctly establishing the value of Hubble constant.

Removed the reference to accuracy required for detection (“5\,\% calibration accuracy would be required for confident detection of gravitational waves and”).

(ii) Figure 2, UL and LL plot ranges could be upto 100 Hz. With the current detectors we are not making any calibration claim below 20 Hz, so it would be good to show the interested region of > 20 Hz. This will also match with the plots on the right.

We want to show that these suspended optics actually behave as one would expect - resonances, etc. (in the left panels), while the “free mass” responses don’t have these resonances. We have edited the caption to say, “Above 20 Hz, in the LIGO detection band, the force-to-displacement discrepancy …” .

(iii) A minus sign in equation (2) might be appropriate.

Indeed. Thank you. We actually missed the minus sign in several places”
Second line in equation 2, equation 3, equation 8.

2.1 Calculation of force and displacement coefficients:

(iv) On page 5, first and second line use 'Rx' and 'Tx' without latex format, to be consistent with later use.

Here, where we are introducing the Tx and Rx terminology, we want the italics for emphasis. But we are changing it elsewhere in the text to rm rather than math rm.

(v) In equation (4) it seems \eta is used as optical efficiency (a number close to one) while in the paragraph before the equation it is mentioned as optical loss (a number close to zero).

We had a mistake and fixed that sentence in response to a comment from Lilli. We have changed “optical loss” to “optical efficiency” in other places in the document to try not to confuse the reader.

Also if \eta is optical efficiency, is the equation(4) consistent? For example, if P_R' is the true power reflecting off of ETM so it has be to larger than measured P_R because some power is absorbed on the way to RX PD. However optical efficiency is a number that is less than or equal to one which means P_R' will be less or equal to P_R which is the opposite of what we want. Similar argument for P_T.

This is embarrassing. Guess we have been looking at these equations for too long. You are right. Both equations 4 and 7 have been edited to correct this mistake. Thanks for catching this!

(vi) "the reflectivity of the beamsplitter that generates" -> "the reflectivity of the small beamsplitter in transmitter module that generates". We haven't provided a full picture of the system (or a figure of it), so it would be good to be explicit in details.

Good point. We added “inside the transmitter module” to that sentence.

(vii) In "weighted geometric mean of 1 and \Xi_{XY}", what is the weight used for '1'? And Why are we using 'geometric mean' instead of 'arithmetic mean'?

This is now addressed directly in the text.

2.2 Calibration of power sensors

(viii) In Figure 3, do the UR and LR plots use different data sets? The UR plots the values are in the range of 0.95 while in LR plot the values are in 0.91 range. Also is the sampling rate 1Hz?

Yes, the UR plot has the means of five ratios of output voltages for each component of the measurements (A-B or B-A). Then, in the LR panel, those multiplied by each other, one A-B multiplied by the subsequent B-A, then we take the square root. So we don’t expect the means to be the same (the BS ratio is not exactly unity and the responsivities of the two detectors are not identical). Yes, the sampling rate is 1 Hz. but these data are plotted every 20 seconds (the length of one measurement suite (5 seconds to measure, the 5 seconds to swap, 5 more seconds to measure, then swap back to original positions).
Summary:

(ix) "The estimated systematic uncertainties ..." -> "In some frequency bands, the estimated systematic uncertainties".

Changed as suggested.

(x) In the summary section, there is mention of uncertainties due to elastic deformation. Maybe it would be useful to mention that the uncertainty due to elastic deformation will need to be considered seriously if we want to calibrate the detectors beyond a few kHz region.

Done. We decided to take out the part on bulk deformation.

Overall comments:

(xi) There is no overall uncertainty budget and hence it is hard for a reader to judge which effect is significant and which is not. Also currently are we including the temperature corrections or are we just telling that such effect exist? And when we include difference between two end station Pcal calibration how are we making sure that we are not double counting rotational effects that could produce such difference but also separately included in the uncertainty budget?

Tables have been re-organized and re-considered. We think they highlight major contributors now. We are pretty confident that we are not double counting. We have tried to explain explicitly how uncertainties are calculated.

(xii) The tables could have some description of the parameters along with the letters representing the parameters. Also alignments in some tables are not consistent.

We have revised the tables. We are planning to add an appendix explaining what all the parameters are.

4/29/20 Rick's comments on v1, through section 2

1. Second line:write out Laser Interferometer …. (LIGO)
   Done. In a footnote. Need to change to numbered footnote.
2. Define Pcal acronym in the abstract, then remove from intro.
   Done in abstract. Just "photon calibrators" used in intro.
3. With increasing frequency -> … The rate of detections by the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo Observatories has increased, yielding …. Maybe put the "Laser Interferom ….. Observatory" in a footnote.
   Done
4. Is citation 2 properly placed?
   It is now.
5. Fig 1 caption: space between standards and (WS)
   Done.
6. Lindblom reference: Omit part about 5% being required for detection. See Kissel and Shivaraj comments. Maybe update references here.
   First part done.
   See Jeff's suggestions. Additional reference added.
7. Shown in figure 1 -> shown schematically in figure 1.
   Sentence okay as is.

8. Magnitudes of the laser power modulations -> amplitudes of the modulated laser power.
   Done.
9. By the free-mass response -> by the response of a free mass.
   Done
10. Give units for S(w), as we do for R(w)
    Done.
11. Cite early LIGO Pcal paper (Goetz et al.) maybe after \vec{b} in the text
    We are citing the paper before equation 2.
12. Second place “the free-mass response” -> the response of a free mass
    Done.
13. Change variables in text, such as P_T and P_R to rm instead of math rm
    Need to do this for all variables, check tables too. Not sure what to do: math rm or rm?
14. Remove comma between atmosphere and enable
    Done.
15. Estimates of losses -> estimates of optical efficiencies ?
    Done
16. Do d_r and d_t stay in math rm because they are signals?
    Not sure what to do here. Yes, according to NIST link that jeff shared.
17. All of the reflected power -> almost all of the reflected power
    Done.
18. (Ct/W) -> ct W^-1 (use \SI) if we can. May not understand ct.
    Had trouble with \SI package. For now updated to ct W^-1
19. (N/ct) -> N ct^-1
    Had trouble with \SI package. For now updated to ct W^-1
20. Change “coefficients” to “calibration factors” everywhere ?? Need to think about this.
    Done.
21. Need minus sign in second term of Eq. 2 and in Eq. 3. Also eq. 8 and 9??
    Done.
22. (M/s^2ct) -> m s^-2 ct -1
    Done.
23. Provides a comparison Could be stronger, e.g. directly compares or something like that.
    Changed to “directly measures the ratio of the calibrations …”
24. Is FFT used after it is defined? If not, remove (FFT)
    Yes, we use it
25. Weighted geometric mean. Is it really weighted? I recall it is. As Shivaraj points out, what is the weighting for 1? We need to focus on this key (and new) section to get the wording right.
    Done
26. Minus signs in Eq. 10? Displacement in opposite direction of forces
    Don’t need it because it is explicitly written in earlier equations 2,3,8.
27. Section 2.2 GS and WS already defined.
    Okay as is. Defined in caption of figure 1 to refer to labeled items in figure.

28. (W/V) -> W V-1 not math rm
    Fixed it.
29. WSs are -> WS is (maybe)
    Changed text to eliminate this issue - need for plural of acronym.
30. No hyphens in 4-in-diameter according to guidelines. Maybe change wording to avoid compound adjective. Same for 3-mm-diameter.
    Both compound adjectives removed.
31. Too many periods in LHO.[16].
    Fixed.
32. Using a spare … sentence could be rewritten
    Sentence rewritten. Broken into two sentences.
33. 5-sec-long Re-word to eliminate compound adjective also 20-sec-long, 9-hour-long
    Hyphens removed.
34. Slight variation -> can we be more specific? Ask Niko how much trend was removed, i.e. how much the temperature changed. Reword sentence.
    Details of the “slight variation” added.
35. Ct/V after \zeta_W needs to be changed to ct V^-1
    Done.
36. Total optical losses -> total optical efficiency
    Fixed.
37. Calibrations of the Pcal end station sensors -> measured responsivities of the Pcal end station sensors
    Need to consider in light of J. Kissel’s comment about not using “calibration” too liberally.
    Decided that “calibration” is what we do and what we want.
38. In-line \rho/\rho_0 equation. Should we have (T) on the left side?
    Changed to add temperature dependence on left side and made expressed equation, rather than in-line.
39. These temperature correction factors -> these responsivity correction factors due to temperature differences
    Changed to “These temperature-related correction factors …”
40. In section 2, where we mention \eta_R, cite section 3 where \eta_R is calculated.
    Dripta fixed.
41. I (Rick) added the the following two sentences to the abstract (see below). This partly in response to questions regarding the “goal” or “purpose” of this document. I consider this to be:
    a. Reporting on the current state of the art in providing displacement fiducials (absolute calibration) of a GW detector, including a factor of two reduction in the lowest uncertainty reported (0.75 % in the RSI paper) and improved methods and confidence in results (from, for instance, combining both end stations.
    b. Giving experts, those working on other GW detectors, for example, details of the methods we have applied and the results we have obtained.

c. Giving the results of our investigations into the EUROMET study and what is being done to address related issues.

Here are the two sentences (maybe need a bit ot tweaking): Estimated uncertainties are a factor of two smaller than the lowest values previously reported. This is partly due improvements in methodology that have significantly increased confidence in the results reported.

May need to echo this in the summary section.

J Kissel second part of comments (4/29/2020)

%%%%%%% Section 3: Measurement Results: %%%%%%%%

- GENERAL PAPER COMMENT: Now that I'm seeing the language throughout the paper, my comment about using the term "calibrating" now becomes a more general comment. The verb "calibrate" has been used to mean a lot of things through out the paper, and it would be much better if we switched to more explicit, less overloaded terms, like "transfer of power responsivity" or "interpreting voltage as force" or "estimating displacement" or "the complete process of estimating displacement from digital counts" ... that kind of thing.

Yes, “calibration” appears many times in this document. There are two key types of calibration: calibration of the interferometers and calibration of the Pcal end station power standards. When we “transfer” the GS calibration from NIST to the WS then to the end station Rx sensors, we are “calibrating them.” We have considered, and may soon start, adding stickers to them that state their calibration (in V/W or in ct/W). In fact, we propose that we calibrate them with about 10x better stated uncertainty than Ophir calibrates our laser power meters (using procedures similar to ours, using a “reference standard” that NIST calibrates for them annually). Except for this ambiguity between “interferometer” and “Pcal fiducial” calibration, which we strive to minimize, I don’t perceive the “overloaded” nature of its use (or misuse). Maybe you can explain further with examples, if you don’t mind.

We think the text reads better and is clearer in this regard now.

- Since section 2 introduced a *LOT* of variables, I think it would be helpful for the caption of table 1 to remind the reader that Force Coefficients are \Gamma, uncorrected displacement coefficients are X_{_R}, the weighting factor for X vs. Y is C, corrected force coefficients are X_{_R}^{c}, and you've only shown the RX pd, and thus the subscript {_R}. Also, the test mass mass, M should have units of kg associated with it, the Force coefficients \Gamma should have units of N.ct^{-1}, and displacement coefficients X should have units of m.N^{-1}.

Tables updated. Parameter table in Appendix is going to be added.

- The sentence "The GS and WS power standards [...]" and the following few *paragraphs* feels like it should be introduced much earlier in the paper, especially if you go further with a recap of the system design and/or summarize the aLIGO PCAL paper (P1500249). It's almost like section 2.2 should be *after* these paragraphs.
Sections 2 and 3 were reorganized, hopefully they are better now.
- GENERAL PAPER COMMENT: The above sentence reminds me that's something I feel missing from the paper in general, a discussion of "what's different between this paper and the last?" Is this a report of the update on design, is it an "improved methods" paper, is it a "we're exposing all the systematic errors that we've found" paper ... A review of the context of this paper early on in the paper would be quite helpful.

Abstract and Introduction section have been edited to address these points.

- 3.1 SUBSECTION STRUCTURE: Even if you don't decide to re-organize the paper, Section 3.1 is *titled* "End station power standard calibration," but the first three paragraphs are talking about the gold standard, and the problems you found in shipping with a figure. Then later, there's a few paragraphs on temperature of the working standards. Maybe divide this section in to a few parts (kinda like I suggest for section 2), one focusing on the gold standard and it's results, the working standard and it's results, and then finally the end stations and its results. At the moment, I feel that all that content is sort of garbled in to a section title that doesn't reflect the entire content of the section.

To calibrate the end station power standards, we follow what is shown schematically in Figure 1: NIST -> GS -> WS -> Rx sensor. So the story starts at the beginning and makes it way to \rho_R. We think we have clarified in this regard.

- Is there a typo in the second to last sentence of section 3.1? You say "together with **the GS and WS responsitivity ratios**, κ_{G} and κ_{W}, [...]" but aren't κ_{G} and κ_{W} **relative temperature coefficients**?

We must have been punch-drunk when we wrote this. Totally screwed up. Thanks for catching this. It now reads, “The calculated values for $\Delta T_{_{LN}}$ and $\Delta T_{_{EL}}$, together with the measured GS and WS temperature coefficients, $\kappa_{_G}$ and $\kappa_{_W}$, are used to calculate $\xi_{_{LN}}$ and $\xi_{_{EL}}$ using equation \,(\ref{eq:xi}).”

- In Table 2, all \rho values should have units of V.W^{-1}, and \zeta_{W} should have units of ct.V^{-1}

Done.

- In Table 3. all \kappa values should have units of K^{-1}, and \Delta T values should have units of K.

Done

- On page 15, just after Eq. 14, you discuss the "free mass" approximation, and that rotation effects are treated as uncertainty, as has *kinda* been said already in Section 1.1. Maybe you don't need to repeat it here in the results section?
However, I'm not sure I have a good place for where to put the discussion of the test mass mass verification...
Perhaps just reducing it to a reference back to the discussion?

We think we have addressed this.

- GENERAL SECTION 3 COMMENT: I feel like, at the point discussing rotation effects, that I've lost where I am, and where we're going. I wonder if it's best to start the section with a revamp of equations (5) through (9), explicitly writing it all out, instead of abbreviating everything.
-- See Attached Picture.
So, with that, it becomes clear what parts of all of these sub-equations are what, and you can organize the section in this way:
Section 3.(x+0): Converting digital signal to volts from the PD, \Zeta.
    Discuss the readout systems of the PDs
    Discuss the AA filtering and the PDs transimpedance amp
    Discuss issues with differing ADCs
    Show zeta.
Section 3.(x+1): Interpreting the volts from the PD as power at the test mass; responsivity transfer and optical losses.
    Discuss the need for power transfer, refer back to figure 1.
    Discuss issues in power transfer,
        lab dependency on temperature
        change in gold standard behavior
        discuss impact of laser speckle
    Show \rho, \xi, \kappa, \Delta T, etc from the gold standard, working standard, etc.
    Show results from \eta
Section 3.(x+2): Converting from Power to Displacement
    Discuss 2*(cos \theta) / c, namlely how \theta is measured, and potential error there
    Talk about measurement of the test mass mass to 10 g
    Discuss about spot positions, and show their estimated value
    Discuss and ahow all parameters used for M/I(a.b) term and their uncertainty
    Remind folks that the difference between S(w) and 1/Mw^2 will be addressed as an uncertainty
Section 3.(x+3): Overall results
    Discuss the comparison between X-end and Y-end and why we do it
    Show results for mu, C, and X

We have re-organized in response to comments and our own assessments. We have not intentionally followed what is suggested here (sorry), but hopefully it is better now and I would not be surprised if it is close to this flow.

%%%%%%% Section 4: Summary and Conclusions: %%%%%%%%

- Ahhhh, OK, so the "final answer" in the paper is X^{c}_{_R,Y} (or the equivalent for X). I think it's worth restating here that these are LHO-only, receiver-module-only, numbers, and to quote transmitter module numbers and LLO numbers, to arrive at the end-user statement of "the" numbers that are the take-away from the paper (for the users, like myself).

We don't want to quote Tx numbers, and we don't think it serves the purpose of this paper to quote LLO numbers too. We will write a technical note with the LLO numbers included for O3 wrap-up.

OORRR, if you'd like to keep the paper "tight" and just talk about LHO receivers, then a LOT of the other parts of the paper should reflect that (abstract, intro, methods, results).

We think it does now.

- I realize the sentence "However, point defects in the ETM high-reflectivity coatings [22] have required beam large displacements to
maximize interferometer sensitivity while suffering the deleterious impacts of operating with mis-centered beams."
Is a direct copy-and-paste from a previous version of the LIGO O3 CAL systematic error paper.

Trying not to be offended (somewhat unsuccessfully), here are the sentences from the four versions of the paper in the DCC. None is "a direct copy-and-paste."

V1: At Hanford, point defects on the arm cavity optics have been limiting the detector's performance due to the increased laser power in O3 [26, 4].

V2: Laser power loss from point defects on the arm cavity optic reflective coatings have limited the detector performance due to the increased operational laser power in O3 [4, 34].

V3: Laser power loss from point defects on the arm cavity optic reflective coatings have limited the detector performance due to the increased operational laser power in O3 [4, 34].

V4: Laser power loss from point defects on the arm cavity optic reflective coatings have limited the detector performance due to the increased operational laser power in O3 [4, 34]. To achieve the best sensitivity possible in spite of the coating defects, the Hanford detector alignment scheme has been modified to position the laser light impinging on arm cavity optics away from defects and to minimize power loss.

Sheila commented on that sentence, suggesting that we pull out discussing of *why* the beam spots moved other than "to avoid point defects," because we don't have strong evidence that doing so improved the sensitivity (yes, it made the detector control system stable, but it didn't improve the sensitivity).
Lilli also axed the word "deleterious"...
Maybe copy the latest version of this sentence from the -v4 version posted to the DCC?

We certainly would not copy any sentences from another paper, and I hope nobody copies any sentences from our paper.
Sentence edited to “... optimize interferometer performance”

- In the next sentence "If the coatings are improved [...]" the phrasing seems a little bit ... I dunno... selfish? Perhaps it's better to just rearrange and tighten up the paragraph,
"Unintended rotation [...] is the second largest contributor."
"Point defects [22] have demanded the detector by operated in an abnormal configuration, with spots far from the center of its optics."
"This results in an amplification of \vec{b}, increasing the impact of this term dramatically."
"Returning the beams to center would reduce this by a factor of 10."
One should also emphasize (again) that this statement is a reflection of LHO only, or make a statement about LLO too.

Don’t understand the “selfish” aspect. Pcal-centric? I don’t think that spots would be moved to center just for the Pcals improved functionality. Getting better Pcal accuracy might be a contributing factor though. And centered beams is the preferred operating state, for a number of reasons, I think. Not understanding this comment, we have left the paragraph as-is, other than the change in the one sentence noted above.

- "Finally, using the interferometer to compare [...] generating a combined *actuation* coefficients [...]" Do you mean *displacement* coefficients here?

Yes. Thank you. actuation -> displacement

- Third paragraph... huh, you're going *back* to discuss the gold standard uncertainty? Seems weird to talk about the first-largest contributor, and the reduction of the GS uncertainty from

0.42% to 0.32% in the second sentence of the first paragraph, and then switch to the second-largest contributor, and then back to NIST and the GS uncertainty.
Consider grouping these topics together?

Removed first sentence of third paragraph. No need to restate the 0.32% since it was stated in the first paragraph. Reads better without it.

- Hrmmm... I wonder ... the discussion of the bilateral study... doesn't seem very "conclusion"-like. Could you get away with talking about it when you talk about the gold standard in either section 2 or 3?

This is the discussion-like part of the “Summary and conclusions” section. Noting other ongoing relevant work and future prospects.

- Do we really want to talk about NCAL? Seems like a side thought. And honestly, I don't think that it should stand out against other efforts in establishing alternative absolute references, like FSM, VCO, or newer methods like ALS-DIFF.
If you really want to talk about other alternative absolute references, then I would zoom out, talk about *all* the other, less awesome, attempts at verifying things.
But honestly, I don't think talking about all this stuff is within the scope of this paper.
(and that's not because I have any selfish plan to publish anything separately about NCAL, I just honestly think it comes out of no where here.)

I don’t think that FSM, or our old VCO, or the ALS_DIFF methods are relevant to this paper. Ncal is mentioned because it has the potential to impact the subject of this paper (see title of paper) in the future. Similarly, NISTs work on improved primary calibration standards is discussed.

- This last paragraph, is what I was hoping for in the introduction -- giving context to this paper. I understand that it's an attempt to "bring us back up and out," with a discussion of how the results of this paper improve the surrounding context, and a mention that the future looks bright, but ... for example, now's not the time to describe how the PCAL system is used, bringing in new terminology like "swept-sine response function measurements" especially when the reader doesn't know what you're talking about when you say "response function"...
Also the "daunting hurdle" sentence is really long...
Let me know if you'd like me to help draft some content for this paragraph after you've considered all the things mentioned about restructuring.

Last paragraph reworded somewhat to address these points.

%%%%%%% Acknowledgements %%%%%%%%

Thank you for the acknowledgment! (I'm not sure I know whom S. Banagiri is... should he be separately thanked "away" from Evan, the LIGO CAL team, and I?)

Sharan Banagiri, grad student from UMinn, was a LSC Fellow at LHO for four months at the beginning of the O4 run. He made important contributions to getting the Pcals up and going for O3 (see https://wiki.ligo.org/LSC/Fellows/LSCFellowsProjectList).
Do we want to thank the VIRGO "team," namely Dimitri and Loic explicitly? I know you've already thanked Dimitri for in-lab measurements while he was at LIGO, but what about their implementation/stewardship of the WSV at VIRGO?

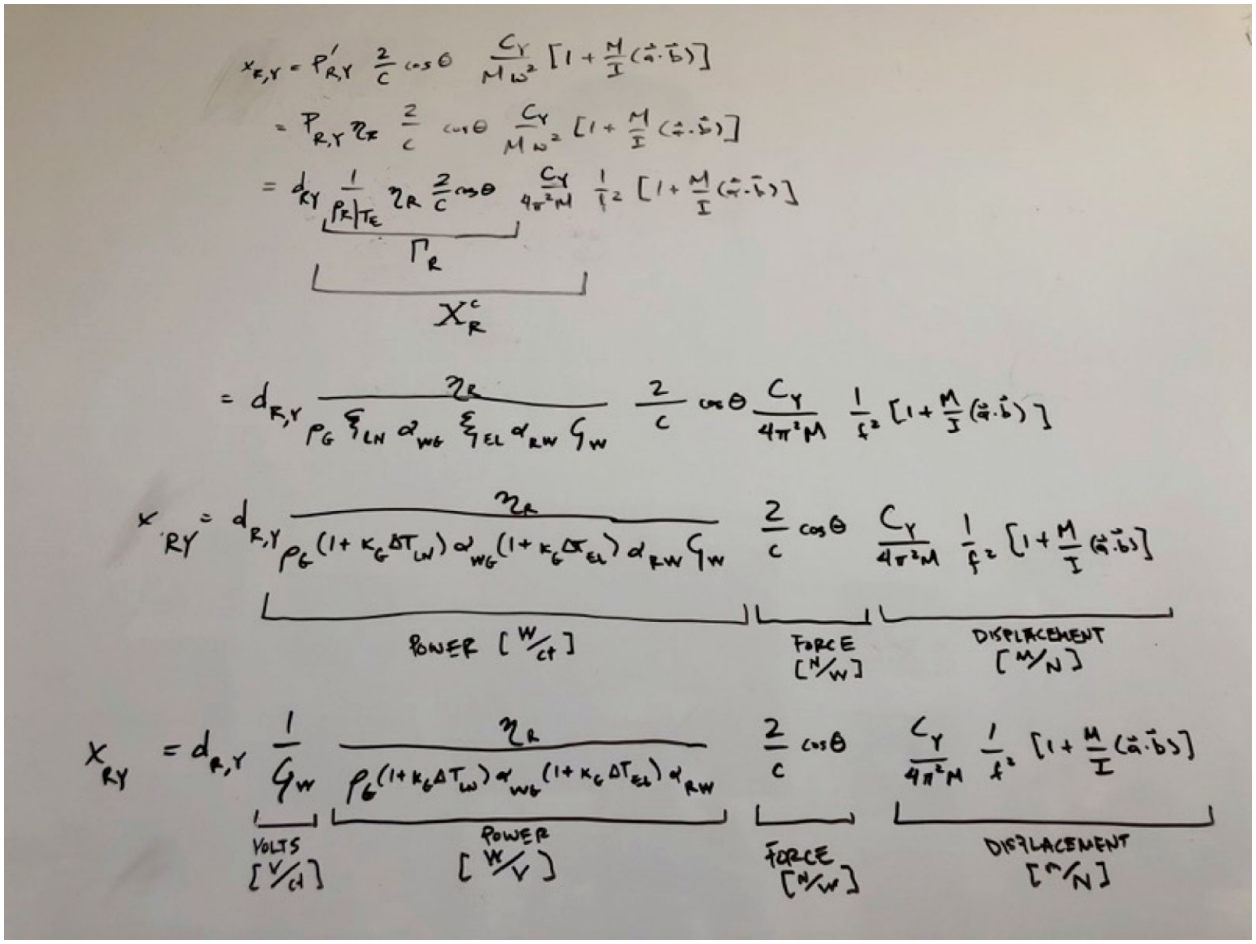
I don't think they have contributed to the material presented in this paper. We did not use any of their data. It is not really an "O3 Pcal paper." More of a methodology and current state of the art paper. (at least that is how I see it).

Same for KAGRA, should you thank Inoue-san, Hano-san, and Tuyenbayev-san?
How about william parker or Raine Hasskew -- er, whomever else helped Joe at LLO?

I don't think the Kagra folks, for the same reasons as the Virgo folks. Again, I don't think the LLO folks who might have helped Joe have contributed to what is in this paper. Maybe Joe will have an opinion.

%%%%%%% References %%%%%%%%
- I know I've said this before, but do let me know if you need me to triple check that all these technical notes are public.
- To make it symmetric with the [22] A. Brooks reference, the DCC number of the Sun L (O3 systematic error paper) is P1900245.

Thanks, there is a lot of ongoing work on references. We will try to make them self-consistent.



4/29/2020 Marco's comments from .pdf markup (transcribed by Sudarshan)

1. Improvements in propagation of laser power calibration via transfer standards to on-line power sensors continuously monitoring the modulated laser power has enabled generation of length calibration ducials with sub-percent accuracy. → I'm not sure I understand this sentence: "Improvements in propagation of... calibration"?

   Changed to: Developments in the propagation of laser power calibration via transfer standards to on-line power sensors continuously monitoring the modulated laser power have enabled generation of length calibration fiducials with improved accuracy.

2. maximize the scientific benefit from these detections,--> of these detections

   We intend to refer to the “detections” of GWs, not the “detectors.”

3. Schematic diagram showing the transfer of laser power calibration from SI units, by calibration of a Gold transfer standard (GS) by NIST, to Working transfer standards(WS), one for each observatory, then to the power sensors (Tx and Rx) located at the interferometer end stations. → Very convoluted sentence. Can you make it clearer? Not sure about the sense of "transfering a calibration from SI units... by a calibration... to a working transfer standard"

   Changed to: Schematic diagram showing the transfer of laser power calibration from SI units via calibration of a {\em Gold} transfer standard (GS) by NIST. Then from the GS to {\em Working} transfer standards (WS), one for each observatory, and then to the power sensors (Tx and Rx) located at the interferometer end stations.
4. The magnitudes of the induced length variations are directly proportional → remove directly
   Done.
5. Figure 2 caption: Maybe you should just write S(\omega) or S(\omega) = 1/M\omega^2 here. Also, do you need a minus sign?

   Yes, minus sign added. Thank you.

6. When power-modulated Pcal laser beams reflect from the surface of the mirror suspended at the end of one of the arms of a gravitational wave interferometer, → I think you already said it's at the end of the arms. It's a bit of repetition IMHO. Maybe you can add it earlier in the intro that they are at the end of the arm and here simply move on

   I think this is the first place we mentioned that that the mass is at the end station and defined ETM.

7. referred to as an end test mass → does the first letter need to be capitalized

   I don’t think so (guidelines say no).

8. Pcal beams on the test mass surface → ETM surface??

We use both to avoid repetition.

9. 1/M\omega^2 → consistency in brackets

   Now using curved parentheses everywhere.

10. plotted in the lower-left panel of figure 2 → You may want to write "The lower-left panel of Fig.~(2) shows ..."

    Left as is.

11. Thus, the fiducial length modulation induced by Pcal forces, x(!), taking into account the longitudinal displacement as well as the apparent displacements induced by unintended rotations, is given by → Taking into account.... the fiducial length... is given by

    Changed as suggested.

12. Page 4, eq 3 → Do you need to repeat this equation which is the same as the previous one? Can't you simply write it earlier in this form and then explain the second term is the uncertainty?
    Done!
13. The accuracy of the fiducials provided by Pcal systems depends directly on the accuracy of the estimation of the laser power P(!) reflecting from the test mass. → repetition

    Sentence removed.

14. that houses the laser that samples → that .. that…

    Yes, “the cat that ate the bird that flew in the window.”

15. They also contain the main Pcal sensor that is located inside the receiver module (the Rx sensor) that receives all of the laser light that reflects → that ...that…..that

    Sentence re-worded.

16. While the reflectivity of the ETM → While to Although

    Changed as suggested.

17. Using the estimates of optical losses, the power reflecting from the ETM can be estimated using either power sensor as → using … using

    Sentence changed.

18. Tx and Rx → Roman font or italic/math font? Be consistent with earlier.

    Italics first time introduced for emphasis, then roman font.

19. beamsplitter that generates the small fraction, less than one percent, of the input light for the transmitter-side sensor. → is the beamsplitter that generates? Sentences are typically too long. I think they should be made clearer

    Changed “generates” to “reflects.”

20. Use of ETM/ end test mass

    Replaced “end test mass” after acronym defined.

21. where the displacement coefficients (m=s2ct), → ??

    Coefficients -> factors. Should be m/ct.

22. The interferometer senses differential changes in the lengths of the interferometer arms, without regard to which end station induced the displacements. → comma needed??

    Thank you. Comma removed.

23. Thus, comparing Pcal fiducials produced at both end stations → the Pcal fiducials

    Added “the”

24. sensitive band of interferometer. → band of the interferometer

    Added “the”
25. The weighted geometric mean of 1 and XY , with weighting factors given by the estimated variances due to uncertainty contributions that are not common to both end stations, is used to calculate the correction factors. → Better to write "The correction factors can be calculated by taking..."

    Sentence re-written and shortened.

26. Calibration of the Pcal power sensors at the interferometer end stations is realized by a three-step process that is shown schematically in gure 1: i) a transfer standard referred to as the Gold Standard (GS) is calibrated to SI units (W=V) at NIST in Boulder, Colorado; ii) the calibration of the GS is transferred to additional transfer standards referred to as Working Standards (WS), one for each observatory, by making responsivity ratio measurements in a dedicated laboratory setup at the LIGO Hanford Observatory (LHO), and iii) the calibration of the WSs are transferred to end station power sensors at each observatory by making responsivity ratio measurements at the end stations → capitalization of each bullets initial letter

    Not sure what to do here. Seems it is a continuation of a sentence and thus they should not be capitalized. We’ll research.

27. The GS is sent to NIST annually for calibration [15]. → ref required?
    Fixed
28. To transfer the GS calibration to the various working standards a series of responsivity ratio → To transfer the GS calibration to the various working standards, a series of responsivity ratio

    Comma added.

29. The GS and one WS are mounted on automated pneumatic slides that alternate the positions of the two detectors between the two output beams → The GS and one of the WS are mounted

    Left as is.

30. Point-by-point division of the recorded voltages in a given configuration minimizes variations induced → minimizes the

Left as is. These variations have not yet been introduced so there are no “the” variations yet.

31. detector positions swapped minimizes→ swapped detector positions minimize

    We think, “... the detector positions swapped minimizes...” is more informative.

32. While the integrating spheres are largely insensitive to incident beam position, angle, polarization and size, they exhibit laser speckle due to the coherence of the laser light that correlates the output time series
    While → Although
    incident → the incident
    and comma after polarization

    Added “the.” While was already changed to although. Comma added.

33. is the average of 100 measurements. → is given by the average of 100 measurements

    Thank you. Changed as suggested.

34. where the beamsplitter ratio variations have clearly been minimized → remove clearly

    Removed as suggested.

35. The standard deviation of individual responsivity ratio measurements → the individual

    “The” added.

36. Eq 12 and 13→ Shouldn't be \rho_{R|T_E} etc instead of \rho_{R}|_{T_E} ? Do you need all these | ? I'm not sure I understand the notations.

    Trying to denote \rho_R evaluated at T_E. Is this incorrect notation?

37. We follow the convention used by NIST and detailed in [19], → in ref [19]

    CQG guidelines suggest referring directly as we have, without the ref. Same for

equations.

38. Calibration of the on-line power sensors at the end stations → The calibration

    Seems better without the “the,” to me. Not a specific calibraton, but calibration of the sensors, in general.

39. Modifications included changes → The modifications

    “The” added.

40. calibrated by NIST in December, 2018 → comma may not be required.

    Indeed! News to me. Changed to December 2018. Removed commas between months and years everywhere.

41. As shown schematically in figure 1, responsivity ratio measurements → the responsivity

    Left as is. Not responding to particular measurements, just that responsivity measurements, in general, are used to transfer ….

42. Also, responsivity ratio measurements between one or more elements of this array of sensors and the GS → the responsivity

    Prefer as-is, for same reason stated in 41, above.

43. are used to determine if changes occurred during shipping → if to whether

    Changed as suggested.

44. the period from Nov. 2018 to Feb. 2020. The mean of the four measurements made immediately before sending the GS to NIST for calibration on Dec → should month be spelled out

    Yes, we changed to spelling out months everywhere.

45. This method assumes the coherence time of the data → assumes that the

    Changed as suggested.

46. record the output of the WS; at the end stations, an analog-to-digital (ADC) converter that is part of the LIGO data acquisition system is used → end the first sentence at WS and better to write: An analog... that ... is used at the end stations.

    Changed as suggested.

47. These are correction factors that account → These correction factors account

    Changes as suggested.

48. Fig 5 caption → should month be spelled out full?

    Yes, all months spelled out now.