Dear Referee,

Thank you very much for your comments and for approving this paper for submission to ApJ. Your positive reviews were received very well and we greatly appreciate the detail with which you gave your specific comments. Individual responses to your comments can be found below.

A few of broader points:

- The authors do identify the coherent nature of speckles across small wavelength regions (i.e. that speckle patterns in multi-mode fibers have spatial correlations between adjacent wavelengths) but still claim that the modal noise-induced centroid error scales as the square root of the number of lines in the spectrum (e.g. as claimed in Section 5). This is not consistent with the speckle coherence statement discussed earlier in the text, since the speckle drifts are not random between nearby wavelengths. This speckle coherence remains an issue for the next generation of instruments relying on frequency combs, particularly those that aim to achieve <1 m/s velocity precision on one or few spectral orders, and should be more addressed in the text.

See comment #12 below.

- While the paper nicely outlines the two major manifestations of modal noise in high resolution spectroscopy, namely hot it can place a fundamental limit on spectral SNR and introduce centroid instabilities in wavelength calibration lines, there is not discussion of how the presented fiber agitation system compares to the expected photon noise floor. The key goal in mitigating modal noise (other than minimizing centroid drift in calibration source spectra) is to ensure the speckle-limited SNR is higher than the expected photon noise limit. Perhaps showing plotting the expected photon-limited SNR vs. the measured SNR on the fiber near field (e.g. in figures such as Figure 6 or 8), would help show the improvements that this system provides.

Our use of the LED source (e.g. in figures 6&8) was meant to give an idea of the photon noise through use of a broadband, wavelength-integrated image. The cameras that we use are also dominated by dark/read noise, so it would be beyond the scope of this paper to compare to the expectations of a photon-noise dominated image (e.g. with a commissioned spectrograph). Though, we do agree that this would be an apt comparison under better experimental conditions.

- The issue of focal ratio degradation induced by this system is not addressed in the paper. While the agitation technique outlined in the paper seems relatively gentle on the fiber cable itself (implying minimal NA upscattering), some discussion or demonstration that this system does not induce significant FRD should be presented.

The most frequent response we’ve gotten about high-amplitude agitation is the effect of FRD for the fiber, so thank you for addressing this in your report. We assumed that the result from Sablowski et al. (2015) would apply to our apparatus, but since you commented on it, we added a section specifically about FRD (Section 6) and Figure 11. We found no significant problem with FRD using our agitator, so hopefully this will alleviate your concerns.

More specific comments:

1) Abstract, 1st sentence:

"Optical fiber modal noise is a critically limiting factor for high precision spectroscopy..."

Suggest removing 'critically'

Removed

2) Abstract, 2nd sentence:

"Unabated, especially when applying highly coherent light sources..."

Suggest changing 'applying' to 'using'

Changed

3) Abstract, 3rd sentence:

"..a luxury not necessarily afforded calibration for the next-generation..."

Suggest changing to "....not necessarily afforded by next-generation..."

Changed

4) Abstract, 6th sentence:

"Therefore, we have filled out the parameter space of modal noise agitation techniques in order to better understand agitation's contribution to mitigating modal noise and to discover the optimal strategy for agitating fibers"

This sentence and the one following are a bit overreaching. This is certainly a novel technique, though I would be careful in calling this the 'optimal' strategy. It would be best to be explicit in stating the quantitative improvements demonstrated by this system, but softening these sentences a bit would better match the results in the paper.

Replaced with: “Therefore, we have filled out the parameter space of modal noise agitation techniques in order to better understand agitation's contribution to mitigating modal noise and to discover an improved method of agitating fibers.”

5) Introduction, 4th paragraph, 2nd sentence:

"As apparent in their name, single-mode fibers only propagate a single electromagnetic mode and should be free from any modal noise."

Suggest changing 'electromagnetic' to 'spatial', since there are technically two different EM modes for the two polarizations.

Changed

6) Section 2, Equation 1:

It should be noted in the text that this mode formula is for a monochromatic source only.

Now reads: “The maximum number of modes for a step-index circular cross-section fiber (propagating a relatively large number of modes) with a monochromatic light source is approximately…”

7) Section 2.1, 1st sentence:

"Due to its high contrast, modal noise can severely decrease the S/N of an RV spectrograph..."

Suggest adding GIANO reference here, in addition to the references cited: Iuzzolino et al, SPI 2014 (http://adsabs.harvard.edu/cgi-bin/bib\_query?arXiv:1407.3052)

Added

8) Section 2.2, 2nd paragraph, last sentence:

"However, since the speckle pattern is smoothly wavelength dependent, the resultant spectral line spread function of a frequency comb is correlated between neighboring lines, meaning any drift due to modal noise is not necessarily randomly distributed across the spectrum."

This is entirely true, but contradicts the root N line centroid scaling described in Section 5. Suggest the authors keep this sentence, since it's an often-overlooked point when discussing modal noise in calibration sources, but reword Section 5 (see later comment).

See comment #12

9) Section 3, 4th paragraph, 2nd sentence:

"For these tests, we feed the FCS with either a 652 nm Toptica diode laser through a single-mode fiber..."

Suggest the authors mention the bandwidth of the Toptica diode laser. The linewidth is ideally quite narrow if it's meant to emulate a laser comb line (<1 MHz), but this is not specified in the text.

Now reads: “For these tests, we feed the FCS with either a 652 nm Toptica DL 100 diode laser (less than 1 MHz linewidth) through a single-mode fiber…”

10) Section 3, 4th paragraph, 4th sentence:

"...our near field camera has a resolution of 0.3 μm, but after using statistical techniques on the fiber images, we have yielded fiber-centering precision to about 0.01 μm."

A bit more detail on the image analysis techniques would help here. Centroiding to these levels of accuracy, particularly in the presence of changing speckle patterns, likely took some effort. Describing the analysis efforts would improve this section.

Now reads: “According to these specifications, our near field camera has a spatial resolution of 0.3 μm. However, by subtracting ambient calibration images, strictly thresholding to remove background counts, and comparing the unweighted and weighted centroids of each fiber image (thus removing camera drift), we have yielded fiber-centroiding precision to about 0.01 μm.”

We recognize that these techniques are not particularly advanced, but as shown in Figure 10, we found a spread in centroids to 0.56 m/s for the LED source. Converted to image motion, this is about 0.009 microns. Thus, we are confident that the FCS can measure centroids to this level of precision.

11) Section 3, 4th paragraph, last sentence:

"The LED source acts as a best-case scenario, since it is relatively incoherent and unaffected by modal noise, and the unagitated acts as a worst case."

This statement is not entirely correct. The LED is indeed subject to modal noise, just perhaps not measurably so in the wavelength-integrated near-field images. If one were to disperse the spectrum of the LED at high resolution, modal noise would still set some fundamental limit on the SNR of the spectrum (see GIANO reference mentioned in earlier comment). Suggest rewording this sentence to reflect this. The LED is a perfectly good control case for estimating the near-field image centroid measurement noise floor, which I believe was the intent behind this sentence.

Now reads: “The LED source acts as a control for our S/N and centroiding noise floor, since it is relatively incoherent and thus modal noise is suppressed when using wavelength-integrating cameras, and the unagitated fiber acts as a worst-case scenario.”

12) Section 5, 2nd paragraph, 2nd and 3rd sentence:

"Importantly, σ\_RV is only the RV error per resolution element or per line from a wavelength calibration source. Averaging over N lines, we can divide...."

This touches on the previously mentioned issue of speckle coherence across wavelengths. Given that speckle patterns are correlated over ~nm scales, so too are the centroid shifts of neighboring calibration lines (assuming a reasonable density of lines per spectral order). As such, the scaling does not average down with each line, but rather more coarsely over sets of lines which are not experiencing centroid drifts in the same direction. This should be cleared up in the text.

Now reads: “Importantly, σ\_RV is only the RV error per resolution element or per line from a wavelength calibration source. Averaging over N lines with independent modal structure, we can divide σ\_RV by sqrt{N} to approximate total RV error. N may not necessarily equal the total number calibration lines, however, since two neighboring wavelengths may propagate with the same number of modes and thus the same modal structure. Assuming two modal structures are effectively independent if the difference between the number of propagated modes is 10, we assert

where and are respectively the minimum and maximum wavelengths of the relevant calibration region. Note that the calibration source needs to be sufficiently dense (i.e. the number of lines is greater than N) to properly use this approximation. Even though Eq. 6 has not been empirically tested, since it requires a comprehensive study on the systematic correlation of modal noise, we believe it to be a rather conservative estimate for statistical reduction.”

We also updated the end of Section 5: “The calculated 60 cm/s error for coupled agitation is the RV error per line in the spectrograph. Thus, the total RV error could be reduced to below 10 cm/s with only 36 mode-independent calibration lines. EXPRES is using a laser frequency comb with approximately 14 GHz line spacing across 450-700 nm fed by a 33 um x 132 um rectangular fiber. Therefore, using Eq. 6, EXPRES will have N=350, reducing the expected RV error of the instrument to less than 3.2 cm/s.”

13) Section 6, general

While the bullet points raised in this section are comprehensively discussed in the text, it would still be helpful to preface these results with a statement about focal ratio degredation. These points are clearly supported by the results displayed in the paper, but the practicality of these recommendations from the perspective of not increasing the A-Omega of light entering the spectrometer remains an outstanding question. (e.g. the suggestion to agitate more fibers will certainly result in more mode mixing, but will inevitably result in either throughput or resolution loss in the spectrometer due to added FRD.)

As stated above, we have inserted a new Section 6, “Agitation and Focal Ratio Degradation,” and Figure 11 to address this issue and found negligible increase in FRD due to our methods. Importantly, this is because we found that simply adding a second device somewhere in the fiber train (rather than increasing frequency of a single device) adds MUCH more modal noise suppression without adding undue stress.

Other changes not suggested by referee:

1. Table 1: Tubulent 🡪 Turbulent
2. Table 1: Mechanical “Excenter” 🡪 “Rotating Excenter”
3. Figure 3: Added mention of iris on input pupil
4. Acknowledgements: Thanked the anonymous reviewer for their comments