Responses to Comments from Anonymous Referee #1

First, we wish to thank this reviewer for the helpful review. Our responses are indicated below and numbered as they were by the reviewer.

General Comments:

3. It looks like the wrong figure was uploaded as it is missing the annotations. Below is the figure 2 that should have been included with the paper. Figure 2 in the original document has been changed to the figure below.

Figure 2

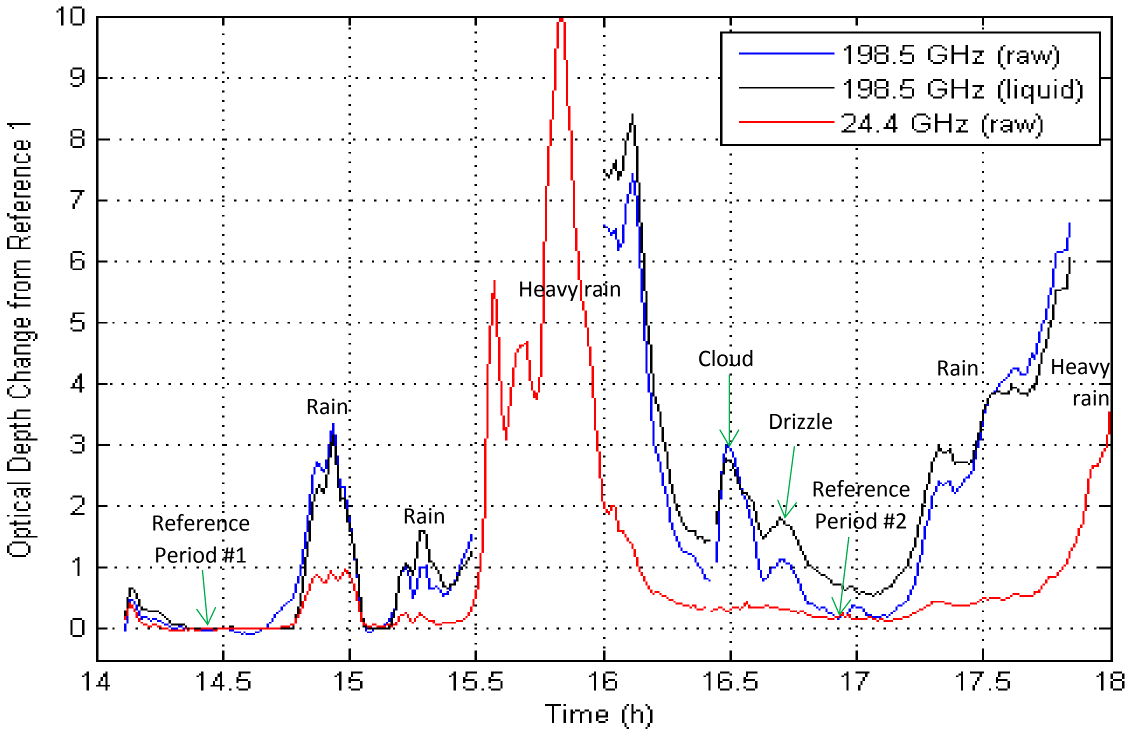

Figure 2. Blue and red lines show observed changes in optical depth at 198.5 GHz and 24.4 GHz relative to reference period 1. The black line shows changes in optical depth at 198.5 GHz due to changes in liquid water after removing the contribution from changes in vapor pressure and temperature.

Specific Comments:

5. In the manuscript we use "precision" to mean "random uncertainty" and "accuracy" to mean "systematic uncertainty." We have made the following change.

Page 1, line 24. The word "precision" will be changed to "random uncertainty"

6. The following sentences were added at the end of the abstract:

ATOMMS' water vapor retrievals from orbit will not be biased by climatological or first guess constraints, will be capable of capturing nearly the full range of variability through the atmosphere and around the globe in both clear and cloudy conditions, and will therefore greatly improving our understanding and analysis of water vapor. This information can be used to improve weather and climate models through constraints on and refinement of processes affecting and affected by water vapor.

7. Change the wording of the sentence beginning on page 1, line 28 to

"Despite its importance, our observations of its distribution in the atmosphere, and its trend with time, as well as our understanding of the factors controlling these are limited [Sherwood et al., 2013]."

This eliminates use of the word "precise."

8. Change the wording of two sentences in the last paragraph on page 2. The sentence beginning on page 2, line 26 contained the word "precisely" in line 27. Eliminate "precisely" by changing that sentence to

"Profiling both the speed of light like GPS RO as well as the absorption of light, which GPS RO does not measure, enables ATOMMS to profile temperature, pressure and water vapor simultaneously from near the surface to the mesopause with little random or systematic uncertainties (Kursinski et al., 2002)."

The sentence beginning on page 2, line 31 contained the word "precision." Eliminate the word precision by changing that sentence to

"Kursinski et al. (2002) found that such a system could provide water vapor retrievals with a random uncertainty of 1 – 3% from near the surface well into the mesosphere."

9. We believe the word "precise" is appropriate as it is used on page 4, line 1. However, we do believe a wording change is warranted for "precise" on page 5, line 3.

The sentence beginning on page 5, line 3 contained the word "precise." Eliminate use of "precise" by changing that sentence to

"This ratio of ratios approach enables measurement of water vapor in the presence of clouds and rain with very small random and systematic uncertainty as we demonstrate below.

10. In order to address this concern, several wording changes are proposed within the paragraph that begins on page 4, line 1. The new wording:

"ATOMMS functions as a precise, active spectrometer over the propagation path between the transmitter and receiver. Retrievals of water vapor from radiance measurements are inherently ambiguous because both the signal source emission and attenuation along the path are unknown and must be solved for, creating an ill-posed problem (e.g., Rodgers, 2000). In comparison to radiance retrievals, ATOMMS has the advantage that the transmitted signal strength is well known and the observed quantity is simply the attenuation along the path, which makes the retrievals much more direct and less ambiguous. The active approach also enables retrievals with small random and systematic uncertainty under conditions of large path optical depths, which is not possible for passive retrievals."

11. Add the following sentence on line 11 of page 4. "The factor of ½ multiplying the optical depth comes about because intensity is proportional to amplitude squared."

12. Four wording changes have been made to address this comment.

(a) Add the following to the sentence after the sentence ending on page 5, line 27.

"The attenuation contributed at higher altitudes along the ray path due to both the limb sounding geometry and the exponential decay in water vapor concentrations with altitude."

(b) Change the sentence that begins on page 5, line 27.

Original Sentence: "We note that the Abel transform isolates the contributions of these layers."

New Sentence: "We note that the Abel transform isolates the contribution from the lowest altitude portion of the signal path."

(c) Change the sentence that begins on page 5, line 28.

Original Sentence: "For a vertical resolution of 100 m, the horizontal length of the lowest layer is approximately 70 km"

New Sentence: For a vertical resolution of 100 m, the horizontal length of the path through the lowest layer is approximately 70 km"

(d) Change the wording of the sentence that begins on page 6, line 12.

Original Sentence: "In this mountaintop demonstration, the atmospheric path from transmitter to receiver was only 5.4 km, such that the water vapor attenuation due to absorption by the weak 22 GHz line was too small to measure accurately."

New Wording (2 sentences): "In this mountaintop demonstration, the atmospheric path from transmitter to receiver took place over a narrow altitude range from 2752 m to 2515 m above sea level and was only 5.4 km in length. Over this short path the water vapor attenuation due to absorption by the weak 22 GHz line was too small to measure accurately.

13. Replacing figure 2 eliminates this issue.

14. Our mistake. The time should be specified as 16:30 in both instances. Changes made.

15. To avoid confusion and for consistency, we have decided to use the term "calibration signal" throughout. The calibration signal amplitude at a particular selected frequency (typically in the wing of the absorption line) is used to remove or reduce unwanted amplitude variations before using the on line signal frequencies to estimate atmospheric absorption.

Here are all the instances of f_{CAL}, calibration frequency, and calibration tone that have been changed. The changes are shown below. If just a single word is changed, the change is indicated in blue.

page 3, line 11. "ATOMMS performance in cloud and rain is achieved via a differential transmission approach using a calibration tone (signal), in contrast to passive IR and microwave sensors systems that work via emission."

page 4, line 20.

Original sentence: "The frequency, f, of one signal is placed on the absorption line of interest while the frequency of the second signal, f_{CAL}, is farther from line center to function as a calibration signal."

Modified sentence. "The frequency, f, of one signal is placed on the absorption line of interest while the frequency of the second signal, f_{CAL}, is farther from line center to function as an amplitude calibration signal."

page 6, line 31. "198.5 GHz was the frequency of the High Band calibration tone (signal) during this experiment."

page 7, line 27. Several changes were made for clarification. This also partially addresses specific comment #16.

Original wording. "For this experiment, one transmitter swept through the tunable frequency range generating a tuned tone that was received by a receiver sweeping through the same tuning sequence. The other tone was fixed at 198.5 GHz in order to function as the calibration tone."

Revised wording. "For this mountaintop experiment, the frequency of the signal generated by one transmitter was swept through a tuning sequence that spanned the instrument's tunable frequency range. This signal was received by a narrowband heterodyne receiver whose second local oscillator was simultaneously swept through its matching tuning sequence. The frequency of the other signal was fixed at 198.5 GHz in order to function as the amplitude calibration signal for measuring differential absorption."

page 8, line 4.

Original sentence. "Calibration tone amplitudes were computed using the same method."

Modified sentence. "The calibration signal amplitudes were computed using the same method."

page 9, line 5.

Original sentence. "The liquid optical depth in Fig. 2 is the liquid optical depth at the calibration tone, f_{CAL} = 198.5 GHz."

Modified sentence. "The liquid optical depth in Fig. 2 is the liquid optical depth measured by the calibration signal, f_{CAL} = 198.5 GHz."

page 11, line 24. "These were reduced by almost an order of magnitude via amplitude ratioing with the calibration tone (signal) [Kursinski et al., 2016]."

page 13, line 3. "Ratioing of the amplitudes of two signals, as was done here, eliminates the effects of liquid particle extinction to the extent that the liquid extinction is spectrally flat over the ATOMMS tuning range and calibration frequencies." No change needed here.

page 13, starting on line 12. "This small 0.8% change in the retrieved vapor pressure provides some indication of how effective the calibration tone (signal) ratioing is in minimizing the sensitivity of the ATOMMS water vapor retrievals to hydrometeors. In the future, the High Band system will have 4 rather than its present 2 tones (signals) in order to place calibration tones (signals) on both the low and high frequency sides of the 183 GHz water vapor line to reveal and compensate for any overall spectral tilt caused by particle extinction as well as other effects."

page 16, lines 32 and 33.

Original wording. "In terms of the number of signal frequencies required to accurately determine the water vapor, we used from 5 to 15 tuned signal frequencies plus a calibration frequency for the water vapor spectral fits. The agreement and consistency of these results indicate that the amplitudes from just a few tuned frequencies and a calibration frequency are needed to produce water vapor retrievals with very small random and absolute uncertainties."

Revised wording. "In terms of the number of signal frequencies required to accurately determine the water vapor, we used from 5 to 15 tuned signal frequencies plus a calibration signal at a fixed frequency for the water vapor spectral fits. The agreement and consistency of these results indicate that the amplitudes from just a few tuned frequencies and a fixed frequency amplitude calibration signal are needed to produce water vapor retrievals with very small random and absolute uncertainties."

page 17, line 18.

Original sentence. "The LEO version of ATOMMS will provide the information necessary to observe and account for such non-vapor effects using at least three simultaneous signal frequencies to place calibration tones (frequencies) on both the low and high sides of the absorption line and the third frequency on the line."

Revised sentence. "The LEO version of ATOMMS will provide the information necessary to observe and account for such non-vapor effects using at least three simultaneous signal frequencies to place amplitude calibration signals on both the low and high sides of the absorption line and the third frequency on the line."

16. We propose to significantly change the wording under the heading "Signal Tuning and Detection," which begins on page 7, line 25. Major changes are shown in blue.

Original text. "The High Band portion of the ATOMMS ground-based prototype instrument simultaneously transmits and receives two continuous wave signals that are tunable from 181 to 206 GHz. For this experiment, one transmitter swept through the tunable frequency range generating a tuned tone that was received by a receiver sweeping through the same tuning sequence. The other tone was fixed at 198.5 GHz in order to function as the calibration tone. There were 122 tuning frequencies in the sweep, separated by 0.25 GHz, except for a gap between 191.5 and 193.5 GHz. This gap is due to the limited receiver response for Intermediate Frequencies (IF) less than one GHz and the first stage local oscillator (LO) being set to 192.5 GHz. This is likely the finest spectral resolution sampling of the 183 GHz line ever achieved in the field.

The dwell time for each frequency of the tuned transmitted tone was 100 ms. The timing of the transmitter-receiver tuning was synchronized using GPS receivers. Each received ATOMMS signal was filtered, down converted in frequency, digitized and recorded. The signal frequency in the final receiver stage ranged from 8 to 35 kHz for each of the 122 tuned frequencies. The frequency and power of the down converted signals were detected using a Fast Fourier Transform (FFT) and the signal amplitude was determined by taking the square root of the integrated signal power from each FFT. The integration time was 50 ms, which is half of the dwell time to allow time for each synthesizer tune to settle. Calibration tone amplitudes were computed using the same method.

One sweep of the frequencies took 12.2 seconds. The instrument cycled through the four combinations of the two transmitters and two receivers before repeating the tuning cycle to help isolate any transmitter or receiver issues. Thus, a full tuning cycle was completed every 48.8 s. The observations from the four different transmit-receive pairs were averaged together to yield new estimates for the ATOMMS signal ratio every 48.8 seconds (Eq. (2)). The resulting integration time for each particular tuned frequency was four times 50 ms or 200 ms."

Revised text. "The High Band portion of the ATOMMS ground-based prototype instrument simultaneously transmits and receives two continuous wave signals that are tunable from 181 to 206 GHz. For this mountaintop experiment, the frequency of the signal generated by one transmitter was swept through a tuning sequence that spanned the instrument's tunable frequency range. This signal was received by a narrowband heterodyne receiver whose second local oscillator was simultaneously swept through its matching tuning sequence. The frequency of the other signal was fixed at 198.5 GHz in order to function as the amplitude calibration signal for measuring differential absorption. There were 122 frequencies in the tuning sequence, separated by 0.25 GHz, except for a gap between 191.5 and

193.5 GHz due to the receiver's limited response for Intermediate Frequencies (IF) less than one GHz and the first stage local oscillator (LO) being set to 192.5 GHz. This is likely the finest spectral resolution sampling of the 183 GHz line ever achieved in the field.

When executing the tuning sequence, the tuned transmitter tone dwelled at a particular frequency in the tuning sequence for 100 ms before moving to the next frequency in the sequence. The timing of the transmitter and receiver tuning sequences were synchronized using GPS receivers. At the receiver, each of the two received ATOMMS signals was filtered, down-converted in frequency, digitized and recorded. The frequency and power of the down-converted signals were determined using a Fast Fourier Transform (FFT), calculated over a 50 ms integration time. The reason that only half of the 100 ms tuning dwell time was used was to allow time for each synthesizer tune to settle. Each FFT-derived signal power estimate was then converted to an amplitude by taking the square root. The calibration signal amplitudes were computed using the same method.

One sweep through the frequency tuning sequence took 12.2 seconds. The instrument cycled through the four combinations of the two transmitters and two receivers before repeating the tuning cycle in order to help isolate any transmitter or receiver issues. Thus, a full tuning cycle was completed every 48.8 s. The observations from the four combinations of transmitter-receiver pairs were then averaged together such that new estimates for the ATOMMS signal amplitude ratios at all of the 122 tuning frequencies were generated every 48.8 seconds (Eq. (2)). As a result, the integration time used to estimate the signal amplitude and frequency for each of the 122 frequencies in the tuning sequence was four times 50 ms or 200 ms.

17. Taken care of with the correctly annotated Figure 2.

18. Several changes were made for clarification and consistency.

Page 8, line 22, original text. "…we used the *am* Atmospheric Model, version 7.2 [*Paine*, 2011] which was shown to fit the ATOMMS measurements to the 0.3% level in previous work with the ground-based ATOMMS prototype system [*Kursinski et al.*, 2012]."

Revised text. "… we used an atmospheric propagation tool known as the Atmospheric Model (am), version 7.2 [*Paine*, 2011], which we will refer to as *am7.2* . This model was shown to fit the ATOMMS measurements to the 0.3% level in previous work with the ground-based ATOMMS prototype system [*Kursinski et al.*, 2012]."

Page 12, line 6, original text. "For the conditions of this particular experiment, based on the AM7.2 model, the sensitivity of the change in derived water vapor due to a temperature change relative to the reference period temperature was approximately -0.17 hPa/°C."

Revised text. "For the conditions of this particular experiment, based on forward calculations made with *am7.2*, the sensitivity of the change in derived water vapor due to a temperature change relative to the reference period temperature was approximately -0.17 hPa/°C."

Page 12, line 29, original text. “This half range represents a conservative estimate of the random uncertainty of the retrieved vapor pressure changes that includes both measurement and am model errors.”

Revised text. “This half range represents a conservative estimate of the random uncertainty of the retrieved vapor pressure changes that includes both measurement and *am7.2* modeling errors.”

Caption of figure 5, current text. “forward calculated ATOMMS ratio using the am Model, version 7.2.”

Revised text. “forward calculated ATOMMS ratio using *am7.2*.”

19. {first comment #19} We have referred to Section 5 already. The current text is “The retrieved path-averaged vapor pressure between the instruments is shown in Fig. 3A. The figure shows 12 different solutions that were used to estimate the random uncertainty in the retrieval of vapor pressure as described in Section 5.”

The following change has been made for clarity: “The figure shows 12 different solutions that were used to estimate the random uncertainty in the retrieval of vapor pressure. The methodology used to compute the 12 solutions is described in Section 5.”

19. {second comment #19}. This is already done on page 10, line 10, where it is stated “The uncertainty associated with this temperature estimation is discussed in Section 5.”

To be more clear that sentence will be moved to the end of the last paragraph of the section “Determining Temperature,” which is page 10, line 20 in the original document.

20. Changes specified in response to comment #18 above.

21. We respectfully disagree with this comment. GPS has very little sensitivity to water vapor via absorption because its frequencies are so low in comparison to the 22 GHz water absorption line. The sensitivity that GPS does have to water vapor is via the propagation delay due to the refractivity of water vapor which is significant basically at temperatures above 240 K (because there is enough water vapor present to see this effect in individual profiles). However, one cannot isolate that water vapor signature directly from the GPS observations alone. One must add additional constraints on the dry part of the refractivity to isolate the wet part of the refractivity buried in the GPS refractivity estimates.

22. We like use of the word “achieve” on page 18, line 2. No change here.

On page 18, line 23, though, we like the reviewer’s suggestion to change “offers” to “would achieve.” Change made in document.

23. Thank you.

Original wording. “However, when we discussed validating ATOMMS instruments to 1% with Holger Vömel, a chilled mirror hygrometer expert at NCAR, he indicated that no in-situ measurements can reliably achieve 1% accuracy out in the field.”

Revised wording. “However, when we discussed validating ATOMMS instruments to 1% with a chilled mirror hygrometer expert at NCAR, we were told that no in-situ measurements can reliably achieve 1% accuracy out in the field (Holger Vömel, personal communication).”

24. Thank you. This is a point worth mentioning. The following sentence has been added after the second sentence in the last paragraph that begins of page 19. “It would be difficult, if not impossible, to locate these sensors close enough to the signal propagation path without interfering with signal itself.”

25. Figure 2 will be replaced with the annotated figure.

Editorial Points:

26. We agree. There should probably not be a space between mm- and wavelength. We will have to check with the editorial staff. Change was made to original document.

27. The word “Uncertainty” will be changed to lower case “uncertainty.”

28. Comma will be added after the word “seconds” on page 11, line 20.

29. Thanks. A hyphen should be used. “sought after” will be replaced by “sought-after” Change made.