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Atmospheric Measurement Techniques Discussions
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Interactive comment on "Boundary-layer water vapor profiling using differential absorption radar" *by* Richard J. Roy et al.

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Dear reviewer #1,

Thank you for your comments and suggestions regarding our manuscript. Listed below are our itemized responses, with the original comment/question displayed in italics.

1. *Page 2, Line 9: Several references to column water vapor are made throughout the paper, this being the first one. Although the surface echo (or cloud for ground based measurements) may be exploited to directly measure the column water vapor, no discussion is presented on the challenges associated with this*

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measurement, specifically, to what accuracy the differential power ratio between the different sounding frequencies need to be measured. Back of the envelope calculations show a relative error of 10^{-4} is required in the relative transmitted power ratio, which is certainly a difficult task. A brief discussion (somewhere in the paper) on the column measurement requirements would be beneficial.

Indeed, we mention multiple times the capability of an airborne (or spaceborne) version of this instrument to measure the total water column using surface returns. However, this is not a focus of this paper, which is concerned with profiling within boundary-layer clouds. Thus, we do not deem it appropriate to discuss the technical or systematic details pertaining to such a measurement.

Furthermore, it is not clear how the reviewer arrived at their back of the envelope calculation. If the gas extinction cross section $\kappa(f)$ doesn't change appreciably in the part of the atmosphere where the majority of water vapor resides, the total column water vapor (TCWV) for surface returns from two frequencies is

$$TCWV = \frac{1}{2\Delta\kappa}\left[\ln\left(\frac{P_e(R_s,f_1)}{P_e(R_s,f_2)}\right) + \ln\left(\frac{C(f_2)}{C(f_1)}\right) + \ln\left(\frac{\sigma_0(f_2)}{\sigma_0(f_1)}\right)\right]. \tag{1}$$

Here $\sigma_0(f)$ is the surface cross section, R_s is the distance to the surface, $[TCWV]$ = kg/m^2, and all other variables are as in the manuscript. The uncertainty from the first term on the right hand side corresponds to radar speckle, and thus decreases (in relative error) as the square root of the number of pulses. The main systematic concern, therefore, is the second term, related to radar calibration. Defining $\alpha = C(f_2)/C(f_1)$, the relative error in the retrieved value is therefore

$$\frac{\sigma_{TCWV}}{TCWV} = \frac{1}{2\tau}\frac{\delta\alpha}{\alpha}. \tag{2}$$

So, if we have an average of 5 g/m^3 of water vapor in the lowest 5 km of the atmosphere, we already have $\tau = 1.5$ for $f_1 = 167$ GHz and $f_2 = 174.8$ GHz.

Thus, a 5% relative error in the retrieved TCWV corresponds to an error in α of 15%. This is a significantly less demanding level of accuracy than that proposed by the reviewer. An identical argument holds for uncertainties in the differential surface cross section.

2. *Page 3, Line 1: Please clarify that the column measurements do require absolute calibration.*

   As is evident from the above analysis, absolute calibration of the radar system is **not** required, but rather only relative calibration at the two frequencies. For the same reasons discussed above, we don't feel this information should be included in the main paper, since no total column measurements are discussed.

3. *Page 3, Line 4: An assumption is made that the effects of multiple scattering are negligible on the received echo within clouds. This subject is not mentioned again in the paper. It is unclear that this assumption is valid and is highly dependent on the cloud water and ice particle size distributions. At the optical frequencies, lack of quantitative knowledge of the multiple scattering limits the utility of the received signal within clouds. The effects of multiple scattering become significantly larger as the beam propagates deeper into the cloud. This effect has been quantified at the microwave frequencies such as Cloud Sat and should be more completely addressed in this paper. A discussion on the impacts of multiple scattering on the humidity retrievals for different cloud particle size distributions and viewing geometries (distance to scattering target (ground vs airborne vs space) should be presented.*

   While multiple scattering effects are a primary concern of any spaceborne millimeter-wave radar, we disagree that discussion of multiple scattering need be a prominent part of the paper, which focuses on near-range ground based testing. However, for completeness in this response we provide a brief quantitative treatment of when this could become a problem. The degree of multiple scattering within a cloudy volume depends on the ratio $\chi = X/\ell_t$, where X is the radar beam footprint at the range of interest and $\ell_t = \beta_s^{-1}(1 - \tilde{\omega}g)^{-1}$ is the *transport* mean free path, which is different from the scattering mean free path $\ell_s = \beta_S^{-1}$ (see R. Hogan, *J. Atmos. Sci.*, 65, 2008). Here β_s, $\tilde{\omega}$, and g are the scattering coefficient, single-scattering albedo, and asymmetry parameter, respectively, integrated over the drop size distribution (DSD). Multiple scattering effects become important when χ is of order unity or larger.

The first attached figure shows the dependence of χ on the characteristic drop diameter of a DSD for clouds and rain at a range of 1 km. The system utilizes a 6 cm primary aperture with a 10 dB taper, corresponding to a far-field 3 dB antenna full width of 1.9 degrees. The scattering parameters are integrated over a modified gamma distribution of the form

$$N(D) = \frac{N_0}{\Gamma(\nu)D_n}\left(\frac{D}{D_n}\right)^{\nu-1} e^{-D/D_n}, \tag{3}$$

where N_0 is the peak number concentration, D_n is the characteristic diameter, and ν is the shape parameter. Here, we use $\nu = 1$ for rain and 4 for cloud. Furthermore, we implement a parametrization of N_0 as a function of D_n, which has been shown to better match observations than e.g. Marshall-Palmer (see Abel and Boutle, Q. J. R. Meteorol. Soc., 2012). This parametrization determines the rain rate for a given D_n. For clouds, we fix the liquid water content (LWC) to 1 g/m^3. Clearly, from the figure we see that multiple scattering is not an issue (i.e. $\chi \ll 1$) for the measurements presented in this work.

To determine when multiple scattering is an issue from a spaceborne platform, it is necessary to use a more realistic antenna size for such a system. Accordingly, the second figure attached shows that same plot for a 1 meter aperture and 10 dB taper, this time for a range of 400 km. In this case, we see that there is a range of diameters for which χ is of order unity. Furthermore, one can simply scale the values of χ for clouds linearly to consider LWC values different than 1 g/m^3. Multiple scattering will thus be an important consideration from a spaceborne platform. However, the modest values of χ mean that the effects are not so deleterious as to render information retrieval impossible, as in the case of in-cloud lidar measurements.

4. *Page 4, Lines 11-13. It should be noted that comparison on sensitivity between pulsed and FMCW is dependent on background signal levels. In high background levels with the FMCW IF bandwidth compared to the background within the gate width of a pulsed system, the advantage quickly diminishes.*

   We do not understand the reviewer's point here, and ask them to clarify if our explanation here doesn't suffice. In short, the background signal level, specifically meaning noise power P_n within a single range bin, is only a function of noise temperature T_n and integration time τ, with $P_n = k_B T_n/\tau$. For all classes of radar, the signal-to-noise ratio is given by $SNR = P_e \tau / k_B T_n$, where τ corresponds to the pulse width. Of course, for conventional pulsed radar, one must use very short pulses to achieve reasonable range resolution (e.g. $\tau = 3.3$ μs for CloudSat), while for chirped-pulsed and FMCW radar, ranging is related to the chirp bandwidth, not pulse duration. Thus, using the CloudSat pulse repetition frequency of roughly 4 kHz, one can achieve the same sensitivity using an FMCW system with 3.3 μs $\times$ 4 kHz $\approx 1\%$ of the transmit power.

5. *Page 5, Line 10. The advantage of selecting such a high chirp frequency (60 MHz) is not clear, especially when the DAR retrievals are done over an equivalent bandwidth of ≈ 2-3 MHz. Please clarify on why the higher chirp frequency was selected.*

   The choice of chirp bandwidth involves a compromise between acquiring more statistically independent measurements (i.e. larger chirp bandwidth) within a given volume, which is advantageous for high-SNR targets where uncertainty is limited by radar speckle, and averaging down the noise within that same volume (i.e. smaller chirp bandwidth) for low-SNR targets. In this work, we chose to purposefully oversample the range dimension with a radar resolution of 2.5 meters in order to achieve low power measurement uncertainty for our desired profile resolution of 27.5 meters. A sentence has been added in the text to clarify this point.

6. *Page 5, Line 16. A linear chirp results in side lobes in the power spectra which can contaminate the signal from the main lobe. Please discuss the logic behind choosing a linear chirp instead of a non-linear chirp such as one with a Gaussian frequency distribution which would result in a Gaussian response in the time domain. A plot showing the power spectra (and resulting side lobes) from a bright scatterer would be beneficial to the reader.*

   In short, the linear chirp is not responsible for side lobes. Side lobes in the range dimension for FMCW and chirped-pulsed radar result from the Fourier transform of the finite duration pulse. Indeed, we do limit side lobes during our digital signal processing step by applying a Hanning window to the time-domain signal before taking an FFT. See page 5 line 14 of the original manuscript. As is well known, application of a Hanning window reduces the first (and strongest) side lobe to -32 dB below the main lobe, thus removing any concern that side lobe effects contaminate adjacent radar signals.

7. *Page 5, Figure 2. Update the figure to accurately represent the bi-directional chirp discussed in the text.*

   The figure has been updated to show both directions of the chirp.

8. *A single table describing the system parameters would be good in section 2.2. Of particular interest is the antenna beam width and spatial side lobes.*

   We have added important properties of the beam profile into a new table in section 2.2.

9. *Page 8, First paragraph. Please clarify why background subtraction is done in the Fourier domain and not in the time domain.*

It is impossible to subtract Gaussian white noise in the time domain; it is the noise *power* which must be subtracted (related to the variance of the white noise in the time domain). This is done using the power spectral density in Fourier space. To see this, we consider the downconverted radar signal in the intermediate frequency (IF) band resulting from a single target volume of distributed scatterers at range r_0. The time domain signal is of the form $s_d(t) = s_e(t) + s_n(t) = A_e \cos(2\pi f_{IF}(r_0)t + \phi_e) + s_n(t)$. Here A_e is the peak signal voltage corresponding to the target echo and $s_n(t)$ represents white noise, which is a random variable with zero mean, and is uncorrelated in time (i.e. $\langle s_n(t_1)s_n(t_2)\rangle \propto \delta(t_1 - t_2)$). Since the noise signal voltage at a given IF frequency originates from a large number of uncorrelated sources, the statistics of each Fourier component of $s_n(t)$ are identical to those within the Rayleigh fading model (i.e. speckle statistics). Clearly we can't subtract $s_n(t)$ in the time-domain signal above, since it is impossible to *simultaneously* measure s_d and s_n. Furthermore, since the term of interest to us (the echo voltage term) contains a randomly fluctuating phase (ϕ_e) from pulse to pulse, we can only measure the variance of the echo voltage amplitude (i.e. the power), as the mean value vanishes. For these reasons, one works with radar signals in the form of power spectral densities.

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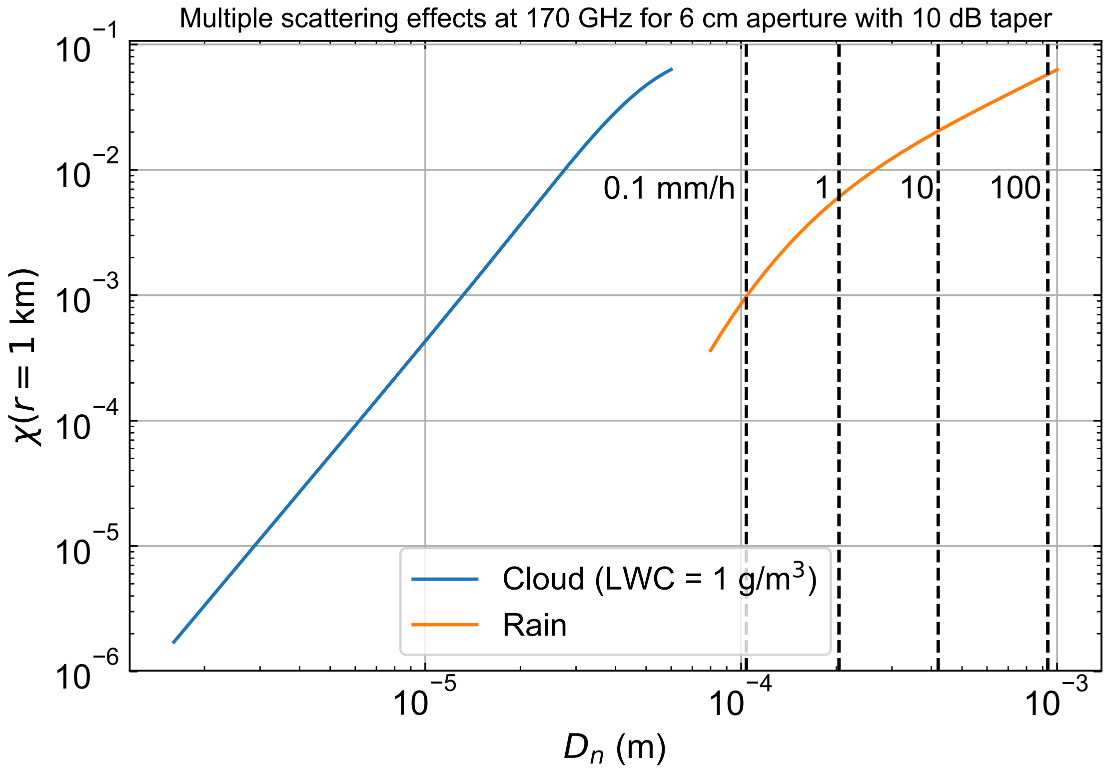

Fig. 1. Multiple scattering parameter dependence on DSD characteristic diameter for cloud and rain at a range of 1 km using a 6 cm primary aperture. See item #3 above for more details.

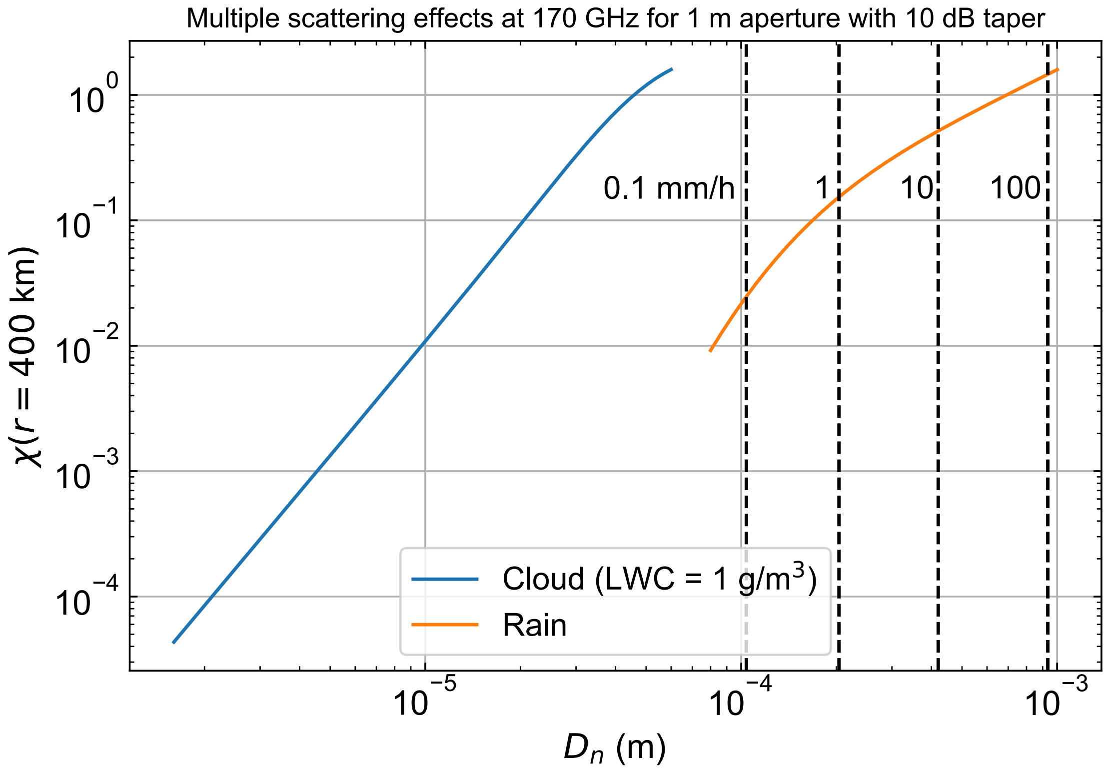

Fig. 2. Same as figure 1, except for the case of a spaceborne G-band radar with a 1 meter primary aperture and a range of 400 km.

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