IITM, Pune, India

Date: 25 Nov 2017

Dear Dr Gianfranco Vulpiani, AMT Handling Editor, EGU-Copernicus

We are thankful to you for your quick decision on our initial submitted work 'publishes as is' on 18 Aug 2017. We have been critically worked out and coming now with extensive revision by accommodating all comments of the AMTD three reviewers. The point-to-point comment and responses with the detailed implementation are prepared separately for the three referees that are followed after this cover letter. The track-change word file of the MS that reflect all the review response actions is also prepared.

We happy that through this revision, our MS mainly improved on

- Proposed TEST algorithm performance under cloud with biota presence (figure 13-14) is answered thoroughly (thanks to AR1 concern). Further, using LDR (thanks to AR2) and SW (thanks to AR3), TEST is now able to work under high number concentrated biota and within cloud biota cases which was actually the weakness of TEST earlier.
- Inferring biota and cloud De-correlation periods (thanks to AR3 and AR1) are now supported (figure 15)
- More relevant technical details (AR3) and pertinent references (AR1) are provided.
- Potential of the current work is highlighted now (AR1).

In fact, we are grateful to you, the Editor(s) and all Editorial team for their services/help and untiring timely support and cooperation. We are also equally thankful to all the three Anonymous Referees, for their hearty services in rendering experience and knowledge based comments, those were valuable in improving the quality and the focus of the paper.

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Thanks-in-advance.

Sincerely Yours,

Madhu Chandra Reddy Kalapureddy

(email: kalapureddy1@gmail.com)

PS:

1. This covering letter include Author responses to comments at Page 2-7 for AR1, Page 8-14 for AR2 and Page 9-22 for AR3.

2. modified Manuscript with figures : AMT2017b25-MS pdf extension

Authors Responses

To the *Interactive comments on* manuscript titled "Simple insect removal algorithm for 35- GHz cloud radar measurements", M C R Kalapureddy et al. *Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2017-254, 2017*

At the outset, we are grateful to the Editor(s) and all Editorial team for their services/help and untiring timely support and cooperation. We are also equally thankful to all the three Anonymous Referees, for their hearty services in rendering experience and knowledge based comments, those are valuable to us for improving the quality and the focus of the paper.

The point-to-point AR1 responses of the authors are as below:

Anonymous Referee #1 (AR1)

AR1-Comment: The study presented a technique which uses high temporal and spatially resolved reflectivity profiles to extract the cloud echoes from the clutter (mainly from the biota). The proposed technique suggested as a simple and efficient solution for clutter removal, compared to earlier sophisticated techniques based on dual polarization and spectral techniques. I think manuscript has several shortcomings, related to technique and assumptions, poor job of literature review, references and lack of solid conclusions. In its entirety, I would recommend rejection of this paper in its present form.

Response: Thank you! We request AR1 now to review the latest modified version of the paper where we re-written the whole introduction part the manuscript (MS) and cited all possible concern references that come under the scope of the paper and responded also to other valuable referee points. Furthermore, clarity on the technique/algorithm and its main application region has now been clearly come through the revision process in the current modified version of the MS at first Para of section 2 (pg 3) and added basis for TEST (Line 292-295, pg 4-5), including new figures (fig 13 to fig 15) show the potential of TEST in screening out clouds by filtering out biota. Further weakness of TEST under challenging conditions like within cloud and high density biota has been overcome using extra measurements like LDR and SW. This can be seen at the last two paragraphs of Results and Discussion. Thus, the main conclusion of the paper is how simplest way one can remove the biota contribution and preserve true cloud hydrometeor echo and its need for the study of important shallow cumulus/ABL clouds before the actual cloud radar echo weighted measurements consider for any research application purpose. The above revision asked necessary modification to the last section (Summary and Conclusions) from page 11 onwards.

AR1-Major comments: The screening technique authors have implemented using simple measures of reflectivity (or SNR) thresholds and its variability to filter out the clutter has been a usual practice in the cloud radar community as a part of post-processing exercise. The challenge of separating insects from the cloud clutter is difficult due to the lack of clear demarcation between their properties as seen by cloud radar. More often than otherwise, the screening process requires more than one variable, which captures the texture, distribution width, and physical properties of these echoes. With this motivation, some of the earlier studies have devoted their efforts to address this problem using different techniques (fuzzy-logic, spectral technique or polarization properties).

Response: Separating biota from cloud is difficult and challenging but not impossible by the cloud radar if one effectively makes use of advancing radar and signal processing technique (e.g., chirping and DSP) that enables to have the provision of high spatial and temporal resolution radar measurements (1st paragraph of System, Data and Methodology) that can demarcate the cloud echo from insects for example through reflectivity texture (e.g., TEST). With our knowledge, TEST, it is first of its kind effort to consider both reflectivity variance (i.e., dBZ texture) and its rate of change through running average for every 4 seconds. The above point pragmatically working as to identify the time coherence or de-correlation periods associated with clouds and biota echo signature (see newly added figure 15 and its description at pg 11). Moreover, the de-correlation can be evidenced through direct third Doppler power spectral moment; spectral width measurements that clearly show biota exhibits less velocity variance thus the relatively quicker time de-correlation at the pulse scale. In Fig. 2, the zoomed portion of Fig 1, the rounded echo confirms the presence of non-hydrometeor information by their duration of maximum 10 sec which is too small for a cloud to form and then suddenly disappear. So the vertical extension and the time duration of the echoes are the two key factors to discriminate cloud from non-meteorological information. Merits and de-merits of TEST has been brought out exclusively with Figure 13 and 14 that are making use of LDR and Spectral width measurements besides to Z to enhance the proposed TEST algorithm capability under tough conditions like cloud under heavily dense insects clutter.

AR1-Comment: The authors haven't clearly appreciated and addressed the insect removal to the detail that it was needed. They have demonstrated the algorithm with several minutes of data, which doesn't warrant the techniques robustness to apply for other conditions. Authors have made several assumptions about the insect layer depth, their decorrelation timescale without presenting any evidence about the location of the shallow boundary layer clouds, where the insect clutter is very critical. Previous studies (e.g., Geerts and Miao 2005; Chandra et al., 2010) have utilized the long-term observations of insect echoes to study the convective boundary layer, where they have shown that the insect decorrelation times may vary from few seconds to few minutes depends on boundary layer organization. The authors would have shown the distribution of the cloud base locations (from the closest ceilometer data) to justify their presumed insect layers below ~2km. I suggest authors to utilize the supplemental observations (such as ceilometer, microwave radiometer) to present the cloud properties and refine their insect-cloud algorithm based on the locations of cloud layer depth.

Response: Unfortunately the suggested useful complemented data was not available at and around the radar site. However using some available GPS RS observations from the radar site, the presence of weaker clouds have been proved with auxiliary Figure A2 (please also see the response to the comment 2 of AR#3). Further, we consider the reviewer's well suggested point on the inclusion of shallow boundary layer cloud case with insects clutter (Figure AR1 and AR2) when both have near same reflectivity values (added Figures 13-14). In fact, thanks to the reviewer that now it is clearly illustrating the potential of TEST that lies mostly to the ABL, where shallow cloud evolves, where the affinity of biota are predominant. Below are two examples of such low level/ shallow cumulus clouds with biota clutter where the fine performance of TEST is evident.

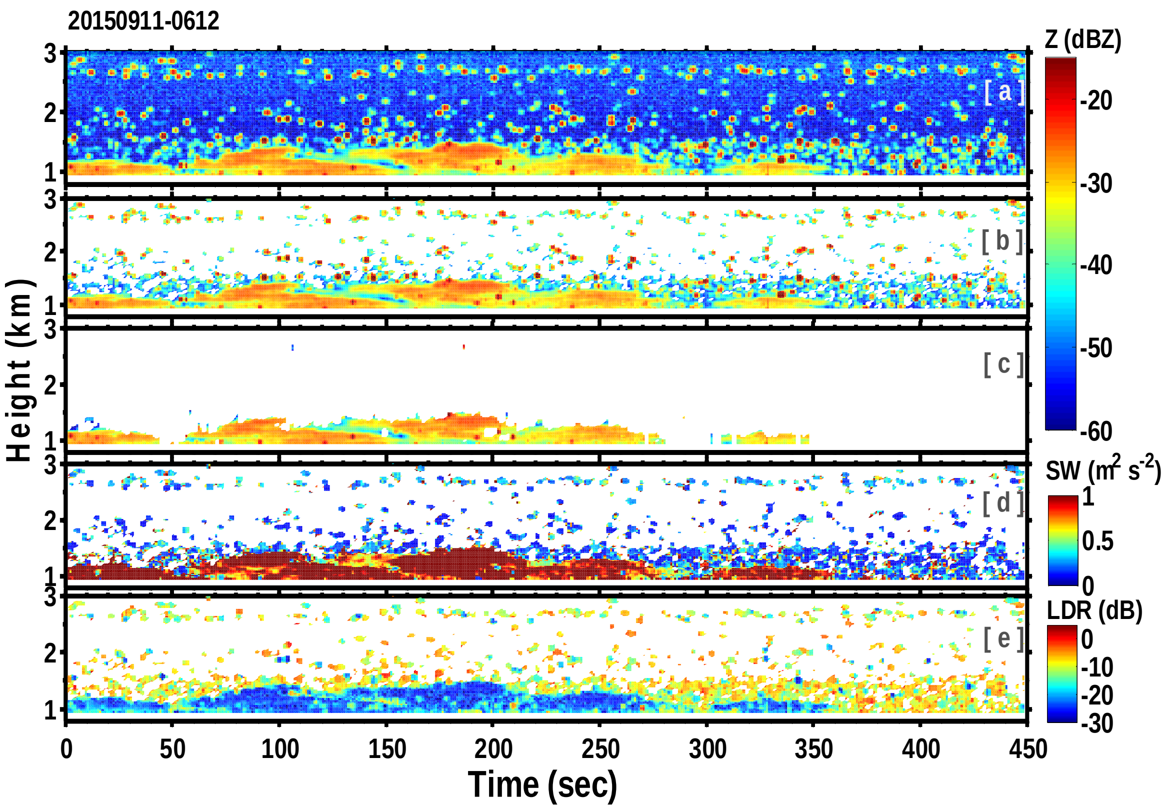

Figure AR1: HTI plot of cloud radar measured (a) Reflectivity (Z), (b) noise removed Z, (c) TEST filtered Z, (d) Spectral Width (SW), and (e) LDR at 0612 UT on 11 Sep 2015.

For demonstration, few typical cases of several minutes have been presented at the beginning but for robustness and application of this algorithm as suggested has been demonstrated with Figure 12 that makes use of several contiguous vertical looking measurements files in a day for more than 6 hours duration. In fact, we are thoroughly using this algorithm for all our cloud radar data (2013-2016) for quality cloud study. Thus, the current work is verified in all kind of atmospheric and environmental conditions around the radar site but only around monsoon seasons of 2013-2016. The typical cases are those (presented in the MS) where the texture differences of reflectivity (with 2-Dim. and HTI plots) and predominant statistical behavior can be clearly seen between insect and cloud. It is evident from that analysis that the biota is confined below 2-2.5 km AGL. For further confirmation of removal of biota, HTI plots for each file in each day have been made automatically within the algorithm for visual re-assurance of the intact cloud vertical structure. Further, presence of biota has also been confirmed using the polarimetric parameters (using earlier published references) from the same radar data, see Figure 11, Figure 13 & 14. We have fixed the maximum low level height as 2.6 km AGL for biota contribution based on reflectivity texture with our manual exposure to all the radar data (i.e., AGL+1.36 km=3.9 km AMSL). In this reference, CBL/ABL depth is not important for the current idea of the paper and importantly for the hilly, less vegetation radar

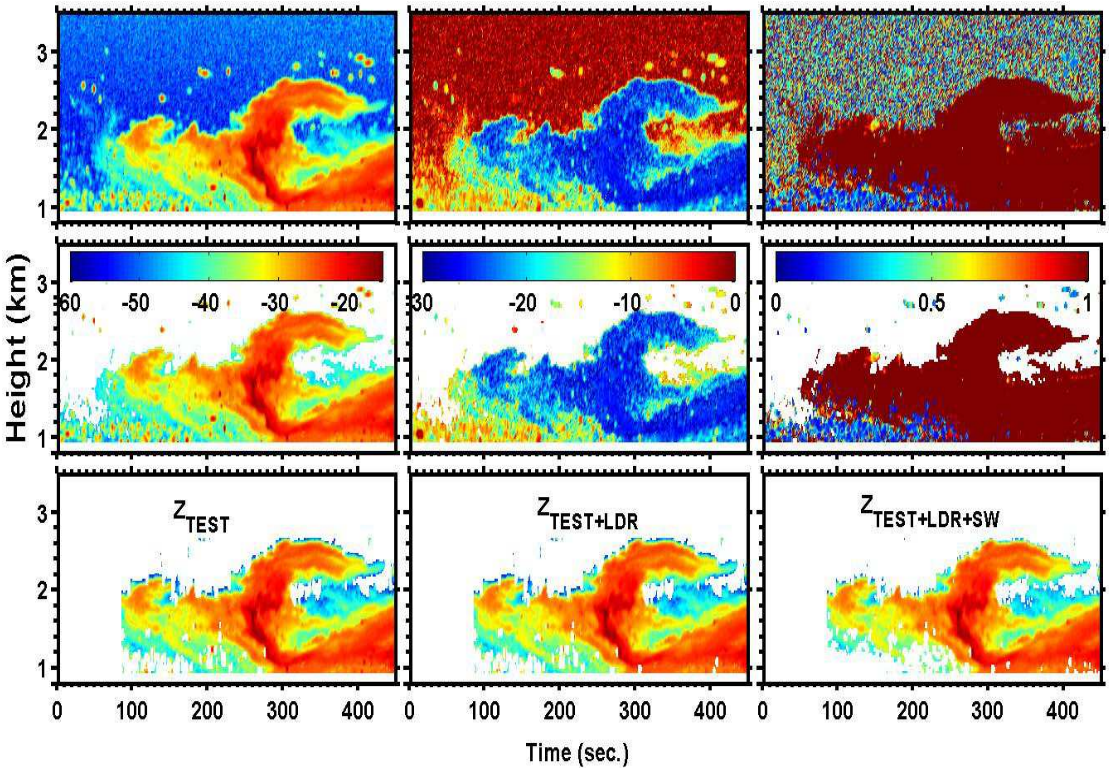

Figure AR2: TEST performance in filtering biota echoes that are co-present with low clouds.

location.

AR1-Comment:As an alternative solution to the computationally intensive spectral techniques for the insect clean-up (e.g., Luke et al., 2008), a computationally efficient technique to minimize insect clutter have been implemented based on fuzzy-logic algorithm (e.g., Chandra et al., 2013), which takes into account both the physical properties of clouds and different radar moments. This technique can be applied with different levels of complexity based on the supplemental observations (Microwave Radiometer/Ceilometer) you have in addition to radar moments. I suggest authors go through this technique for more details.

Response: Yes, We agree about the computationally intensive spectral technique. Hope you may agree with us that spectral technique is memory and labor intensive too!. Importantly, this paper proposes a 'simple' algorithm that makes use of only off-line radar spectral moments profile viz., LDR, Spectral width and Z. Systematic characterization of Z variability using the local atmospheric vertical structure knowledge besides to the theoretical, statistical, and echo tracing tools are the key components of this study.

AR1-Comment:The basis of the present technique is that the reflectivity distribution could be effective in separating insects from clouds, which may not be the case always. There could be instances when the range of reflectivities from the shallow passive clouds could be similar to the insects (refer to panels, a1 and a2 from the Fig. 13 as in Chandra et al., 2013). This study has taken into account not only the physical properties of cloud (e.g., liquid water path) but also texture signatures in the reflectivity field, the variability of the scatterers inside the radar range resolution from the spectrum width variable-one of the main predictors in insect-cloud separation.

Response: Yes, we have mainly considered the texture signature with Z. For much clairty, TEST algorithm flowchart Figure 6 at pg 6 and its explanation modified slightly at pg 7 (point 4). Agree, Our experience with one second radar data is that most of the insects density might be contributed either one or non insect in the radar beam in a second. The above figure AC1 mentioned case has been explained as Figure 13 in MS. (Figure AR2 is complementing to figure 13).

AR1-Comment:The authors would have shown the technique demonstration effectively with few figures. I feel that there are some figures (Figure 8a and 8b, Figure 11) which don't serve any purpose. Some of the references (cited in the lines 64-98) related to the clutter removing techniques implemented at other frequencies (C- S-Band) were not necessary.

Response: Yes, optimal usage of Figures has been tried. The purpose of Figure 8a and 8b in this paper is vital since it is inferring the Time-series characteristic difference between smooth meteorological cloud returns with its counterpart, noise or biota. Height time variant natures of noise and biota irregularities (more than 1 dB around mean, Z or its SD) are intermittent whereas such time variability is limited to less than 0.5 around mean Z for cloud. Also it is evident from the Figure 8 that insects de-correlation period is always less

than 4-5sec.Thus, height time variant nature of Z and corresponding SD gradient is the key for biota identification. Similarly, Figure 11 demonstrate the important polarimetric capability of the radar as well as to confirm the presence of cloud and biota using polarimetric variables.

Authors Responses

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The point-to-point AR2 responses of the authors are as below:

Anonymous Referee #2 (AR2)

AR2-Comment: I think the NER algorithm should be removed from this paper. There are much more general ways for thresholding between signal and "salt and pepper". I should be done by the radar software. so that it adapts automatically to the processing parameters.

Response: NER curves are potential part of the used algorithm required to identify the cloud peak at first place and then backtracked for to its weakly echoing boundary regions. Thus, NER curves are required for complete recovery of cloud structure (see latest figure 2 for point and volume target NER curves). Moreover, the developed algorithm is the part of our automatic off-line data processing software for the quality control of the cloud radar data. And it will also be useful for those who want to use it in the post processing data set.

AR2-Comment: I think the TEST algorithm for filtering insect echoes from the radar data is helpful if it is used in combination with LDR-filtering and or dual frequency filtering. The author comes to this conclusion in the lines around 285 and I agree to it. In the rest of the paper the algorithm is described as a standalone alternative to LDR or dual-frequency filtering. It should be clearly said that this does not work as in regions with much insects the insect signatures are as smooth as butter. There they are volume filling targets.

Response: It has been found with our numerous examples that LDR threshold alone is not able to remove all the biota (e.g., added Figure 13) but inauspiciously affecting the weak cloud portions that are not sufficient enough to excite the cross pol. channel weakest returns due to the cross-pol. isolation restriction of the antenna on the LDR values (see figure 10 and 11 and related discussions at pg 8). Therefore, TEST+LDR filtering is definitely helping for the cases when biota density is more (added Figure 14, pg 37 and its discussion at pg 10) or biota echo co-exists inside the cloud (Figure 13). Still, pure cloud returns are noted to be not possible even by TEST+LDR besides that this combination was also severely affecting the weak cloud portions. Thus, the TEST alone is found to fulfill the requirement significantly of both biota removal as well as recovery of weaker cloud

portions using NER curves excepted to cases of high number density of biota or biota existing within the cloud. The NER curves hold the key again here. However, after TEST process, to eliminate further those portions of Z values which are possible biota contamination within cloud inferring from the both LDR and SW thresholds for the preserving the true cloud returns (see Figure 13i, pg 36).

AR2-Comment: The theoretical background of the algorithm should be explained more general: actually the signal from insects has a longer de-correlation time than signal from volume filling targets.

Response: That could be apparently true if one have high density insect presence with course resolution observations. For our case, insect density is observed to be moderate and that the echo de-correlation time found to be very much shorter than cloud duration. This can be evidently seen with added figure 13, figure 14 and figure A3. Most importantly we demonstrated now with Figure 15 that cloud de-correlate longer than biota those discussion can be seen at page 11 before section 4.

AR2-Comment: The signal from volume targets is a sum of many signals with statistical phases and amplitudes which causes noise with normal distribution (central limit theorem). Therefore even if the volume is filled with stationary targets (droplets falling with different speeds, some exiting the volume, some entering) each line of of the un-averaged complex spectra is normal distributed noise with zero mean and a variance corresponding to the power in the doppler spectrum. The doppler spectra are the abs-square of the complex spectra and therefore they are still noisy. Due to squaring the distribution is transformed from normal to exponential. After averaging over 1 s this noisiness has smoothed out by 1/sqrt(nave). In contrast the signal from a single insect is not noisy at all if its SNR is large. But there is another reason causing variance in the biota signals. Typically the insects are advected through the radar beam, entering with apparent downward velocity and leaving with apparent upward velocity. The pass through time depends on beam width (deg), height, and wind speed. this causes a spiky spectra. if there are not too many insects, then there is a maximum in the variance spectrum of biota signals at 1/(pass through time). For this reason the variance spectrum of volume targets is white and for biota with moderate densities it has a maximum at the frequency corresponding to the 1/(pass through time). The TEST-procedure extracts the variance caused by biota by cancelling the high frequency variance of the volume targets by 1 second averaging and by cancelling the low frequency variance with high pass filtering the variance of reflectivities. The remaining medium frequency componets of the variance spectrum is dominated by the beam passing of the single insects, and therefore it can be used for recognising if the signal is from biota or clouds. Without understanding the author found that the test method works in many cases. In cases with too high or too low wind speed this simplified filtering may fail.

Response: The proposed algorithm makes use of time series of 0^{th} moment profile data from the Doppler spectra. So, it is essentially off-line processing of 0^{th} moment time series data for running average of below 5 seconds window. So, there is much concern on biota (insects/birds) number density within the radar sample area than wind speed (observed to

be insignificant under light and moderately dense insect condition) as for as TEST performance on off-line moments data is considered. Thus, no need to involve the atmospheric wind or biota velocity details with TEST. To give more clairty further on it, we have chosen two contrasting wind speed day where low level jet (LLJ) shows strong (weak) winds at altitude of ~ 2 km AMSL derived from radar using VAD/VPP method (see belwo figure AR3) and found that TEST filtering working well during both high and low wind speed as well (see below figure AR(4, 5) for performance of TEST).

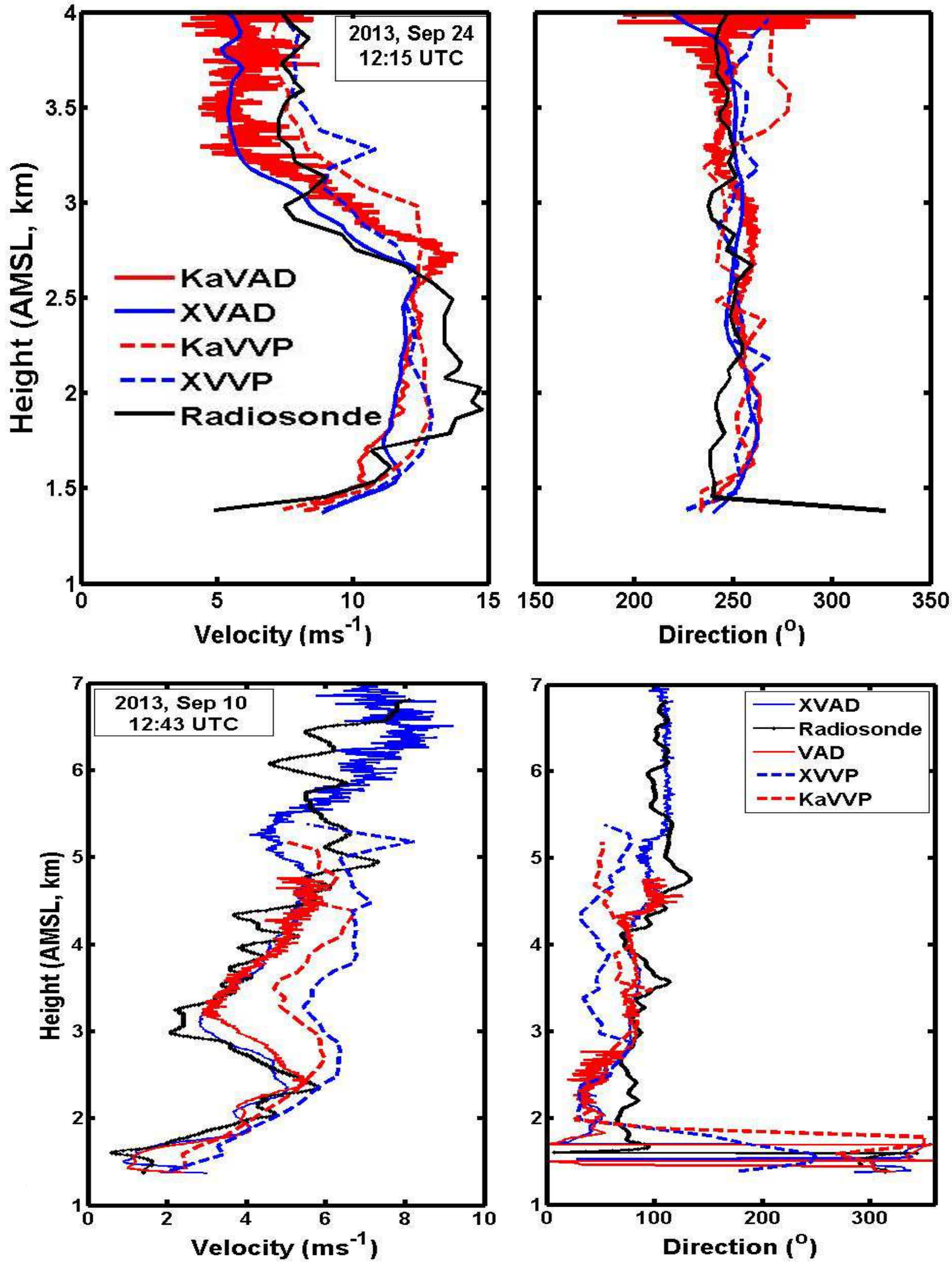

Figure AR3: VAD/VPP based wind profiles from KaSPR volume mode observations on 10 (weak ABL wind) & 24 (strong ABL wind) Sep.2013.

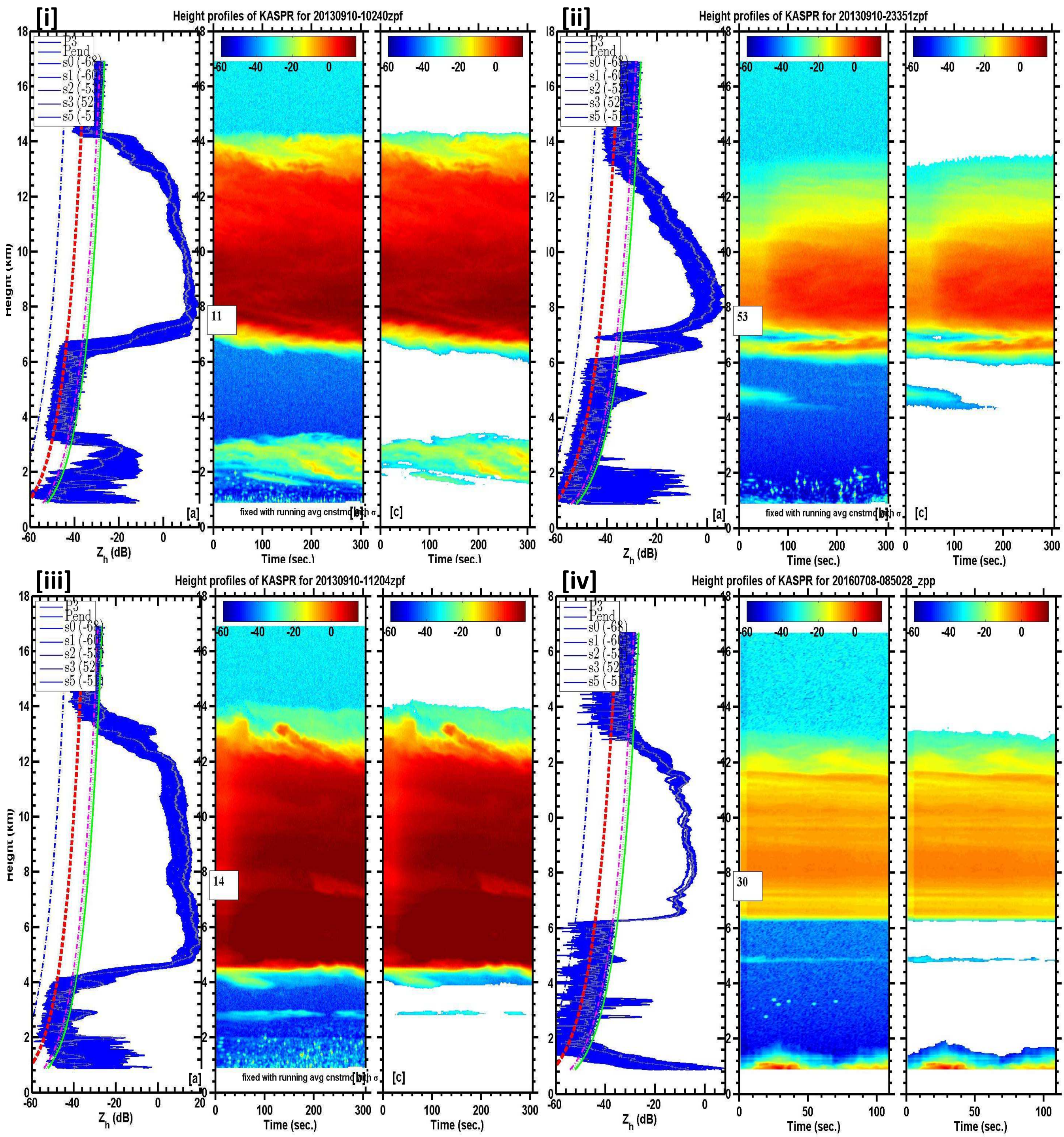

Figure AR4: TEST performance in filtering biota under strong low level Wind Speed (>10 m/s) day at 2.3 km AMSL for three cases on 10 Sep 2013 (i-iii) and case for active monsoon day on 08 Jul 2014 (iv).

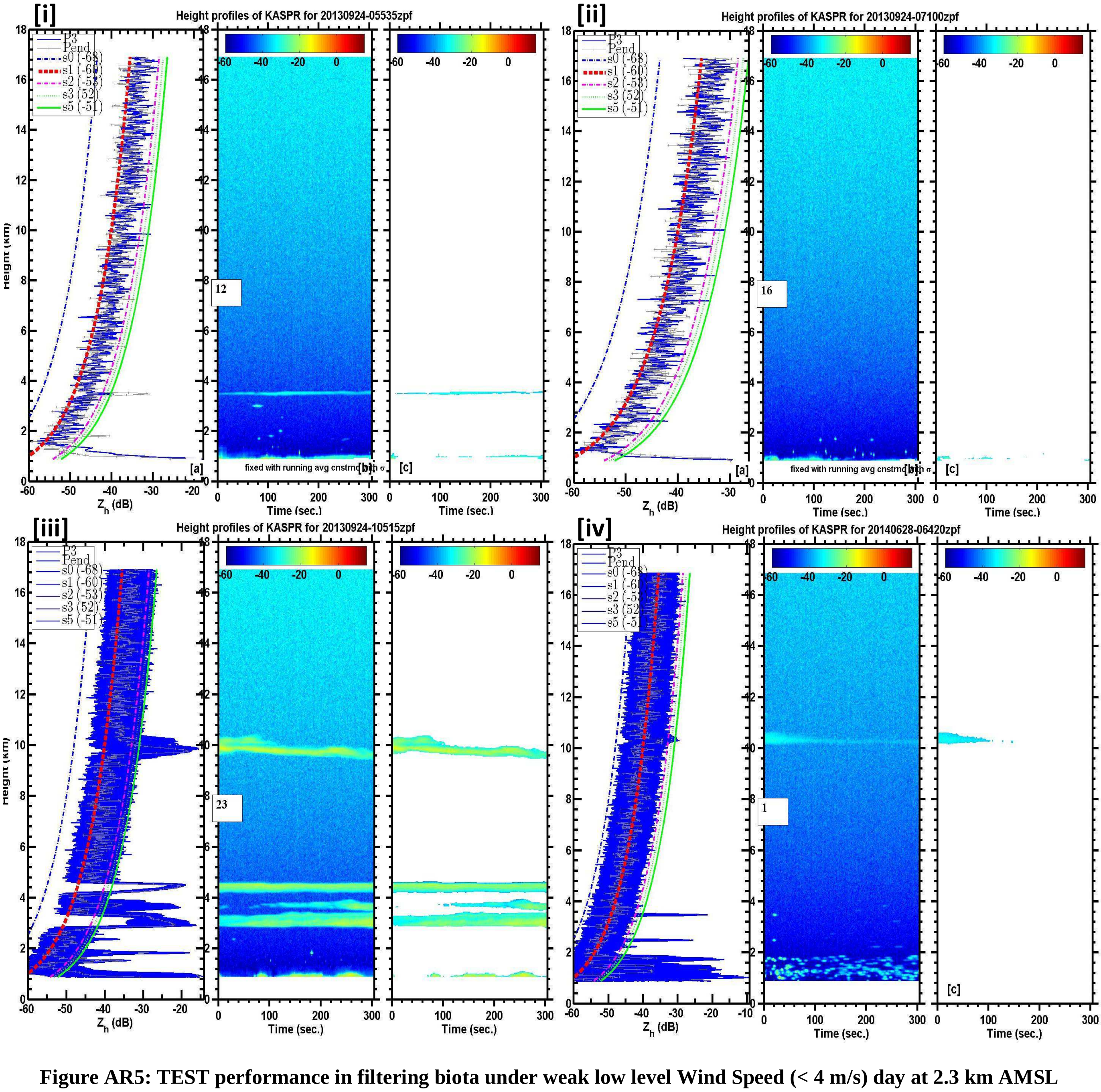

Figure AR5: TEST performance in filtering biota under weak low level Wind Speed (< 4 m/s) day at 2.3 km AMSL for three cases on 24 Sep 2013 (i-iii) and case for break monsoon day on 28 Jun 2014 (iv).

Some minor notes:

AR2-Comment:45: sensible âA˘T> sensitive

Response: Suggestion has well taken. However it cannot be seen now due to re-writing of Introduction.

AR2-Comment:56: to our experience the reflectivities of biota are below 0 dBZ, reflectivities of rain are above 0 or 5 dBZ.

Response: Okay! Correction made accordingly at line no 70.

AR2-95: T-matrics âA˘T> Rayleigh

Response: Thank you! Suggestion is implemented at line no 256.

AR2-Comment:96: I would change the sequence from large to small 1 droplets with .1 mm : -60 dBZ 64 droplets with 0.05: -60 dBZ 1e6 droplets with 0.01: -60 dBZ

Response: Thank you! sentence is modified now at line no 259.

AR2-Comment:I guess the author wants to say that hydro meteors are volume filling targets in most cases. For a single spectral component or say a single drop D size Z = N Dˆ6/V, where V is the radar volume which about 1000 to 25 000 mˆ2 depending on height, and N is the number of droplets in the radar volume. In case of single target N=1 and therefore Z_single target = Dˆ6/V or Z_volume traget » Dˆ6/V. As D can be inferred from the terminal falling velocity which is roughly the doppler velocity at least for larger droplets, it can be found by analysing data that hydrometeors are volume filling in the majority of cases. Sometimes large droplets in the beginning of a rain event are rather single targets.

Response: Yes, we assume that the hydrometeors are mostly volume filling / distributed targets. Agree that single big rain drop case could be point target but that yields very strong reflectivity where identification of cloud is much easy or exclusive in that sense that cloud echo can mask the weaker insect echo.

AR2-Comment:98: is the PRF of this radar really adjusted to such a low value. this would allow for a maximum range of 300 km which is not useful in vertically pointing mode. a prf of 7 to 10 khz is more adequate in vertical mode. this allows a much larger velocity range. but this is not relevant for the scope or this paper.

Response: Yes. Thank you! We used near 5 kHz ie., prt is around 201 micro seconds with maximum range of 30 km. Necessary change made at line 260.

AR2-Comment:I cannot understand or even guess the mening of this sentence. 126: ..more than 2 m/s and the de-correlation

Response: **Thanks you for letting us the missed clarity in writing. The mistake has been corrected at line no 290 and such needed clarity and correction can be seen with subsequent part of the MS. Regarding de-correlation, we are inferring indirectly with our time series echo coherence pertinent to biota and cloud using running average with a hypothesis (see line no 291-295) and subsequently presenting a shallow cumulus cloud presence with biota (figure 13a) case and proving the de-correlation time of biota and cloud echoes using ACF with figure 15.**

AR2-Comment:137: This method will be fully explained in the following section âAˇT> It seems it is in the rest of this section and then in the section Results and discussion beginning in line 214

Response: **Agree and implemented at line 321. Thank for the correction suggested.**

AR2-Comment:139: fixing âAˇT> thresholding

Response: **Yes, Implemented at line no 323.**

AR2-Comment:227: This is not true for cyrus clouds. The have a very soft top.

Response: **Hope AR2 means it cirrus clouds, even those clouds have soft top they have to come above the noise floor so it is equally applicable to cirrus clouds as well.**

Authors Responses

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The point-to-point AR3 responses of the authors are as below:

Anonymous Referee #3 (AR3)

AR3-Gen. Comment: Millimeter-band radars are very sensitive to detect small targets such as cloud droplets and also insects and other biological particulates (biota) present in great number in the lower atmosphere. Polarization measurement is an efficient mean to discriminate cloud echoes from non meteorological scatterers that share in common very low reflectivity. Unfortunately most radars are not equipped with polarization measurements. This short paper proposes for these standard radars a simple technique able to separate meteorological and non-meteorological echoes. It uses only successive vertical reflectivity profiles acquired by a 35-GHz radar operated at vertical incidence with a 50 m pulse length and one second temporal sampling. Because of the high spatial and temporal resolution, most of the time only one or no biota target is present in the pulse resolution volume. In contrast, cloud echo is due to millions droplets that fulfill the pulse volume. As a consequence signal variability at a given range between two vertical profiles is much more important for biota scatterers than for cloud echoes. Signal variability is given here by the standard deviation of the reflectivity over the time of five profiles that corresponds to the typical duration of the biota echoes crossing the antenna beam. The threshold value that separates distinctly biota from cloud is obtained from statistical analysis of a large radar observation set. Indeed this value should be adjusted for a radar having different characteristics. The topic of this study enters the scope of the journal and responds to a real issue for anybody who wants to extract physical quantities from radar signal. The work is put into perspective with past equivalent investigations through a large panel of bibliographic references. The work based on well chosen graphics is convincing and above all the methodology is validated with polarization measurements provided by the same radar. In conclusion this paper that presents a good scientific interest is suitable for publication in Atmospheric Measurement Techniques Journal. However this recommendation is subordinated to the authors consideration of the following comments.

Response: we are grateful to the reviewer's learned summary of the work and thankful for intimate resonance with the central idea of the paper. In fact, above concise summary is so

fascinated that it has been adopted with little changes at the last section of the Manuscript!. We do agree on the underlined reviewer statement that with little adjustment to TEST, it will be able to work with other radar (please see below figure AR6 where we drop our 1 sec Z measurements of KaSPR (MS figure 7) to every 4 second and 16 second interval

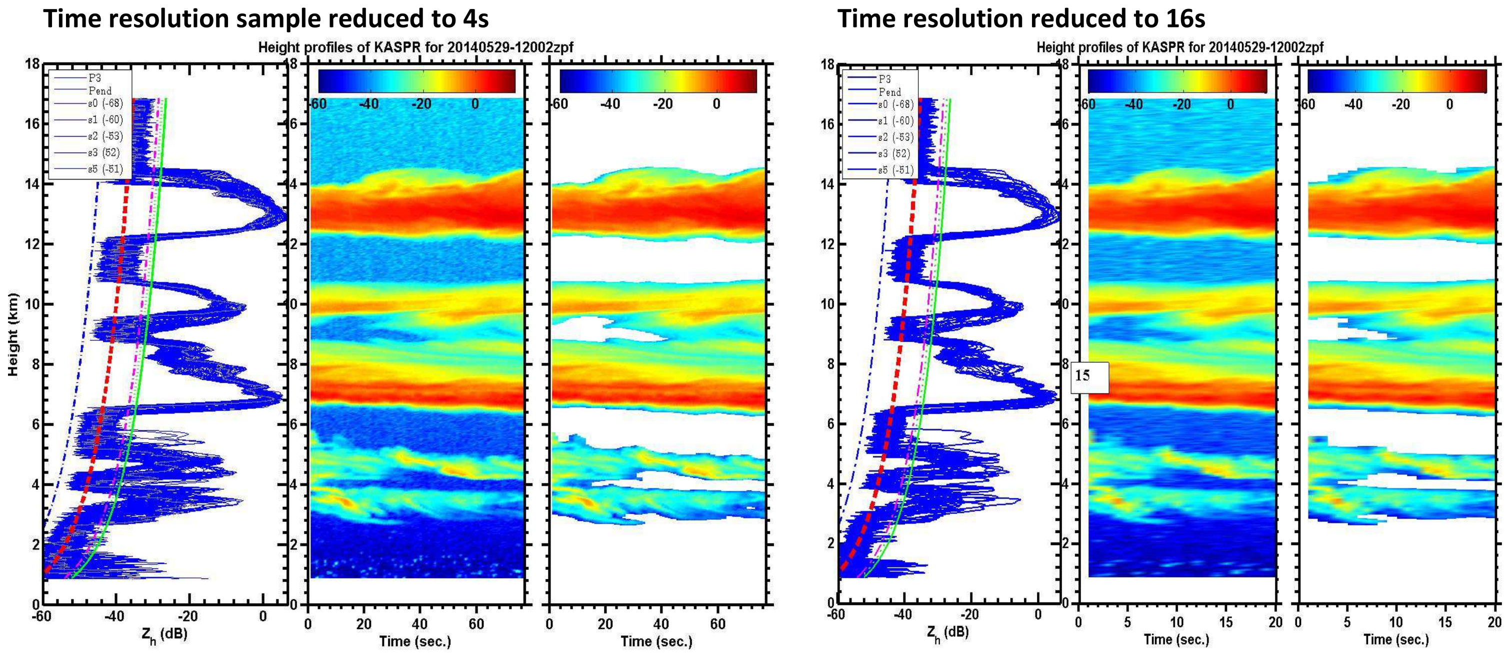

Figure AR6: KaSPR 1s (see figure 7 in MS) resolution Z profiles are re-sampled at 4s (left three panels) and 16 S. Biota echo seen differently at different time interval sampling.

Table AR1: How under above resolutions need to tackle for TEST to perform on biota

Temportal Resolution	**1 sec (KaSPR; MS figure 7)**	**4 sec**	**16 sec**
higher than S1 curve by	**3-4 dBZ**	**3-4 dBZ**	**3-4 dBZ**
σ (dB) threshold to filter biota	**5-7 dBZ**	**15 dBZ**	**20 dBZ**
Z_{ABL} (dBZ)	**-45**	**-45**	**-45**
σ_{ABL} (dB)	**0.5-0.9**	**0.5-0.9**	**0.5-0.9**

Main review points

AR3-Comment: 1) Lines 48 to 50 give the list of the source of non-meteorological echoes which comprises insects and other biological particulates (biota). The title refers only to insect and in the text the word insect is nearly always used. Even if the insects is the main source of biological echoes it is a restrictive term. I propose to use in place the word biota introduced by the authors.

Response: Agreed and implemented! Insect word replaced with biota for the whole MS.

AR3-Comment: 2)- In figure A2 strong vertical gradient of humidity is associated with the presence of cloud echoes. We may deduce that also strong refractivity index gradient exists which can be a potential source of Bragg or specular echoes. For information an explanation that this type of echoes, observable with UHF and VHF band radars, has a very low probability to be detected by millimeter-band radars will be welcome.

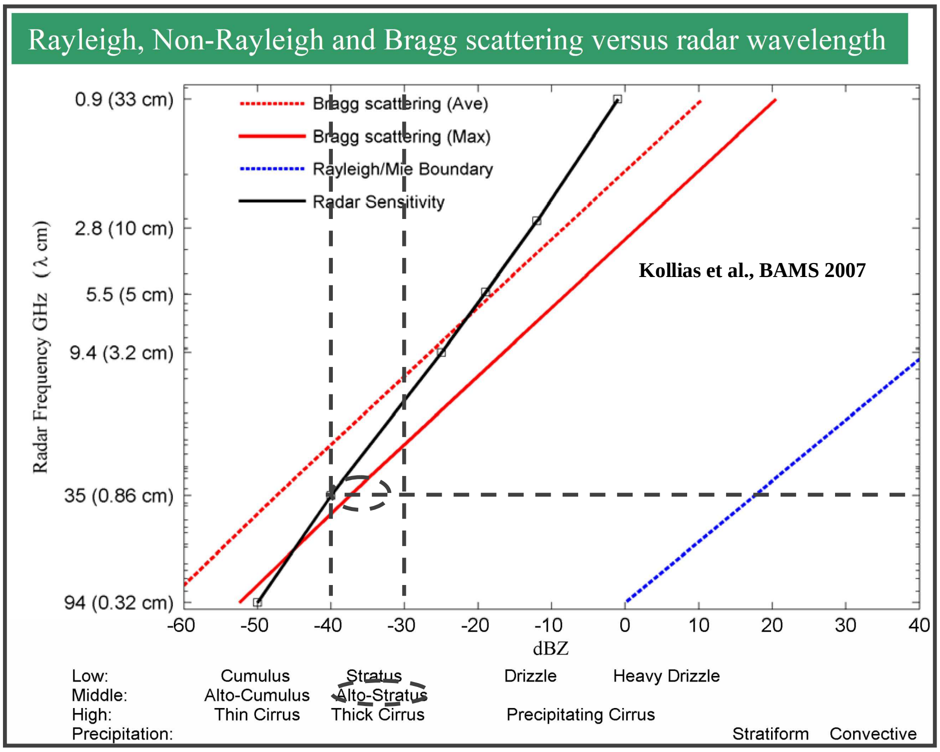

Figure AR7: Atmospheric radar echo scattering Vs radar wavelengths (taken from Kollias et al., BAMS 2007).

Response: Yes, indeed it is welcome at cloud radar to see clouds at unsaturated elevated cloud layers that is evident at relatively cooler (T ~ -10°C) height level. This may be something that with increasing altitude even relatively less RH close to above 75-80% is sufficient enough to consider as cloud possibly due to the lower saturation vapor pressure associated with predominant ice than water above the zero degree isotherm levels?! ..Speculating! Furthermore! Possible sensitivity of the 35 GHz cloud radar (~ -36 dBZ; dashed circled region with aside pasted figure AR7 (ref: figure 6 of Kollias et al., BAMS 2007)) to the strongest refractivity index gradient observed to be contributing mainly from huge water vapor gradient (of ΔRH >75% and ΔT < 2°C within ~400 m atmospheric slab centered at ~5.2 km altitude; see Figure A2 of the MS) with Alto-Stratus cloud could have been close

correct guess to this happens. This further confirms the sensitivity of the cloud radar to detect weaker shallow depth clouds.

AR3-Comment: 3)- The sensitivity of the radar is -60 dBZ at 1 km range (line 95). This value seems to me very optimistic according to the radar characteristics. Give some details on the radar calibration.

Response: Yes, KaSPR operated in zenith FFT mode with below configuration: 50 m range resolution, 25 m range gate spacing, 1:10 pulse compression ratio (0.75* 10 i.e., 75% efficient pulse compression), 5 kHz PRF, 128 FFT length/14 coherent averaging, 20 post averaging will have the minimum detectable reflectivity at 1 km is

dBZ= -20log(50) – 10log(0.75*10) – 10log(14) – 10log(√20) +4.4 = -56.3

Where difference between the calibration constant and noise floor (+55.4 – 51 = +4.4)

So, the minimum detectable reflectivity at 1 km is -56.3 dBZ (it could be -53.3 dBZ only if a 3dB threshold above Pn/(FFT length*√incoherent integration) that yields a false alarm rate of less than 1%).

AR3-Comment: 4)- May be the high radar sensitivity is due to the use of pulse compression (Table 1). If this mode is used give the effective pulse length, the code moments number and the lower range gate available for the data set presented in the paper.

Response: Yes, used the 3.3 µs pulse length with 10X pulse compression (i.e., compressed to 0.33 µs in the digital signal processor of the system). So, the radar data set used for this work has the effective pulse length of 50 m and lowest range gate available is at 942 m AGL.

In details, KaSPR employs an improved variation of the well known Linear Frequency Modulated (LFM) pulse compression technique. The KaSPR pulse compression technique is amplitude taper (window) (using a Tukey taper with 0.7 taper coefficient; Window function) on the transmitted LFM pulse and the compression is implemented in the digital signal processor system using a least mean squared filter (Mudukutore et al., 1998) to achieve much improved (lower) range side lobes, compared to un-tapered LFM pulse compressed with a matched filter. *Ref:* Mudukutore, A., Chandrasekar, V., & Keeler, R. J. (1998). Pulse compression for weather radars. *IEEE Transactions on Geoscience and Remote Sensing*, *36*(1), 125-142. DOI: 10.1109/36.655323. **These details are added now in section 2 at pg 3 last para.**

AR3-Comment: 5)- The term point target is used line 102 for non-meteorological echo. In fact a scatterer is named punctual echo when it is alone in the pulse volume. In that case echo duration is related to the time taken by the target to cross the radar beam, to its radar cross-section and its position relative to the beam axis. All these factors explain the signal variability of biota echoes.

Response: Yes, agree. In fact the word 'point' used for those biota target echo that can be seen as point/round discontinuous returns (e.g., figure 2 and figure 13 a). Further with NER curves it has shown they follow point and volume radar equation (see modified figure 2 and below figure AR8).

AR3-Comment: 6)- In fig.1, and others equivalent figures, a range (r) correction of the radar signal of the form r2 is used (line 109). It is correct for volume echoes such as cloud echoes, for point targets it is inadequate. The range correction for such backscatters has the form r4.

Response: Yes, agreed. Suitable modification has been made with the text and figure AR8 as pasted below. The suggested range correction for the possible point target is assumed to be confined mostly below 3 km altitude. These curves are also added now and shown as gray dashed curves with their start point are almost maintained. It is interesting to note that the maximum value of mean noise floor (s14; dashed grey lines) is well within s5 (green) curve that was chosen in this work to first qualify the signal above the noise floor either for cloud or insects echo which has been selected for further process to find the time coherence or correlation periods in the next stage to keep only the cloud. Thus this point has already taken care.

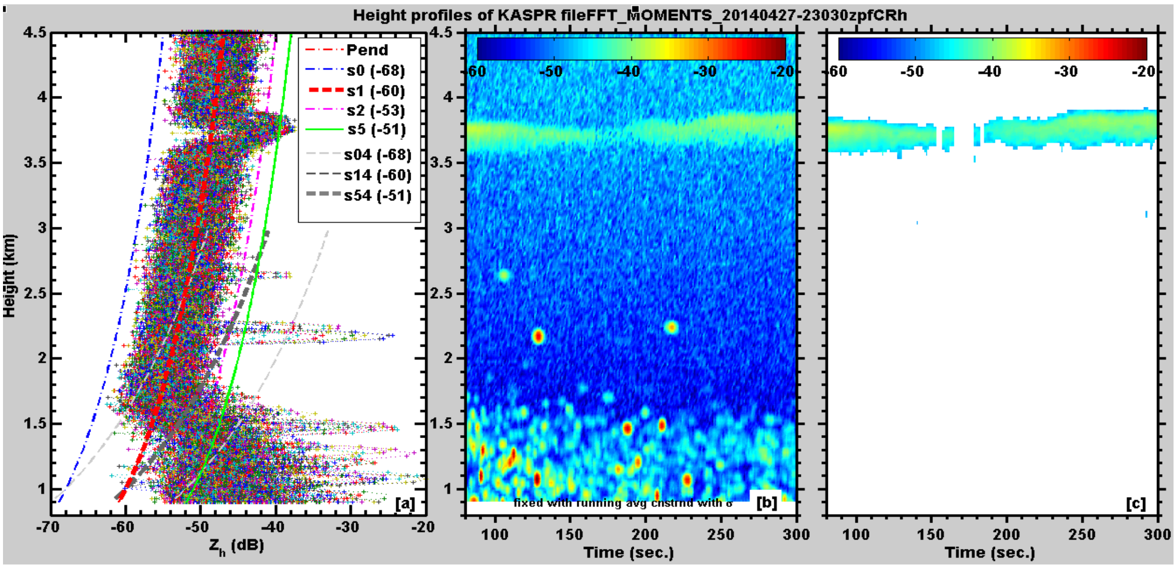

Figure AR8: Radar Sensitivity curves are now using range correction to the radar backscattering based on the volume (r^2 form) and point radar equation (r^4 form).

AR3-Comment: 7)- When there is an echo at a certain range, the signal at the receiver output is the sum of the receiver noise voltage and the detected backscattered wave. It is therefore necessary to remove the noise power in order to get the backscattered power. It is evident that this has not been done for the presentation showed in the figures such as fig.1.

Response: Yes, the only spectral moment's profile data has been used in this work (that ensure through signal to noise ratio check for having only backscattered power). This has

stated now clealry at the start of section 2. In fact, under weak or no sensible atmospheric targets within the radar sample volume of any radar range gate, the radar spectral moments computation software tracks to pick up the close by background random noise floor peak from the Doppler power spectrum. Actual cloud radar spectra under clear-air condition will have only noise floor at all FFT bins and even at all range gates. It is also quite obvious the case where there was no sensible targets in the cloud radar probing region. Under such void of sensible cloud radar target range gates, the moment's estimation code quite possible to pick up a random noise peak relatively closer to within the Doppler Spectra FFT/velocity bins based on spatial and temporal continuity information. This might have been the reason to have noise Z estimates from the zeroth moment profile. Good thing with this mean background noise is that it is helping to retrieve weaker cloud boundaries some extent using theoretical NER curves.

AR3-Comment: 8)- Line 111: Receiver noise is made of thermal noise generated within the receiver chain and also of other sources which are taken into account through the noise figure of Table 1.

Response: Yes, correction implemented at line no 275-276.

AR3-Comment: 9)- Give more details on the computation of the running mean and standard deviation (line 136) of the successive vertical profiles of reflectivity. In particular it is important to precise if these quantities are computed before or after noise removal.

Response: Mean and standard deviation of the successive vertical profiles of reflectivity (after noise removal) are computed. In fact, we used offline spectral moments data for this entire work. It is first attempted to find out the noise floor using sensitivity (NER) curves and found that S5 curve is near 3-db higher than the maximum observed noise floor of the KaSPR. Once noise is removed only those echoes are allowed which are higher than S5 curve to segregate cloud and biota. Biota point returns are mostly confined below 3 km altitude with significant shift of mean noise floor just below 1.5 km towards higher (S14 curve; based on the point target NER i.e., r^4 X $Z_{start\ range}$) but this still lies well within S5 curve (see above figure at the response of AR3 comment 6) to allow for further process to refine them using standard deviation or time coherence to determine cloud or not. Then de-correlation time of cloud and biota have been found out using running mean and standard deviation of different time interval. Cloud being an meteorological echo changes gradually and so having de correlation period more 40-110 sec. But for insects being spurious in nature it de-correlated quickly, within 4-10 sec. From this computation 4sec has been taken as a key segregator between biota and cloud.

AR3-Comment: 10)- Line 161: Receiver noise is not en echo but a signal generated in the receiver chain.

Response: **Admitted the mistake, correction implemented at 1st paragraph of Results and Discussion, line no 342, 361, 362, and 364.**

AR3-Comment: 11)- A statistical de-correlation time is introduced line 174. I do not understand very well how it is computed. I think it is related to the standard deviation of the reflectivity. Give the formula that links de-correlation time and reflectivity standard deviation. In figures 3 and in the text the unity used for the standard deviation is not given.

Response: **Yes, it is related to the 4-point running mean and standard deviation. (here SD is for Z thus its unit dBZ apply). It is hypothesizing here (provided now in MS at page 290-295) that the running mean and standard deviation of ~4 seconds reflectivity profiles (i.e., sliding interval of 4 seconds) works in identifying all non-hydrometeor returns. Furthermore, the time coherence of radar returns at every range sample can be checked for every 4 seconds as window period to infer the echo power de-correlation time or degree of coherence period associated with biota return. In order to prove this, the below figure AR9, is worked out to find the correlation where left panel represents the typical HTI plot of Z measurements for low level/ shallow cumulus cloud in the presence of biota and right panel shows the simple auto correlation function (ACF) having lag (0-300 sec) correlation corresponding to the reflectivity time series of shallow cumulus cloud (base, mid, top) and biota heights at 1.5 and 2.6 km. From the ACF analysis it is clear that biota shows quicker (~4 seconds) de-correlations periods than cloud (~ 40-170 seconds). It is also to be noted that clouds may show varied de-correlation periods above 30 seconds but insects mostly de-correlate very much less than 10 seconds. Hence, the hypothsis for TEST proves here with. These discussions and newly added figures (13-15) are can be seen with MS at page 4, 10-11 and 37-39 .**

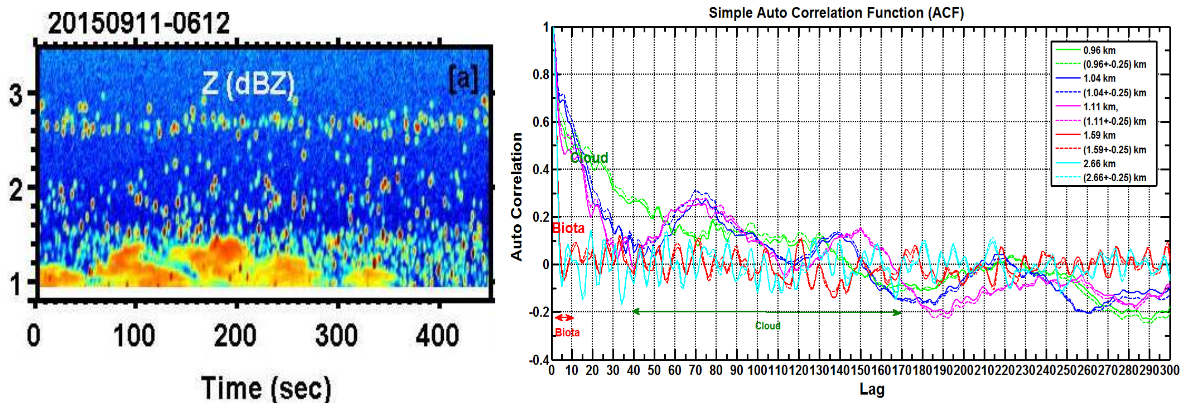

Figure AR9: Shallow cumulus cloud present with biota (HTI plot) and (right panel) is AFC based 0-300 lag correlation for cloud and biota.

AR3-Comment: 12)- lines 218 to 219 ...biota that are found to extend less than 2-4 height bins each of 25 m... : vertical spreading of a point echo is expected to extend over half pulse. How do you explain this large spreading that can approach 2 pulse lengths. Is the use of a compressed pulse that produces this increase.

Response: Yes partially. In fact, the used pulse width is 3.33 µs with 10X LFM chirp compression with sampling in range (range gate spacing) at every 25 m. So, the uncompressed range bin width of ~500 m that become 50 m after 10X pulse compression. It is quite possible that biota movement can confine sometime in-between two range gates then the biota echo spreading can confine maximum of 100 m. This could be the reason. However, small correction has now made in the MS that biota echo extends maximum of 2 range gate intervals of each 50 m or 4 range gate spacing of each 25 m. See these detials with MS at line no. 368-370, pg 6, and line no. 438-439 page 7 and modified first Para of MS Section 2.

AR3-Comment: 13)- I suppose that the radar has Doppler capability because line 263 and 264 PulsePair and Fourier Transform are cited. Doppler spectra width contains information at the pulse scale on the de-correlation time of the echoes. It could have been used instead of the reflectivity standard deviation. Did you try to analyze this quantity to discriminate echo type.

Response: Yes, KaSPR having Doppler capability and the 2nd moment velocity variance/Spectral width measurements are available. Thanks to referee that TEST results has now been able to cross checked and found that less spectral width values (~0.3 m^2s^{-2}) confirmed the shorter coherence time / short temporal correlation associated with biota. Thus TEST, used running mean and S.D from set of 4 profiles, is working to ensure the biota and cloud through their de-correlation time less than 5 sec. interval. Therefore, TEST is simple but potential because that makes use of single Z parameter but critically through to track its change both at spatial and temporal levels. However, TEST output Z needs to further constrained with SW and LDR thresholds that are found be advantageous to have best possible cloud only radar returns mainly within cloud region. New Figure 13 and the relevant discussions have been added in this regard to the MS at page 10-11.

A simple biota removal algorithm for 35-GHz cloud radar measurements

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Abstract. One of the key parameters that must be included in the analysis of atmospheric constituents (gases and particles) and clouds is the vertical structure of the atmosphere. Therefore high-resolution vertical profile observations of the atmospheric targets are required for both theoretical and practical evaluation and as inputs to increase accuracy of atmospheric models. Cloud radar reflectivity profiles can be an important measurement for the investigation of cloud vertical structure in a resourceful way. However, extracting intended meteorological cloud content from the overall measurement often demands an effective technique or algorithm that can reduce error and observational uncertainties in the recorded data. In this work, a technique is proposed to identify and separate cloud and non-hydrometeor returns from a cloud radar measurements. Firstly, the observed cloud reflectivity profile must be evaluated against the theoretical radar sensitivity curves. This step helps to determine the range of receiver noise floor above which, it can be identified as signal or an atmospheric echo. However it should be noted that the signal above the noise floor may be contaminated by the air-borne non-hydrometeor targets such as insects, birds, or airplanes. The second step in this analysis statistically reviews the continual radar echoes to determine the signal de-correlation period. Cloud echoes are observed to be temporally more coherent, homogenous and have a longer correlation period than biota and noise. This step critically helps in separating the clouds from biota and noise which show shorter de-correlation periods. The above two steps ensure the identification and removal of non-hydrometeor contributions from the cloud radar reflectivity profile which can then be used for inferring unbiased vertical cloud structure. However these two steps are insufficient for recovering the weakly echoing cloud boundaries associated with the sharp reduction in cloud droplet size and concentrations. In the final step in order to obtain intact cloud height information, identified cloud echo peak(s) needs to be backtracked along the either sides on the reflectivity profile till its value falls close to the mean noise floor. The proposed algorithm potentially identify cloud height solely through the characterization of high resolution cloud radar reflectivity measurements with the theoretical echo sensitivity curves and observed echo statistics for the cloud tracking (TEST). This technique is found to be more robust in identifying and filtering out the contributions due to biota and noise which may contaminate a cloud reflectivity profile. With this algorithm it is possible to improve monsoon tropical cloud characterization using cloud radar.

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1.0 Introduction

Short wavelength (millimeter-wave) Doppler radars are well known as cloud radars for their high sensitivity that is required to sense the cloud droplets or ice crystals to infer cloud properties at high resolution (e.g., Lhermitte, 1987; Pazmany et al., 1994; Frisch et al., 1995; Kollias and Albrecht, 2000; Sassen et al., 1999; Hogan et al., 2005). The atmospheric radar echoes in the optically clear boundary layer are mainly either from Bragg scattering through refractive index irregularities due to turbulence in the atmosphere (wind profilers; e.g., Ecklund et al., 1988; Gossard 1990) or particle scattering from hydrometeors and biota which is air-borne biological targets such as birds and insects, and waste plant materials e.g., dry leaves, pollen or dust (also known as “atmospheric plankton” or atmospheric “biota” or simply “insects”; Wilson et al., 1994; Lhermitte, 1966; Clothiaux et al., 2000; Teschke et al., 2006;). Although insects (hereafter biota) are probably the principal contaminants because of their size and dielectric constant, spiders, spider webs, and other organic materials have been detected in the atmosphere through the use of nets and other means (Sekelsky et al., 1998). Furthermore due to reduced scattering efficiency in the Mie region, cloud radar observations at 95 GHz are found to be less (~5 dBZ) sensitive to biota than observations at 35 GHz (Khandwalla et al., 2003). Cloud radar signals frequently encounter this biota, within a couple of kilometers altitude close to the Earth surface, confined mostly to the Atmospheric Boundary Layer (ABL). These echoes from the biota in the ABL have reflectivity values comparable to those from the clouds, and thus they contaminate and mask the true cloud returns (Luke et al., 2008). Though the nature of shallow clear air radar echoes was first doubtful, but later, these echoes over land in the CBL were proved to be contaminated by particle scattering from biota rather than to refractive index gradients (e.g., Gassard 1990; Russell and Wilson, 1997). Importantly the nature of clear-air echoes are a nuisance for radar based studies on CBL clouds since they may contaminate the true cloud echo (e.g., Martner and Moran, 2001). However, these clear-air echoes can be advantageous in understanding and characterizing the CBL (e.g., Chandra et al., 2010; 2013). But in order to utilise the potential purpose of cloud radar for studying clouds, one needs to identify and preserve the true cloud echoes from biota contamination that is mostly confined within the atmospheric boundary layer (ABL). The ABL shallow/ low level cumulus clouds are strongly linked to the rain making mechanism at lower region of the cloud vertical structure and hold a key factor in predictability of cloud feedback in a changing climate (Tiedtke 1989; Bony et al.2006; Teixeira et al. 2008) but their representation remain unresolved in large scale modeling. This gives rises to the need of most possible unbiased and systematic observational study of shallow cumulus cloud to unravel its morphological as well as characteristic features. Therefore, the current work focuses on identifying and filtering biota echoes in order to significantly improve the quality of cloud radar data. This allows better characterization of the tropical Cloud Vertical Structure.

Review of previous studies shows that different techniques have been attempted to remove non hydrometeor echoes, for example, static techniques for the ground clutter (Harrison et al., 2014; 2000), return signal-level correction (Doviak and Zrni´c, 1984; Torres and Zrni´c, 1999; Nguyen et al., 2008), dynamic filtering (Steiner and Smith, 2002), and operational filtering (Alberoni et al., 2003; Meischner et al., 1997). The aforementioned studies were mostly confined to the use of single polarization radar. However, a new possibility has been developed

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Deleted: sensitivity at high spatial and temporal resolutions that is used to infer important information on microphysical and dynamical structure of cloud (e.g., Lhermitte, 1987; Frisch et al., 1995; Kollias and Albrecht, 2000; Sassen et al., 1999; Hogan et al., 2005). Cloud radar, especially 35 GHz, is not only sensitive to hydrometeors (cloud particles and rain drops) but also to air-borne biological targets such as birds and insects, and waste plant materials e.g., dry leaves, pollen or dust (also known as “atmospheric plankton” or atmospheric “biota” or simply “insects”; Lhermitte, 1966; Teschke et al., 2006). Although insects are probably the principal contaminants because of their size and dielectric constant, spiders, spider webs, and other organic materials have been detected in the atmosphere through the use of nets and other means (Sekelsky et al., 1998). Furthermore due to reduced scattering efficiency in the Mie region, cloud radar observations at 95 GHz are found to be less sensitive to insects than observations at 35 GHz (Khandwalla et al., 2003). Cloud radar signals frequently encounter this biota, within a couple of kilometers altitude close to the Earth surface, confined mostly to the Atmospheric Boundary Layer (ABL). These echoes from the insect in the ABL have reflectivity values comparable to those from the clouds

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Formatted: Font: (Default) Times New Roman, 10 pt using dual-polarization information to identify the non-meteorological clutter echoes (Zrnic´ and Ryzhkov, 1998; Mueller, 1983; Zhang et al., 2005). With the advent in Doppler spectral processing, it is possible to have improved clutter mask (Bauer-Pfundstein and Görsdorf, 2007; Luke et al., 2008; Warde and Torres, 2009; Unal, 2009). As mentioned, one of the non-hydrometeor echoes is due to the insects and air-borne biota and these unwanted echoes are problematic for studies involving meteorological information such as wind measurements (Muller and Larkin, 1985) and true cloud returns (Martner and Moran, 2001). As a consequence, observations of biota were done using variable polarization and multiple frequency radars operating initially in the centimeter wavelength (Hajovsky et al., 1966; Hardy et al., 1966; Mueller and Larkin, 1985). At millimeter wavelength radar, Bauer-Pfundstein and Görsdorf (2007) showed effective LDR filtering of biota while Khandwalla et al. (2003) and Luke et al. (2008) showed that dual-wavelength ratio filters are more effective than the linear depolarization ratio filters. Dual-polarization also offers a wide variety of methods (e.g., Gourley et al., 2007; Hurtado and Nehorai, 2008; Unal, 2009; Chandrasekar et al., 2013). Fuzzy logic classification techniques for the identification and removal of spurious echoes from radar are also in use (e.g., Cho et al., 2006; Dufton and Collier, 2015; Chandra et al., 2013). From the above summary, it is therefore evident that most of the studies either concentrate on the polarimetric capabilities of radar or computationally intensive spectral processing of radar data to filter out echoes contaminated by non-hydrometeor targets. The importance of the current work presented here lies in the development of an algorithm that uses solely high spatial and temporal resolution reflectivity measurements. These high spatial and temporal resolution (25 m and 1 sec) measurements enable the characterization of irregular echoes associated with the spurious nature of radar returns due to biota. This method is simple and does not require spacious complex spectral data (and associated complicated analysis) or expensive advanced dual-polarimetric or dual-wavelength techniques.

2.0 System, Data and Methodology

This investigation employs vertically oriented Doppler spectral moments profile observations of IITM's Ka-band scanning polarimetric radar (KaSPR) for the study of vertical cloud structure. In details, KaSPR employs an improved variation of the well known Linear Frequency Modulated (LFM) pulse compression technique. The KaSPR pulse compression technique is amplitude taper (window) (using a Tukey taper with 0.7 taper coefficient; Window function) on the transmitted LFM pulse and the compression is implemented in the digital signal processor system using a least mean squared filter (Mudukutore et al., 1998) to achieve much improved (lower) range side lobes, compared to un-tapered LFM pulse compressed with a matched filter. Thus, KaSPR uses the 3.3 μs pulse length with 10X LFM chirp compression with effective range resolution of 50 m (i.e., compressed to 0.33 μs) and sampling in range (range gate spacing) at every 25 m with pulse reception frequency of 5 kHz. So, the radar data set used for this work has the range samples at every 25 m with start range gate available are at 942 m AGL. KaSPR has been providing high resolution (25 m and 1 sec.) resourceful measurements of cloud and precipitation at a tropical site (Mandhardev, 18.0429^0 N' 73.8689^0 E, 1.3 km AMSL) on a mobile platform since June, 2013. Its other main technical features are given in Table 1. KaSPR possesses sensitivity of ~ -60 (-45) dBZ at 1(5) km, it is therefore sensitive to the cloud droplet. According to T-matrix Rayleigh computations, single 0.1 mm size of target

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at ~35 GHz may have the reflectivity ~ -60 dBZ whereas, near 63 (1000000) of 0.05 (0.01) mm size is required to give the same reflectivity. Furthermore in one second if there are 5000 (pulses per second) hits on the target in the radar scattering volume, the mean of those 5000 samples at a range bin (height) will be affected by the mean characteristics of target such as composition, orientation, number density and kinematics associated with it. Therefore, it is safer to assume that the atmospheric or meteorological targets (in this case cloud particle) are distributive in nature and passive in the sense that their motion and/or orientation are in resonance with the kinematics of the background atmosphere. By comparison birds and insects are point targets in nature and active in the sense that they can change their motion, direction and orientation within a few seconds. This leads to the irregular nature of intermittent or spurious radar returns characteristic of atmospheric biota due to the much smaller de-correlation time associated with them. This study utilizes the high resolution profile of cloud radar reflectivity factor (Z) to construct the cloud vertical structures by filtering out the returns from the noise and biota.

Figure 1a represents the height profiles of 0^{th} moment (radar echo peak power) based Z on 27 Apr 2014 at 2303 UT with various theoretical radar sensitivity (noise-equivalent reflectivity, NER) curves (S0-S5; the range profile correction with the start range sensitivity value of reflectivity, i.e., $r^2 x Z_{start\ range}$, where r is range or height and Z is reflectivity, for S1, Z is -60 dBZ, for example). These different NER or sensitivity curves are utilized to qualify the observed radar returns that are indeed above the NER, the inherent radar receiver noise level. The receiver noise level is the inherent thermal noise associated with electronic components in the receiver chain and also of other sources which are taken into account through the noise figure (Table 1) and it remains approximately constant over the length of the pulse returns. However, range correction is intuitive in the radar equation due to the decrease in echo signal strength with increasing height (for vertical orientation). In order to determine the noise range in every range bin, S0 to S5 are computed and overlaid on Z. This allows for identification and characterization of the signal that overlays the background system noise level. As discussed earlier, the signal at any level may have contributions due to either volumetric meteorological cloud particulates and/or strong non-meteorological/non-hydrometeor point targets (e.g. biota). In Figure 1a the echoes at ~3.7 km and below 2 km can be marked as cloud and biota respectively as it exceeds the profile S5. The noise variations around 15 dB are mostly confined in between S0 and S2 with S1 as mean NER. Contrasting echo texture associated with the cloud and atmospheric biota is evident from the height-time-intensity (HTI) plot of Z in Figure 1b. This is a weak cloud case having reflectivity ~ -38 dBZ at ~3.7 km altitude with the presence of intermittent, non homogeneous echo texture from the biota below 2.7 km altitude. Near similar weak cloud case of -38±2 dBZ at 5.4 km altitude is confirmed as cloud with the sharp increase in relative humidity of ~ 80% at that altitude by collocated GPS-RS measurements but is not shown here (see Figure A2). Biota echoes are observed to be confined most densely below 1.7 km and fall in the reflectivity range of -50 to -20 dBZ. The observed standard deviation (S.D) is always more than 2 dBZ and in directly inferring de-correlation period of ~4-5 sec (returns due to biota are observed to vanish at an interval of ~3-8 sec; see the lower part of the HTI plot). On the de-correlation period, it is hypothesizing here that the running mean and standard deviation of ~4 seconds sliding window reflectivity profiles work in identifying all non-hydrometeor returns. Furthermore, the time coherence of radar returns at every range sample can be checked for every 4 seconds as window period to infer the

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echo power de-correlation time or degree of coherence period associated with biota return based on the S.D of Z value. Two sensitivity (S1 and S5) tests have been performed on Z profile to quantify as noise floor, biota and the meteorological cloud returns. All the tests have been affected due to the presence of non-meteorological echo due to biota even though these are mostly present in the ABL. Reflectivity values associated with the cloud boundaries are very faint and are noticed to be fall within or close to system noise floor by 2-5 dBZ. The profile S5 seems to be better in screening out the cloud echoes by 10 dBZ higher level than system mean noise floor but this can eliminate significant portion of the weakest reflectivity area at the cloud edge (Figure 1d). Apart from clouds, biota also shows higher reflectivity values than S5. Figure 1d is similar to Figure-1b except, it is completely screened out for cloud by applying typical threshold of radar system sensitivity profile, S1 and S5. In addition to this, in case of Figure 1c, contiguous set of four reflectivity profiles have been considered for computing running mean and standard deviation. The method followed to generate Figure 1c is the main objective of this paper and is outlined by the flowchart in Figure 6. This method will be explained below and results and discussion section contains its thorough information. In this case, insect reflectivity values are similar to those of the cloud but their altitude levels are significantly different. The contribution due to biota can therefore be removed by S5 curve thresholding and leaving the contribution due to clouds untouched (Figure 1d). Thus, for the simultaneous presence of cloud and biota echoes at around same altitude this NER method fails to identify the contributions separately. This NER method also fails whenever there exist sharp reflectivity changes, usually seen with cloud boundaries/edges. This issue therefore demands the development of a robust algorithm that explores the fundamental difference between cloud and biota returns so that it could be identified and separated out these factors automatically.

In order to make the algorithm more robust for running it automatically, a close re-inspection of Figure 1b infers that cloud returns are much more regular and near homogeneous when compared to biota's returns, which appears to be spurious or intermittent in occurrence. Therefore, the NER criterion works reasonably well for the case of homogeneous, isolated stable cloud layers but its robustness will be in question whenever there are vigorous and quick changes associated with cloud edge and/or structure (will be explained in the discussion of cloud 1-2 in Figure 5). An additional criterion makes the current algorithm robust for complete revival of cloud information from the Z observations by utilizing the de-correlation periods of biota (close to 3-5 sec). During this time interval significant changes are not seen within the cloud. To explore this fact, in the next section the same weak low level cloud case has been chosen further to understand the coherence period associated with cloud and biota.

3.0 Results and Discussions

Figure 2 takes the same case as in Figure 1 but confined below 4 km and 80-300 s, (left panel). The added new NER curves in gray color (S04,S14 andS54; The range correction for the point clear-air target (confined below 3 km) with the start range sensitivity value of reflectivity, i.e., $r^4 x Z_{start\ range}$, where r is range and Z is reflectivity, for S14, Z is -60 dBZ, for example). Figure 2 reveals three main type of radar signal region namely (1) consistent radar returns characterized by the smooth and gradual change(s) associated with cloud particles (at ~ 3.7 km height), (2) sharp (gradient) and spurious radar returns (at altitude below 2.7 km) due to point target(s) and (3) receiver noise

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floor. In order to locate the above signal types easily, various sensitivity or NER (i.e., S0-S5) curves have been utilized. The second type of signal is associated with a characteristic point target (which has sharp reflectivity gradient feature due to the target's limited spatial as well as temporal spread associated with the radar scattering volume). The third type, noise floor (not radar echo but signal generated in the receiver chain of the radar), is seen to be confined mostly in between S0 and S2. The right panel in Figure 2 corresponds to HTI plot where the echo texture pertinent to the above mentioned three echo types can be clearly visualized. The cloud echoes spreads in the altitude region of approximately 300 m (3.6-3.9 km) with consistent smooth and gradual evolution with its weakest and/or broken structure during 165-190s. In contrast to this the observed irregular point or rounded texture of biota echo spread is seen to be limited temporally around 3-7 seconds and spatially within two (four) range gates (range samples) size (i.e., < 100 m) with strongest reflectivity at its center. This indicates that one second temporal resolution might be good enough to see the biota as point or rounded echo texture. When biota density is more in the lower altitude levels, it is difficult to clearly identify the boundary of one point target from another. Such a scenario, though rare, can lead to misidentification as clouds. The coexistence of cloud and transient high density flocks of biota adds complexity which becomes almost impossible to discriminate. However, this issue is observed to be rare and limited to lowest altitudes only.

To investigate the similarities and contrasting features associated with various contributions to the cloud reflectivity profile, it is important to explore further the case of Figure 1. Statistical echo coherence periods associated with three types (cloud, biota and noise) have been computed for their identification and separation. Both the cloud at ~3.7 km narrow region and biota returns below ~ 1.5 km in Figure 3 are evident above the maximum noise level. Both cloud and biota parts of the Z profiles are expanded to allow for review of the mean (Figure 3b and 3d) and standard deviation (S.D or σ; Figure 3c and 3e) of Z for every set of consecutive 15 profiles. Figure 3b shows the patterns of the seven mean cloud reflectivity profiles are organized and more consistent or correlated to one another during 105 seconds, this is in comparison to less organized reflectivity profiles due to biota that are much less consistent or correlated with one another in figure 3d. Moreover, the corresponding seven σ profiles show differences for cloud that is less than 1.5 σ (figure 3c). By comparison differences in profiles due to biota are more than 4.0 σ most of the time (figure 3e). It is seen that the mean cloud reflectivity peak values gradually extend from 3.7 to 3.8 km where the corresponding standard deviation values are less than 1σ. In order to further test the minimum de-correlation time associated with cloud and biota, the averaging time is reduced to a set of 5 profiles (5 sec) with the same data (see Figure 4). In this case also, Figure 4c depicts σ for all the seven mean cloud reflectivity profiles are below 1.5 dBZ with peak <1σ. This manifests that volumetric distribution nature of cloud particles is statistically more homogeneous or show less dispersion. However, Z values associated with biota show random behavior with significant dispersion >1.5σ dBZ (Figure 4e). This high dispersion in the Z values infers that the echo due to biota de-correlates quickly within ~5 second time interval (see Figure 4d-4e). It is seen from Figure 3 that for vertical levels from 0.9 km to 1.5, the sharp peaks in reflectivity profiles and strong dispersion of > 3σ dBZ are associated with the return from biota. This is attributed mostly to the observed intermittent point target nature of biota echoes plausibly due to the rambling or meandering motion of biota within the radar sampling volume.

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Moreover, the inherent radar system noise (random in nature) dispersion is observed to be in between the cloud and biota (1.5-3.0 σ dBZ). It is evident from the top panels of Figure 3-4 that cloud reflectivity profiles show relatively consistent trend and correlation among the contiguous mean profiles computed from the set of 15 Z profiles than computed from the 5 profiles. This may be mainly due to the homogeneities or in-homogeneities associated within the chosen data sets those are independent to one and another. Therefore, in order to preserve the real time sequence of observations for the study of cloud evolution as well as to recover underlying smooth trends pertinent to natural clouds, a four-point moving or running average is applied on the time series of Z data instead of deriving a simple average. The four seconds is the optimal moving average time for yielding the best cloud results (Figure 5) by characterizing the cloud to biota echoes coherent to incoherent property during the moving average period. By this four point running average, biota echo become incoherent due to its short de-correlation period (~4 sec) whereas those echoes de-correlating over longer periods indicate the presence of clouds. To understand the degree of dispersion, along with σ the absolute deviations in mean and median values have also been analyzed. Their relation with σ is seen to be as mean absolute deviation slightly smaller than σ as σ/1.253 where as median absolute deviation smallest as σ/1.483. This work makes use of the statistical mean and σ but using above relation one can relates the present results with other statistical central tendencies of data distribution. Next, the filtering of noise and biota from the presence of cloud using the cloud radar reflectivity profile will be explored. The segregation has been carried out using theoretical radar echo sensitivity curves and statistically computed echo de-correlation periods and finally tracking the cloud echo peak to its adjacent sides till it is close to the S1 profile for the cloud height. The above set of tasks, Theoretical Echo Sensitivity and observed Echo based Statistics for cloud height Tracking (TEST), is repetitively performed on the cloud radar Z measurements under an algorithm whose flowchart can be seen in Figure 6. The algorithm used in this work is named as TEST and can be summarized below:

1. Wherever the moving mean Z values in the profile are equal to or above the S5 can be qualified as cloud or biota echo. This step ensures removal of the system noise floor.
2. Those altitude regions of the qualified echo are then further scrutinized to identify clouds using the minimum thickness of greater than 100 m (to strictly avoid biota that are found to extend less than 2 range gate each of 50 m) and mean standard deviation below 1.5σ dBZ.
3. In order to keep the identified cloud's structure, intact, the identified cloud peak(s) are tracked back on either side (towards upper and bottom heights) up to around (preferably 1-2 dBZ) the mean noise profile S1.
4. In order to remove the isolated echo floor, those are probable not cloud but the existence is due to the abrupt disconsolation at the subsequent running average by the restrictions of step 2, frequency count of Z profile has been constrained as height levels where the Z frequency count falls below 5% of total measurement duration used to drop those isolated echoes.

It is interesting to note that the cloud echo regions are always stronger and above the mean noise fluctuations i.e., S1. Therefore at the left side of the curve, S0 to S1, always appears as a void region in the 2-dimentional reflectivity

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plot wherever there is a presence of cloud, no matter weak or strong (just below 4 km in the left panel of Figure 1 and 3). This causes sharp boundary gradients between cloud and noise in the vertical profiles of Z and hence with the corresponding σ. This can be used as a visual criterion for detection of cloud.

Figure 7 is similar to Figure 1 but it represents a multi layer pre-monsoon cloud system for the period 1200-1205 UT, 29 May 2014. Various labeled altitude regions (biota, noise and cloud) of the vertical reflectivity structure show typical mean features that can be broadly classified the returns into cloud and non-cloud (biota and noise) portion. Furthermore, Figure 7 shows the typical variety of cloud layers existing within the vertical structure of tropical cloud as well as morphological features pertinent to pre-monsoon thunderstorm activity. The cirrus layer at 12-14 km shows gradual structural change having peak reflectivity values of ~ 5 dBZ. Here, the high reflectivity values contribute to form single deep convective cloud by merging with the cloud layer that exists at lower heights.

Figure 8a and 8b reveal the reflectivity time series associated with the labeled non-cloud and cloud portion of Table 2 respectively. Noise and biota shows max 2 dBZ fluctuations around the 4-point-running mean reflectivity whereas for biota the max fluctuation is 3-5 dBZ (bold solid line). It can be understood that noise values increase gradually with altitude with σ values ~ 2.3 whereas sharp boundary gradients associated with biota and ragged shallow cloud regions (cloud 1&2 in Figure 7) also show higher σ values > 3 dBZ. Stable or layer cloud regions (cloud 4 & 5 in Figure 7) show significantly standard deviation below 2σ (dBZ). Further, it is interesting to examine the time series plots for the contrasting variations between the biota and noise and cloud regions with Figures 8a and 8b. The range of dBZ variability is 4-10 for biota and 2-4 for noise and for cloud that is less than 1 within an interval of 5-10 seconds. The corresponding variability in standard deviation (S.D) is observed to be 4-10 σ for biota, 1.5-3.5 σ for noise and ~ 1 σ for cloud (<1 σ for cloud peak) except for weaker cloud regions. These statistical characteristics of all types of observed cloud echoes have been tabulated in the Table 2.

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Figure 9 demonstrates the application of the work presented here and illustrates the significant differences between the uncorrected (Figure 9a) and corrected (Figure 9b) reflectivity profiles. The peaks in frequency distribution of uncorrected cloud reflectivity profiles at just below -50 dBZ, in between -50 and -40 and just above -40 dB are the predominant contributions from noise (middle panel of Figure 9a). These noise regions bias severely the corresponding histogram frequency distribution at three different altitude levels that are associated with the Johnson's tri-modal cloud distribution (extreme right panel of Figure 9a). In order to infer the distribution of cloud reflectivity values in the various altitude regions pertinent to tri-modal cloud vertical structure (Johnson et al., 1999), the observed vertical structure is subdivided into warm or low (<3.6 km), mixed or mid (3.6 km $\geq$ altitude $\leq$8.6 km) and ice or high (>8.6 km) phase and/or level clouds. The plots of uncorrected reflectivity distribution clearly shows skewness towards lowest values of reflectivity (below -50dB, -40 dB and -30 dB for low, mid and high level respectively seen with right panels of Figure 9a). This is mainly due to the predominance of noise contribution except for the low cloud regions where the contribution of biota is also included. After applying the TEST algorithm the corrected reflectivity distribution peaks at -42dB, -35 dB and -22 dB for low, mid and high level respectively (right panel of Figure 9b) reflects the actual scenario of the cloud system. This method is simple and

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has potential to bring out the statistically significant micro- and macro-physical characteristics from meteorological information (i.e., cloud) and hence for better characterization of the cloud vertical structure over a region.

In order to test the merit of the current algorithm on filtering out the non-hydrometeor contribution with Z profile, the parametric thresholds on Pulse-Pair (PP) processed Z and few polarimetric variables profiles of the cloud radar measurements have also been considered in place of usual Fast Fourier Transformation (FFT) process. The FFT process is capable to provide only polarimetric parameter, i.e., linear depolarization ratio (LDR). Figure 10 is similar to the Figure 1 that illustrates FFT (top) and PP (bottom) processed Z profiles on 28 Aug 2014 but are 15 minutes apart from one another (0415 and 0400 UT respectively) which causes some dissimilarities in the observed three layer cloud structure between the two plots (upper and lower panel). Minimum range of the noise floor in the Z profiles (2-D plot in the first panel) is seen to be grater for PP than FFT processing. The TEST algorithm performs in a similar way for both the FFT and PP processed Z profiles and is able to isolate the cloud structure as best as possible. Figure 11 explores further the polarimetric capability of the KaSPR in separating out the meteorological/hydrometeor contribution with Z by using critical threshold on the PP-polarimetric measurements that correspond to the bottom panels of Figure 10. The top panels of Figure 11 stand for HTI plots of, three polarimetric parameters namely, LDR, Φ_{dp} and K_{DP}. Computation of LDR is inherently limited to the cross polar isolation of the radar system that is -27 dB for KaSPR. Hence, high LDR values above -17 dB are mostly seen with biota and low LDR values below -17 dB are seen with cloud. Low to lower LDR values (i.e., <-17 dB to -25 dB) are strictly confined within the peak values of co-polar reflectivity (> -10 dB) of cloud altitude regions, ~ 8-10 km. Except the inherent limitations associated with LDR, these results are in agreement with earlier reported results (e.g. Bauer-Pfundstein and Görsdorf, 2007 and Khandwalla et al., 2003). The LDR, Φ_{dp} and K_{DP} threshold values are set below -17 dB, 56^0 and -15^0 km^{-1} respectively, can be used to filter out biota from the corresponding Z profiles that are shown at lower panels of Figure 11. The threshold used for Φ_{dp} and K_{DP} are subjective depending on the observed case for better filtering of biota. These polarimetric threshold methods are although successful in filtering out the non-hydrometeor contributions but they are bound to sacrifice the weaker portion of the cloud where polarimetric computations are not perfect. Thus, polarimetric method is incapable to preserve the weaker portions of the whole cloud regions where the TEST method is noticed to perform better (bottom right panel of Figure 10). This further proves the efficiency of the proposed TEST method. This has implemented in the post-processing of high resolution reflectivity measurements. The method developed here is far simpler and provides a superior solution to filtering out signal due to noise and biota and preserve cloud data in the form of pure hydrometeor reflectivity measurements which can be used to infer the true characteristics of clouds.

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Figure 12a demonstrates further application of the current work on filtered cloud reflectivity profiles (bottom plot) by considering the six hours evolution of variety of tropical cloud systems. On 21 May 2013, a typical convective cloud system present during pre-monsoon season was observed. This event is composed of three systems, first three hours (00:00-03:12 UT) shows stratiform cloud confirmed from bright band occurrence at an altitude of 4 km AGL, convective system around 0500 UT, which is a cumulus congestus initially , and above it cirrus (ice) cloud in the altitude range of 13-14 km. The screened out reflectivity profile can therefore be utilized to fully characterize the tri-modal cloud episode as shown in Figure 12b. The mean reflectivity profile with standard deviation bars reveals the nature of important phase change regions associated with cloud vertical structure. The change in cloud processes in the cloud vertical structure is closely associated with the phase of cloud water that is strongly linked with the predominant change of temperature.

Finally, Figure 13 and Figure 14 are cases of much worthy to discuss the merits and demerits of the TEST algorithm for shallow cumulus clouds present with biota. In fact this is the concluding figure of the work where besides to the Reflectivity based TEST (first column), LDR (second column) and SW (last column) measurement of the same cloud radar are also considered. Second row panels in figure 13 are differing from first only by filtered out for noise using sensitivity curve S5 and to allow cloud and biota presence with the radar measurements. The higher level biota is noted to be much organized just above 2.5 km. Shallow ABL cloud regions show LDR values <-20 dB whereas insects shows varied LDR values in the range of -25-to -5 dB. Thus, LDR alone is not sufficient to remove all insects (figure 13e). Smaller echo coherence period associated with biota are further confirmed with less spectral width values (<0.3 m^2 s^{-2}; figure 13f). Higher spectral width values, of the order of ~ 1 m^2 s^{-2} of the cloud indicates the random motion of the smaller particles of cloud within the radar scattering volume are affected by the ABL turbulence. The discussed TEST algorithm (fig 13g) is able to screening out the cloud and filter out the biota part significantly. Further, TEST fails to isolate relatively stronger biota returns exits within the cloud due to the missing of strong reflectivity gradient (both in short intervals of height and time scale) which fails to give needed high standard deviation values to filter out those. In order to ensure those as biota and then to isolate those returns, the LDR values larger than -14 dB and SW values much smaller than 0.5 m^2s^{-2} have been chosen here. Identified isolated biota returns outside the cloud by TEST and the above critical thresholds with LDR and SW are found to be similar significantly excepted at few places. It infers that, using threshold value alone either with LDR or SW measurements threshold value fails to filter out all biota returns due to either persistent low LDR or high SW values associated with those biota. However, it can be seen with figure 14 (similar to figure 13 but a typical case of high number density of biota noticed on 10 Sep 2013 during 0738-0742 UT) that TEST alone unable to remove biota (figure 14g) but using LDR it becomes much promising (figure 14f). Furthermore, in case of weakly turbulent cloud portions, they posses near comparable lower SW values as that of biota, under such condition it is complicated to screen out clouds using SW along (see figure 14i). Similar way, LDR alone is observed to be difficult in filtering all biota and screen out weak clouds. However, these two diverse and independent radar parameters, Doppler spectral width and power based polarimetric LDR measurements of KaSPR will be an additional measures on the identification of cloud to non-hydrometeor echoes of the radar.

It infers from all the above discussions, that the biota presence has been confirmed more than one way by considering LDR that infers the liquid body presence in the atmosphere (cloud particle, bird or insect), small spectral width values infers less velocity variance or spread within radar sampling volume. Small velocity variance associated with biota is obviously due to the sole presence of air-borne biota that usually takes advantage of

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dynamics of the atmosphere (initially for flight up by the convective updrafts and later by advection for horizontal flight at higher levels). Moreover, the velocity spread due to biota is very limited to smaller value than volumetric small cloud particles those are in general relatively light weight, high in number density and more vulnerable to small scale local turbulence or entrainment process which gives rise to higher spread or dispersion of velocities to have high spectral width values observed with cloud particles associated with shallow cumulus cloud. Considering all these facts, It is interesting to note that the combined TEST, LDR and SW yields best cloud alone results than any other combination where both cloud and biota co-exists within radar sampling height. Clouds show high spectral width values ~ 1 m^{2}s^{-2}. Lower spectral width values pertinent to biota infer that velocity variance of scatters within radar scattering volume is predominantly due to the presence of airborne biota (without much flight maneuver). This could be the reason to have much smaller time coherence or degree of correlation of Z value with biota is much smaller (e.g., 4-5 seconds) than clouds. Thus biota echo de-correlation times are small or quicker at the transmitted pulse scale. In order to confirm the precise de-correlation periods associated with the observed biota and cumulus clouds (figure 13a) that are assumed to be vertical radar transact across ABL, simple auto correlation function (ACF) has been used with the time series data of Z corresponding the biota at 1.59 and 2.66 km and cloud levels at lower/base, mid and top (single range gate (solid line) as well as averaged to its top and bottom range gate (dashed line). The ACF's lag, 0-300, correlations for the cloud and biota are clearly seen with figure 15. Thus, from the ACF analysis it is clear that biota shows quicker (~4 seconds) de-correlations periods than cloud (~ 40-170 seconds). Moreover, it is interesting to note that single height level (solid line) observations are showing relatively weaker correlation than averaged (dashed line) one, this is much significantly seen with cloud echoes that confirms that clouds are have high degree of phase coherence, mainly because of clouds are wide spread (both time and space) in nature, that becomes additive to have high correlation than single level whereas for quickly de-correlating biota or random noise there is no much difference between them. Thus, clouds show varied de-correlation periods above 30 seconds but biota mostly de-correlate very much less than 10 seconds. Hence, the hypothsis proposed for TEST is proved here with.

4.0 Summary and Conclusions

Millimeter-band radars are very sensitive to detect small targets such as cloud droplets and also insects and other biological particulates (biota) present in great number in the lower atmosphere. Polarization measurement is an efficient mean to discriminate cloud echoes from non-hydrometeor scatterers that share in common very low reflectivity. Unfortunately not all radars are equipped with polarization measurements. This paper proposes for these standard radars a simple technique able to separate meteorological and non-meteorological echoes. It uses only successive vertical reflectivity profiles acquired by a 35-GHz radar operated at vertical incidence with a 50 m pulse length and one second temporal sampling. Because of the high spatial and temporal resolution, most of the time only one or no biota target is present in the pulse resolution volume. In contrast, cloud echo is due to millions droplets that occupy the pulse volume. As a consequence signal variability at a given range between two vertical profiles is much more important for biota scatterers than for cloud echoes. Signal variability is given here by the standard

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deviation of the reflectivity over the time of four profiles that corresponds to the typical duration of the biota echoes crossing the antenna beam. The threshold value that separates distinctly biota from cloud is obtained from statistical analysis of a large radar observation set. Indeed this value should be adjusted for a radar having different characteristics. This study responds to a real issue for anybody who wants to extract physical quantities from radar signal. The methodology used is validated with polarization measurements provided by the same radar.

It has been demonstrated that high resolution vertically oriented zeroth moment (reflectivity) measurements of cloud radar are solely assured to segregate the hydrometeor and non-hydrometeor contributions with it. Theoretical noise equivalent reflectivity curves are used to remove the system noise and importantly for recovering the weak cloud boundaries that are very closely hidden within the mean noise floor (curve S1) of the radar system. The simple statistical variance of continual radar echoes show the contrasting different characteristic of signals like high dispersion (more than 2σ) is associated with the highly spurious and intermittent echoes of biota and low dispersion (less than 1σ) is associated with coherent nature of echoes of cloud hydrometeors and for noise it is in between 1.5 and 3.0 σ. Furthermore, these characteristic features are mainly holding a key to demarcate the returns of cloud hydrometeor to those from biota and noise. Running mean and standard deviation of off-line reflectivity profiles for ~4-5 seconds that works well to filter out all non-hydrometeor returns. In this way, the time coherence of radar returns at every range sample was checked for every 4 seconds as off-line window period to infer the de-correlation period associated with biota that show promise in identifying and filtering out the biota returns. The proposed TEST algorithm evaluates the observed cloud radar reflectivity profiles with combined theoretical radar sensitivity curves and statistical variance of radar echo and then tracks the cloud peak at either side to obtain the complete cloud height profile. In case of azimuth and elevation radar surveillance scans (PPI and RHI, for example), there is a regular change in the radar sampling area that disables to have exclusive set of measurements required to perform the TEST method. But this method is advantageous and easily adaptable for better characterization of any high-resolution vertical profile measurements. The robustness of TEST is also proved through polarimetric and spectral width measurements and found that that works much better, particularly within the cloud region, at the cloud radar frequencies. TEST constrained using LDR found much promising under high density biota condition whereas superior performance of combined TEST constrained with both LDR and SW has witnessed with highly turbulent shallow convective clouds. Such scrutinized reflectivity profiles have been further utilized to investigate the important CVS pertinent to the various phases of the Indian Summer Monsoon with the aim of improved prediction. Hence, the proposed TEST algorithm is able to extract the possible unbiased meteorological cloud vertical structure information with the cloud profiling radar. This enables carrying out the pragmatically effective research investigations on the seasonal and epochal tropical cloud characteristics.

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Figure Captions

Figure 1. (a) Vertical looking cloud radar measured sample ten reflectivity height profiles on 27 April 2014 during 2303-2308 UT. S0 to S5 are the theoretical noise equivalent reflectivity curves with their respective threshold values in bracket. HTI plot of (b) the same reflectivity profile for the duration of 306 sec (c) screened out reflectivity profile for the receiver noise floor and the biota (insects) using running average constrained with standard deviation (d) constrained with NER (S5).

Figure 2. (left) Same as 1(a) but for 220 profiles. Extra NER curves here in gray color (S04, S14 and S54) are computed on the basis of the point target radar equation (i.e., $r^4 x Z_{start\ range}$, where r is range and Z is reflectivity, e.g., S04, Z is -68 dBZ) (right) HTI plot of Z profiles. Smoothly varying homogeneous cloud layer is at altitudes of 3.5-3.8 km and sharp, rounded and spurious kind of echoes below 2.7 km are due to biota.

Figure 3. (a) Same as 1(a) but for 105 profiles. (b) mean and (c) standard deviation of 15 profiles of Z pertinent to cloud height region (3.5-3.9 km) and (d) and (e) same as (b) and (c) but pertinent to biota height region (0.9-1.5 km).

Figure 4. Same as Figure 3 but for total duration 35 sec; the mean and standard deviation profiles are for every 5 second interval.

Figure 5. Same as Figure 3 but for total duration 10 sec; the mean and standard deviation profiles are for 4-point-moving average.

Figure 6. TEST algorithm flow chart that identifies and filter-out the biota and noise echoes for screening-out the cloud contributions with the Z measurements.

Figure 7. (a-c) Same as 1(a-c) but on 29 May 2014 during 1200-1205 UT for the duration of 306 sec. Statistics corresponds to the labels on the Z profile can be seen in Table 2.

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Figure 9b. Same as 9a but it is corrected by filtering out noise and biota. The correction applied to Z profile allows to pop-up the true meteorological cloud reflectivity distribution.

Figure 10. Same as 7 but for vertical looking KaSPR measurements at 0400 UT on 28 Aug 2014 using (top) FFT processing (bottom) 15 minutes prior one using PP processing. PP case will be used further to evaluate the polarimetric algorithm performance.

Figure 11. HTI plots of (top panel) LDR, Φ_{dp} and K_{DP} parameters pertinent to PP processed data of Figure 10 and (bottom panels) biota filtered reflectivity after applying corresponding polarimetric thresholds of the respective top panels.

Figure 12a. (Top) Same as Figure 7b (uncorrected) and (bottom) same as Figure 7c (corrected) but integrated for duration of 0000-0630 UT taken at an interval of ~ 15 minutes on 21 May 2013

Figure 12b. Same as Figure 9b but excluding middle panel for the corrected Z data of figure 12a.

Figure 13. Cloud radar measurements of reflectivity (Z), LDR, Spectral Width (SW) with noise (a-c) and filtered out for noise using S5 curve (d-f), TEST algorithm screened output Z for clouds (g), g + biota filtering using LDR > -14 dB (h), h + SW filter for biota using SW < 0.5 m^2s^{-2} (i).

Deleted: **Figure 13.** Cloud radar measurements of reflectivity (Z), LDR, Spectral Width (SW) with noise (a-c) and filtered out for noise using S5 curve (d-f), TEST algorithm screened output Z for clouds (g), g + biota filtering using LDR > -14 dB (h), h + SW filter for biota using SW < 0.5 m^2s^{-2} (i). ¶
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Table 1: KaSPR specifications

Radar specifications	value
RF output frequency	35.29 GHz
Peak power	2.1 kW
Duty cycle	5 % max.
Pulse widths (selectable)	3.3 µs (50-13000 ns)
Pulse compression ratio	1:10 (1-100)
Range gate spacing (resolution)	25 (50) m
Transmit polarization	H or V-pol linear; Pulse-to-pulse polarization agility
Receiver polarization	Simultaneous Co- and Cross-polarization linear
Receiver noise figures	2.8 dB min
Sensitivity at 5.0 km	-45 dBZ
Tx & Rx loses	1.15 & 0.3 dB
IF output to digital receiver	90 MHz
Antenna diameter	1.2 m
Antenna Beam width	0.5^0
Antenna gain (includes OMT loss)	49 dB
First side lobe level	-19 dBi min.
Cross-polarization isolation	-27 dB

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Table 2: Statistical mean and standard deviation of cloud radar reflectivity corresponds to the selected height regions, which are labeled, on the Figure 7.

Label	Mean Z for 305 sec (4 sec) dBZ	σ for 305 sec (4 sec)
Biota (1.2-1. 7 Km)	-54.1(-55.0)	4.08 (3.4)
Noise 1 (2.1-2.4 Km)	-52.9 (-52.4)	2.33 (1.9)
Noise 2 (5.9-6.2 Km)	-44.4 (-44.2)	2.22 (2.3)
Noise 3 (11.1-11.6 Km)	-39.1 (-39.1)	2.30 (2.2)
Noise 4 (14.7-15.2 Km)	-36.7 (-36.9)	2.29 (2.2)
Cloud 1 (3.7-3.9 Km)	-36.2 (-28.3)	5.99 (12.7)
Cloud 2 (4.8-5.1 Km)	-31.8 (-22.7)	5.54 (4.5)
Cloud 3 (6.8-7.2 Km)	-0.4 (0.3)	2.60 (3.5)
Cloud 4 (9.8-10.2 Km)	-10.9 (-9.9)	2.03 (3.1)
Cloud 5 (12.8-13.2 Km)	3.1 (1.4)	0.86 (1.0)

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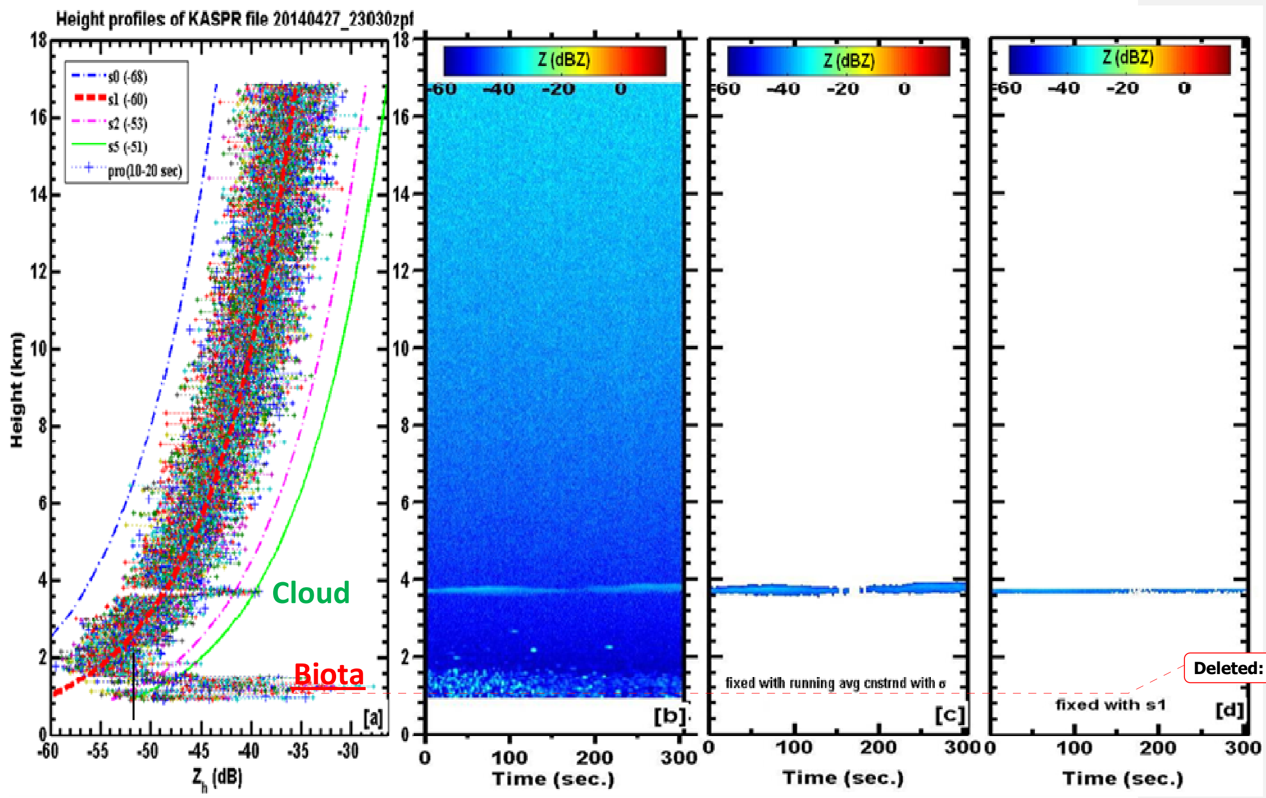

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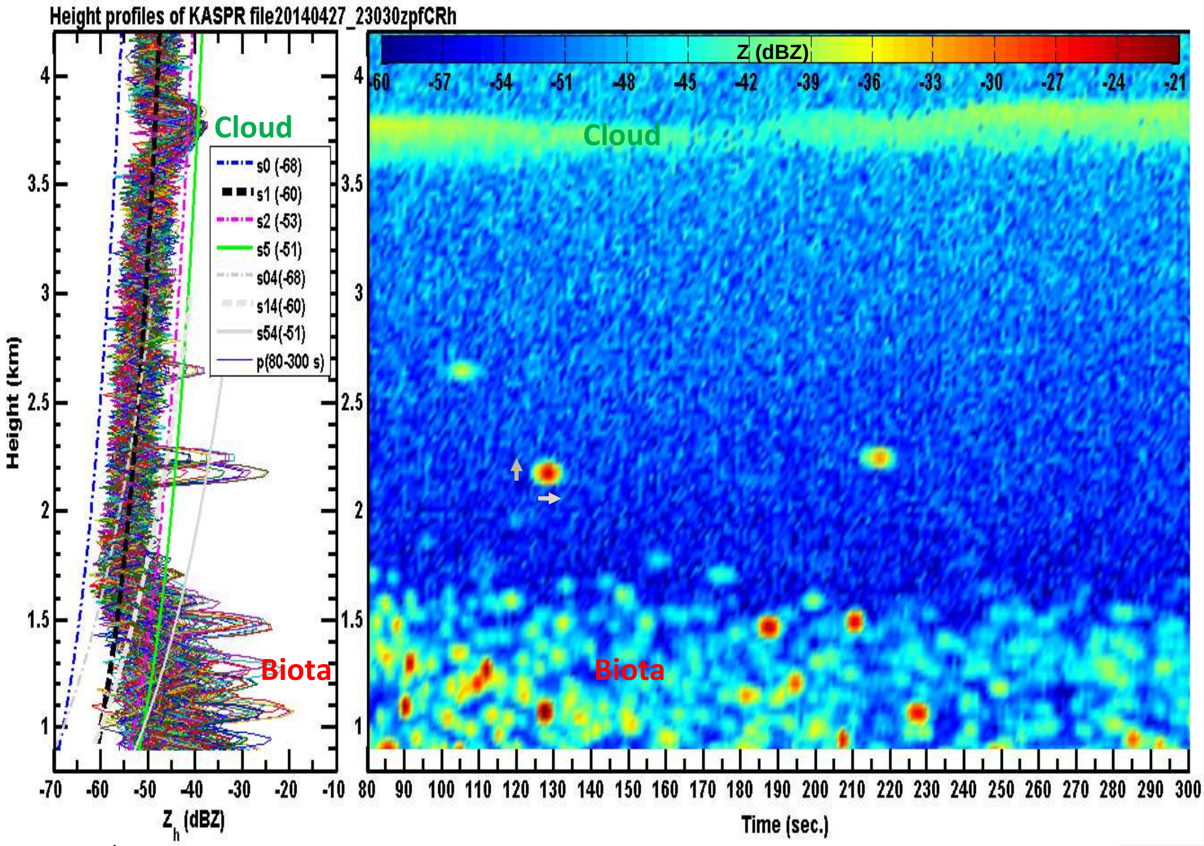
Figure 1: (a) Vertical looking cloud radar measured sample ten reflectivity height profiles on 27 April 2014 during 2303-2308 UT. S0 to S5 are the theoretical noise equivalent reflectivity curves with their respective threshold values in bracket. HTI plot of (b) the same reflectivity profile for the duration of 306 sec (c) screened out reflectivity profile for the receiver noise floor and the biota (insects) using running average constrained with standard deviation (d) constrained with NER (S5).



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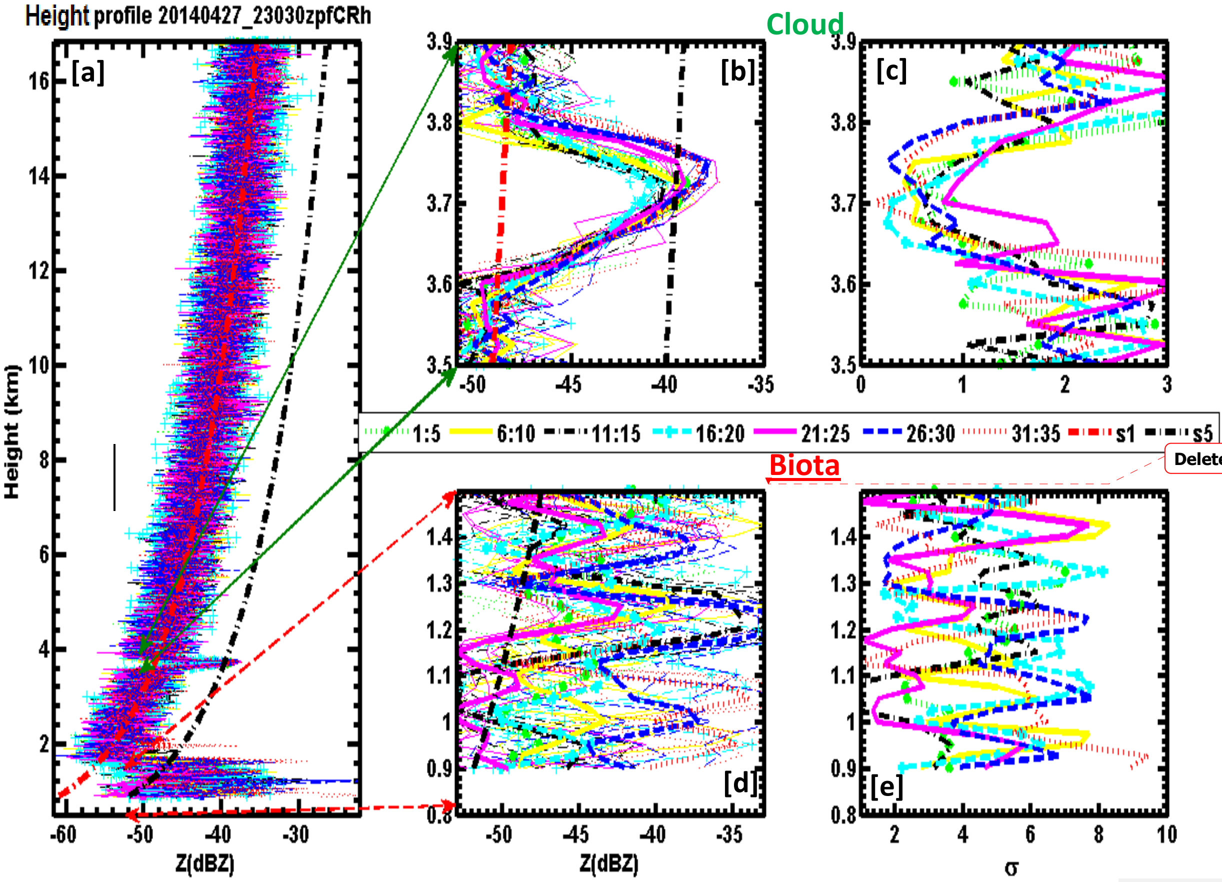

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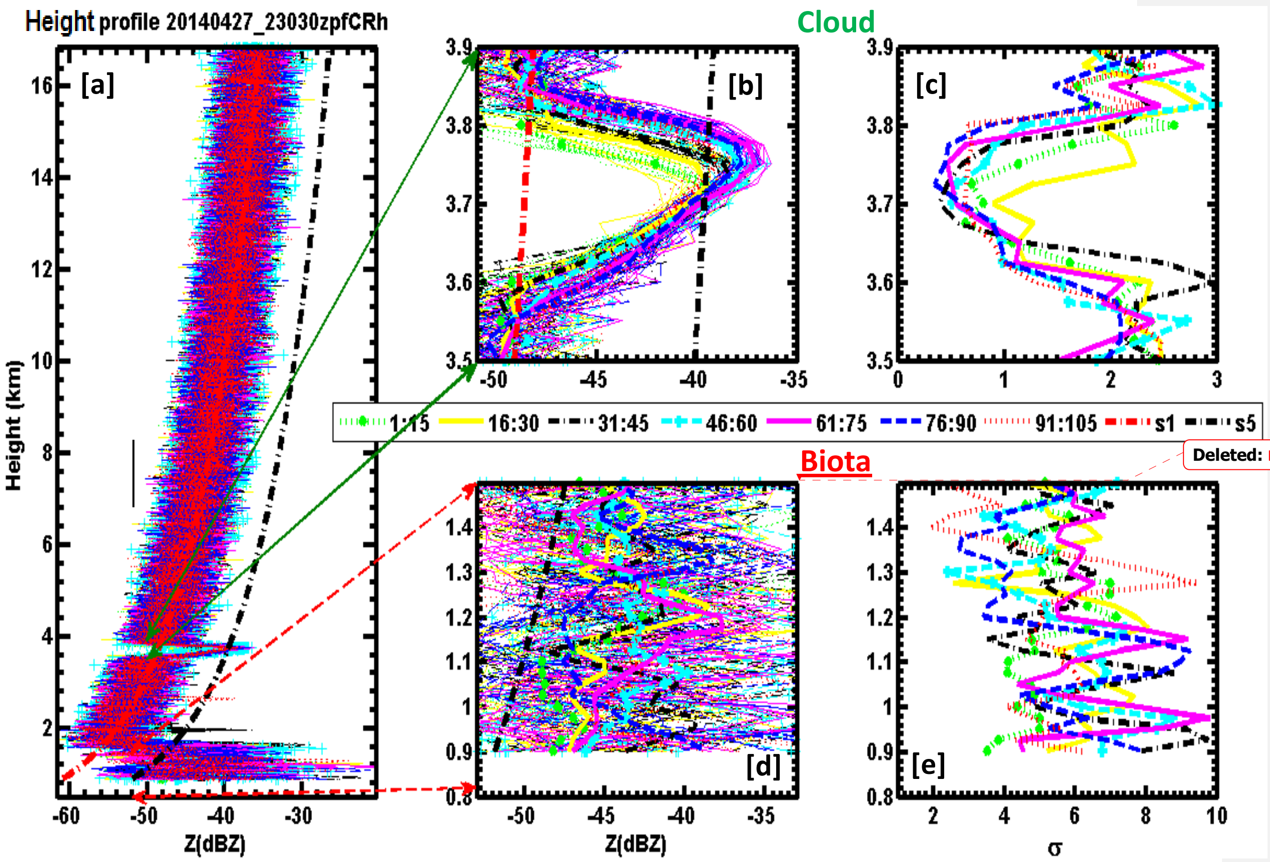

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Figure 4: Same as Figure 3 but for total duration 35 sec; the mean and standard deviation profiles are for every 5 second interval.

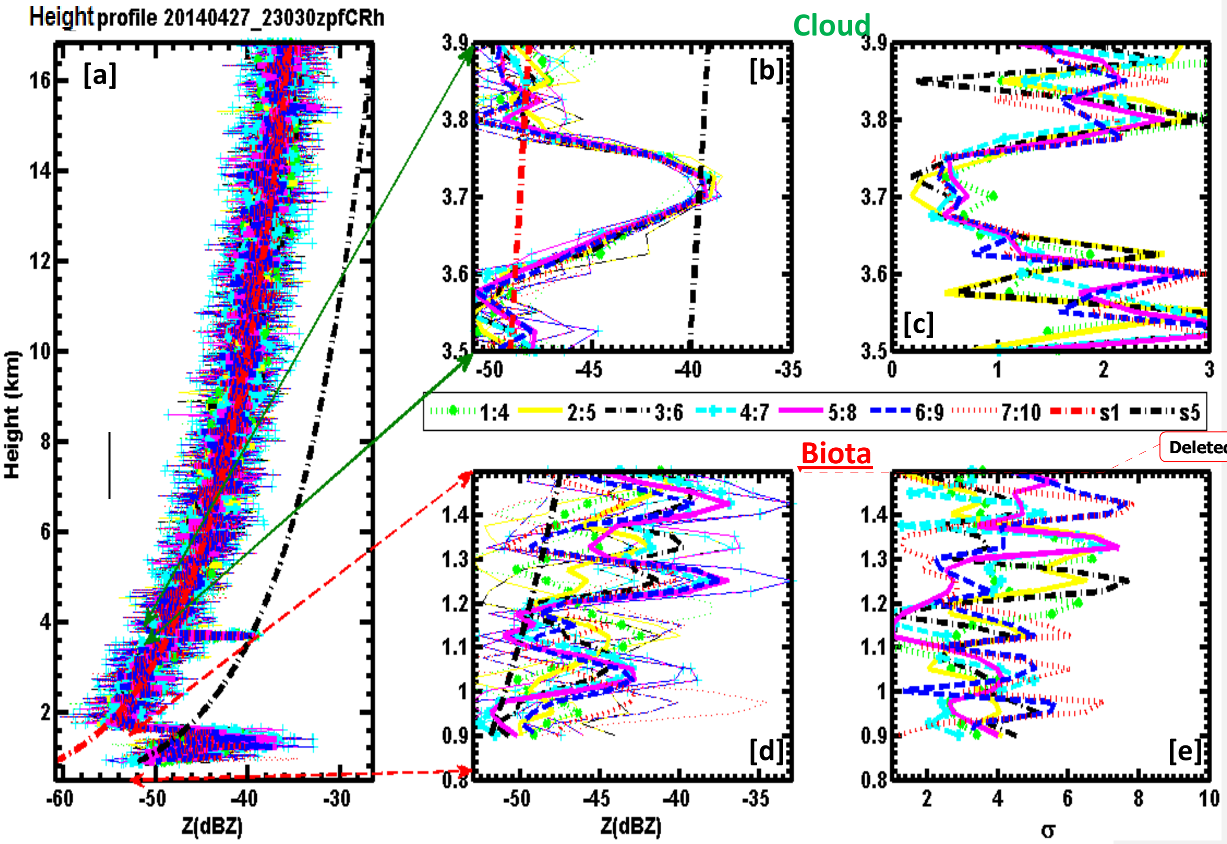

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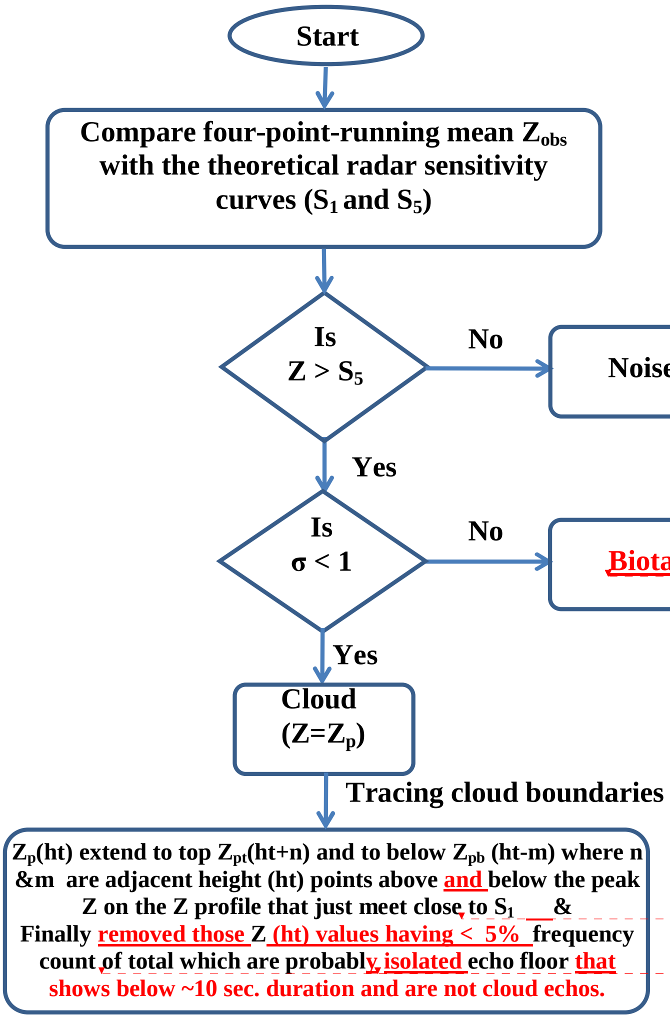
Figure 5: Same as Figure 3 but for total duration 10 sec; the mean and standard deviation profiles are for 4-point-moving average.



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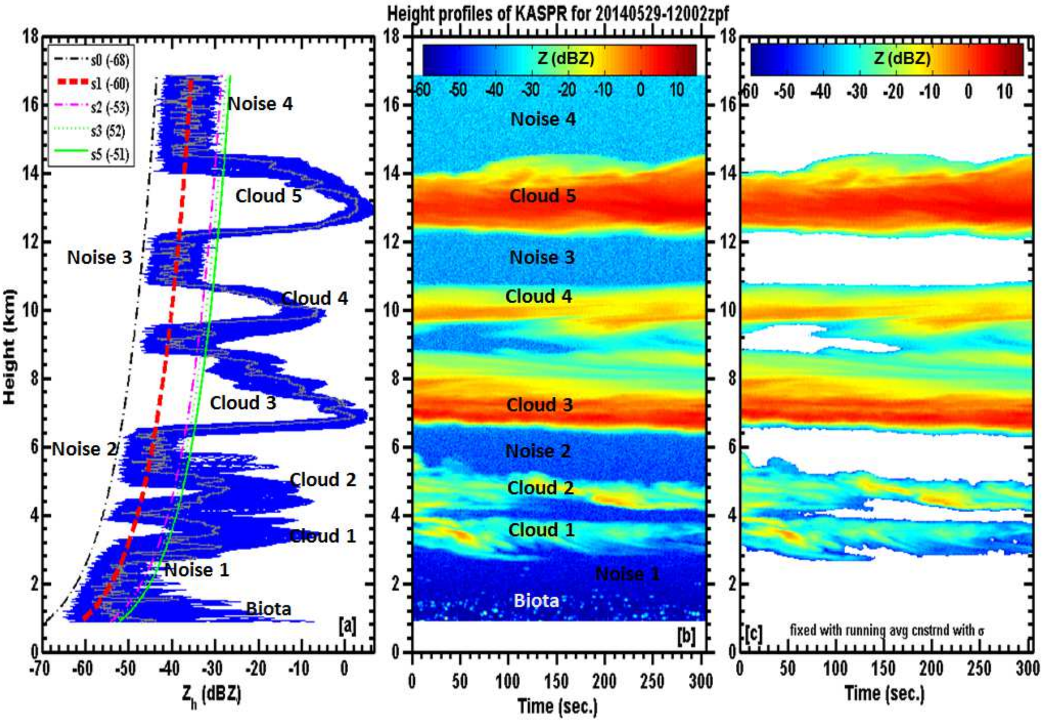

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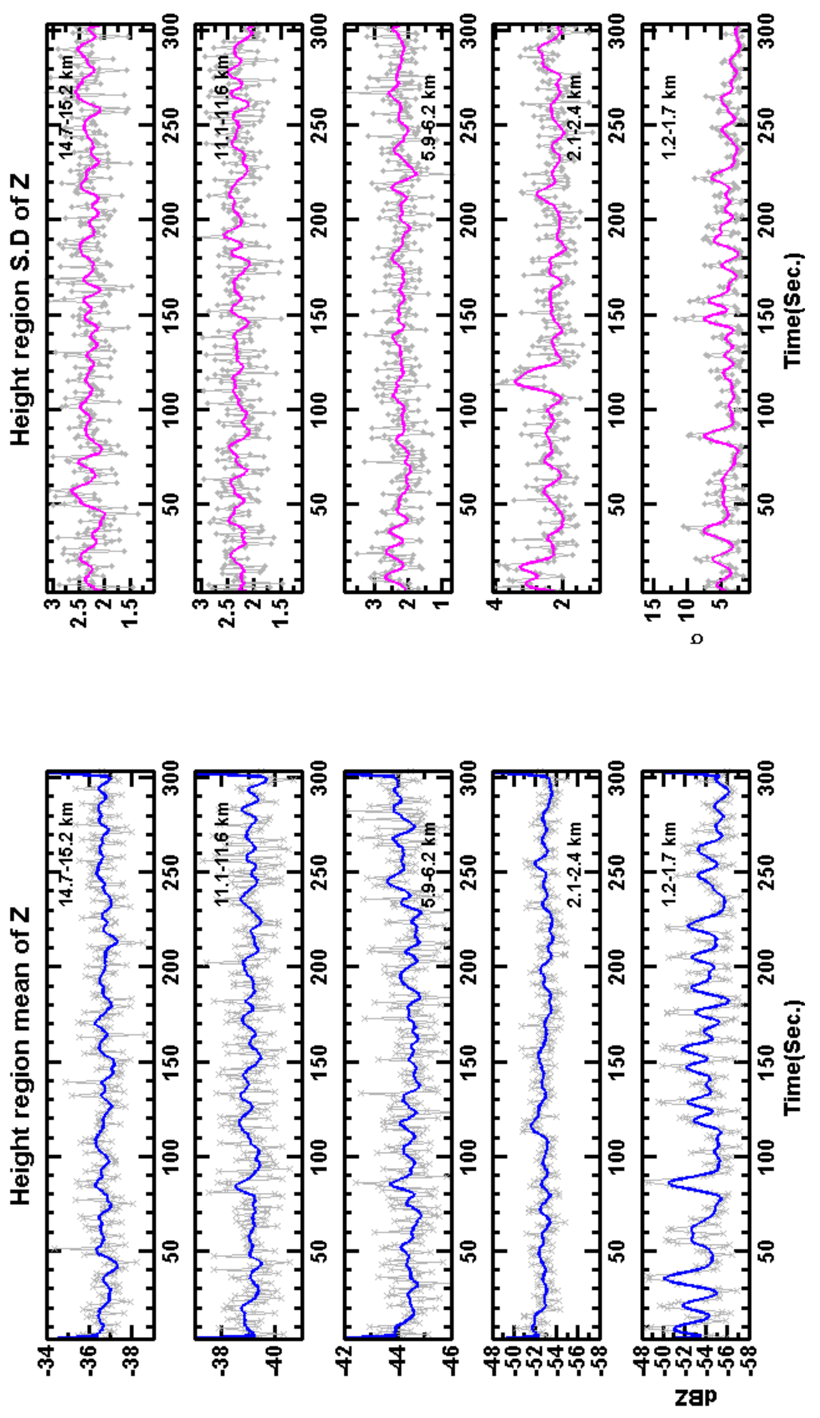

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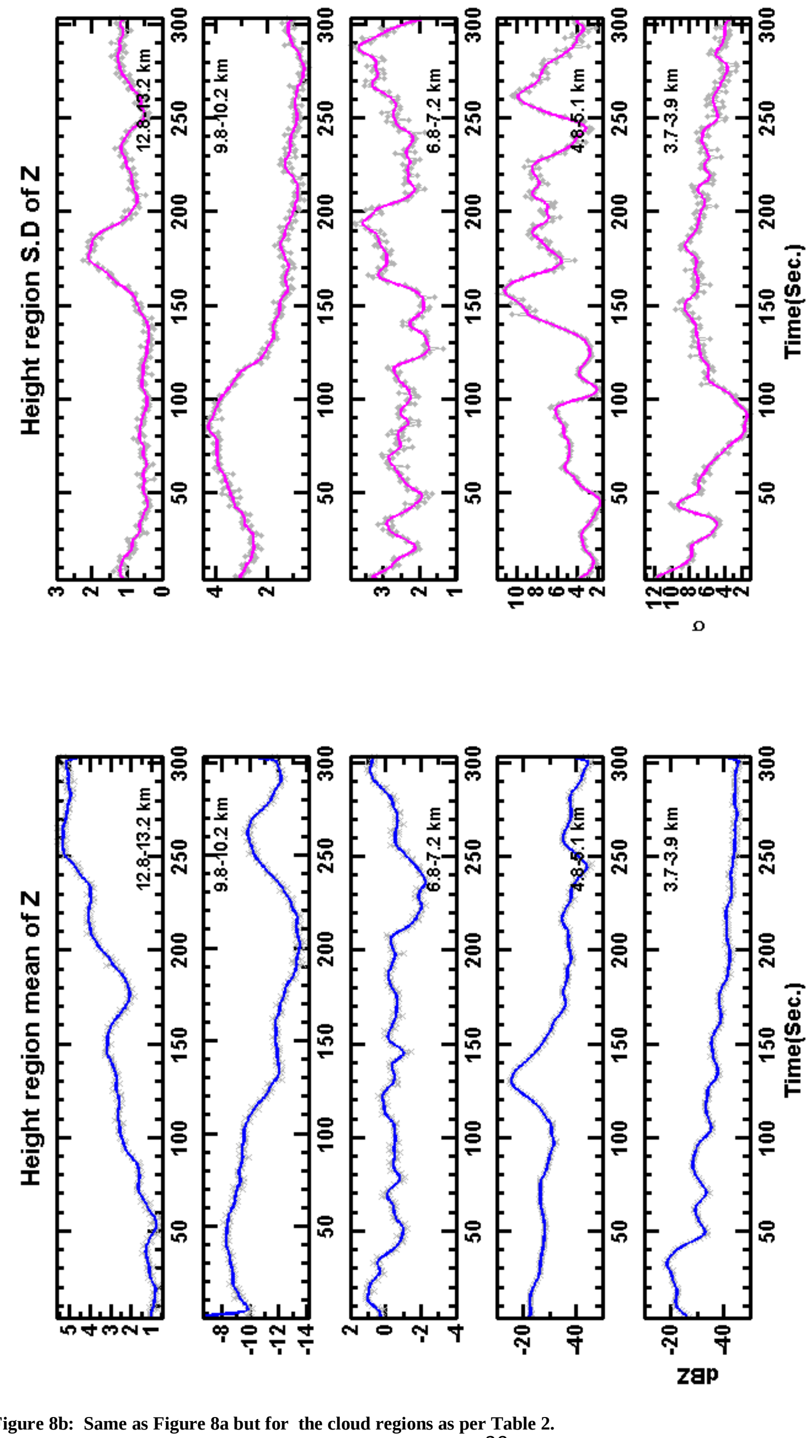
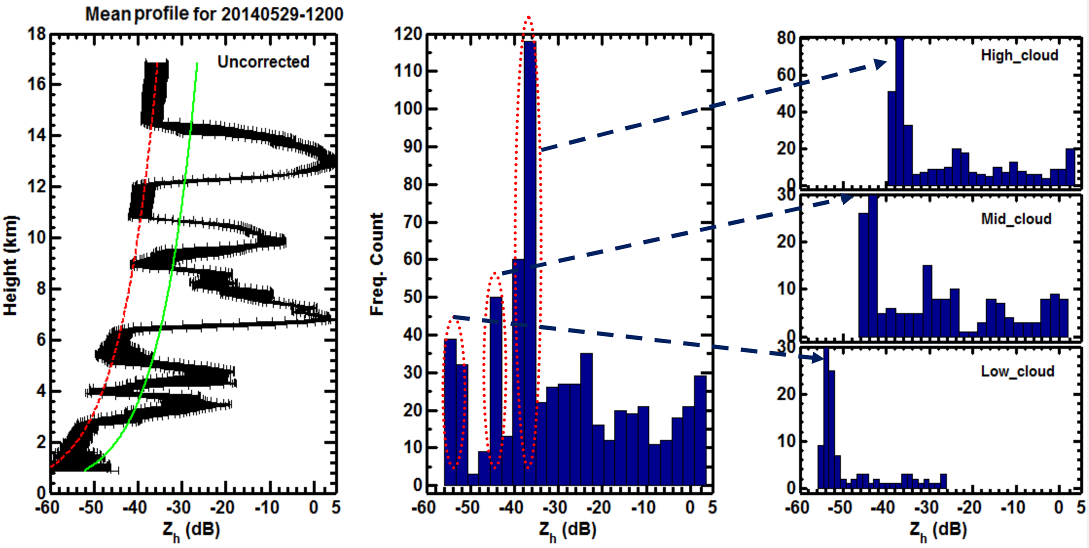


Figure 8b: Same as Figure 8a but for the cloud regions as per Table 2.



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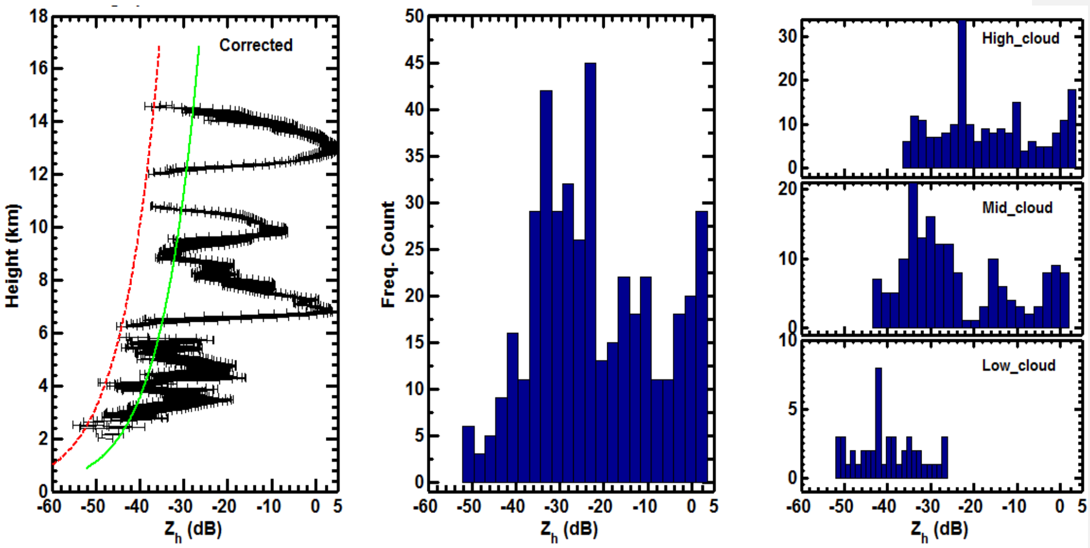

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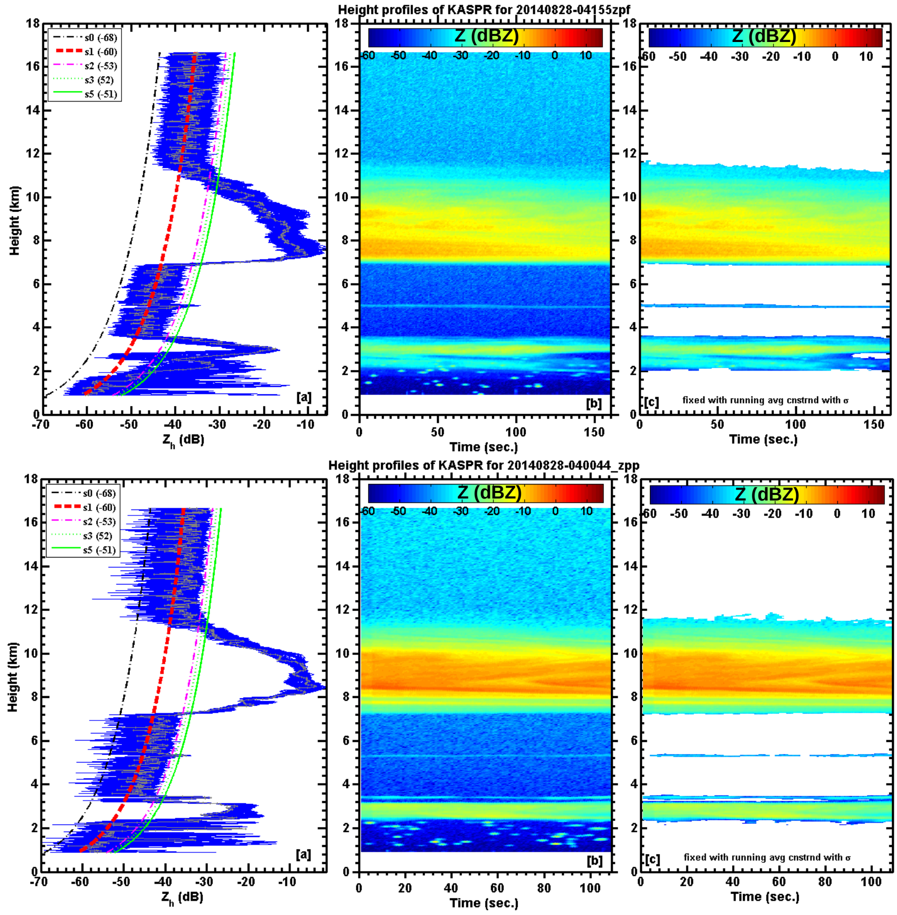

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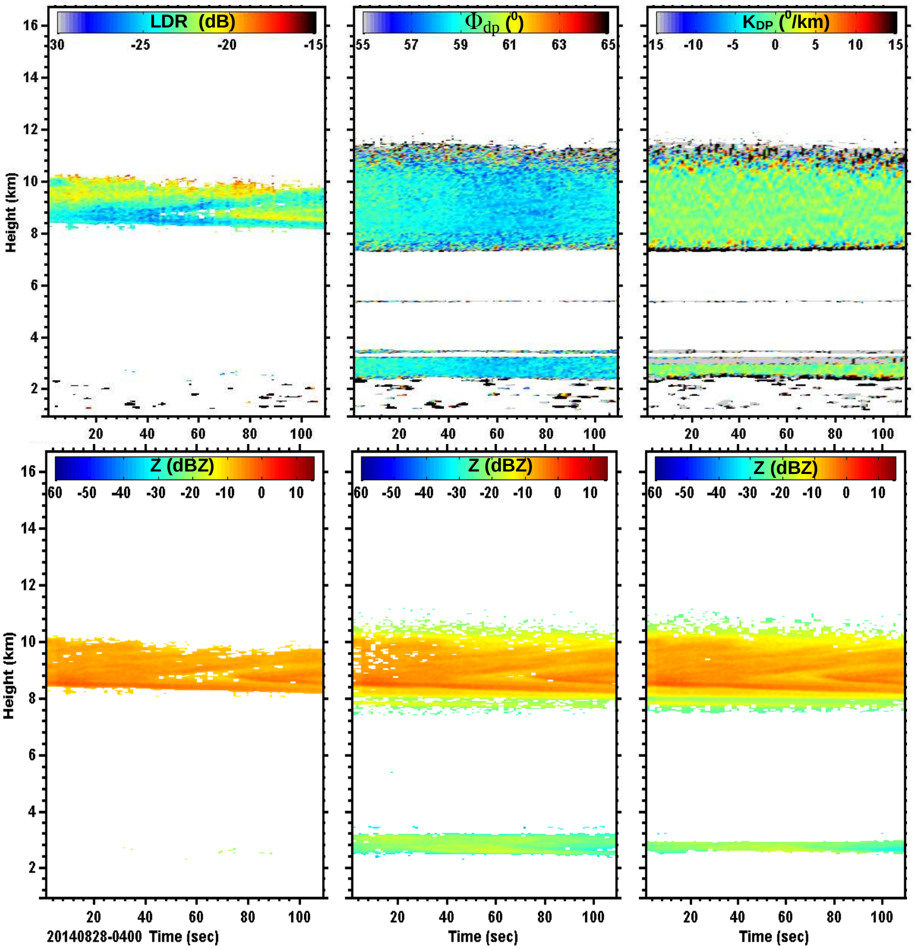

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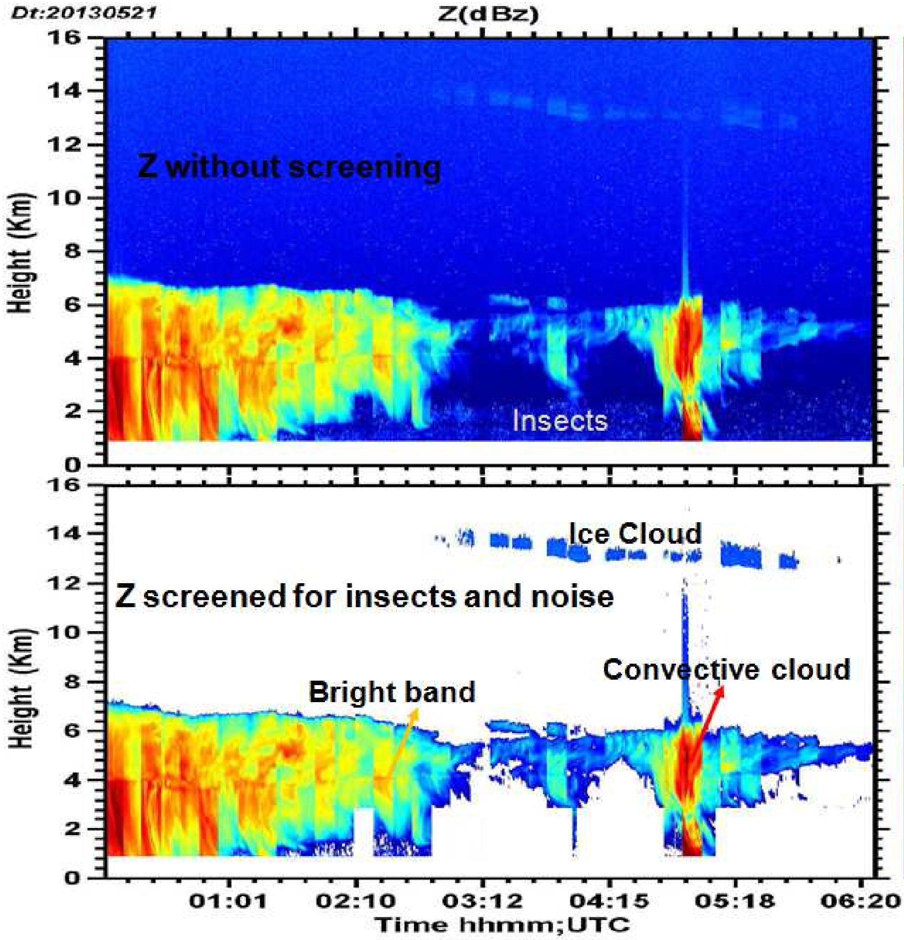


Figure 12a: (Top) Same as Figure 7b (uncorrected) and (bottom) same as Figure 7c (corrected) but integrated for duration of 0000-0630 UT taken at an interval of ~ 15 minutes on 21 May 2013

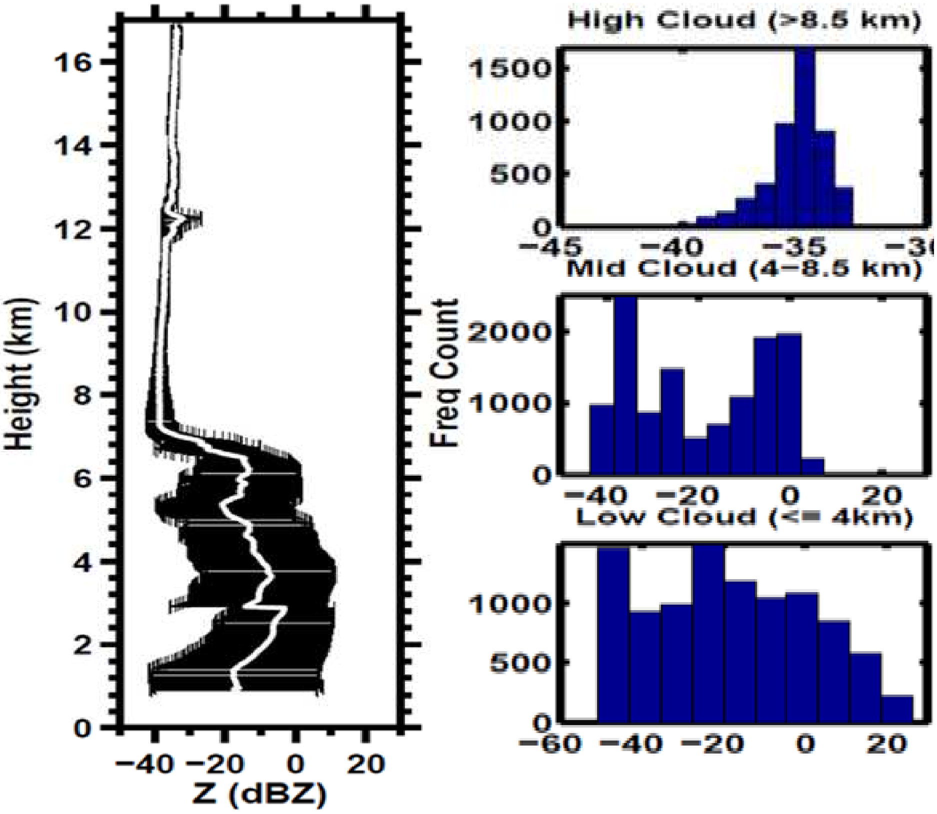
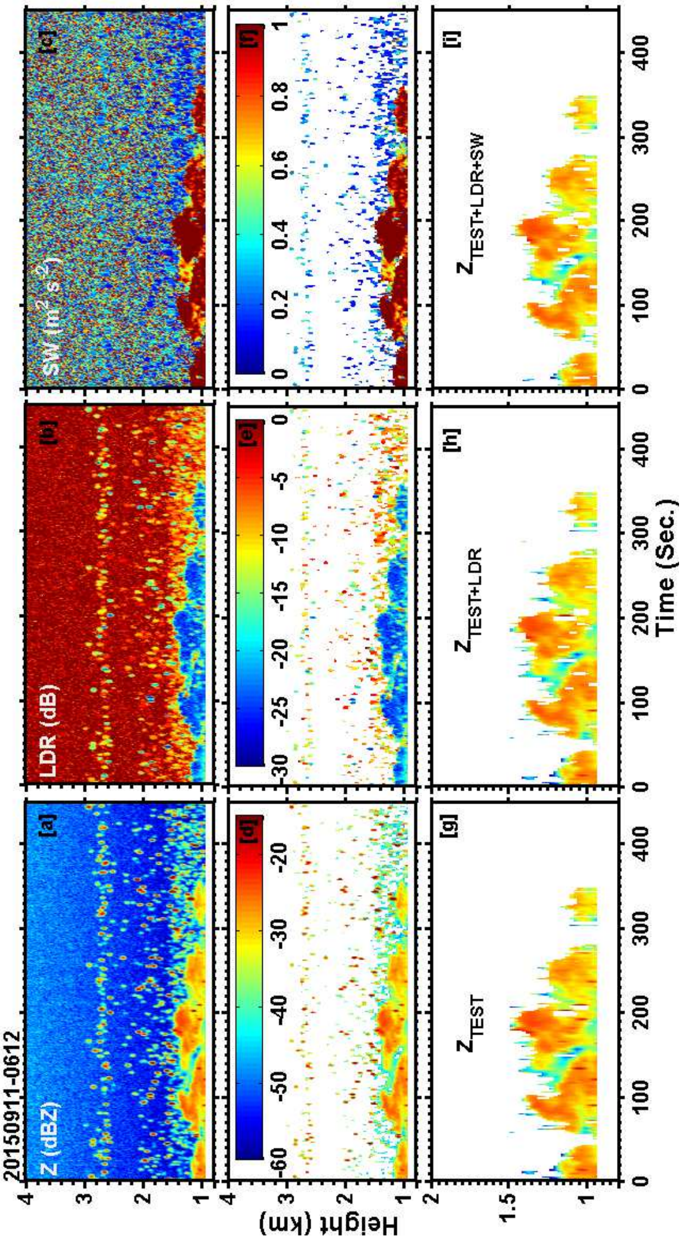


Figure 12b: Screened-out cloud radar reflectivity mean and standard deviation profile with the tri-model cloud reflectivity frequency distribution.



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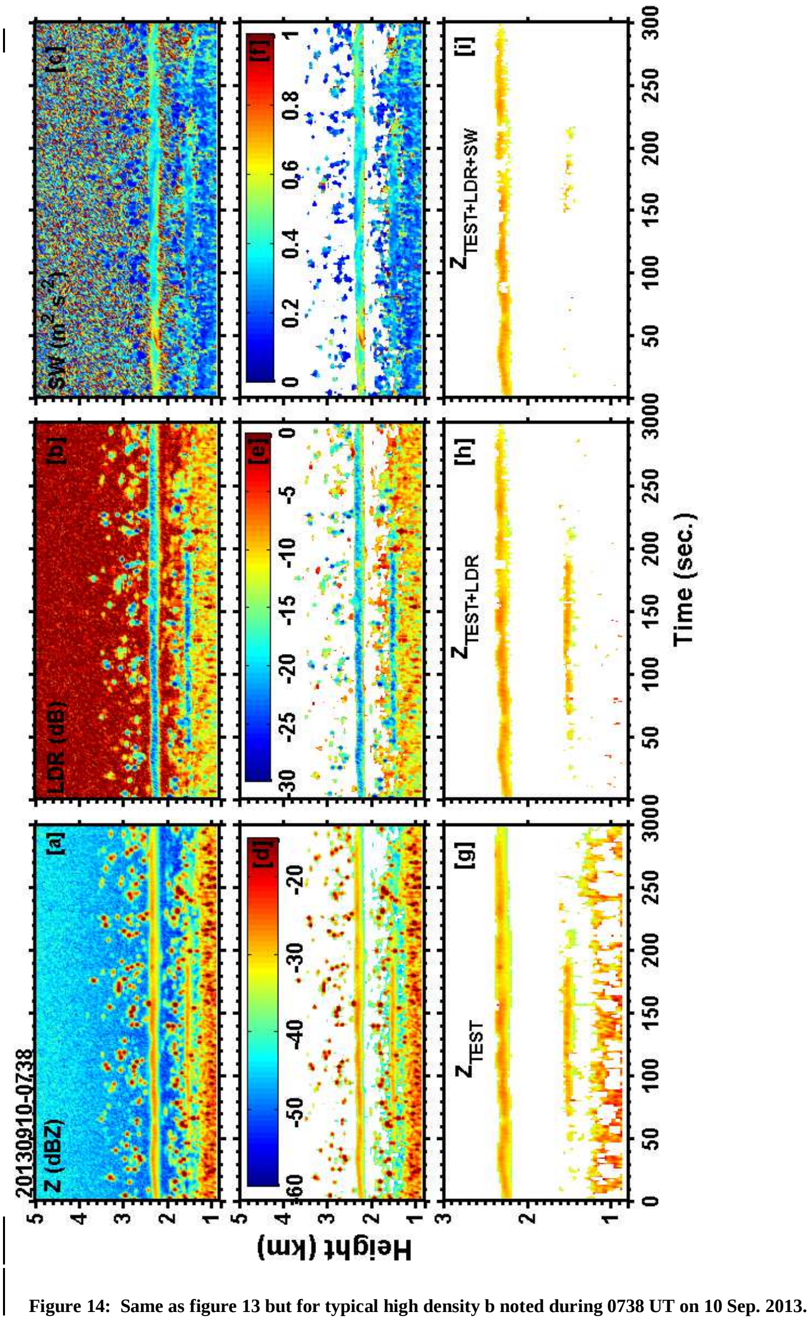

Figure 14: Same as figure 13 but for typical high density b noted during 0738 UT on 10 Sep. 2013.

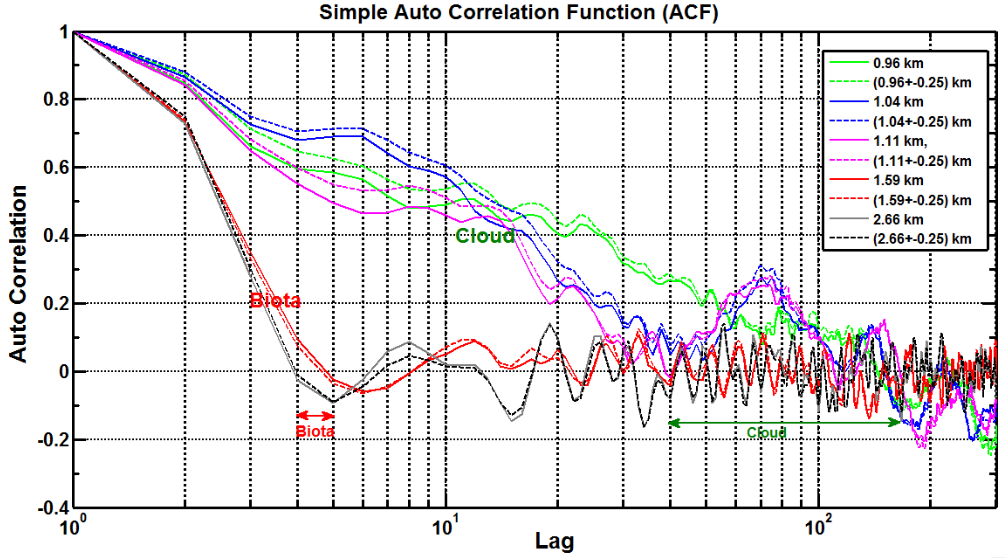

Figure 15: Simple ACF inferred de-correlation periods associated with shallow cumulus cloud (base, mid and top) and biota height levels with the reflectivity measurements of figure 13a.

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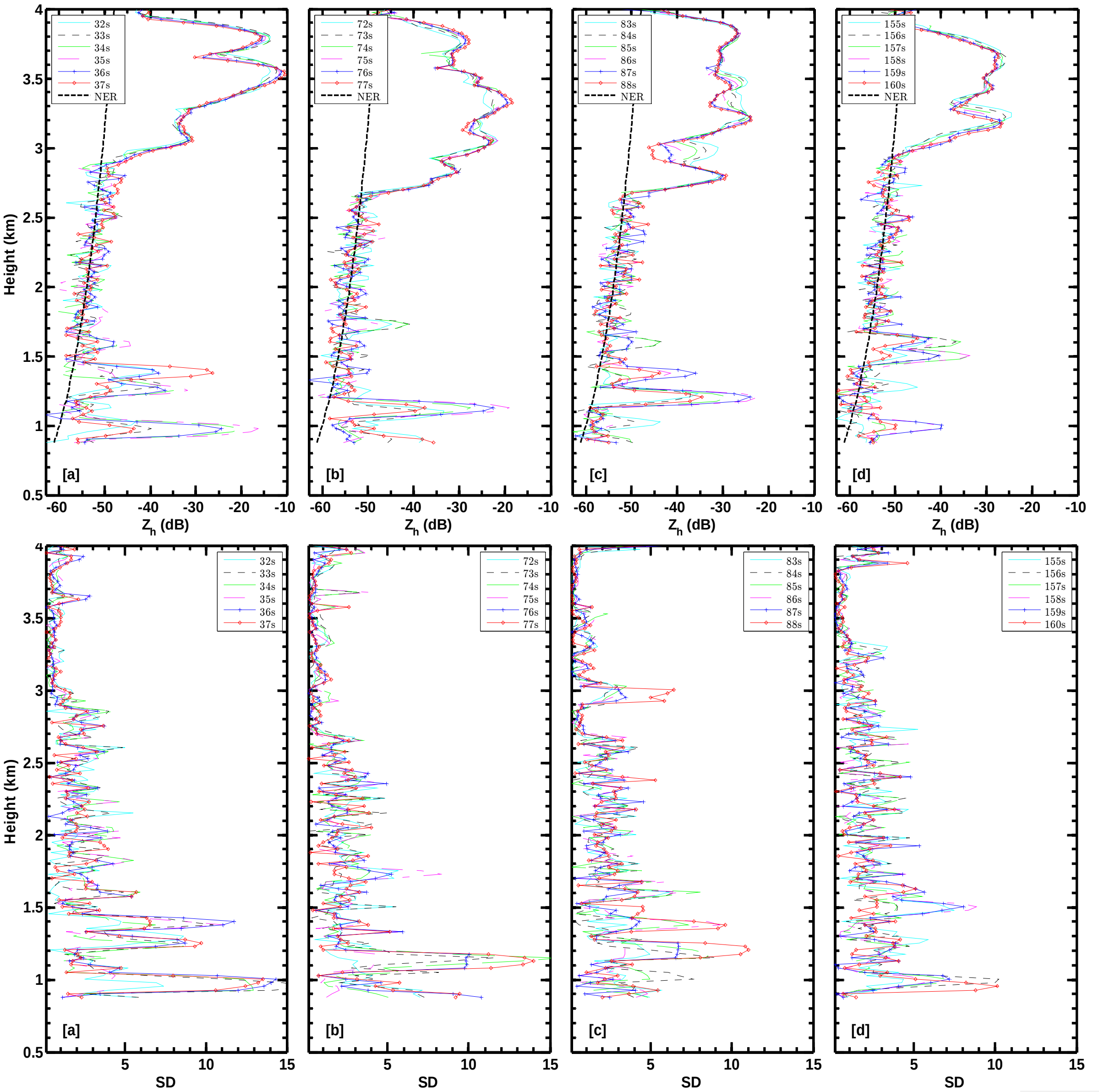

Figure A1: Instentaneous height profiles of Z during 1200-1205 UT on 29 May 2014 with centered numer profile notice to be the strong biota return identified with HTI plot of figure 4b. Bottom panesl correspond to standard devation (SD) from four point running average.

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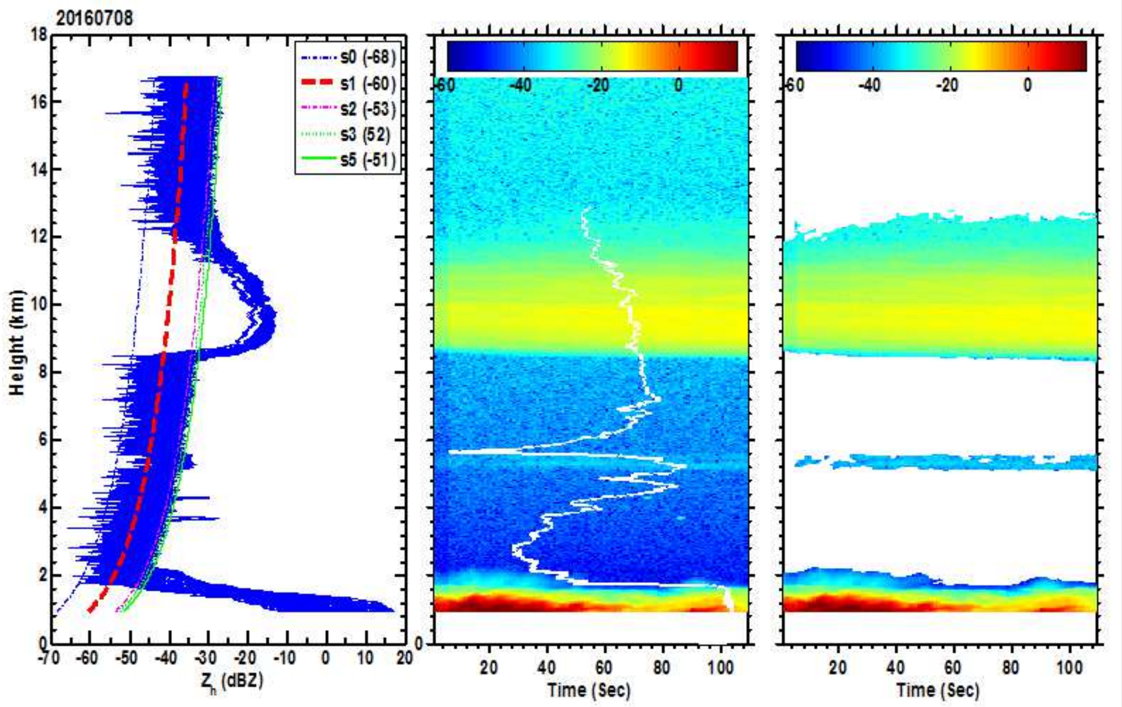

Figure A2: (Right-middle-left) Same as 1(a-c) but on 08 Jul 2016 during 0531 UT for the duration of 108 sec. S0-S5 are NER curves. Collocated GPS-RS relative humidity (%) profile had shown as while solid line in the middle panel.

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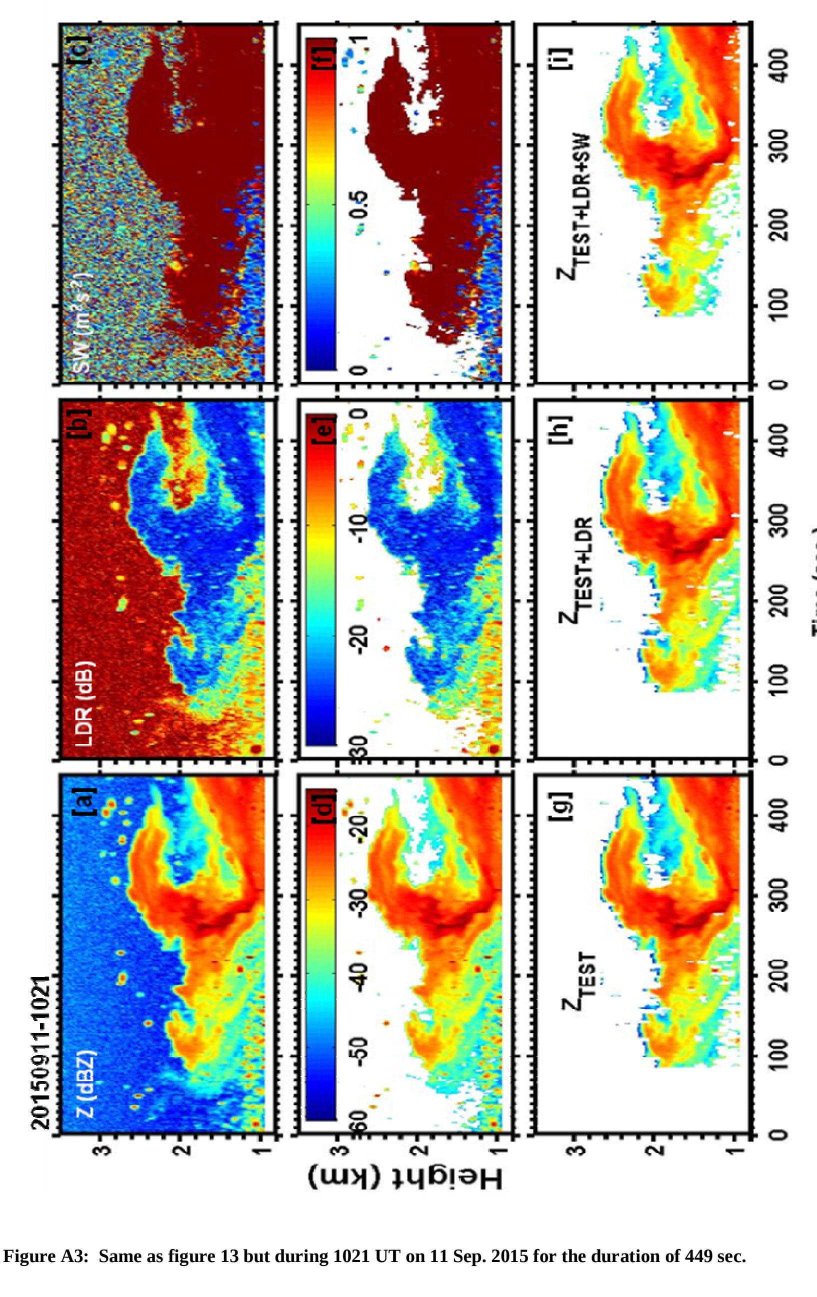

Figure A3: Same as figure 13 but during 1021 UT on 11 Sep. 2015 for the duration of 449 sec.

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, and thus they contaminate and mask the true cloud returns (Luke et al., 2008). The identification and removal of returns from such non-meteorological targets (biota and receiver noise) is one of the prime tasks that is required to perform before using the meteorological (cloud and precipitation) returns received by the cloud radar data, for the research and analysis purpose. The current work focuses on identifying and filtering non-hydrometeor echoes in order to significantly improve the quality of cloud radar data. This allows for the improved characterization of the tropical CVS.

Review of previous studies shows that different techniques have been attempted to remove non meteorological echoes, for example, static techniques for the ground clutter (Harrison et al., 2014; 2000), return signal-level correction (Doviak and Zrni´c, 1984; Torres and Zrni´c, 1999; Nguyen et al., 2008), dynamic filtering (Steiner and Smith, 2002), and operational filtering (Alberoni et al., 2003; Meischner et al., 1997). The aforementioned studies were mostly confined with the use of single polarization radar. However a new possibility has been developed using dual-polarization information to identify the non-meteorological clutter echoes (Zrnic´ and Ryzhkov, 1998; Mueller, 1983; Zhang et al., 2005). With the advent in Doppler spectral processing, it is possible to have improved clutter mask (Bauer-Pfundstein and Görsdorf, 2007; Luke et al., 2008; Warde and Torres, 2009; Unal, 2009). As mentioned one of the non-meteorological echoes is due to the insects and air-borne biota and these unwanted echoes are problematic for studies involving meteorological information such as wind measurements (Muller and Larkin, 1985) and true cloud returns (Martner and Moran, 2001). As a consequence, observations of insects were done using variable polarization and multiple frequency radars operating initially in the centimeter wavelength (Hajovsky et al., 1966; Hardy et al., 1966; Mueller and Larkin, 1985). At millimeter wavelength radar, Bauer-Pfundstein and Görsdorf (2007) showed effective LDR filtering of insects while Khandwalla et al. (2003) and Luke et al. (2008) showed that dual-wavelength ratio filters are more effective than the linear depolarization ratio filters. Dual-polarization also offers a wide variety of methods (e.g., Gourley et al., 2007; Hurtado and Nehorai, 2008; Unal, 2009; Chandrasekar et al., 2013). Fuzzy logic classification techniques for the identification and removal of spurious echoes from radar are also in use (e.g., Cho et al., 2006; Dufton and Collier, 2015). From the above summary, it is therefore evident that most of the studies either concentrate on the polarimetric capabilities of radar or off-line spectral processing of radar data to filter out echoes contaminated by non-meteorological targets. The importance of the current work presented here lies in the development of an algorithm that uses solely high spatial and temporal resolution reflectivity measurements. These high spatial and temporal resolution (25 m and 1 sec) measurements enable the characterization of irregular echoes associated with the spurious nature of radar returns due to insects. This method is simple and does not require spacious complex spectral data (and associated complicated analysis) or expensive advanced dual-polarimetric or dual-wavelength techniques.

requiredof due to the Though the nature of shallow clear air radar echoes was first doubtful, but in later stage,these echoes over land in the CBL were proved to be contaminated by particle scattering from biota rather than to refractive index gradients (e.g., Russell and Wilson, 1997). But in order to utilise the potential of cloud radar of studying cloud one needs dTare strongly linked to the rain making mechanism at lower region of the cloud vertical structure and a factor in predictability of cloud feedback in a changing climate (Tiedtke 1989; Bony et al.2006; Teixeira et al. 2008)buteir representationrisesof shallow cumulus cloud its.biota