Fractal based technique for identifying multiple layers in sodar echograms depicting foggy conditions

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Presented by

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Organization of the talk

- Basics of planetary boundary layer and mixing height
- Basics of sodar echogram formation
- Mixing height estimation
- Explanation for multiple layers due to fog formation
- Results of mixing height estimation
- Fractal and fractal dimension (FD)
- FD computation methodology
- Results of FD for multiple layered structure
- Observations on results and its relevance

Planetary Boundary Layer Formation

- Coriolis force
- Gravity
- Speed of rotation of earth
- Temperature at ground and gradient
- Kinematic heat flux at ground level
- Local wind speed

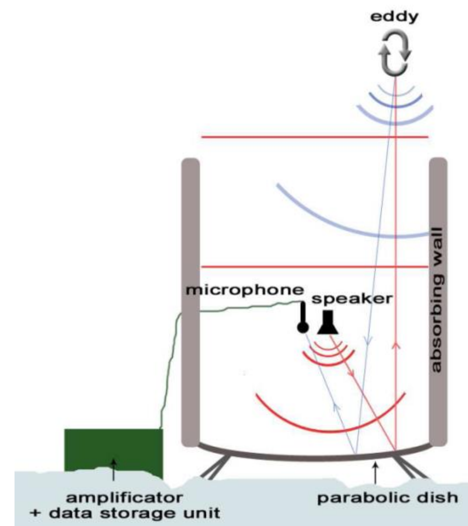
Importance of Mixing Height

- Mixed layer height is an important meteorological parameter
- It affects near-surface atmospheric pollutant concentrations
- It determines the volume of air into which pollutants and their precursors are emitted.
- The air quality estimation models use this parameter
- Wind energy generation requires estimation of mixing height

Fog Formation

- ✓ In a normal temperature profile, warm air rises and condenses. This has the potential of cloud formation.
- ✓ During day, sea breeze blows away from sea and return path is from land back to sea.
- ✓ During night, land breeze blows from land towards sea – fog formation can happen
- ✓ During capping inversion phenomenon which occur at high altitude, a layer of cold air zone sits above the layer of warm air.
- ✓ A boundary is created where the cloud formation is capped by the inversion profile.
- ✓ A strong cap initiates foggy condition.

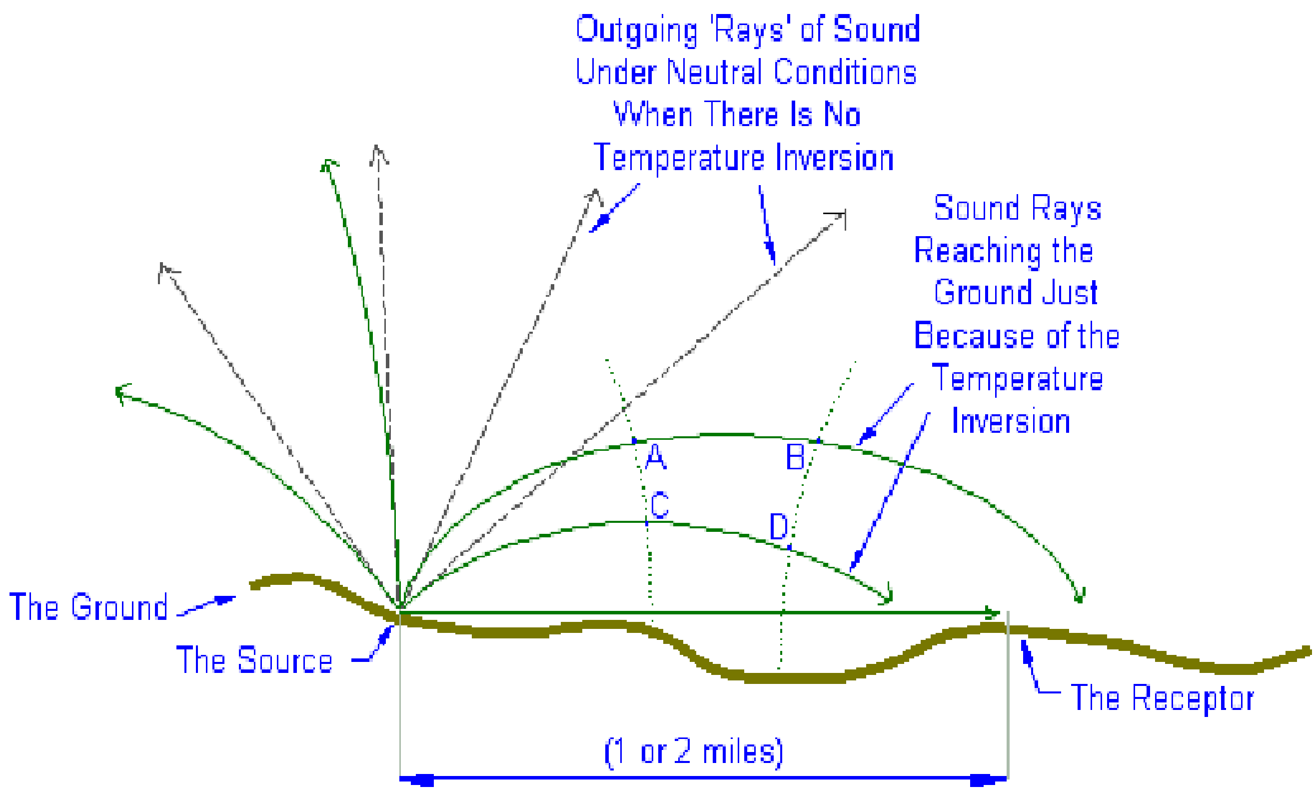
Sodar echogram



SOnic **D**etection **A**nd **R**anging also known as **SODAR** is very efficient way to explore the time evolution of lower atmosphere. Acoustic pulses of short duration are transmitted upwards using an acoustic antenna. These pulses gets refracted and backscattered due to temperature inhomogeneity and gets recorded in SODAR. (pictures taken from website of Halley British Antarctic Survey)

Backscatter due to temperature inversion

(based on drawing by Mike O Connor)

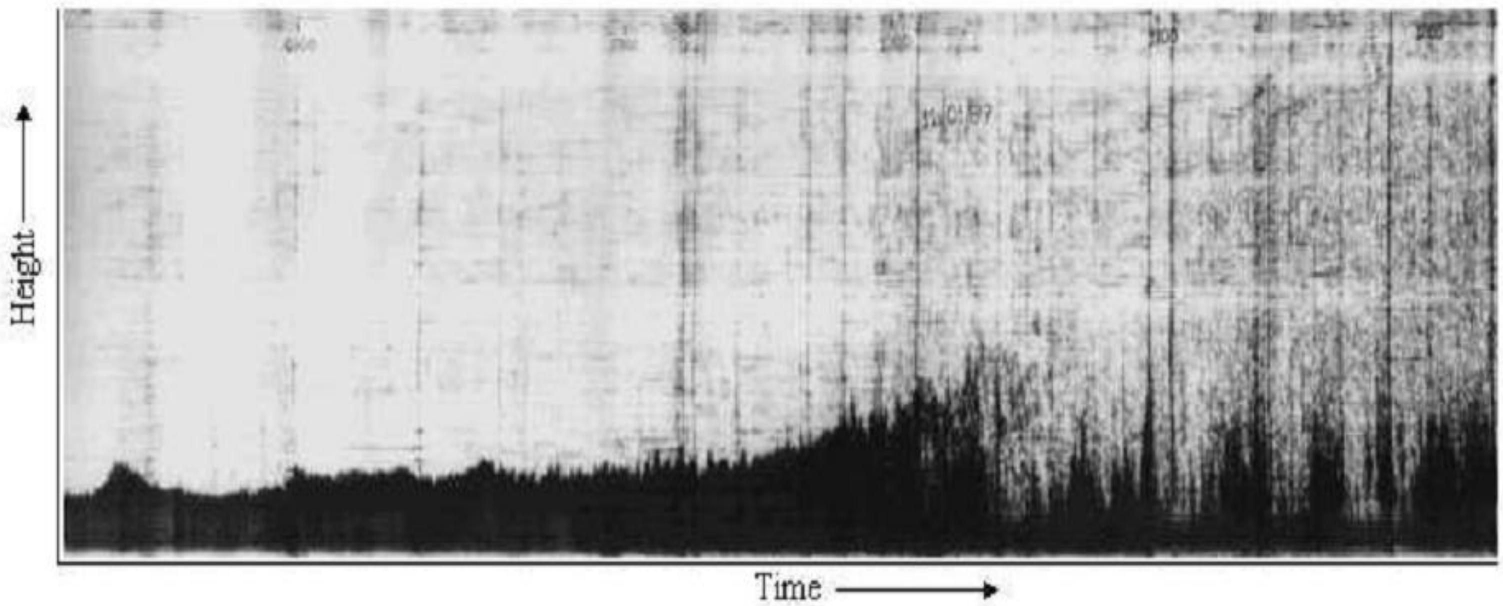


Conceptual diagram showing the influence of temperature inversion

Typical patterns in Sodar echogram

- Rising inversion structures form during morning hours
- Convective plume structures form during daytime, with the strength and shape depending on insolation
- Falling inversion structures form during evening after Sun goes down
- Flat inversion structures are typically formed on calm nights

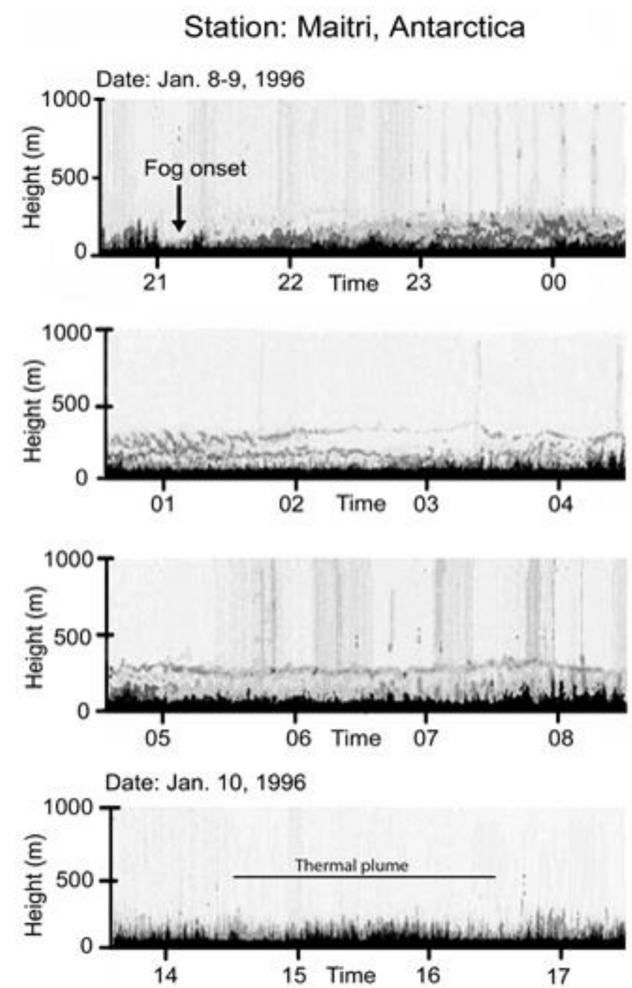
Typical Sodar echogram morning-noon
(taken from Sodar installed in ISI Kolkata)



Mixing Height Estimation

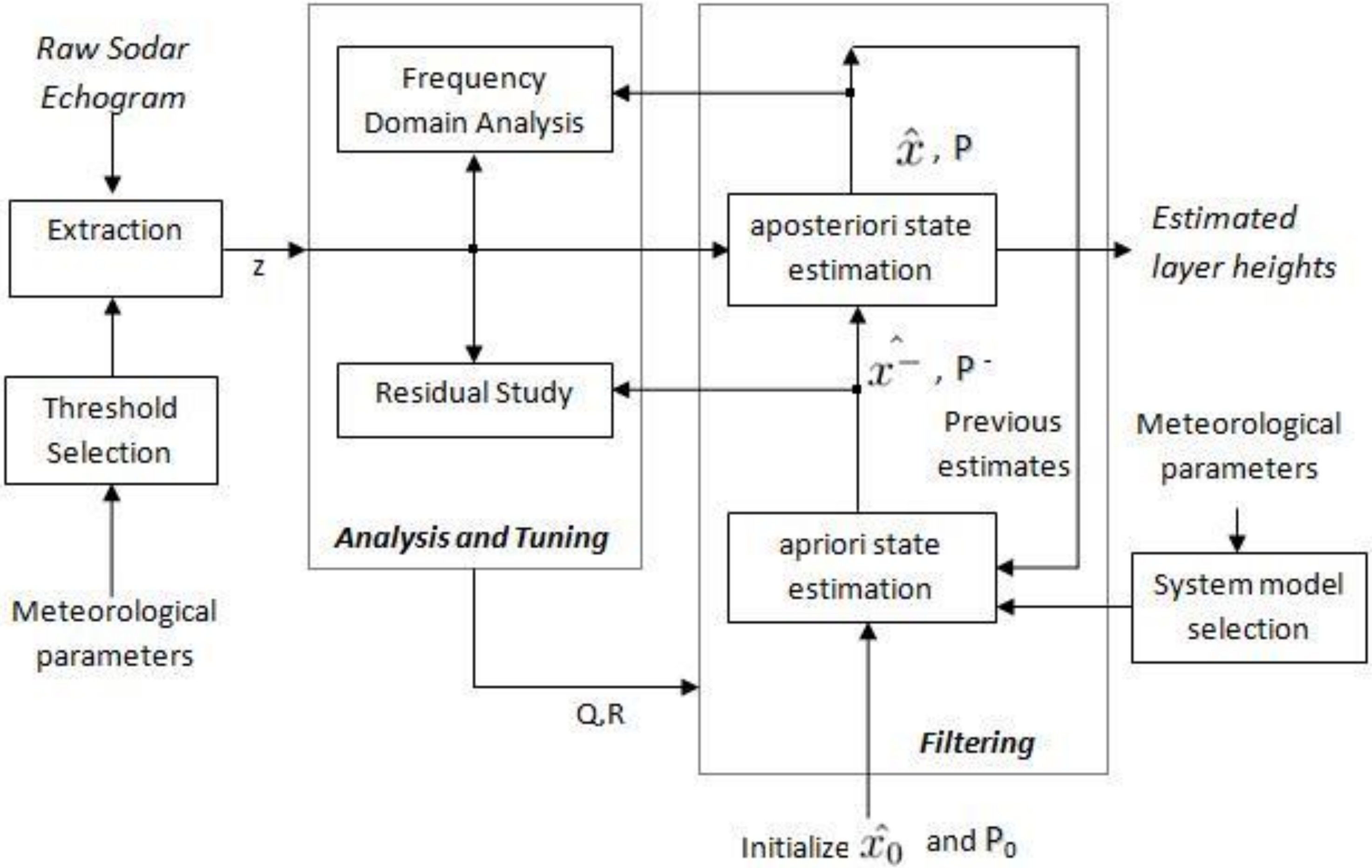
The mixing height in the lower atmosphere can be estimated by employing suitable computer based signal processing techniques. Following are some of the approaches :

- Image processing approach
- Pattern Recognition techniques.
- Kalman Filter approach.
- Fractal – self-similarity approach.

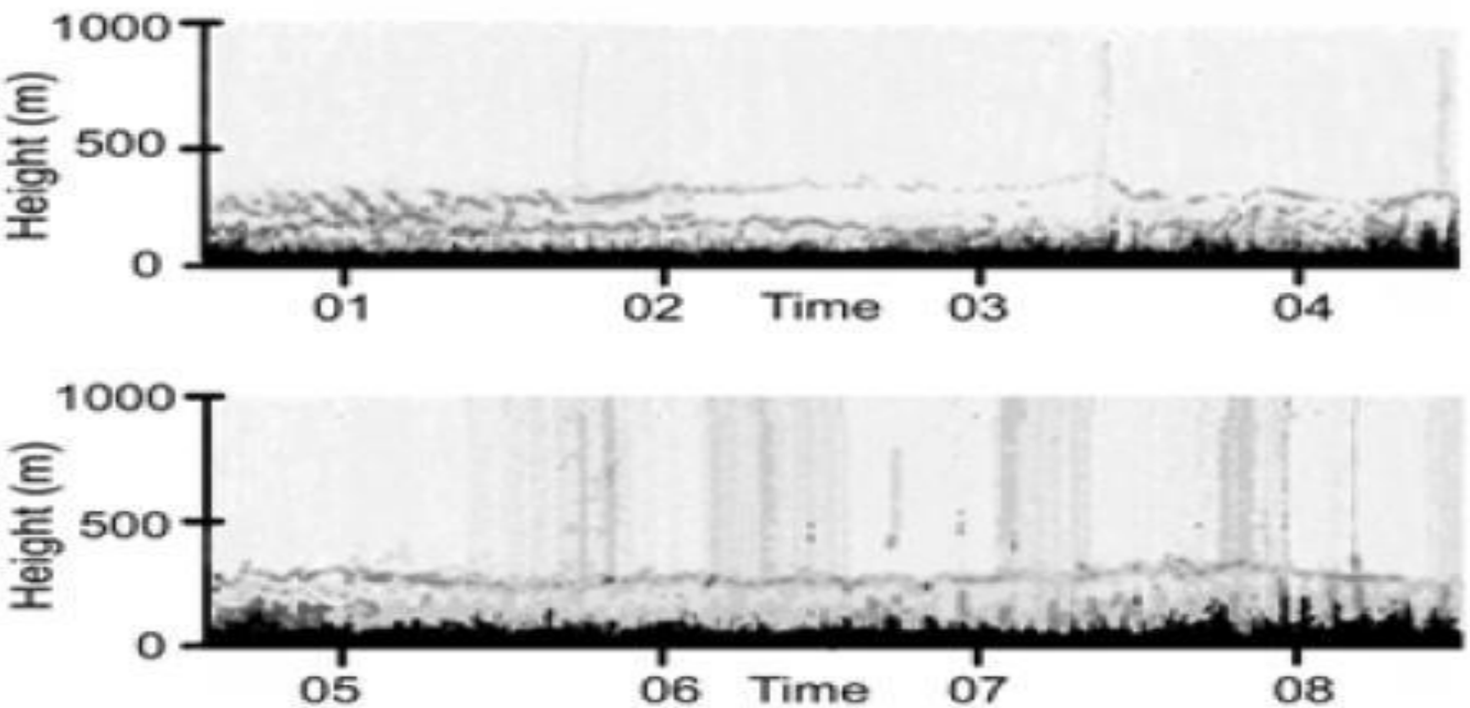


Mixing Height Estimation Approach

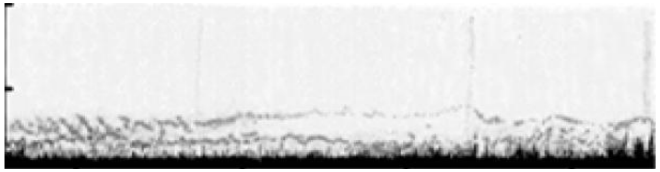
(taken from Fluctuation and Noise Letters 11(4); December 2012)

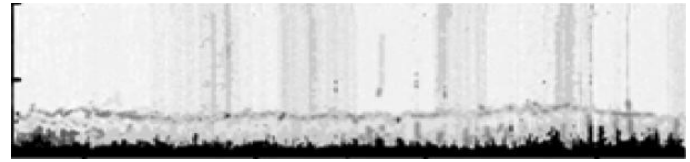


Capping Layer - Sodar Image
(captured at Maitree Station, Antarctica)

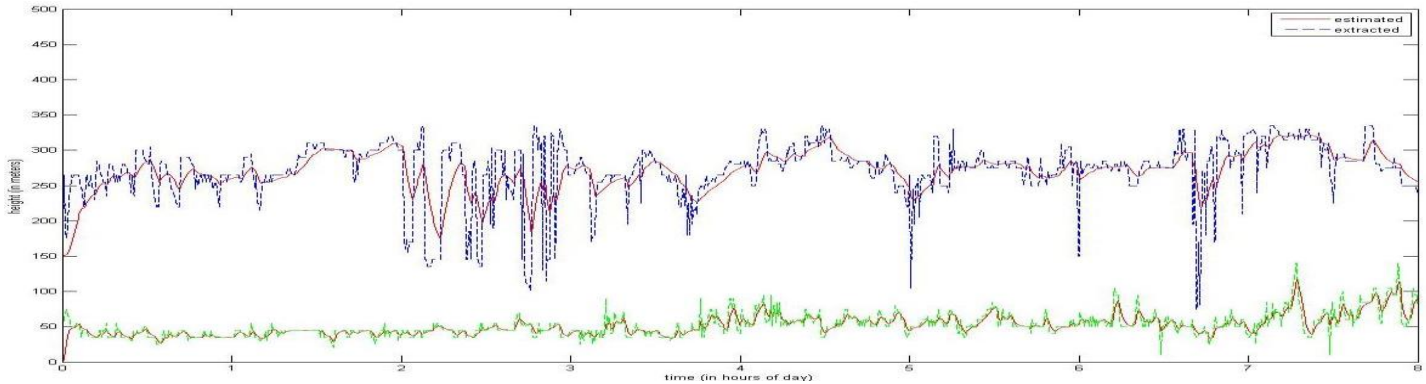


Capping and Inversion - Estimation

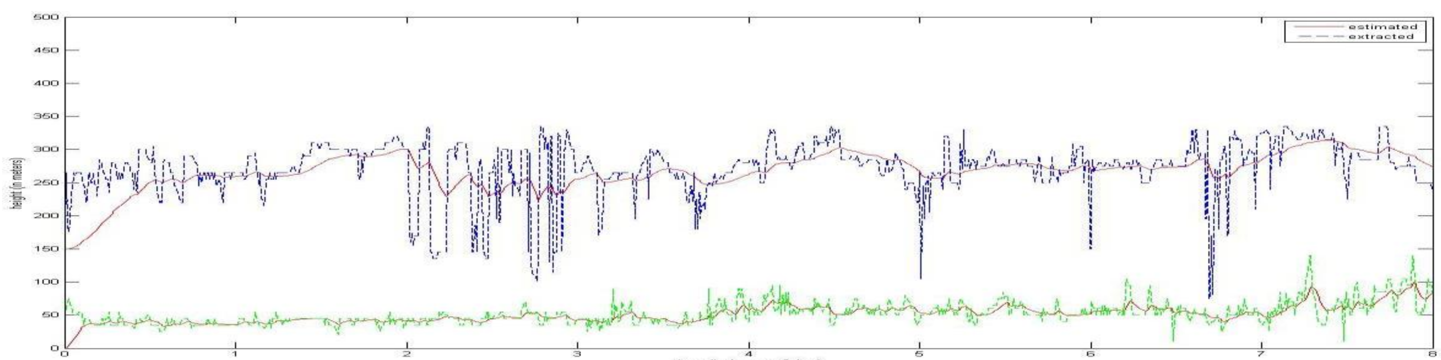




Qc=0.01 and QI=0.01 , Rc=1.0 and RI=0.1

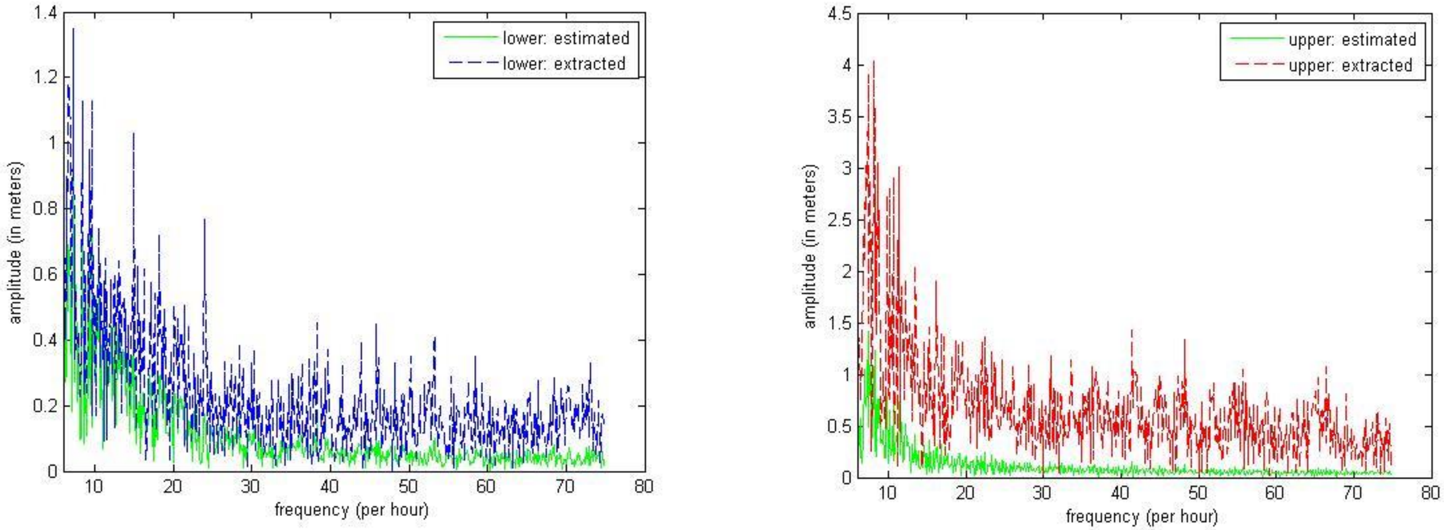


Qc=0.001 and QI=0.001 , Rc=1.0 and RI=0.1



Capping and Inversion Layer – Frequency

(Fluctuation and Noise Letters 11(4); December 2012.)



FFT analysis of the inversion and capping layers

Limitations of estimation scheme

- The proposed scheme is only for two layered structure and can be extended to multilayered structure.
- The system has been assumed to follow a random constant model but during fog formation and deformation stages, a ramp model might be better suited.
- KF equations assumes system to be linear and noise model to be a Gaussian model. Some natural fluctuations gets suppressed. This can be tackled using a fractal based approach.

Concept of Dimension

- Hausdorff Dimension: Generalizes the notion of dimension in a real vector space.

$$d_H(\theta) = -\lim_{\varepsilon \to 0} \frac{\log N_\theta(\epsilon)}{\log \epsilon}$$

- Fractal Dimension:

  Statistical quantity that gives an indication of how completely a fractal appears to fill the space, as one zooms to finer and finer scales.

  e.g. Box Counting Dimension

Box counting dimension of a set S

- Let **N(r)** be the minimum number of n dimensional cubes of side length **r** needed to cover S. if $N_S(r) \sim 1/r^d$ as r -> 0, then the box counting dimension of S is **d**.

$$\lim_{r\to 0} (N_S(r) / (1/r^d)) = k$$

  - Taking log on both sides:

$$\lim_{r\to 0} (\log N_S(r) + d \log r) = \log k$$

  - $$d = \lim_{r\to 0} ((\log k - \log N_S(r))/ \log r)$$

  - $$d = \lim_{r\to 0} (\log N_S(r))/ \log (1/r))$$

So, plotting log(N(r)) vs log(1/r), the points should lie on a straight line with slope d. This is the **log-log approach** to find the box counting dimension.

Box – Counting

Algorithm : Box Counting

Input: Normailized Concetration Density in ncd

Output: Number of box counted in nob

for $i = 0$ to 255, increment $i = i + box\_size$ **do**

  for $j = 0$ to 255, increment $j = j + box\_size$ **do**

    max_cd of the current box $max\_zc :=$ CD_FUNC(i, j, box_size, ncd);

    max_cd of the right of current box $max\_zr :=$ CD_FUNC$(i, j + box_size, box_size, ncd)$;

    max_cd of the top of current box $max\_zu :=$ CD_FUNC$(i + box_size, j, box_size, ncd)$;

    $nob := nob + (\text{int})\frac{|max\_zc - max\_zu|}{box\_size} + (\text{int})\frac{|max\_zc - max\_zr|}{box\_sz}$;

  end for

end for

function CD_FUNC(x, y, box_sz, cd_arr)

  for $row = x$ to $x + box_sz$ **do**

    for $col = y$ to $y + box_sz$ **do**

      $max\_cd :=$ maximum intensity for $cd\_arr[row][col]$;

    end for

  end for

end function

Proposed methodology

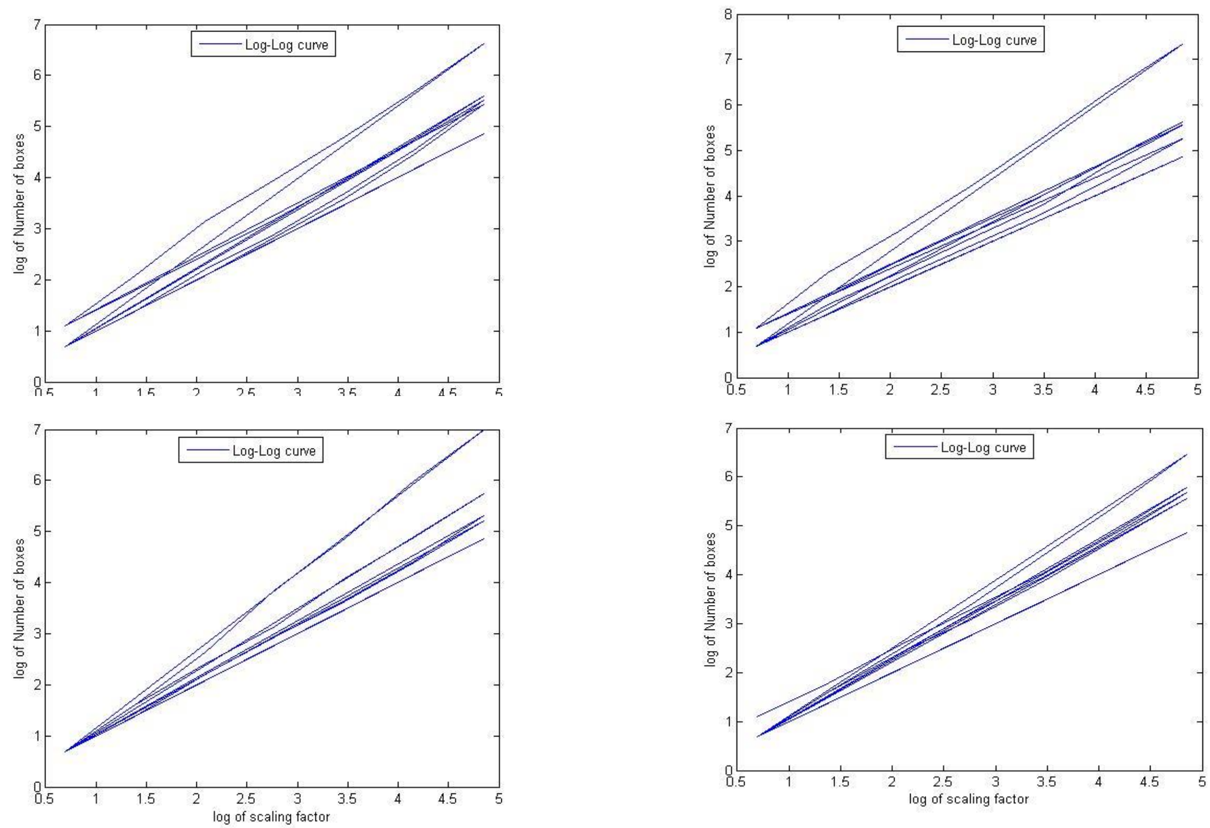
- Designing an algorithm for extracting the mixing height through fractal dimension and hence finding the fractal properties of the region near the mixing height.
- Finding out discriminatory features in the pattern of the available sodar echogram so as to predict the onset of turbulent weather condition.
- Analyzing the FD for each height range to see whether there is a perceptible change in FD in the mixing height zone over the rest of the space.

Algorithms for FD computations

1. Get the discrete raw data values from sodar echograms as (*height x time*) array.
2. For each height level, keep a note of the intensity readings for a moving window of 256 intervals of 24 secs (i.e. 2 hours) duration. We take successive differences of intensity between the current and previous time interval and store in a 2D array where the rows to be interpreted as height.
3. Count the number of boxes required to cover the intensity values in a height zone. And this is to be done taking successively smaller box sizes (in multiples of 2).
4. Calculate Fd= (log(no_of_boxes))/(log(Scaling Factor)) heightwise
5. Plot on the log-log scale the number of boxes vs inverse of the size of boxes. Ideally this should give a straight line whose slope leads to the limiting value of FD.
6. Analyze the result to find the fractal properties in the inversion-capping zone.

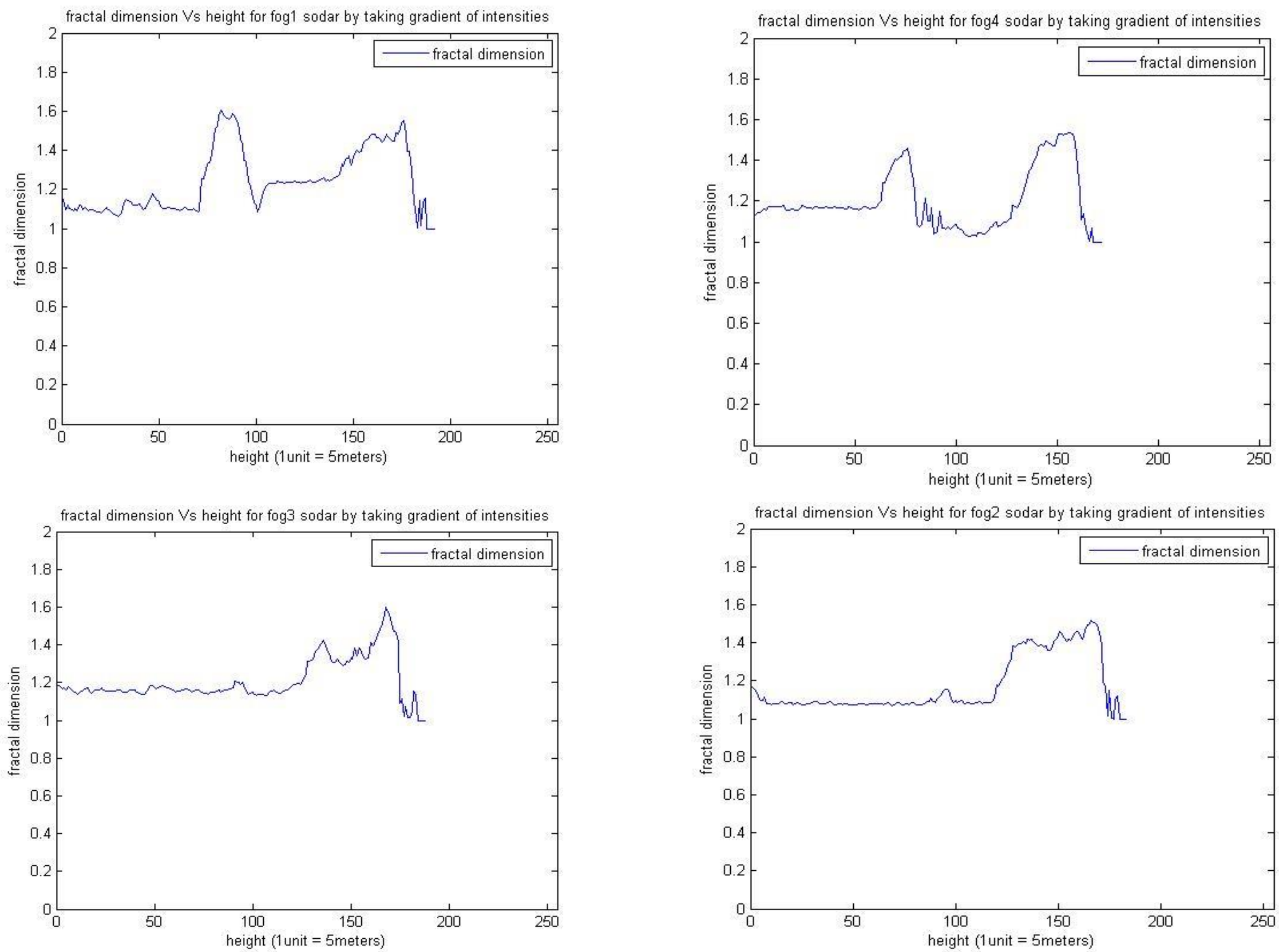
Box count plotted against scale factor

Log-log plot



Plot of log (boxcount) vs log (scale factor) for fog formation and dispersion stages (top 2 plots) and fog formed stages (bottom 2 plots)

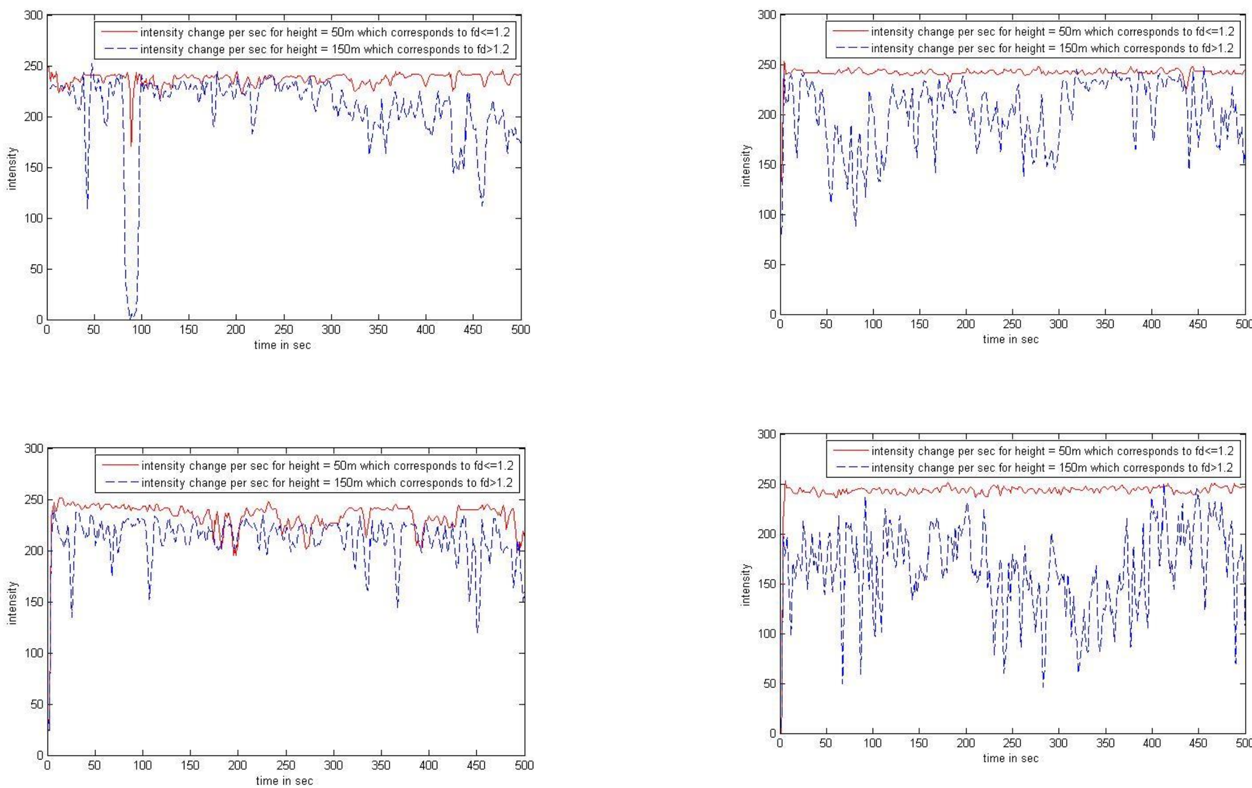
Fractal Dimension change with height



Fog formation and dispersion stages (top 2 plots) and fog formed stages (bottom 2 plots)

Intensity Changes at some typical height

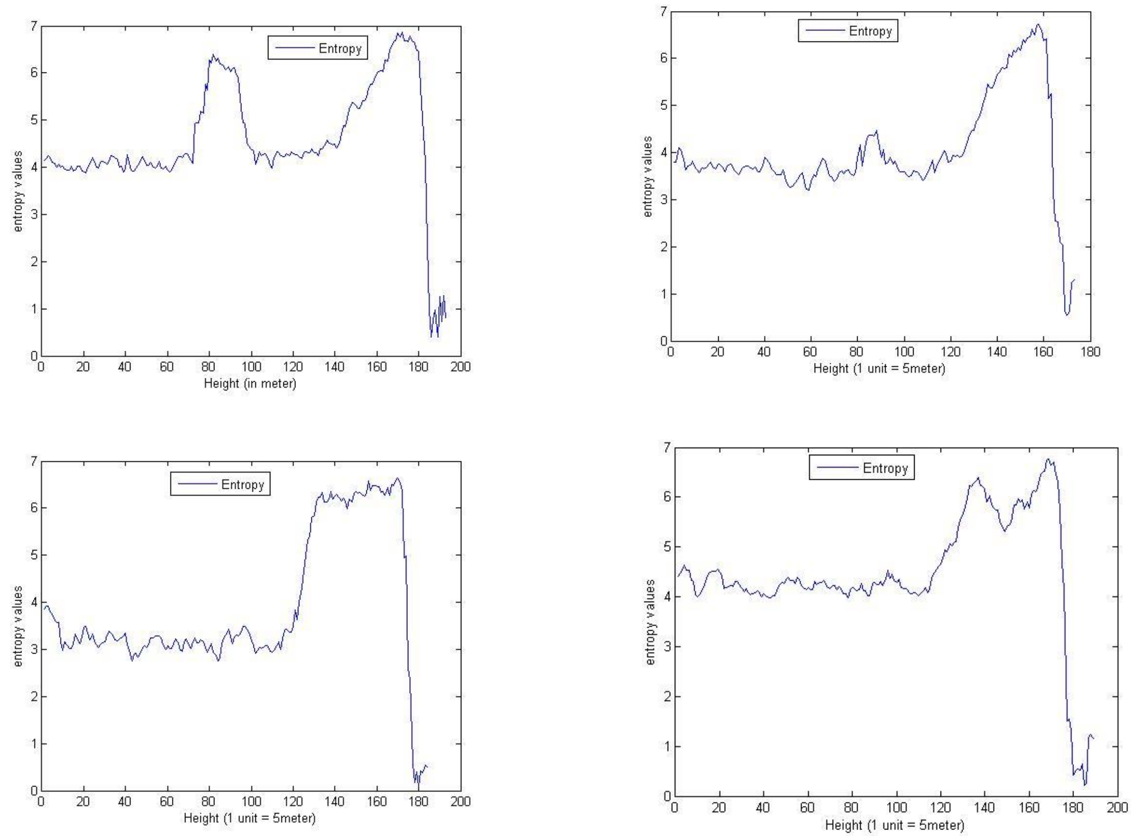
Plot of intensity vs time at given height



Plot of intensity vs time axis for two ranges of fractal dimension

Entropy changes with height

Plot of entropy vs height



Plot of entropy vs height for fog formation and dispersion stages (top 2 plots) and fog formed stages (bottom 2 plots)

Observation

1. Fractal dimension in the region of mixing height range of below 300m stays around 1.2-1.3 with two distinct peaks at around 60m and at around 200m and in rest of the height regions FD remains very low.
2. When compared to the height extraction through noise filtering method, there is good correlation.
3. Log-log plot is linear with slope showing correctness of the algorithm tallying with FD. The linearity of log-log plots indicates the turbulent zone do exhibit fractal nature.
4. Entropy plot vs height is quite similar in nature to FD plot, implying distinct feature in mixing zone.

Time Complexity of Approach

For an echogram of H height bins taken over T time samples, it can be shown that

- *Filtering method gives time complexity O(c HT^2)*

– for T columns, H elements are compared to get two heights, then time and measurement update is done T times to get the filtered estimate over c iterations needed for convergence

- *Fractal based method works in O(HTlogT)*

-- for each of H height bins, box counting is applied on 2-D data of size T, where max() is computed in linear time for successively halved sizes.

Advantages of Fractal Approach

- *There is a significant improvement in time complexity over the filtering method*
- *The mixing height range detection by the two methods is comparable*
- *Fractal method retains the natural fluctuations that may be interpreted as noise and thereby get filtered in the noise filtering approach*
- *Fractal method generates additional information for meteorological analysis*

Discussion

- *There is a perceptible contrast of FD in the mixing height zone with respect to other height zones*
- *Advantage of working with Antarctic sodar data is low ambient noise level.*
- *The study can be useful for taking environment related decisions from the fractal attribute of monitored data*

Connecting with air quality models

- *Mixing height is an all important parameter for air quality modelling*
- *Multiple layered sodar echogram structures that form during foggy condition present challenges for air quality modelling*
- *We have observed through modelling that Spatial distribution of Aerosol concentration data has self similar properties* Exploring the Self Similar Properties for Monitoring of Air Quality Information; ICAPR-2015.
- *This points to the relevance of this study as an area with great future research prospects*

Conclusion

- To extract multiple layers within PBL, noise filtering approaches with linear systems and white Gaussian noise have some limitations.
- Self similarity features of PBL from raw sodar data has been examined and it is observed that FD ranges within approx 1.2 – 1.3 around the mixing height zone.
- The inversion and capping layers can be distinguished by changes in FD with height.
- This can be useful for Urban data containing many variations in terms of noise and disturbances.
- Meteorological parameters like turbulence and convection strength can be explored in this approach.

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Thank You!

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