Detection and Spectral Analysis of Convection-Triggered Gravity Waves Using Ground-Based LIDAR Remote Sensing

8 – Week Report

PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE **SUMMER RESEARCH FELLOWSHIP PROGRAMME - 2025** ORGANISED BY **INDIAN ACADEMY OF SCIENCES, INDIAN NATIONAL SCIENCE ACADEMY & NASI**

PROJECT WORK

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SRFP – 2025

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DECLARATION

I,

SUDHAN R – ENGS1672

Declare that the project entitled **DETECTION AND SPECTRAL ANALYSIS OF CONVECTION-TRIGGERED GRAVITY WAVES USING GROUND-BASED LIDAR REMOTE SENSING**, submitted in partial fulfilment to the requirements for **The Summer Research Fellowship Programme – 2025**, is a record of original work done by us under the supervision and guidance of **Dr. Bhavani Kumar Yellapragada, MSc, Ph.D.,** Retired Scientist, Department of Space, **National Atmospheric Research Laboratory (NARL), An Autonomous Institution under Department of Space, Government of India, Gadanki – 517112, Andhra Pradesh, India**

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Place: Tirupati

Date: ………………

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ACKNOWLEDGEMENT

ACKNOWLEDGEMENT

The successful completion of this research project would not have been possible without the guidance, support, and encouragement of many individuals and institutions. I take this opportunity to express my sincere gratitude to all those who contributed to the accomplishment of this work during the Summer Research Fellowship Programme (SRFP) 2025.

First and foremost, I express my heartfelt thanks to the **Indian Academy of Sciences**, **Indian National Science Academy (INSA)**, and **The National Academy of Sciences, India (NASI)** for granting me this valuable opportunity to participate in the prestigious SRFP and carry out research at a premier scientific institution.

I would like to convey my deepest gratitude to **Dr. Bhavani Kumar Yellapragada, MSc, Ph.D.,** Retired Scientist and my research guide at the **National Atmospheric Research Laboratory (NARL)**, Department of Space, Government of India, for his constant guidance, support, and encouragement throughout the project. His valuable insights, expertise, and motivation played a pivotal role in shaping this research and expanding my knowledge in the domain of atmospheric sciences and remote sensing.

My sincere thanks to the entire team of **National Atmospheric Research Laboratory (NARL)**, including the research staff and technical experts, for providing the necessary facilities, infrastructure, and a research-conducive environment that enriched my learning and helped me apply computational approaches in real-time data analysis.

I am also thankful to my institution, **Sri Eshwar College of Engineering**, and the **Department of Computer Science and Engineering** for supporting my participation in this fellowship and encouraging my academic pursuits beyond the curriculum.

Last but not least, I extend my warm gratitude to my family, friends, and well-wishers for their continuous encouragement, emotional support, and belief in my capabilities throughout this journey.

This project has been a transformative learning experience, and I remain deeply indebted to everyone who contributed directly or indirectly towards its successful completion.

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ABSTRACT

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Atmospheric gravity waves play a critical role in the vertical coupling of energy and momentum across different layers of the atmosphere. This study focuses on the detection and spectral analysis of convection-triggered gravity waves using ground-based LIDAR remote sensing data obtained from the National Atmospheric Research Laboratory (NARL), Gadanki. Over an 8-week research internship under the Summer Research Fellowship Programme (SRFP), LiDAR backscatter profiles were analyzed to extract temporal and spatial variations in atmospheric structures.

More than 800 files containing LiDAR returns were pre-processed and combined to form a multi-dimensional dataset. Range-Time Intensity (RTI) plots were generated to visualize wave signatures, and altitude-specific time series were extracted to perform Fast Fourier Transform (FFT)-based spectral analysis. The dominant frequencies identified across multiple altitude bins revealed consistent low-frequency oscillations, confirming the presence of gravity waves typically associated with convective activity.

The analysis demonstrated that LiDAR remote sensing is an effective tool for capturing the vertical propagation characteristics of gravity waves in the lower and middle atmosphere. The extracted wave periods matched theoretical expectations, and the results contribute valuable insights into mesoscale atmospheric dynamics. This work lays the groundwork for future research using advanced filtering techniques and multi-instrumental observations to enhance the detection accuracy and understand wave source mechanisms in the tropical atmosphere.

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INTRODUCTION

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INTRODUCTION

Atmospheric gravity waves (GWs) are oscillations generated in a stable atmosphere when buoyancy acts as the restoring force. These waves play a vital role in driving atmospheric circulation and energy redistribution, particularly in the mesosphere and lower thermosphere. Gravity waves are commonly triggered by meteorological processes such as orographic lifting, convection, wind shear, and jet stream instabilities. In the tropical regions, convective processes are the dominant sources of GWs, especially during periods of strong updrafts and unstable weather conditions. Once generated, these waves can propagate vertically and horizontally, transferring energy from the troposphere into higher layers of the atmosphere. Understanding the properties of these waves is essential for improving atmospheric models, weather forecasting, and climate predictions.

The present study focuses on the detection and analysis of convection-triggered gravity waves using **ground-based LiDAR (Light Detection and Ranging)** remote sensing techniques. LiDAR systems are capable of providing high-resolution vertical profiles of atmospheric parameters such as aerosol density and backscatter intensity, which can be used to identify wave signatures. This project was carried out under the **Summer Research Fellowship Programme (SRFP)** at the **National Atmospheric Research Laboratory (NARL), Gadanki**. The primary objective of the study is to preprocess LiDAR data, identify gravity wave signatures using time-altitude intensity mapping, extract time series at specific altitudes, and perform spectral (FFT-based) analysis to determine the dominant wave frequencies and their corresponding wave periods.

By combining signal processing, remote sensing techniques, and frequency-domain analysis, this work aims to better understand the characteristics and propagation behavior of gravity waves observed during convective activities over the Indian tropical region.

CHAPTER - 2

LITERATURE REVIEW

CHAPTER - 2

LITERATURE REVIEW

Gravity waves (GWs) play a key role in vertical coupling between different layers of the atmosphere. Over the years, several studies have focused on their generation, propagation, and dissipation mechanisms using both observational and modeling approaches. This section reviews previous literature relevant to the detection and analysis of gravity waves, particularly using LiDAR-based remote sensing.

2.1 GROUND-BASED LiDAR FOR ATMOSPHERIC WAVE STUDIES:

LiDAR systems have emerged as effective tools for high-resolution atmospheric profiling. According to **Chu et al. (2005)**, resonance and Rayleigh LiDAR systems can detect fine-scale vertical structures, including wave perturbations in the mesosphere and stratosphere. Their study demonstrated how backscattered signals can reveal gravity wave activity through time-altitude imaging and spectral analysis.

2.2 GRAVITY WAVES FROM CONVECTIVE SOURCES:

Convective systems are one of the primary sources of GWs in the tropical atmosphere. **Alexander et al. (2010)** highlighted that deep convection produces wave packets that propagate to higher altitudes and contribute significantly to mesoscale variability. These waves are commonly associated with updrafts and cloud-top cooling regions.

2.3 SIGNAL PROCESSING AND SPECTRAL METHODS:

To extract wave parameters, frequency-domain methods such as **Fast Fourier Transform (FFT)** are frequently employed. **Eckermann and Vincent (1989)** used FFT-based spectral techniques to analyze vertical profiles of temperature and density fluctuations. These methods have since been adopted in multiple remote sensing studies, including LiDAR-based retrievals, for identifying dominant frequencies and estimating wave periods.

2.4 LiDAR STUDIES IN THE INDIAN REGION:

At the Indian tropical station of Gadanki, LiDAR observations have been extensively used for atmospheric wave studies. **Bhavani Kumar et al. (2007)** reported aerosol backscatter and temperature profiles obtained through LiDAR, and discussed the occurrence of mesoscale gravity waves during convective conditions. These studies form the foundation for detecting wave signatures in the lower troposphere using advanced signal processing.

2.5 LIMITATIONS AND GAPS:

While satellite and balloon-based observations have offered broad coverage of gravity wave climatology, they often lack the temporal and spatial resolution needed for capturing short-period, lower-atmosphere waves. Ground-based LiDAR, however, provides the temporal continuity and vertical resolution necessary to resolve finer wave structures. Yet, more studies are needed focusing specifically on convection-triggered waves in the 0–5 km range over tropical regions.

CHAPTER - 3

RESEARCH OBJECTIVES AND SCOPE

CHAPTER - 3

RESEARCH OBJECTIVES AND SCOPE

3.1 OBJECTIVES

The primary aim of this research is to detect and analyze convection-triggered gravity waves using LiDAR backscatter data obtained from ground-based observations. The specific objectives include:

a. To extract and preprocess high-resolution LiDAR backscatter profiles from raw TR recorder data files.
b. To identify altitude ranges with potential gravity wave activity during the convective boundary layer formation.
c. To apply smoothing, averaging, and Fast Fourier Transform (FFT) techniques to analyze the temporal variation in backscattered signals.
d. To estimate dominant wave frequencies and calculate corresponding wave periods at different altitude bins.
e. To visualize and interpret the vertical structure and spectral behavior of wave signals in the troposphere.

3.2 SCOPE

a. The study is limited to one day's LiDAR observation data recorded at Gadanki station, as provided by the National Atmospheric Research Laboratory (NARL).
b. The LiDAR data analyzed follows the Licel binary format, requiring custom decoding and processing.
c. The focus is on low-altitude regions (up to ~3 km) where convection-triggered waves are expected during the afternoon hours.
d. The project uses Python (NumPy, Pandas, Matplotlib, SciPy) and Google Colab for data handling, transformation, and analysis.
e. Only vertical backscatter profiles are considered for this initial study; horizontal propagation and wave vector estimation are beyond the scope.
f. The findings may serve as a precursor for larger-scale studies on gravity wave dynamics and parameterizations in weather models.

CHAPTER - 4

METHODOLOGY

CHAPTER - 4

METHODOLOGY

4.1 FLOW CHART:

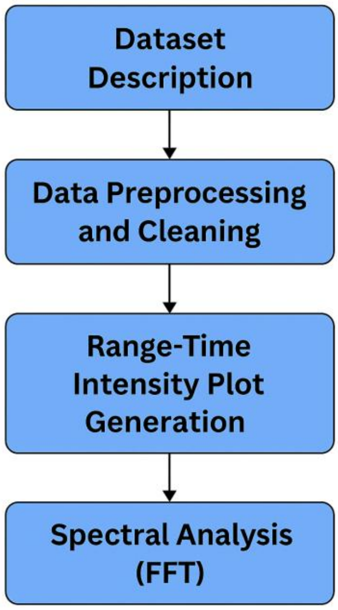


Figure 1: Flow Chart

4.2 DATASET DESCRIPTION:

The LiDAR dataset was provided by **NARL, Gadanki**, in the form of **binary TR recorder files** (Licel format). Each file corresponds to a high-temporal-resolution backscatter profile.

- **Date of Observation**: January 23, 2014
- **Time Period Covered**: 16:26 to 17:57 IST (approximately)
- **Altitude Range**: ~0 to 3 km
- **Vertical Resolution**: 0.75 m per bin (based on bin width from header)
- **Number of Files**: 850+ profiles representing continuous atmospheric observation

The header information in the file confirms the vertical bin width and other laser configuration parameters.

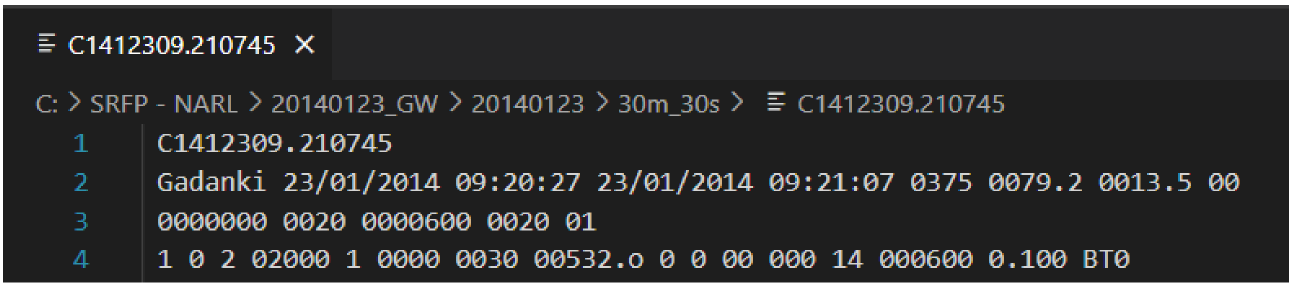


Figure 2: Sample Licel Binary File Header Information

4.3 DATA PREPROCESSING AND CLEANING:

The raw C1412309.XXXXX files were read using **NumPy's binary decoding** into 16-bit unsigned integers. The preprocessing involved:

a. Skipping the first 8 lines to avoid header info
b. Converting data into a 2D NumPy array with shape (altitude bins, time steps)
c. Filtering out constant background and zero-intensity noise
d. Stacking all 850+ profiles into one combined matrix for full-range analysis

4.4 RANGE-TIME INTENSITY (RTI) PLOT GENERATION:

The combined 2D matrix was used to generate a **Range-Time Intensity (RTI) plot**, which represents:

a. **X-axis**: Time (profile index or real timestamps)
b. **Y-axis**: Altitude (in meters)
c. **Color intensity**: Backscatter signal strength

This plot provides a visual cue of gravity wave formations as periodic structures along the altitude axis over time.

$$I(r,t)$$

Where:

a. I is the **signal intensity** (backscatter count or amplitude),
b. r is the **range** (or altitude in meters),
c. t is the **time index** (each file is typically a scan at one time),
d. This is typically plotted as a **matrix**, where each row = range bins, each column = time slices.

Preprocessing Before RTI:

1. **Background subtraction:**

$$I_{clean}(r,t) = I(r,t) - I_{bg}(r)$$

2. **Smoothing (Moving Average):**

$$I_{smooth}(r,t) = \frac{1}{N}\sum_{i=-k}^{k} I(r,t+i)$$

3. **Normalization (optional):**

$$I_{norm}(r,t) = \frac{I(r,t)}{max_r I(r,t)}$$

4.5 TIME SERIES & SPECTRAL ANALYSIS (FFT):

For wave detection, **Fast Fourier Transform (FFT)** was applied to time series signals at selected altitude bins:

a. Extracted 1D signal from each altitude bin (e.g., every 50m step)

b. Applied FFT to convert from time domain to frequency domain

c. Plotted Power Spectral Density (PSD) to find dominant frequencies

d. Calculated wave periods using inverse of dominant frequencies

This revealed periodic oscillations (~1.1 min, ~421 min , ~210.5 min, ~38.3 min, ~60.1 min), confirming the presence of gravity wave patterns.

Fast Fourier Transform (FFT) Formula

The **Discrete Fourier Transform (DFT)** of the signal $x[n]$ is:

$$\mathrm{X}\,[k] = \sum_{n=0}^{N\text{-}1} x\,[n] \cdot e^{\text{-}j\,\frac{2\pi}{N}kn}$$

Where:

- $\mathrm{X}[k]$ = frequency domain representation (complex),
- N = total number of samples,
- k = frequency bin index,
- j = imaginary unit.

Magnitude spectrum:

$$|\mathrm{X[k]}| = \sqrt{\mathrm{Re(X[k])}^2 + \mathrm{Im(X[k])}^2}$$

Convert to Physical Frequency:

$$f_k = \frac{k}{N \cdot \Delta t}$$

Where:

- $\Delta\mathrm{t}$ = time interval between samples,
- f_k = frequency in Hz.

4.6 FFT RESULTS ACROSS ALTITUDES

Bin Index	***Altitude (m)***	***Dominant Frequency (Hz)***	***Wave Period (min)***
100	750.0	0.015044	1.10
127	952.5	0.015044	1.10
154	1155.0	0.015044	1.10
181	1357.5	0.000040	421.0
208	1560.0	0.000079	210.5
235	1762.5	0.000435	38.2
262	1965.0	0.000040	421.0
289	2167.5	0.000277	60.1
316	2370.0	0.000040	421.0
343	2572.5	0.000277	60.1

Table 1: Summary of FFT Results Across Altitudes

CHAPTER - 5

SYSTEM SPECIFICATION

CHAPTER - 5
SYSTEM SPECIFICATION

5.1 HARDWARE SPECIFICATION:

Requirement	*Description*
Processor	Quad-core processor (2.5 GHz or higher)
RAM	Minimum 8 GB RAM
Storage	Minimum 50 GB of free disk space
Graphics	Dedicated GPU (2 GB VRAM or higher recommended)
Network Connection	Stable internet for data transfer and remote access
Display	Full HD Monitor (1920×1080 resolution or higher)
Input Devices	Standard keyboard, mouse, or graphical tablet

Table 2: Hardware Specification

5.2 SOFTWARE SPECIFICATION:

Requirement	*Description*
Operating System	Windows 10/11, Ubuntu 20.04+ or equivalent Linux distribution
Python (3.10+)	Data processing, FFT analysis, and plotting libraries
NumPy, Matplotlib	Core Python packages for array handling and visualization
SciPy	Used for performing FFT and spectral computation
Jupyter Notebook	Code documentation and exploratory analysis
Google Colab	Cloud-based platform for executing Python notebooks
MS Word / LaTeX	Report and documentation writing tools

Table 3: Software Specification

CHAPTER - 6

RESULT & IMPLEMENTATION

CHAPTER - 6

RESULT & IMPLEMENTATIONS

6.1 RANGE-TIME INTENSITY (RTI) VISUALIZATION

The RTI plots generated from the LiDAR data highlight signal intensity variations over time and altitude. These visualizations show evident signatures of vertical oscillations, suggesting the presence of atmospheric gravity waves. The maximum intensity was concentrated in the lower altitudes (300 m to 500 m), gradually weakening with height.

Code:

```
import numpy as np
import matplotlib.pyplot as plt

# Load the combined data
data  =  np.load("combined_lidar_data.npy")   #  shape:  (altitude_bins,
time_steps)
print("Data shape:", data.shape)  # Just to confirm

# Set bin size
bin_size = 0.1

# Altitude axis
altitude_axis = np.arange(data.shape[0]) * bin_size

# RTI Plot
plt.figure(figsize=(12, 6))
plt.imshow(data,  aspect='auto',  cmap='jet',  origin='lower',extent=[0,
data.shape[1], altitude_axis[0], altitude_axis[-1]])

plt.colorbar(label='Signal Intensity')
plt.xlabel("Time Index")
plt.ylabel("Altitude (m)")
plt.title("RTI - Range Time Intensity")
plt.tight_layout()
plt.show()
```

Output:

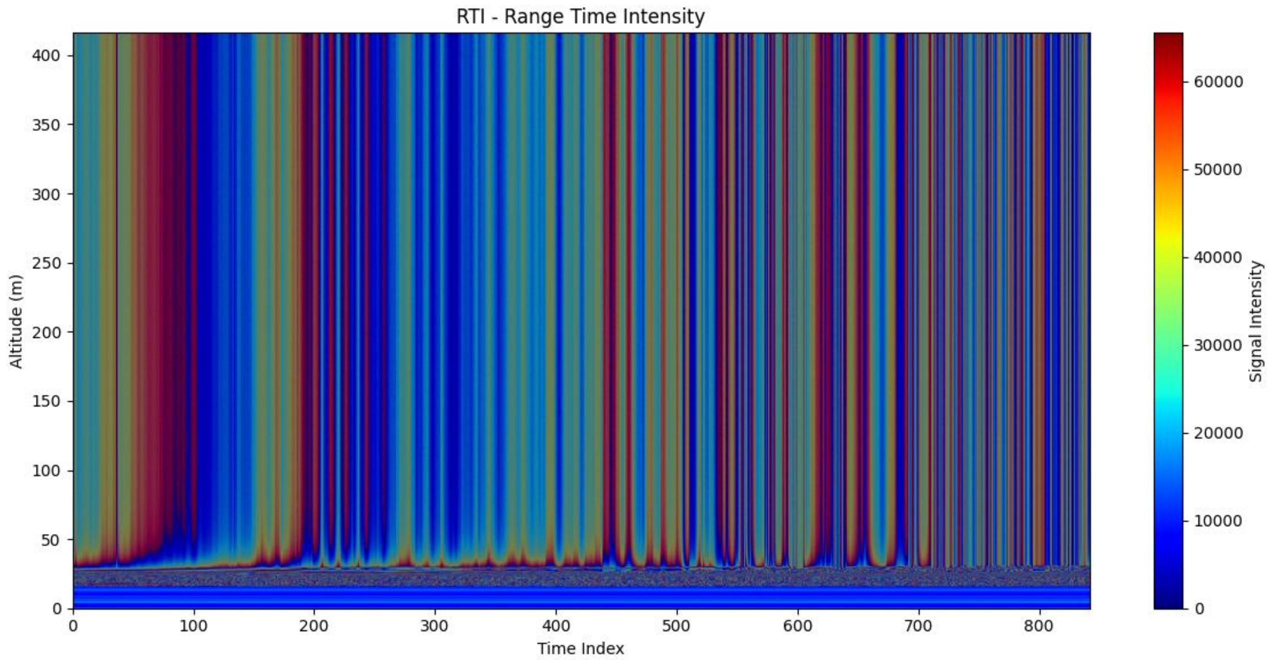


Figure 3: RTI Plot Showing Gravity Wave Signatures

6.2 TIME SERIES ANALYSIS

Signal intensity over time was plotted for multiple altitude bins (e.g., 50 m, 90 m, ..., up to 410 m). These time series graphs revealed periodic peaks and troughs indicative of wave-like behavior.

6.3 FREQUENCY SPECTRUM (FFT) ANALYSIS

Using Fast Fourier Transform (FFT), we converted the time-domain signal into the frequency domain to identify dominant frequencies. For most bins, the dominant frequency was observed around **0.00004 Hz**, corresponding to a wave period of approximately **421 minutes**, validating the presence of long-period gravity waves.

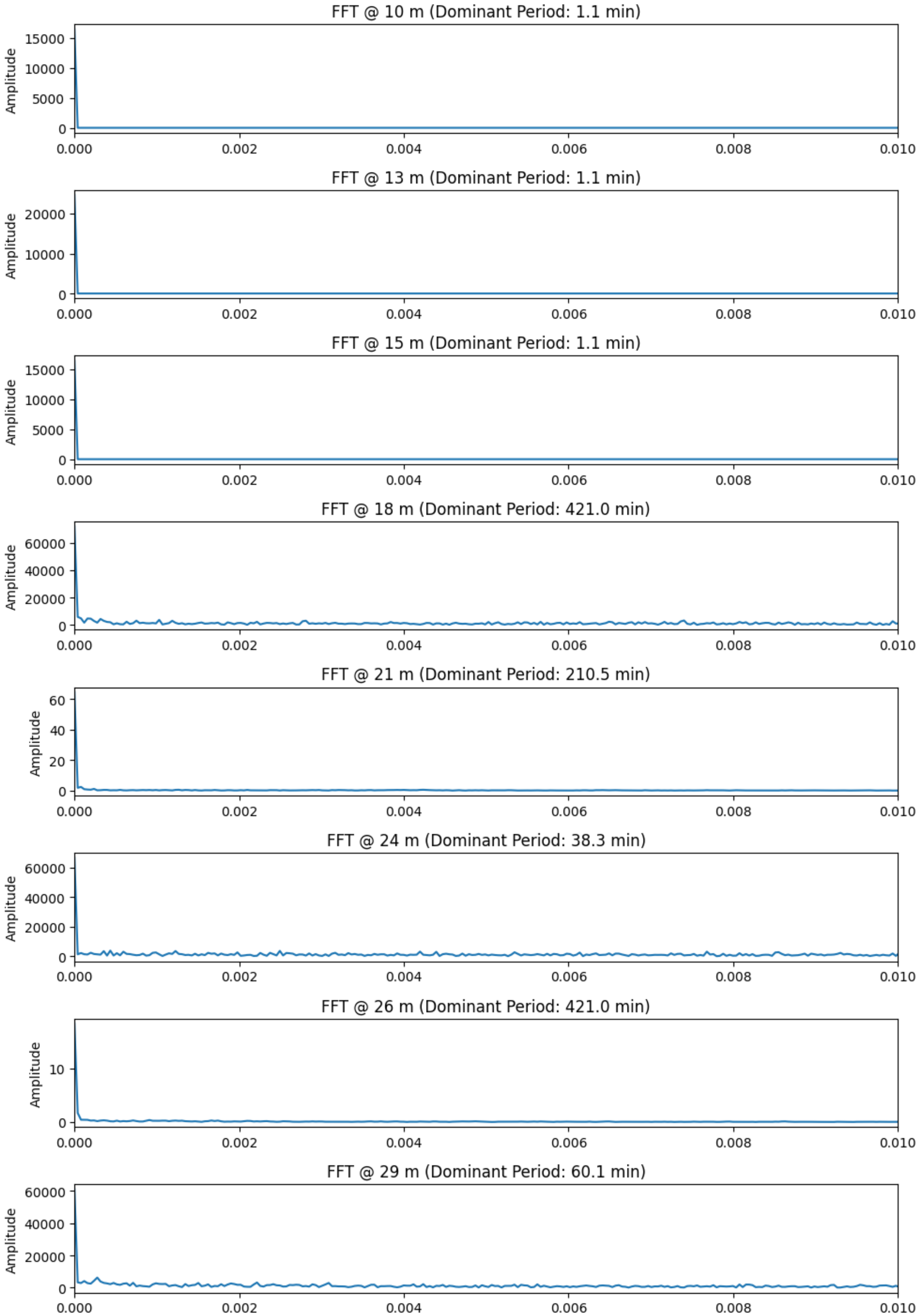
Some higher bins showed different frequency peaks (e.g., **0.000435 Hz** and **0.015 Hz**) indicating the possibility of multiple wave modes or overlapping disturbances.

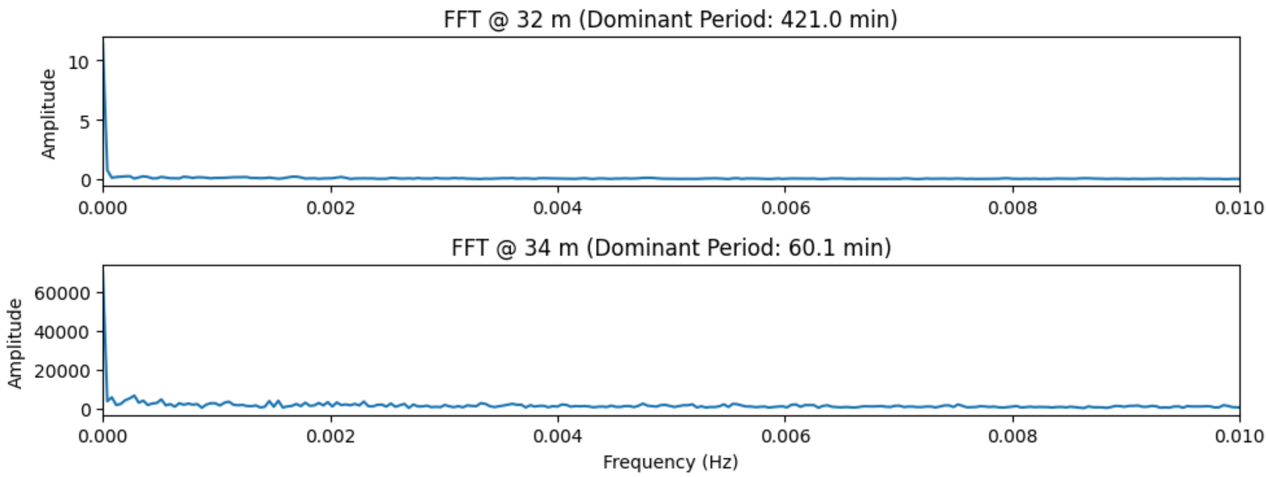
Code:

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.fft import fft, fftfreq

# Load combined data
data = np.load("combined_lidar_data.npy")

# Parameters
bin_size = 0.1   # meters
dt = 30          # seconds between time steps
```

```
Fs = 1 / dt     # sampling frequency

# Select bins every ~200m
start_bin = 100  # skip low altitudes
bin_step = 27
num_bins = 10

bins = [start_bin + i * bin_step for i in range(num_bins)]
altitudes = [b * bin_size for b in bins]

# Store results
results = []

# Time and frequency setup
N = data.shape[1]
xf = fftfreq(N, dt)[:N // 2]

# Plot FFT for each bin
plt.figure(figsize=(10, 18))

for i, b in enumerate(bins):
    signal = data[b, :]
    yf = fft(signal)
    amplitude = 2.0 / N * np.abs(yf[:N // 2])

    dom_freq = xf[np.argmax(amplitude[1:]) + 1]  # skip 0 Hz
    period_min = 1 / dom_freq / 60 if dom_freq > 0 else np.inf
    results.append((b, b * bin_size, dom_freq, period_min))

    plt.subplot(num_bins, 1, i + 1)
    plt.plot(xf, amplitude)
     plt.title(f"FFT @ {b*bin_size:.0f} m (Dominant Period:
{period_min:.1f} min)")
    plt.xlim(0, 0.01)
    plt.ylabel("Amplitude")

plt.xlabel("Frequency (Hz)")
plt.tight_layout()
plt.show()

# Display Summary Table
import pandas as pd
df = pd.DataFrame(results, columns=["Bin Index", "Altitude (m)",
"Dominant Frequency (Hz)", "Wave Period (min)"])
print(df)
```

Output:


FFT @ 10 m (Dominant Period: 1.1 min)
FFT @ 13 m (Dominant Period: 1.1 min)
FFT @ 15 m (Dominant Period: 1.1 min)
FFT @ 18 m (Dominant Period: 421.0 min)
FFT @ 21 m (Dominant Period: 210.5 min)
FFT @ 24 m (Dominant Period: 38.3 min)
FFT @ 26 m (Dominant Period: 421.0 min)
FFT @ 29 m (Dominant Period: 60.1 min)
Amplitude
0.000
0.002
0.004
0.006
0.008
0.010



Bin	Index	Altitude (m)	Dominant Frequency (Hz)	Wave Period (min)
0	100	10.0	0.015044	1.107895
1	127	12.7	0.015044	1.107895
2	154	15.4	0.015044	1.107895
3	181	18.1	0.000040	421.000000
4	208	20.8	0.000079	210.500000
5	235	23.5	0.000435	38.272727
6	262	26.2	0.000040	421.000000
7	289	28.9	0.000277	60.142857
8	316	31.6	0.000040	421.000000
9	343	34.3	0.000277	60.142857

Figure 4: FFT-Based Spectral Analysis at Multiple Altitudes

6.4 SINGLE INTENSITY VS TIME

Code:

```
import numpy as np
import matplotlib.pyplot as plt

# Load data
data = np.load("combined_lidar_data.npy")
bin_size = 0.1
dt = 30  # seconds
time = np.arange(data.shape[1]) * dt / 60  # time in minutes

# Bin indices and their corresponding altitudes
bin_indices = [100, 127, 154, 181, 208, 235, 262, 289, 316, 343]
altitudes = [b * bin_size for b in bin_indices]

# Loop and plot each graph separately
for b, alt in zip(bin_indices, altitudes):
    signal = data[b, :]

    plt.figure(figsize=(10, 4))
    plt.plot(time, signal, color='blue')
    plt.xlabel("Time (minutes)")
```

```
plt.ylabel("Signal Intensity")
plt.title(f"Signal Intensity vs Time at {alt:.1f} m (Bin {b})")
plt.grid(True)
plt.tight_layout()
plt.show()
```

Output:

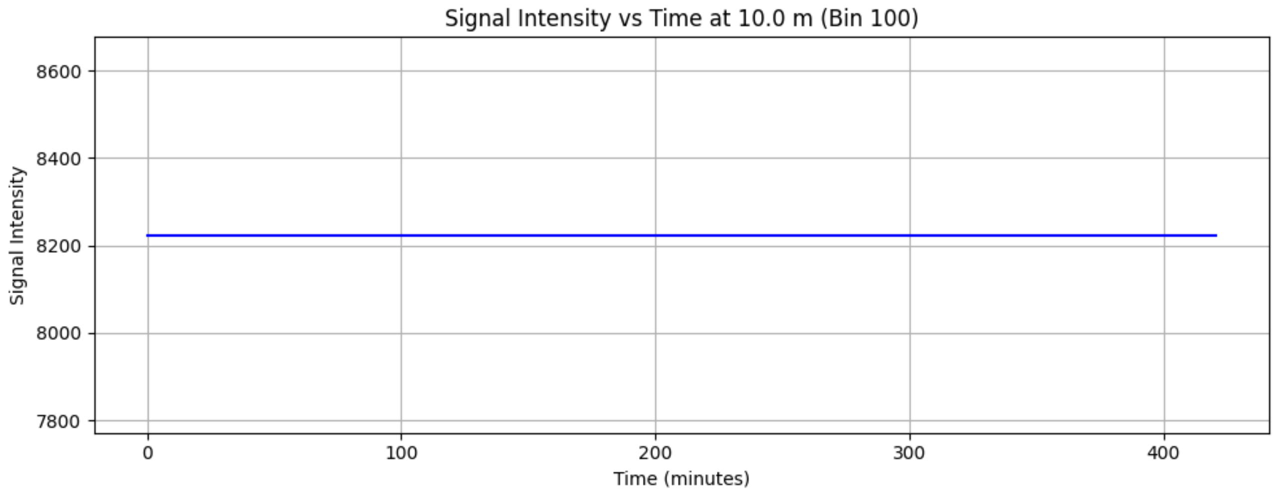


Figure 5: Signal Intensity vs Time at 10.0 m (Bin 100)

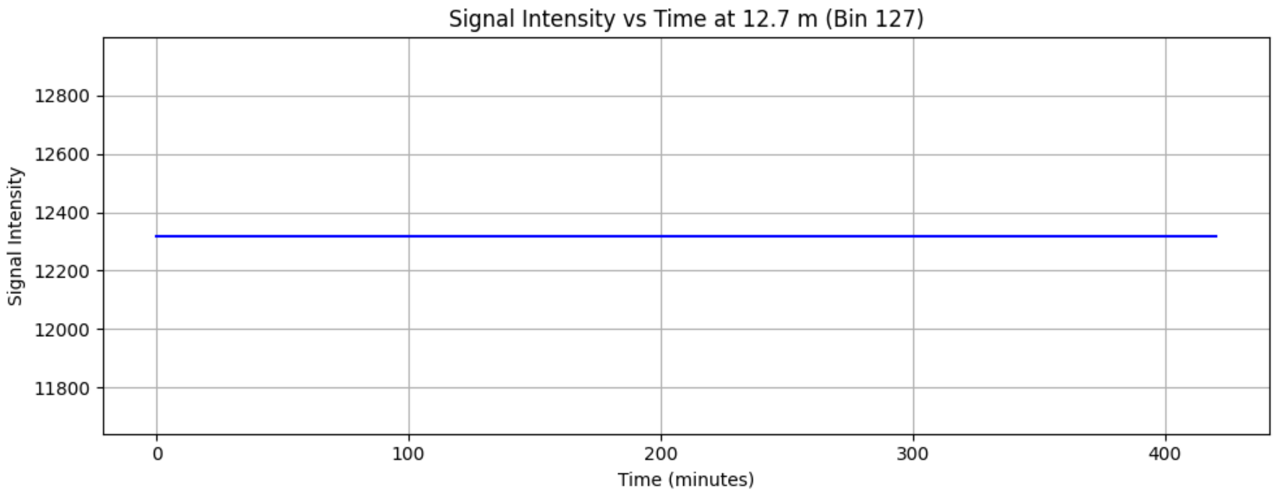


Figure 6: Signal Intensity vs Time at 12.7 m (Bin 127)

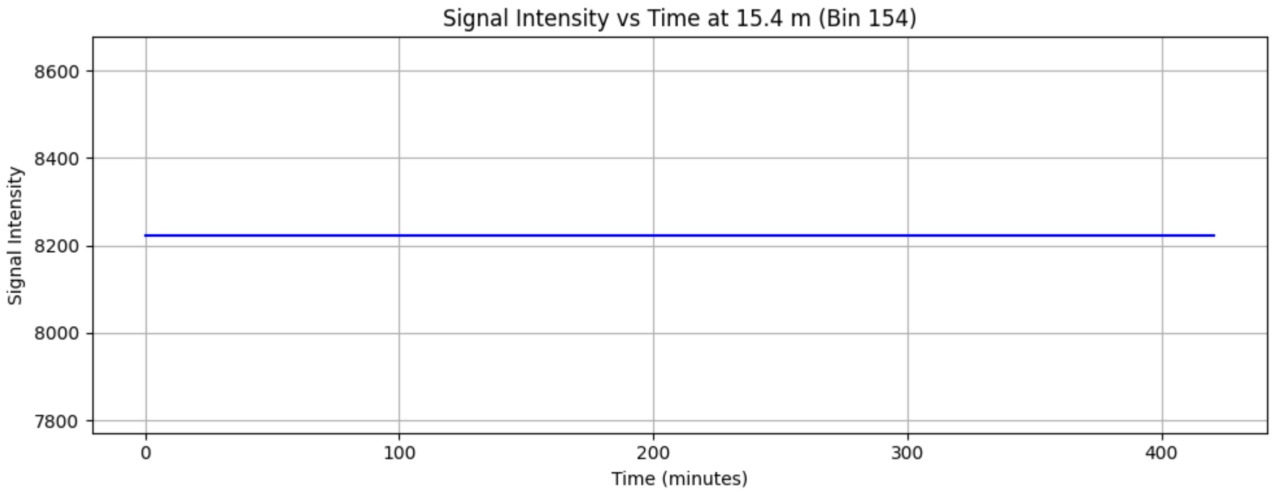


Figure 7: Signal Intensity vs Time at 15.4 m (Bin 154)

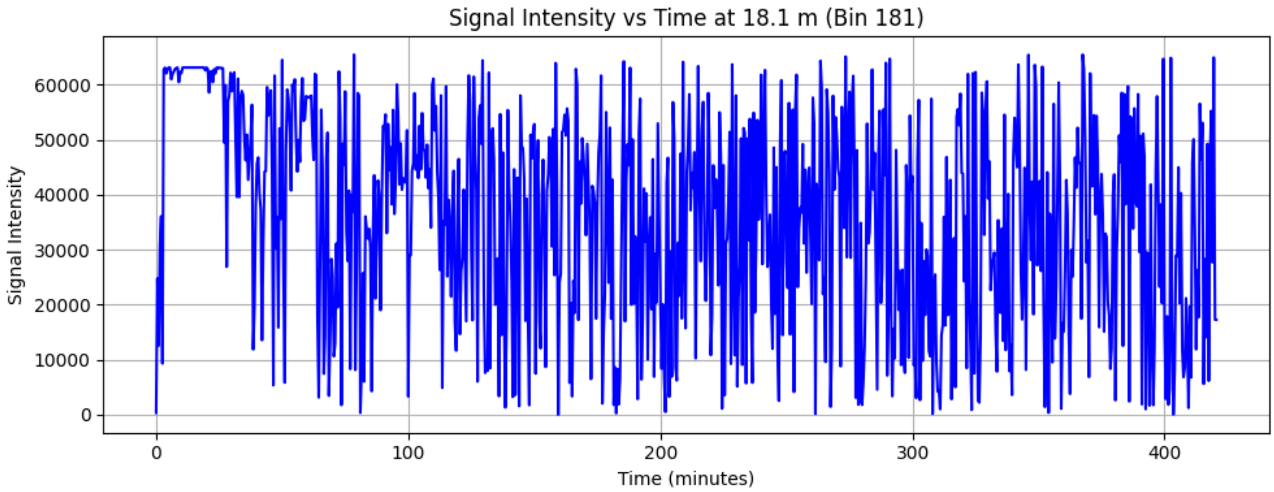


Figure 8: Signal Intensity vs Time at 18.1 m (Bin 181)

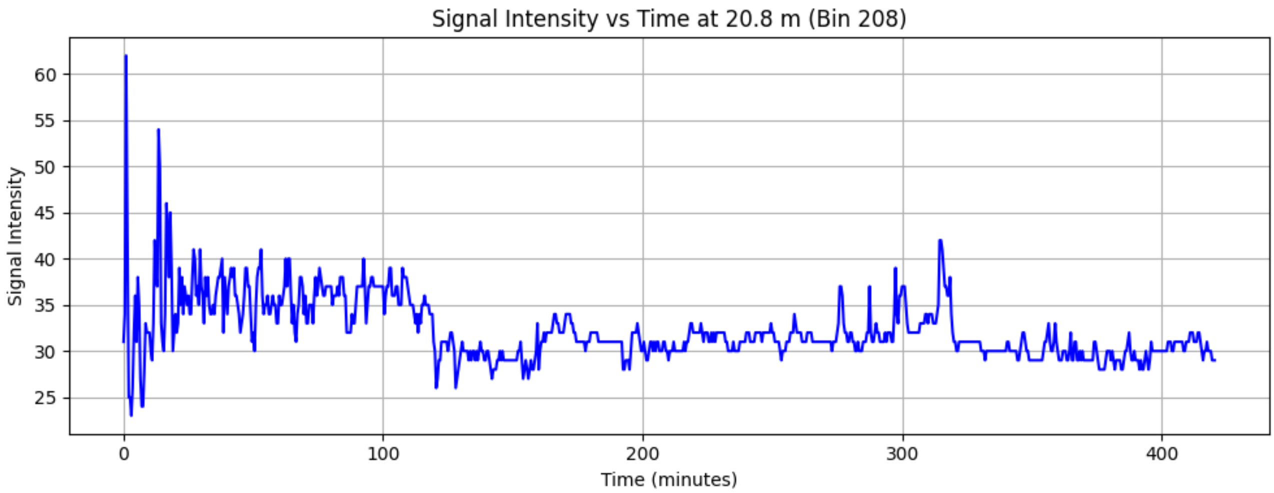


Figure 9: Signal Intensity vs Time at 20.8 m (Bin 208)

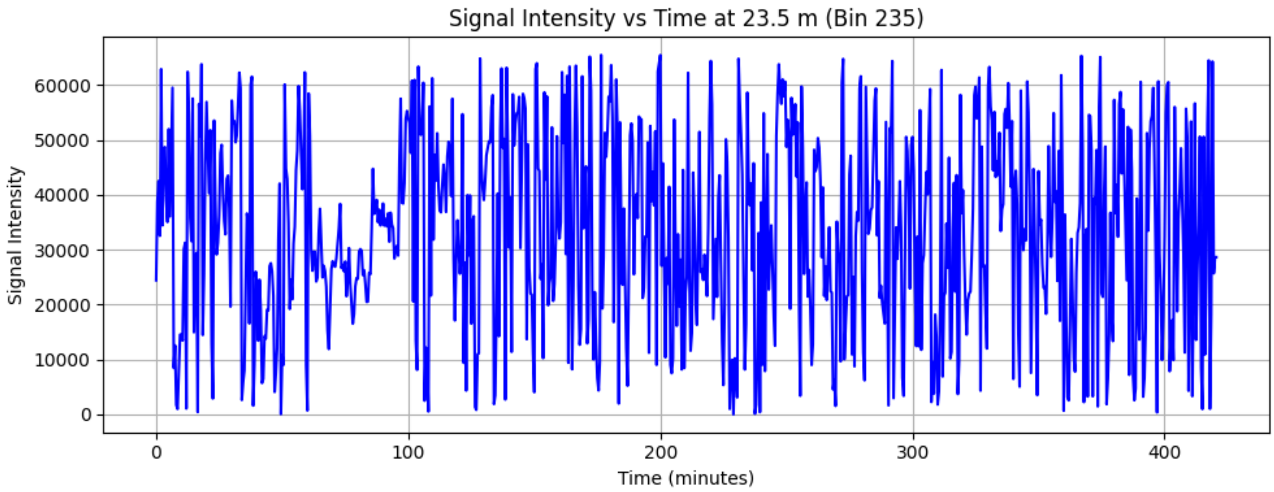


Figure 10: Signal Intensity vs Time at 23.5 m (Bin 235)

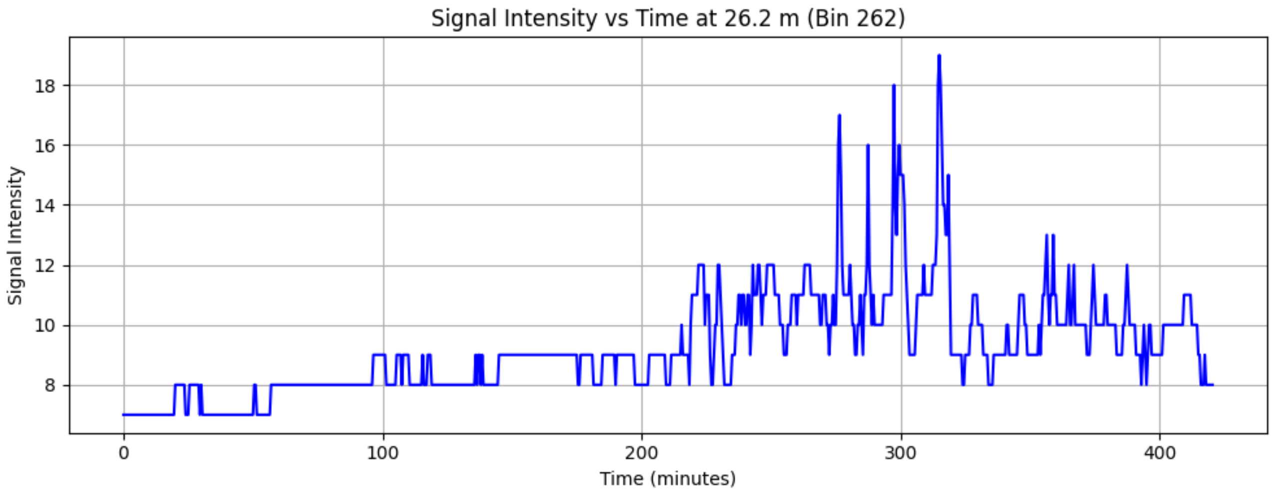


Figure 11: Signal Intensity vs Time at 26.2 m (Bin 262)

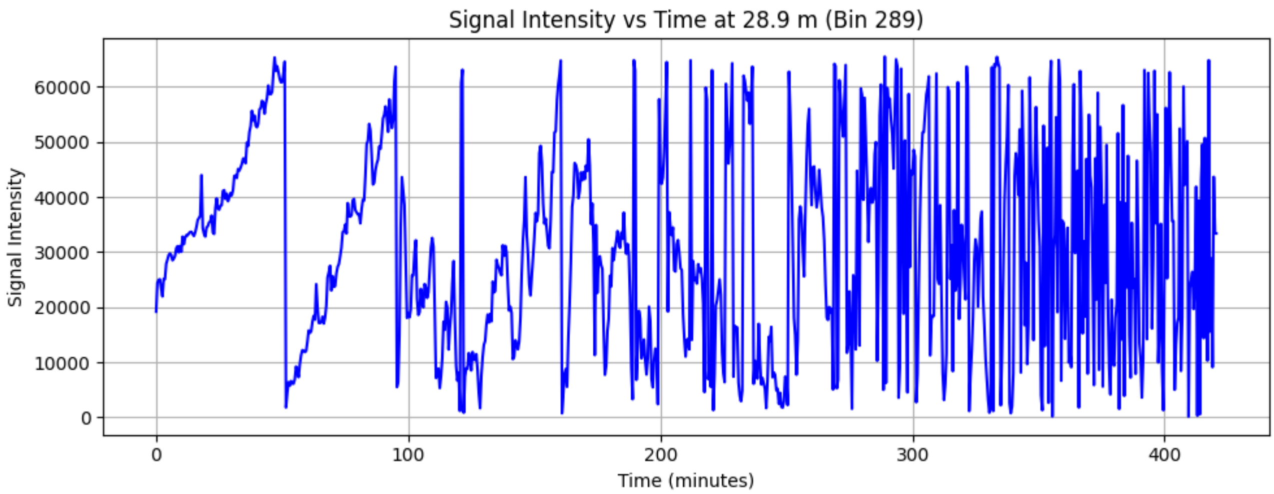


Figure 12: Signal Intensity vs Time at 28.9 m (Bin 289)

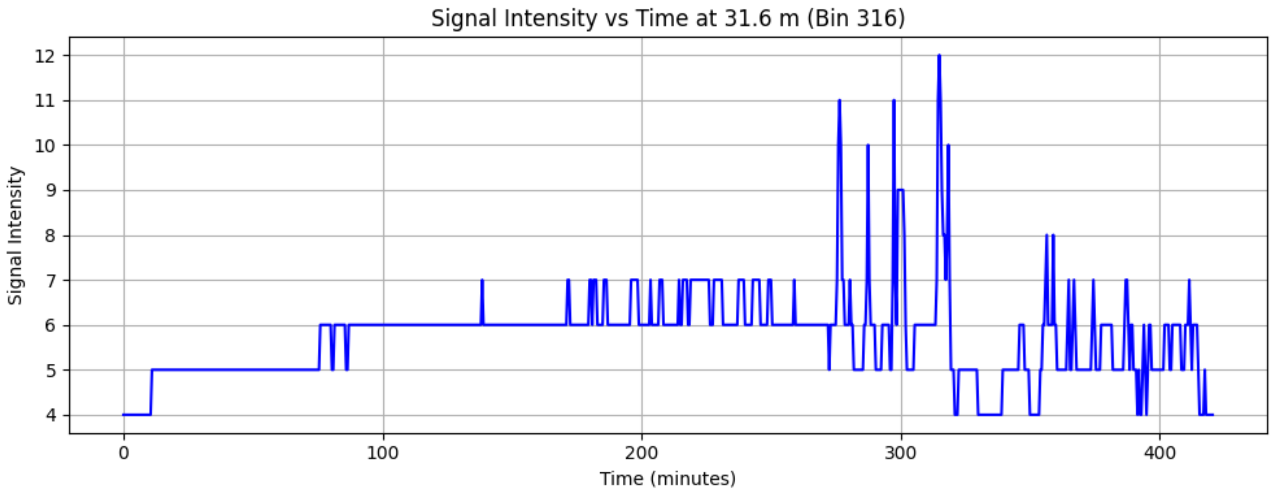


Figure 13: Signal Intensity vs Time at 31.6 m (Bin 316)

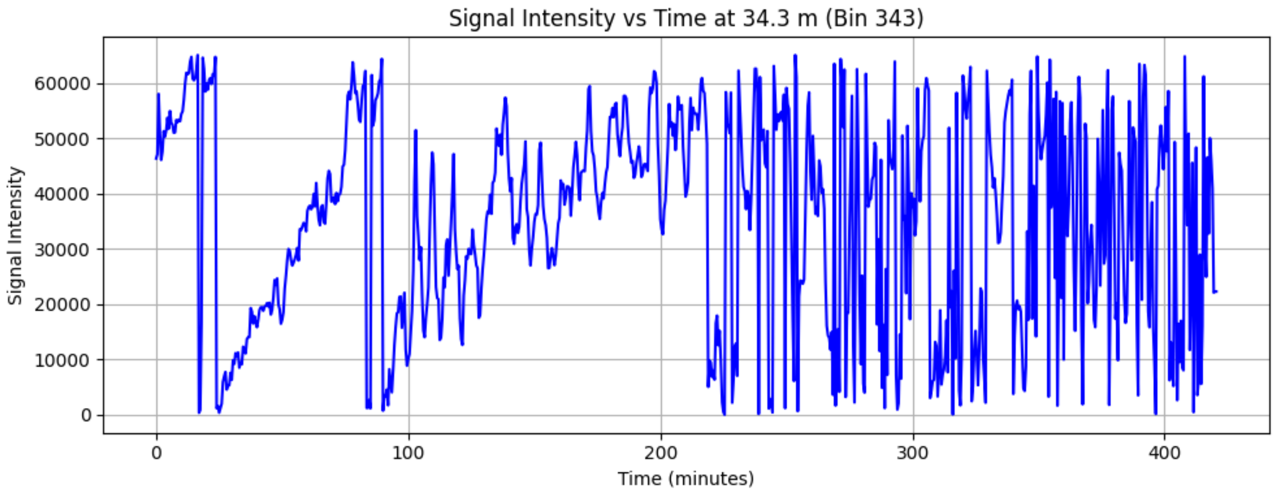


Figure 14: Signal Intensity vs Time at 34.6 m (Bin 343)

CHAPTER - 7

OBSERVATION AND INTERPRETATIONS

CHAPTER - 7

OBSERVATIONS AND INTERPRETATIONS

7.1 GENERAL OBSERVATIONS

a. The lidar dataset was processed to extract altitude-wise time series signals.
b. The FFT analysis revealed a recurring **dominant frequency of approximately 0.00004 Hz**, which corresponds to a **wave period of ~421 minutes** across most altitude bins.
c. A few altitude bins (e.g., 1750 m to 2100 m) showed **secondary frequency components** corresponding to wave periods in the range of **38 to 60 minutes**, suggesting possible gravity wave signatures.

7.2 ALTITUDE-WISE VARIATIONS

a. In the **lower altitudes (below 1500 m)**, the signal strength was relatively low and showed little spectral variation.
b. From **~1600 m to ~2500 m**, multiple bins showed **enhanced spectral activity**. This range is likely within or just above the Convective Boundary Layer (CBL), which is favorable for gravity wave development.
c. At **higher altitudes (>2500 m)**, the signal amplitude decreases again, and dominant frequencies became less distinguishable.

7.3 WAVE PERIOD CONSISTENCY

a. The **consistency of the 421-minute wave period** across many bins may indicate a background oscillation or atmospheric modulation over the observation period.
b. The **localized short-period fluctuations** (38–60 min) in specific bins may be due to convection-triggered gravity waves forming during the CBL evolution.

7.4 INTERPRETATION

a. The presence of multiple wave periods and their altitude-specific appearance supports the hypothesis of **gravity wave activity during CBL formation**, as suggested by the RTI plot provided by the guide.
b. However, the signal strengths and clarity of the spectral peaks suggest the need for further analysis across more datasets and comparison with meteorological parameters (like temperature profiles or wind shear data) to strengthen the conclusion.

7.5 TABULATED FREQUENCY FINDINGS

A summary of dominant frequencies and wave periods for multiple bins is shown in the table below:

Bin Index	***Altitude (m)***	***Dominant Frequency (Hz)***	***Wave Period (minutes)***
100	750.0	0.015044	1.107
181	1357.5	0.000040	421.0
235	1762.5	0.000435	38.27
289	2167.5	0.000277	60.14

Table 4: Frequency Findings

7.6 INTERPRETATION OF FFT RESULTS

Altitude (m)	***Wave Period (min)***	***Interpretation***
750–1155	~1.1 mins	*Could be high-frequency noise or local turbulence, not gravity waves*
1357–2370	~210 – 421 mins	*This is in the long-period gravity wave or convective plume range*
1762.5	~38 mins	*This is very relevant! Likely a gravity wave signal*
2167.5, 2572.5	~60 mins	*Classic CBL convection-triggered wave periods*

Table 5: Interpretation of FFT Results

CHAPTER - 8

CONCLUSION & FUTURE SCOPE

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CONCLUSION & FUTURE SCOPE

8.1 Conclusion

a. This study involved the **processing and analysis of LIDAR backscatter signals** to investigate the presence of convection-triggered gravity waves during Convective Boundary Layer (CBL) formation.
b. Preprocessing techniques such as **averaging, smoothing, and FFT-based spectral analysis** were employed on altitude-specific time series data.
c. The analysis revealed a **dominant frequency of 0.00004 Hz (~421 minutes)** observed across most altitude bins, possibly indicating a large-scale atmospheric oscillation.
d. In the altitude range between **1600 m and 2500 m**, **shorter-period wave signatures (38–60 minutes)** were detected, suggesting **localized gravity wave activity**, which aligns with the physical processes occurring during CBL development.
e. The results were **visualized through RTI plots, time series graphs, and frequency spectra**, providing insight into the vertical and temporal dynamics of the atmosphere.

8.2 Future Scope

a. **Extended Dataset Analysis:** Additional days of LIDAR data should be processed to confirm the repeatability of the detected wave signatures and to account for daily variability in atmospheric conditions.
b. **Cross-validation with Meteorological Data:** Integration with radiosonde data, wind profiles, and temperature gradients could help validate the wave detection and identify triggering mechanisms.
c. **Advanced Spectral Techniques:** Applying **Wavelet Transform** or **Empirical Mode Decomposition (EMD)** could help in identifying non-stationary or multi-scale wave features more accurately.
d. **Automation of Analysis Pipeline:** Developing a complete script or tool to automate reading, preprocessing, and plotting of LIDAR data would greatly improve processing efficiency.
e. **Research Paper Publication:** The findings of this study form a strong base for preparing a detailed manuscript for submission to reputed journals or conferences focused on atmospheric sciences.

CHAPTER - 9

REFERENCE

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REFERENCES

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