Processing of Rayleigh Lidar Density Fluctuations using the "Interleaved" Method

Satyaki Das(a,b), Richard Collins(a,b), Jintai Li(a)
(a) Geophysical Institute, University of Alaska, Fairbanks,
Fairbanks, Alaska 99775, USA
b) Department of Atmospheric Sciences, University of Alaska, Fairbanks,
Fairbanks, Alaska 99775, USA
sdas8@alaska.edu

Abstract: The Rayleigh Temperature and Density Lidar (RDTL) at Poker Flat Research Range (PFRR) characterizes gravity wave activity in the middle atmosphere through measurement of atmospheric density fluctuations. To date the measurements have been used to analyze wave activity in the 40-50 km altitude range using the noise variance subtraction method. We apply the recently developed interleaved method to the existing RDTL data acquisition process and present the results. We compare the results obtained from the interleaved method with the previously used noise variance subtraction method. The method shows significant differences in the estimates of the gravity wave activity at higher altitudes.

1. Introduction

The Rayleigh Temperature and Density Lidar (RDTL) installed at Poker Flat Research Range (PFRR), Chatanika, Alaska (65°N, 147°W) can measure high resolution densities from 40 km to 85 km under nighttime conditions. The density fluctuations have been used to characterize the gravity wave activity in the upper stratosphere and lower mesosphere (40-50 km). The gravity wave activity is characterized by calculating the specific potential energy based on the variance of the gravity wave fluctuations. These gravity wave retrievals have been used to show how gravity wave activity is modulated by the wind systems in the Arctic middle atmosphere during Stratospheric Sudden Warming events [1].

Over the past several years the RDTL has been upgraded with a new receiver system that employs a larger telescope and has yielded an increase in signal levels of a factor of 3-4. This has prompted the retrieval of gravity wave activity at higher altitudes to better understand gravity wave coupling in the stratosphere and mesosphere. The "interleaved method" of processing lidar signals that yields unbiased estimates of gravity wave activity has recently been developed [2]. Here we apply the new method to RDTL measurements to characterize gravity wave activity and compare it to the retrievals from the traditional processing technique that uses a noise subtraction method [2].

2. Lidar System Noise

The RDTL is a photon counting lidar system, where the statistical noise in the system arises from the photon counting process [3]. The noise appears as an additive white noise with a Poisson distribution in the signal. As the lidar signal decreases with altitude the relative uncertainty in the fluctuations increases. This increase in this noise is clearly evident in the vertical wavenumber spectra in figure 1. The spectra are calculated over 10 km intervals from 40-50, 50-60, 60-70, and 70-80 km. The spectra show a red spectrum with the power of the wave fluctuations concentrated at low wavenumbers (below 1 km^{-1}) added to a white spectrum, or noise floor, of the associated with the noise fluctuations. The Signal to Noise Ratio (SNR) in each spectrum is calculated as the ratio of the fluctuation power to noise power over the bandwidth from 0 km^{-1} to 0.5 km^{-1}. The total power is determined by integrating the spectrum. The noise power is determined by integrating the noise floor over the same altitude and then the power associated with the wave fluctuations is the difference between the total power and the noise power [4]. Clearly the SNR decreases with altitude, from 31.1 at 40-50 km to 0.78 at 70-80 km. The decrease in SNR reflects both the increase in the noise fluctuations as well as the increase in fluctuation power as the wave fluctuations increase with altitude. The estimate of the noise floor is biased as the noise floor represents an average that is growing exponentially with altitude over the range of the spectral estimate.

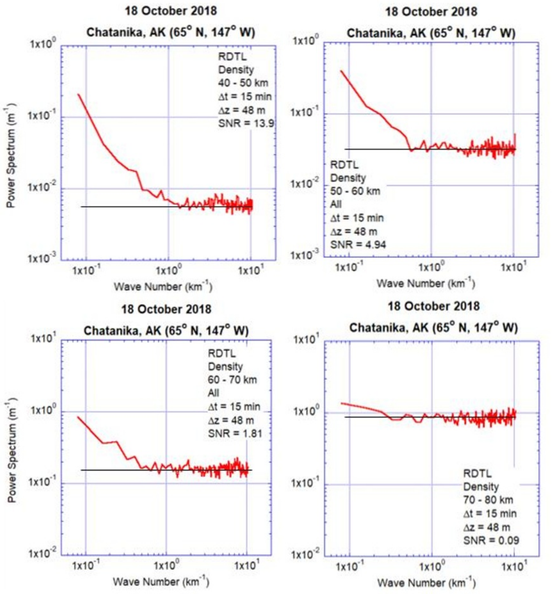

Figure 1. The power spectrum of RDTL signal with wavenumber on 18 October 2018.

3. The Interleaved Method

The lidar density retrieval above 120 km is dominated by statistical fluctuations as the echo from the air is negligible. The autocorrelation function calculated for the portion of the profile above 120 km is shown in figure 3. The resolution of the profile is 48 m. The autocorrelation function in figure 2 shows that the noise fluctuations are uncorrelated with no correlation for lags of 1 or greater.

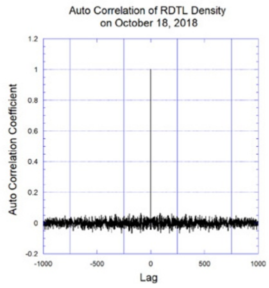

Figure 2. Autocorrelation of the lidar density at over altitudes above 120 km.

This has prompted the use of separating the lidar profiles at each time into two profiles based on successive ranges bins, an even profile (denoted ‘e’) based on the even ranges (0, 2, 4…) and an odd profile (denoted ‘e’) based on the even ranges (1, 3, 5…) [5]. The even and odd profiles are interleaved.

The even and odd profiles are then processed separately to generate two distinct sets of density profiles, ρ_e, ρ_o, background density profiles, ρ_{0e}, ρ_{0o} and fluctuations ρ_e', ρ_0' respectively. and odd bins and the specific potential energy is calculated by,

$$\overline{E}_p = \frac{1}{2} N^2 \xi^2 = \frac{1}{2} \{\frac{g}{N}\}^2 \operatorname{cov}(r_{e,} r_o) \quad (1)$$

Where $r_e = \rho_e'/\ \rho_{0e}$ and $r_0 = \rho_0'/\ \rho_{0o}$ are the relative density fluctuations in even and odd bins, respectively, g is the gravitational constant, N is the buoyancy frequency (determined from the corresponding background temperature profile) and ξ is the rms vertical displacement. Similarly, the mean-square vertical displacement is given by,

$$\overline{\xi^2} = \frac{g^2}{N^4} \sqrt{\operatorname{cov}(r_e, r_o)} \qquad (2)$$

4. Results

The method is applied to RDTL measurements of gravity wave activity on the night of 18-19 October 2018. The measurements are made between 1844 LST and 0603 LST (0344-1503 UT). The relative density fluctuations retrieved from the entire profile (all range bins), even range bins, and odd range bins are shown as functions of altitude and and time in figure 3.

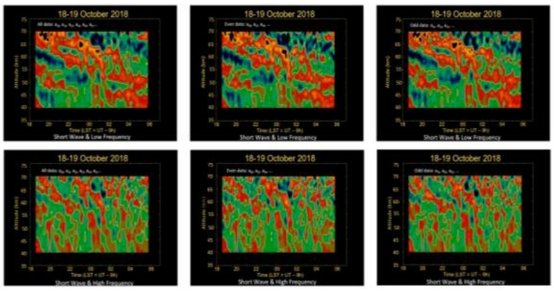

Figure 3. Relative density perturbations as a function of time and altitude when all (left), even (middle) and odd (right) altitude bins are used.

The upper panels show the fluctuations over the 40 km to 70 km altitude region relative to the background, while the lower panels show the fluctuations over the 40 km to 70 km with spectral components of longer than 4 h removed. The density profile were low pass filtered at 2 km. The fluctuations clearly show downward phase progressings indicative of upwardly propagaing waves. For all period fluctuations the rms relative density fluctuations are 1.94 %, 1.96 % and 1.92 % respectively for all, even and odd data. The rms relative density fluctuations for the short period (< 4 h) fluctuations are 1.11 %, 1.10 % and 1.11 % in all, even and odd data respectively.

The rms gravity wave fluctuations are calculated over progressive 10 km intervals from 40-50 km to 65-75 km using the noise subtraction method with all range bins (all) and the interleaved method using even and odd range bins (interleaved). The results are plotted as a function of altitude in figure 4.

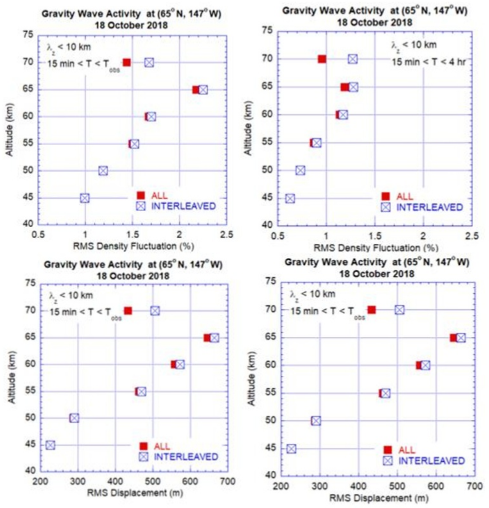

Figure 4. Variation of gravity wave rms density and displacement fluctuations with altitude.

The rms density fluctuations from both the methods yield similar results at lower altitudes and the difference between the two retrievals increases with altitude. This is due to the fact that at the lower altitudes the signals have high SNR and the noise estimate in the traditional method is not a significant source of error. As the SNR increases the variance subtraction method becomes biased and the estimates of the rms fluctutaions are lower than those from the interleaved method.

The variaton of the of the specific potential energy and the noise estimates with altitude are plotted in figure 5. The estimates are for both all the spectral components (upper panels) and the short period components (lower). As expected the noise streadily increases with altitude. The difference in the estimates of the variance subtraction retrieval and the interleaved retrieval become more apparent with as the noise grows with altitude. The variance subtraction retrieval is biased to lower values than the interleaved retrieval.

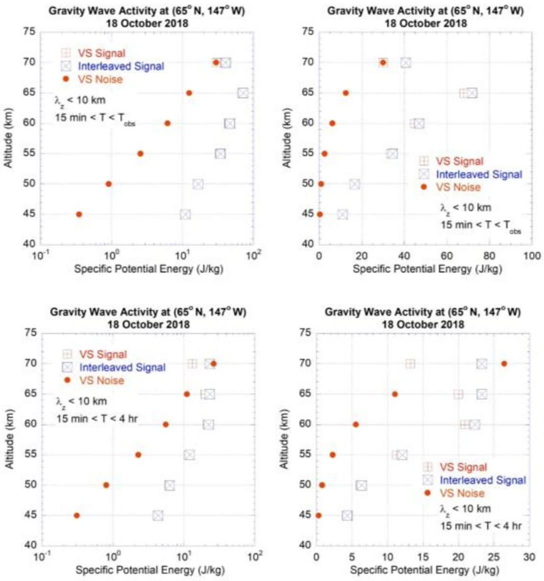

Figure 5. Variation of specific potential energy (SPE) and noise with altitude.

The bias in the variance subtraction method is important for interpreting gravity wave propagation. The decrease in gravity wave energywith altitude could be erroneously interpreted as dissipation of gravity waves with altitude. These effects are more apparent in the short period wave fluctuations where the SNR is lower.

5. Conclusions

The need to understand gravity wave propagation and coupling in the atmosphere has prompted the development of novel approaches to processing lidar data with low SNR. The interleaved method uses the fact that the noise in lidar signals is uncorrelated between adjacent range bins. The method has been applied to Rayleigh lidar data from Chatanika, Alaska. Comparison of the conventional retrievals with the interleaved retrievals shows differences that grow with altitude and could bias the interpretation of how gravity waves are propagating in the middle atmosphere.

6. References

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