Wind fields and aerosol structures from the REAL at M^{2}HATS

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Abstract: We deployed the Raman-shifted Eye-safe Aerosol Lidar (REAL) at the Multipoint MOST Horizontal Array Turbulence Study (M^{2}HATS) in Tonopah, Nevada, from July through September of 2023. The REAL scanned horizontally over a linear array of 50 sonic anemometers at 4 m AGL and spaced 5 m apart. 60° wide sector scans of elastic aerosol backscatter were collected every 17 s. The Typhoon wavelet-based motion estimation algorithm was applied to the images to derive vector flow fields. The observations will allow us to determine the filtering effect of this PIV-style wind measurement technique and contribute to testing the multipoint Monin-Obukhov Similarity Theory.

1. Introduction

Monin-Obukhov Similarity Theory (MOST) [1] is the theoretical foundation for understanding the surface layer of the atmospheric boundary layer. While enjoying great success, the original MOST fails to scale some important statistics in the convective surface layer, such as the large-scale turbulence spectra, rendering the surface-layer similarity in MOST incomplete. The recently proposed multipoint MOST (MMO)[2,3] overcomes the shortcomings of MOST. The spectra of velocity and potential temperature, the variances of the vertical velocity and potential temperature, and the mean velocity profile, have also been derived analytically. To validate the predicted spectra and obtain the non-dimensional coefficients in the prediction, measurement data are required. Traditionally spectra are obtained using 1D data or time series. However, such 1D spectra contain aliasing effects, i.e., higher wavenumbers in a direction different from the one-dimensional data are aliased into the data, appearing at lower wavenumbers, causing misinterpretation of the scales and magnitudes of the turbulent velocity fluctuations. To largely remove the aliasing effects, 2D or ring-integrated spectra are needed, requiring 2D wind fields. In M^{2}HATS, we used a sonic anemometer array and REAL to provide the resolved wind field from 5 m to 250 m and from approximately 100 m to 2 km scales, respectively.

Fig. 1: REAL deployed at the M^{2}HATS experiment in Tonopah, NV, from July to September 2023.

2. REAL

The original Raman-shifted Eye-safe Aerosol Lidar (REAL) [4-6] (Fig. 1), developed at NCAR EOL from 2002 -- 2007, was deployed to collect horizontal scans of elastic backscatter and 2D vector flow fields in the atmospheric surface layer. The transmitter employs a powerful Nd:YAG laser and a high-pressure gas cell to generate pulses at 1.54 microns wavelength through stimulated Raman scattering in methane. The wavelength-converting gas cell features a coating-free, multiple pass, and non-focused optical design, Stokes injection seeding, and internal gas recirculation [7]. Operational conversion efficiencies of about 25% are achieved. The

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REAL transmits approximately 130 mJ pulses, 6 ns in duration, at 10 Hz. The receiver includes a 40 cm diameter Newtonian telescope and two InGaAs avalanche photodiodes for polarization sensitivity [6]. The data acquisition system uses a 2-channel analog-to-digital converter with 14-bit resolution sampling at 100M samples per second.

The REAL is housed in a mobile facility consisting of two 20-foot (6 m) long shipping containers on a 48-foot (14.6 m) long flatbed trailer. When deployed the platform stands firmly upon 4 manually adjustable leveling legs. High-precision and accuracy tiltmeters constantly measure the attitude of the optics table. The laboratory container on the front of the trailer is temperature stabilized, HEPA-filtered, and it has large uninterruptible power supplies to maintain operation through challenging field conditions. A rooftop scanner permits full hemispherical scanning.

3. Typhoon

Typhoon [8] is a software that applies a wavelet-based motion estimation algorithm to consecutive pairs of 2D images. As a global method, it solves for the displacement of aerosol image features simultaneously in the entire domain, whereas local methods such as cross-correlation [9] break the motion field estimation into many independent sub-problems. Typhoons also provide a dense solution, which is a displacement vector at every pixel. The flow field is estimated by minimizing a functional which combines a data model and a regularization term. A user-defined parameter balances the two terms. Typhoon is written in C/C++ with calls to CUDA to perform the calculation in a massively parallel fashion in real-time. It runs on a Linux server with Nvidia GPUs inside the REAL laboratory container.

Before applying Typhoon, the REAL backscatter data is first range corrected and band-pass median filtered, then interpolated from its native polar coordinate system with $\Delta r = 1.5$ m and $\Delta\theta = 0.4°$ to a Cartesian coordinate system with an arbitrary resolution, chosen for this project to be $\Delta x = \Delta y = 8$ m. The wind estimation is restricted to the regions of the scan containing coherent aerosol features, and the process corrects for image distortions due to the lidar scanning motion [10,8].

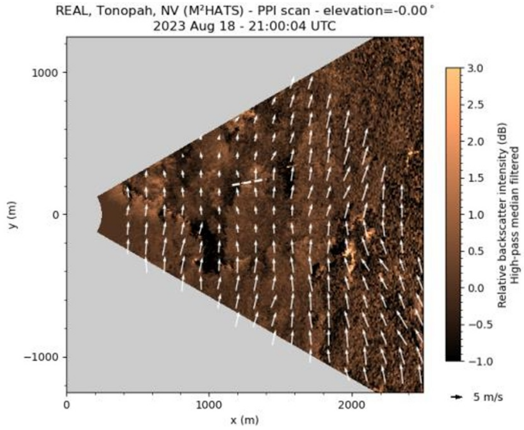

Figure 2. A single vector flow field derived from two consecutive scans of the REAL using the Typhoon motion estimation algorithm during M^2HATS. Vectors shown are a subset of the full-resolution field derived by Typhoon. The white dashed line indicates the position of the 250-m wide linear array of sonic anemometers.

4. Field Experiment

The M^2HATS experiment took place from 23 July to 25 September of 2023, 12 km ESE of the town of Tonopah, Nevada. The region is a high-altitude (1655 m ASL) desert environment. The experimental site was located in a broad (O10 km) and almost flat valley less than 1 km south of the 15/33 runway of the Tonopah Airport (TPH). The site was on land owned by Nye County, Nevada. The wind blew consistently from the south during the day. Many observing systems were deployed, including a 250-m wide linear array of 50 sonic anemometers at 4~m AGL, 2 flux towers, a distributed temperature sensing system, 3 Doppler lidars, 2 profiling radars, and 2 micropulse water vapor DIALs with temperature sensing capability. Radiosondes were launched twice per day. The REAL was located at 38.040712° latitude and -117.087482° longitude. It scanned horizontally at 5 m AGL from 60° to 120° azimuth at 4° s^{-1}.

5. Results

Over 629 hours of REAL data (about 153,000 scans, 0.8 TB) were collected over a wide range of meteorological conditions. The derived vector flow fields amount to about 26 GB.

Because of the importance of unstable daytime conditions, we typically operated the REAL from morning until evening. While the REAL almost always detected useful backscatter signal to at least 2 km range, the aerosol conditions were challenging for lidars in that (a) the air was often very low humidity, high visibility, and not contaminated by human-made sources of pollution, and (b) ideal conditions for motion estimation only occurred when the wind speed was strong enough to lift naturally occurring dust from the surface.

6. Next steps

The analysis of this new data set is in progress. In the future, we will compute 1D and 2D spatial power spectra from the velocity fields. We will compare the 1D spectra to those from the array of sonic anemometers to determine the transfer function of the lidar velocity fields. We will then compute the ring-integrated spectra and use the transfer function to estimate the true velocity spectra. The spectra will be compared with those predicted by MMO.

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