Simultaneous Na and Fe Doppler Lidar Measurements of Wind and Temperature at Table Mountain

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Abstract: We present the simultaneous and common-volume Na and Fe Doppler lidar measurements of wind and temperature in the mesosphere and lower thermosphere (MLT) at Table Mountain, north of Boulder. This is the first ever measurements of the MLT region with two resonance Doppler lidars simultaneously, providing a unique opportunity to evaluate the two state-of-the-art Doppler lidar technologies. Such observations will also enable the sophisticated studies of two different meteoric metal species (Na and Fe) and how they respond to various physical and chemical processes.

Keywords: Resonance Doppler Lidar, Wind, Temperature, Meteoric Metal Layers, and MLT Region

1. Introduction

There are compelling scientific motivations to study the whole atmosphere from the ground to the thermosphere. Lying above the troposphere are the stratosphere, mesosphere and thermosphere. The natural upward extension of the Earth’s atmosphere ultimately leads to its interaction with space above ~50 km altitude, where atmospheric neutral gases entwine with the dynamic plasma of space. The ionosphere, consisting of three main parts historically named as D, E, and F regions, is embedded in the mesosphere and thermosphere. This space-atmosphere interaction region is known to be essential for sustaining life on Earth by absorbing extreme radiation, ablating meteoric materials, dissipating energetic particles and fields from space, and regulating gaseous escape, while balancing the influences from the Earth itself in the form of wave energy and momentum originating from the lower atmosphere [1]. However, the properties and processes that govern the space-atmosphere interactions are not sufficiently described to fully understand their roles in atmosphere’s development and evolution, largely owing to the lack of measurements with sufficient coverage, accuracy, precision, and resolution. Lidar measurements of neutral winds, temperatures, and species through the whole atmosphere certainly help address these challenges to enable explorations of the space-atmosphere interactions.

Profiling wind and temperature in the middle and upper atmosphere demands lidar technologies beyond coherent Doppler lidars, namely the direct-detection Doppler lidars for wind measurements and various techniques for temperature measurements including Rayleigh and Raman integration lidar, Fe Boltzmann lidar, and Doppler lidar [2]. Among them resonance fluorescence lidars, sensing meteoric metal layers (e.g., Fe, Na, K, Ca, Ca’, etc.) in their main deposition regions of 80–110 km, have made significant contributions to the middle and upper atmosphere studies (see a summary in [2]). Very recently, Fe Boltzmann lidar observations have discovered neutral iron (Fe) layers in the thermosphere up to ~200 km in altitudes in Antarctica, directly measured neutral temperatures to ~170 km, and revealed close correlations of thermospheric Fe layers with geomagnetic storms [3,4]. Such discoveries have opened a new door for groundbased instruments to explore the space-atmosphere interaction region. Unfortunately, the broadband Fe Boltzmann lidar is not capable of wind measurements. Therefore, we choose narrowband resonance (Na and Fe) Doppler lidars for the development of whole atmosphere lidars.
2. **Operation Principles of Resonance Doppler Lidars**

Na and Fe Doppler lidars exploit the very large absorption cross-sections of Na and Fe free atoms in the mesosphere and lower thermosphere-extended region where quenching is not an issue so resonance fluorescence is achievable. The absorption lines of Na at 589 nm and Fe at 372 nm experience Doppler broadening due to thermal motion and Doppler shift due to bulk motion. By measuring the Doppler broadening and shift with narrowband lasers, temperature and wind can be derived simultaneously [2].

![Na Resonance Fluorescence Signals](image1)

![Detected Na Signals with Broadband Receiver](image2)

![Rayleigh and Mie Signals at Temperature = 280 K](image3)

![Detected Rayleigh/Mie Signals with Broadband Receiver](image4)

**Figure 1.** Resonance Doppler lidar versus other direct-detection Doppler lidars.

It is worth to note the differences between resonance Doppler and other direct-detection Doppler lidar (DDL) techniques. First, resonance absorption experiences 1 time of Doppler shift and broadening, while Rayleigh scattering experiences 2 times of Doppler shift and broadening. Second, resonance Doppler lidar has its frequency discriminator (i.e., the atomic absorption line) in the upper atmosphere and space, but other DDLs must have human-made narrowband frequency analyzers in the receivers. When scanning a narrowband laser through an absorption line, the returned fluorescence intensity exhibits the absorption lineshape along laser frequency; however, such a scan through Rayleigh scattering only results in a flat intensity over frequency if broadband receivers are employed, as demonstrated in Figure 1. Therefore, resonance Doppler lidars can employ broadband receivers to collect all fluorescence photons, thus possessing much higher optical efficiency than other DDLs equipped with very narrowband receivers.

![Calibration curves for 3-frequency Na and Fe Doppler lidars](image5)

**Figure 2.** Calibration curves for 3-frequency Na and Fe Doppler lidars on the left and right, respectively.
To achieve the highest resolution and precision while keeping high accuracy for the upper atmosphere observations, the three-frequency ratio technique is employed in the Na and Fe Doppler lidars [2], instead of the laser frequency scanning method used in laboratory laser spectroscopy. The master laser is locked to a fixed frequency, usually a peak feature of sub-Doppler saturation-absorption spectroscopy, and acousto-optic modulators (AOMs) are used to shift laser frequency below and above the peak. By switching outgoing lidar pulses among peak, blue-shift (plus) and red-shift (minus) frequencies sequentially and repeatedly, two ratios \( R_T \) and \( R_W \) can be formed from 3-frequency Rayleigh-normalized lidar signals, which correspond to the ratios of effective backscatter cross-sections in physics, e.g.,

\[
R_T = \frac{N_{\text{Norm}}(f_+,z) + N_{\text{Norm}}(f_-,z)}{N_{\text{Norm}}(f_{\text{peak}},z)} = \frac{\sigma_{\text{eff}}(f_+,z) + \sigma_{\text{eff}}(f_-,z)}{\sigma_{\text{eff}}(f_{\text{peak}},z)}
\]

(1)

\[
R_W = \frac{N_{\text{Norm}}(f_+,z) - N_{\text{Norm}}(f_-,z)}{N_{\text{Norm}}(f_{\text{peak}},z)} = \frac{\sigma_{\text{eff}}(f_+,z) - \sigma_{\text{eff}}(f_-,z)}{\sigma_{\text{eff}}(f_{\text{peak}},z)}
\]

(2)

As illustrated in Figure 2, the calibration curves computed from atomic physics have mesh structures for both Na and Fe Doppler lidars. The measured \( R_T \) and \( R_W \) ratios will determine one cross point from the mesh, thus a pair of temperature and line of sight (LOS) wind values can be inferred simultaneously.

3. Instrumentation of Na and Fe Doppler Lidars

Both Na and Fe Doppler lidars employ the double-pass dual AOMs in transmitters to shift lidar pulse frequencies by ±750 MHz and ±742 MHz, respectively, but their laser systems are completely different. The Na Doppler laser has a “MOPA” configuration of master oscillator (CW ring dye laser) and power amplifier (pulsed dye amplifier) [2], while the Fe Doppler laser is an injection-seeded, frequency-doubled Pulsed Alexandrite Ring Laser (PARL) custom designed and made by Light Age, Inc. in collaboration with Chu Research Group at the University of Colorado Boulder [5]. Sophisticated technologies, such as Fe Doppler-free saturation-absorption spectroscopy and optical heterodyne detection at 744 and 372 nm, are applied in the Fe Doppler lidar to lock a 372-nm external cavity diode laser (ECDL) to $^{56}$Fe peak frequency for providing an absolute frequency reference, and then to beat with the 372-nm lidar pulses to measure the frequency of every pulse. By tuning the frequency of a 744-nm ECDL injection seed laser, the 372-nm lidar pulses are stabilized onto the $^{56}$Fe peak frequency. Owing to the high-efficiency receiver architecture [6], both Na and Fe Doppler lidars have achieved high optical efficiencies, leading to very high return signal levels, especially for the Na Doppler lidar. To obtain 3-dimensional winds, the lidar beam is split into three for west, north and zenith directions with three prime-focus Newtonian telescopes of 81-cm in diameter pointing to the same three directions. An example is shown in Figure 3 for temperature, zonal wind, and meridional wind measurements. The off-zenith angle was 20 deg.

![Figure 3. Temperature, zonal and meridional winds measured on 13 October 2015 at Table Mountain near Boulder. The vertical and temporal resolutions are 1 km and 15 min.](image-url)
4. **Simultaneous and Common-Volume Observations at Table Mountain**

Illustrated in Figure 4 is an example of simultaneous and common-volume measurements of temperature and vertical winds by Fe and Na Doppler lidars at Table Mountain (40.13°N, 105.24°W) in January 2016.

![Figure 4. Temperatures and vertical winds measured simultaneously by Fe Doppler lidar (top row) and Na Doppler lidar (bottom row) on 28 January 2016 at Table Mountain Lidar Observatory, Boulder.](image)

5. **Conclusions**

The simultaneous and common-volume measurements by two completely independent Fe and Na Doppler lidars show strikingly consistent temperature and vertical wind patterns with tidal and gravity waves, demonstrating the robustness of resonance Doppler lidars’ measurement principles. The nearly vertical phase features occur in both lidar-measured vertical winds with similar enhancement times, which may indicate some real geophysical processes to explore. Many science endeavors will be enabled by such unprecedented measurements. For example, the cross-correlation between temperatures, vertical winds, and densities measured by two Doppler lidars will eliminate the biases induced by single lidar’s error correlation, leading to accurate estimates of vertical fluxes of heat and constituents.