An all-solid-state transportable narrowband sodium lidar for mesopause region temperature and horizontal wind measurements

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Abstract

A new all solid-state narrowband sodium resonance lidar based upon a new combination of well-established technologies is proposed. This combination retains the best attributes, and eliminates the drawbacks of two different sodium resonance lidar transmitter approaches. Current all solid-state sodium lidar such as operated by Shinshu University are appropriate for and have demonstrated operation in harsh environments such as Antarctica. However the spectral control is weak in comparison to the high spectral resolution sodium resonance lidars operated by Colorado State University (CSU) at Fort Collins and ALOMAR (Arctic Lidar Observatory for Middle Atmospheric Research) Norway. The transmitter of CSU-type sodium lidar are limited by liquid dye lasers and are only appropriate for laboratory type environments. What is proposed here is an all solid-state lidar similar to the Shinshu lidar approach, but spectrally improved with all the narrow band innovations and resulting performance of the CSU pioneered lidar. The proposed lidar includes: Precision seeding by Doppler-free spectroscopy of continuous-wave 589 nm light, which is produced by the sum-frequency-generation of two Nd:YAG lines of 1319 nm and 1064 nm; tandem acousto-optic frequency shifting; and sodium-vapor Faraday filters for daytime observation. The combination of these mature technologies results in a high resolution, all solid-state sodium fluorescence lidar capable of measuring mesopause region temperature and horizontal wind on a 24-hour continuous basis, weather permitting. This proposed lidar, adroitly comprised of proven and robust all solid-state technologies, is suitable for mobile deployment to remote locations with harsh environments.

1. INTRODUCTION

The worldwide research community for upper atmospheric/space physics needs lidar systems for measuring mesopause region (80-105 km) temperature and horizontal wind. This need has been articulated in the recent NSF/CEDAR (Coupling, Energetics, Dynamics of Atmospheric Regions) lidar report [1] and the CEDAR Phase III report [2]. To maximize the scientific returns from dynamics studies, any newly built lidar system should be transportable. High spectral resolution (narrowband) sodium lidar is particularly attractive as its temperature and horizontal wind measurement capabilities have been fully demonstrated when housed at fixed locations. Here we propose a new narrowband sodium lidar comprised of a combination of mature technologies. This new arrangement will retain all the precision capability of its narrow band CSU predecessor without the difficulties associated with dye lasers, potentially becoming a turnkey instrument with ease of operation and robustness on par with the Antarctic deployed Shinshu lidar. This proposed lidar will have full temperature and wind capability on a 24-hour continuous basis, and yet a modest price. Because it is based on proven technologies, the risk associated with the new instrumentation is minimal. Since the United States is about to deploy an Advanced Mobile Incoherent Scatter Radar (AMISR), this is an opportune time to consider a complementary mobile lidar system that can measure dynamical parameters (temperatures and winds) in this largely inaccessible and poorly understood region of the earth's atmosphere. Because it is mobile, this lidar has great versatility and could be operated stand-alone, deployed with various instrument clusters, and also be available for as yet unforeseen science opportunity.

2. CURRENT METAL RESONANCE LIDAR TECHNOLOGIES AND SCIENCE ENABLED

There are a number of metal resonance lidars already deployed. These include sodium, potassium and iron systems. In principle, they all have the potential for both temperature and wind measurements in the mesopause region (80-105 km). However, at this point only the sodium system has demonstrated this capability, whereas the potassium lidar [3] and iron lidar [4] are limited to temperature measurements only. The sodium system is the oldest, yet according to a recent analysis [5], it out performs other metal systems theoretically, characterizing its complimentary but justifiable status as a "gold standard". We propose an all solid-state mobile sodium resonance lidar transmitter for mesopause temperature and wind measurements. Along with the receiver system, the proposed lidar can be housed in a large 10 m (32 ft) long trailer, or in two 20 ft long standard sea containers, one temperature stabilized for the transmitter and the Faraday filters, and the other for receiving mirrors or telescopes. The expected measurement capability and accuracy of the proposed lidar assuming the use easily obtainable 25" diameter telescopes will be given first. To assure the practicality of our uncertainty estimation, we scale these estimates from the measurement accuracy of the CSU Na lidar system. This report of an all-solid-state sodium lidar will then be given in two separate sections: the transmitter design and then receiver system.

3. EXPECTED MESOPAUSE REGION TEMPERATURE AND WIND MEASUREMENT CAPABILITY

We estimate the measurement capability of the proposed lidar from scaling the achieved capability of the CSU Na lidar system. The temperature and wind uncertainty between 84 and 97 km with 1-hr, 2-km resolution in summer noon (the worst case scenario) and winter night (the best condition) to be less than about 11 K and 17 ms^{-1}, and 0.6 K and 1.1 ms^{-1}, respectively. The measurement uncertainties of the proposed mobile lidar with two beams pointing 30^o from Zenith for different seasons and times of the day are given in Table 1. Note that these errors are for a minimum of 13-km altitude range. The errors at the peak of the sodium layer are considerably less.

Table 1. Measurement capability of proposed lidar

Summer noon Range: 84-97km ΔT <11K ΔV<17 ms^{-1}	Summer Midnight Range: 84-100km ΔT <1.1K ΔV<1.7 ms^{-1}
Winter noon Range: 82-98km ΔT <2.6K ΔV<5.6 ms^{-1}	Winter Midnight Range: 84-100km ΔT <0.6 K ΔV<1.1 ms^{-1}

4. THE TRANSMITTER OF PROPOSED LIDAR

The basic design of the proposed lidar is to implement precision three frequency seeding to existing Shinshu type amplification. So we review the Shinshu type lidar transmitter, address its limitations, and finally present the proposed transmitter, with limitations overcome. An all solid-state lidar [6] was built by Continuum lasers for Shinshu University of Japan, using two Continuum pulsed single frequency pulsed Nd:YAG lasers, one at 1319 nm and the other at 1064 nm to sum-frequency generate light pulses at 589 nm. It was deployed to Antarctica for more than two years, demonstrating robustness and remote deployment [7]. However the system as deployed was not capable of measuring horizontal wind. To achieve single-mode operation each pulsed YAG laser has its own cw seed laser. The frequency of each seed laser was preset by a wave meter to values for sum-frequency generation of 589 nm light. Then, the single-mode pulsed outputs of the two lasers are combined in a nonlinear (KTP) crystal to sum-frequency generate light pulses at 589 nm. The frequency of the pulsed light at 589 nm depends upon the accuracy of the wave-meter used to set the frequency of the cw seed lasers without the benefit of Doppler-free spectroscopic feedback to attain ~1MHz absolute frequency stability. Unless this is remedied, the lidar can only measure temperature, not wind, because 1 MHz uncertainty corresponds to ~0.6 ms^{-1} in the line-of-sight wind and only ~0.15 K in temperature.

4.2 The proposed transmitter

The proposed transmitter, shown in Fig. 2, begins with sodium resonance radiation that is produced by a low power, continuous-wave SFG (Sum Frequency Generator) [8]. This laser combines 1064 nm and 1319 nm light within a 5cm long $LiNO_3$ crystal to produce sodium resonance radiation at 589 nm. With less than 1mW power demand, the 3mW low conversion efficiency SFG is both simple and rugged. This device has demonstrated tuning across the Na D_2 line, a range of 4 GHz as shown Fig. 1 [8]. The scan range is wide enough to measure the Faraday filter transmission function, and its derivative spectrum, Fig. 1 from the same paper, can be used as an absolute frequency marker. By feedback tuning the frequency of either 1064 nm seed laser or 1319 nm seed laser, one can lock the output of 589 nm to one of the spectral features in Fig. 1, e.g., the D_{2a} Lamb-dip at ~2.7 GHz.

After producing ideal sodium resonance light, the next step is to produce high power pulsed light at the same frequency. This is done by using the remaining continuous-wave (cw) IR light beams, that were at the precise frequencies needed to generate cw 589 nm light at the D_{2a} peak, to seed the pulsed 1319 nm & 1064 nm Nd:YAG lasers. The light from the pulsed Nd:YAG lasers is subsequently sum-frequency mixed again within a nonlinear crystal to produce high power light that is nearly identical to the cw sodium resonance radiation provided by the low-power SFG. Of course the pulsed light, though nearly Fourier transform limited, is not identical to the cw 589 light, but shifted slightly with a minor frequency chirp, a common characteristic of all pulsed lidars. An intermediate step, after low power SFG conversion but before pulsed amplification, is the implementation of an AOM (Acousto-Optic Modulator) to split the cw

1064 nm seed light into three separate frequencies. The three frequency shifting of ν_0, ν_0 + 558 MHz, and ν_0 - 558 MHz on command, shot by shot yields frequency agility necessary for simultaneous temperature and wind measurement. Here, the AOM is tandem and dual pass. Each pass shifts 279MHz totaling a net shift of 558MHz. The Fort Collins and ALOMAR lidars each have AOM's identical to what is proposed here, with the exception that they shift 589 nm light by an amount of ±630 MHz.

The Nd:YAG lasers adjust longitudinal cavity length in order to maintain resonance with the seed. In operation, the cavity length of a seeded Nd:YAG laser oscillator is piezo-adjusted slightly to achieve minimum Q-switch delay time, and it takes a few pulses to stabilize the seeded cavity. In this special case, three separate frequencies seed the 1064 nm Nd:YAG. If all three frequencies match a longitudinal mode of the master oscillator, each frequency provides mutually reinforcing feedback to change the cavity length to minimize Q-switch delay time. This ensures a capability for arbitrary seed frequency cycling on a shot by shot basis. Since the longitudinal mode spacing of this particular 1064 nm pulsed laser is 93 MHz, we choose 558 MHz (which is close to the 630 MHz used in the CSU system), which is exactly six times 93 MHz, so that all three frequencies can be tweaked into resonance with the master oscillator by the same piezo-adjustment.

5. THE RECEIVER OF THE PROPOSED LIDAR

Temperature stability is required for the optics and electronics. Telescopes on the other hand are often exposed outside. For that reason we propose using two sea containers, one for the transmitter and one for the receiver with dimensions 8'x8'x20'. The receiver container will have with clear Plexiglass dome rooftop apertures for the telescopes and beam steering underneath. No additional environmental isolation is anticipated for the telescopes. The transmitter container, housing everything else, will have stable habitat control, friendly to both humans and equipment. The receiving signal will be fiber-coupled from the receiving telescopes in the receiver container into the Faraday filters housed in the transmitter container. Two containers also has the advantage to allow future upgrade with more or bigger receiving telescopes or mirrors, as well as possible addition of a Rayleigh lidar for measurements below 85 km. The received signal from two telescopes will be separately coupled into two receiving fibers. The diameter and numerical aperture of the fiber must be chosen so that it will match the optics of the photo detection system (a PMT or an avalanche diode), with or without the used of a Faraday filter. To switch from nighttime observation to that under sunlit conditions, we simply insert the ultra-narrow band Faraday filter, which rejects background daylight, into the receiving path between the fiber output and the photo detection system, which contains a photo detector and a 1 nm wide interference filter. The optics design is straightforward. The performance of the Faraday filter and associated optics design is outside the scope of this paper, but has been proven successful with the lidar system at CSU.

6. SUMMARY AND FUTURE PROSPECTS

In summary, we proposed an all-solid-state sodium resonance lidar system that is capable of measuring mesopause region temperature and horizontal wind on 24-hour continuous basis, weather permitting. The technology on each component in the proposed lidar system has been tested in lidar operation and its operation proven robust and satisfactory. The proposed system is housed in two 8x8x20 ft long standard sea containers and as such they can be transported on land by a semi-truck or by commercial ships on the ocean. Although it can stand alone, the proposed system is intended to operate in a location with cluster instrumentation to pursue dynamic studies of the mesosphere and lower thermosphere.

The proposed Na lidar is designed for semi-automatic operation. The lidar instrument is designed to be semi-automatic and can be monitored remotely. However a human is still necessary to maintain the habitat and resources for the lidar, but not a great deal of expertise is required. Using VNC viewers, an experienced operator can diagnose and assist in any problems that may occur. Recently, such operation was tried successfully between Fort Collins, CO and ALOMAR, Norway.

When totally implemented, this mobile system will be a system that is capable of observing mesopause region temperature and horizontal winds on 24-hour continuous basis, weather permitting. These data are poised for study of tides and gravity waves and their interactions and variability [9]. With expansion to four beams and four telescopes, the system can also be configured to measure vertical wind, momentum flux and heat flux. The system can be operated almost continuously with a technical staff, a graduate student or an undergrad with modest training. With the deployment of such a system in a site with radar like AMISR and collocated cluster of passive instrumentation, the benefit to the CEDAR community and other interested scientists can be easily imagined.

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Fig. 1 Sodium D2 fluorescence line and differential spectra as produced by a low power SFG. From Ref. [8].

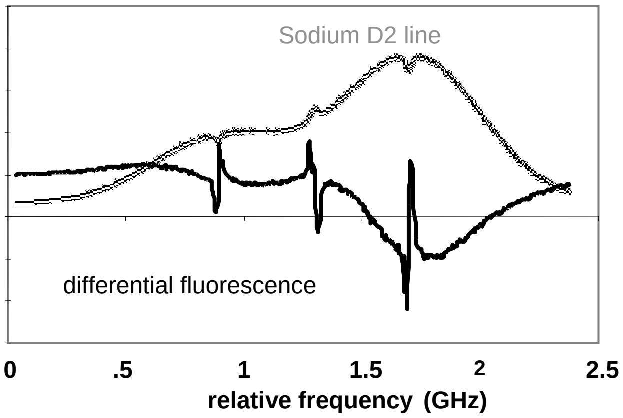
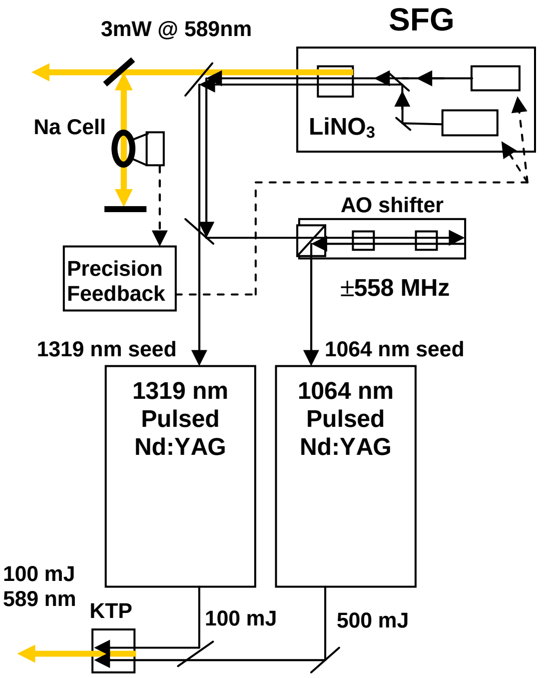


Fig. 2 Schematic setup of the proposed transmitter.



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