DEVELOPMENT OF RAYLEIGH DOPPLER LIDAR SYSTEM FOR MEASURING MIDDLE ATMOSPHERE WINDS

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ABSTRACT

Measurement of middle and upper atmosphere winds is needed to understand the structure and dynamics in these regions. Rayleigh Doppler lidars can give continuous information of winds routinely. Details of the ongoing development of Rayleigh Doppler lidar at National Atmospheric Research Laboratory, India are described here. The system with 5.3 W-m^2 average power aperture product employs Double Edge technique with etalons, and is expected to give ~5 m/s wind accuracies with one hour time integration and 1 km range resolution at a height of 60km. This paper gives configurational details, system specifications and performance simulations which are aimed at measuring middle atmosphere winds.

1 INTRODUCTION

Climatological description of the wind field is required for interpreting most of the middle and upper atmospheric dynamical data. As an example, the waves generated in the troposphere, which strongly affect mesospheric circulation, are filtered by the zonal stratospheric winds. The level of dissipation and /or breaking of these waves in the mesosphere depend strongly on the wind direction and intensity. Knowledge of the steady state structure and the dynamic redistribution of various chemical species in the middle atmosphere, particularly at lower or tropical latitudes is important to study the whole atmosphere as a coupled system. In spite of numerous theories put forward for the interaction between the waves and the general circulation, a full understanding of the processes and meaningful theories require a complete description of the wind fields.

However, measurements of structure and dynamics of the middle and upper atmosphere are extremely difficult on a routine basis. Despite the extensive instrumentation at NARL, Gadanki (13.5° N, 79.2° E) (NARL has MST Radar, LAWP and a Rayleigh/Mie lidar) for atmospheric studies, we have been unable to measure winds in the region between 25-65 km, the so called gap region. This region can only be probed either by rockets or high altitude balloons. Although the measurements are accurate and precise, both the rocket and balloon campaign becomes expensive (both in maintenance aspect and individual sounding), if winds of high temporal resolution are required. In this context, a Rayleigh Doppler Lidar could be an important tool in such applications. The lidar also gives excellent temporal and spatial resolutions and it can also be operated during both daytime and nighttime.

The lidar can provide absolute and quasi-simultaneous profiles of both components of the horizontal wind without any ancillary source of data (like radiosonde, rocket etc measurements). The system is capable of recovering typical flow patterns like large shear and intense jets, weak winds and wavy vertical structure. It can be employed in various geophysical studies involving upper troposphere and stratosphere circulation. While daily averaged profiles can serve in the study of the vertical structure of the large scale wind , the detailed analysis of the short scale and the smaller amplitude perturbations observed during the night of the measurement can give insight into mesoscale processes such as gravity waves. It allows long-term survey of the stratospheric and lower mesospheric circulation. A long term database can be constituted to infer climatology of the mean wind at low latitudes as reported by Souprayen *et al* (1999) [10]. The instrument gives excellent mean winds in the middle atmospheric region with fairly good resolutions.

Lidar measurements of winds at lower altitudes below 30 km have been standardized using CW infrared lasers and heterodyne detection. But above 30 km, CW/heterodyne technique becomes less sensitive. A Rayleigh Doppler lidar, operating in incoherent mode, gives excellent wind and temperature information at these altitudes with necessary spectral sensitivity. The instrument relies on Rayleigh scattering from air molecules and is designed to cover the height range of 30-65 km and operate during night times.

The augmentation is being envisaged keeping in mind the following objectives:

- **Measurement of stratospheric and lower mesospheric winds**
- **General circulation of the atmosphere**
- **Momentum flux and the energy budget of the stratosphere and mesosphere**
- **Studies of the mesospheric turbulence arising from the breaking of the ascending waves**
- **Climatology and continuous monitoring of the velocity fields**

Technical objectives

Measure Doppler shifts in wavelength domain and convert them into winds by knowing tilt angle
Obtain Zonal (EW/U) and Meridional winds (NS/V) and, if possible, vertical winds

The combination of lidar and radars installed at NARL gives an opportunity of simultaneous observations of the structure and dynamics of the atmosphere in a broad range of altitudes. Even though in principle, the system can be designed to measure winds in the lower atmosphere also where Mie contribution is dominant, this aspect is not considered, as this is not the region of our interest. Wind measurements in the height regions below 30km, which is very much needed, is being planned as a future extension to the activity.

2. PROPOSED CONFIGURATION OF RAYLEIGH DOPPLER LIDAR

The configuration of the proposed Rayleigh Doppler lidar system closely follows that of Indo–Japanese lidar system, the description of which is given by Bhavani Kumar and K Raghunath et al (2000) [3].The configuration is similar to that of NICT's proposed Doppler lidar at Alaska [9], ALOMAR [12], CNRS, [4]. The lidar system measures winds and temperatures from the spectral shift due to the motions of atmospheric molecules with background winds and the broadening of the signal by the atmospheric molecules, energised by the incident laser pulse.

An Nd:YAG laser with an energy of ~600 mJ at 532 nm is employed at 20Hz repetition frequency. The laser line is frequency stabilized against an iodine molecular line for single longitudinal mode of operation. An optical fiber collects the light and guides the photons to a Fabry-Perot interferometer, scrambling the light homogenously. The free spectral range of 6 GHz is determined based on the assumption that the Doppler broadening of the Rayleigh backscattered light by the random motion of the air molecules is about 2.5 GHz (FWHM) for temperatures between 200-280°K. Double Edge technique is adapted in which the backscattered signal is made to fall on two identical etalons spaced at a frequency separation. The signal is detected by means of Photo Multiplier Tubes (PMTs) or Avalanche PhotoDiodes (APD). As the vertical velocity is usually very small, LOS component of the horizontal wind is measured. The shift in the wavelength is given by well-known relation given in Eq 1.

$$\Delta\lambda(z) = 2\lambda_o \sin\theta\, \upsilon_h(z) / c \qquad (1)$$

where λ_o is the emitted wavelength. θ is the line-of-sight from the zenith (usually 30-45degrees) and c is light speed in the medium. As the vertical velocities are smaller in magnitude and therefore inaccessible to the measurements, the study is limited to determine the two horizontal wind components. The lidar receives the signals in at least three directions. In higher altitudes, the wind error is primarily due to the statistical standard error and spectral broadening (Cramer-Rao Lower Bound) and is independent of the wind velocity and is only height dependent.

2.1 Laser source

The important specifications which has a bearing on the wind measurements are line width and stability of the laser source. The laser line width is chosen taking into consideration the smallest molecular line width that can broaden due to ambient temperatures. Stability is chosen taking into consideration the smallest winds that need to be measured. Accordingly, line width of ~150 MHz at second harmonic and a stability of ~2 MHz is chosen.

2.2 Telescope configuration

Monostatic biaxial configuration with tilting type with optical fiber feed to the etalons is being planned. The details of the system are given in Fig. 1.

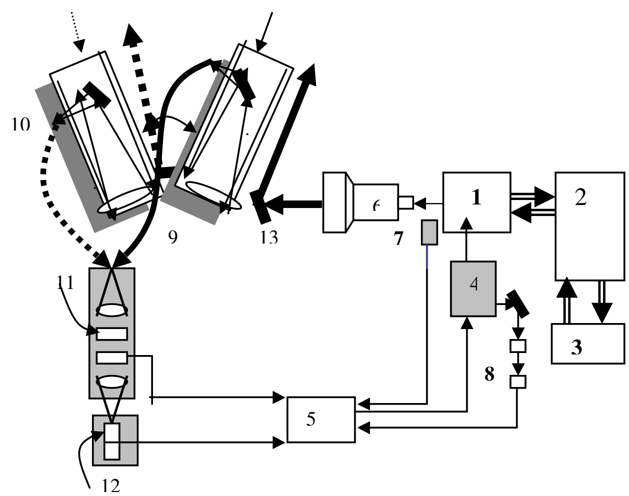

Fig.1: Block diagram of the proposed Rayleigh Doppler lidar. 1. Laser source 2. Electronics cabinet 3. Water recirculator 4. Seeder 5. Data acquisition and control unit 6. Beam expander 7. Photosampler 8. Feedback optics 9. Telescope 10. optical fiber 11. Etalon 12. Detector 13. Beam steering mirror

The transmit beam is made coplanar to the receive beam by using a beam steering mirror.

2.3 Technique

Double Edge technique with two etalons as narrow band pass filters will be employed as it gives better resolutions than its counterpart in imaging i.e. Fringe Imaging technique**.** The etalons are kept in temperature and pressure stabilized chambers.

2.4 Detector and data acquisition system

PMT/APD based detector with data acquisition system for return signal collection is designed.
To track the instabilities in the laser source and etalons, a pulse- to-pulse calibration technique is planned. The Lidar Control software will integrate the telescope tilt software, timing circuitry, time integration and range integration.

2.5 Data analysis

For the systems employing Edge technique, the Doppler shift of the backscattered echo is measured, by inter-comparing the signal detected through each of the two narrow band-passes of a single dual Fabry-Perot interferometer tuned to either side of the emitted line.

The method of data analysis, is as described by Chanin *et al* (1989)[4] and Tepley *et al* (1993) [11]. The backscattered signal is compared with reference laser signal. The amplitude of the output signal from FPI is compared with a lookup table (Doppler shifts Vs Amplitude) obtained by scanning the etalon around the laser central wavelength. It is expected that it is possible to scan the etalon with a frequency resolution of 1MHz. Zonal and Meridional winds can then be determined as in the case of MST Radar. The flow of the data processing is like in Fig. 2.

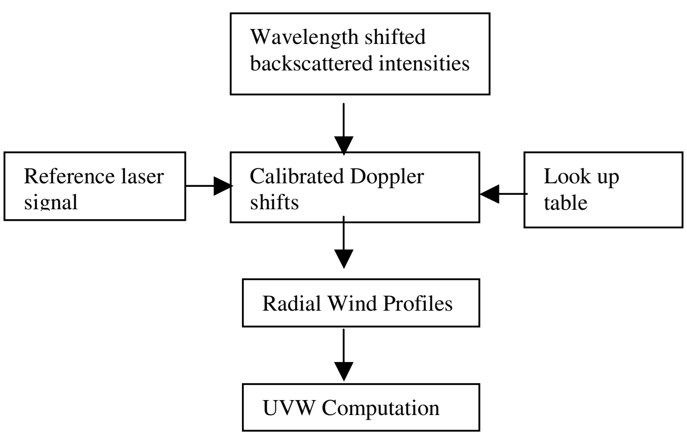

Fig. 2: Flow chart for computing UVW

The Atmospheric Data Processor (ADP) [1], [2] used at NARL is a proven method for computation of UVW.

2.6 Doppler lidar performance simulations

An important factor in simulating the performance of a Doppler lidar is specifications of the instrument operating parameters. A wide range of potential choices of specifications have been used for the simulations including types of techniques. For the system simulation experiments described here, the two types of direct detection Doppler lidar configurations namely Fringe Imaging and Double Edge Techniques are considered.

Sensitivity of the lidar system is a key factor in assessing the performance of a wind measuring instrument. Several parameters determine the sensitivity of the instrument, including laser pulse energy, laser pulse repetition frequency, receiving telescope diameter, optical efficiency of the lidar system, number of pulses averaged, and range to the target. Hence the important parameter is the total number of backscattered photons actually detected and processed by the lidar receiver. To get enough sensitivity, multiple pulse accumulation and range gate integration are carried out.

Fig. 3 shows expected wind error performance with 1 hr time integration and 1km range resolution on a clear sky night.

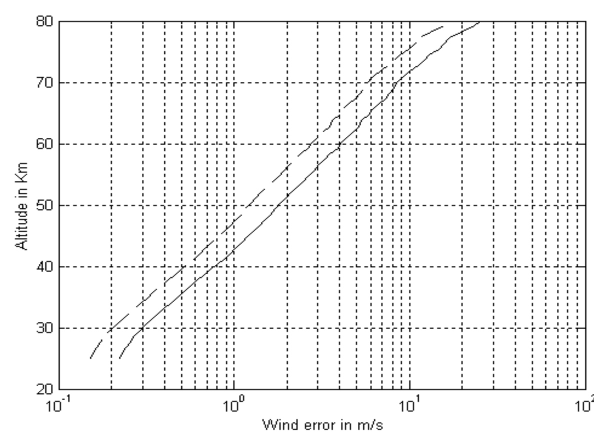

Fig 3: Wind error performance with laser power changes (solid line is for 11W and dashed line is for 24W) as carried out for Double Edge technique

For simulation purposes, the photon counts from Rayleigh channel of NARL/CRL lidar is taken for different atmospheric conditions viz. **clear sky nights, high backscatter ratio nights and cloudy nights.** Simplified analytical models provided by Jack A Mckay [7],[8] is considered for simulations than that computationally complex models provided by Mc Gill et al [5],[6] taking into account various system related issues viz. laser line profile, etalon defects, target broadening mechanism (molecular and aerosol) with typical specs of etalon and detector. This gives initial insight into the system performance. Optical and quantum efficiency of 30% is taken, with APD as detector. From these data, the performance of the lidar instrument is inferred and statistical properties, the line-of-sight, LOS mean wind speed were calculated. The specifications of each sub system thus generated are given in Table 1.

Table 1: Specifications of the Rayleigh Doppler lidar system

Performance Specifications	
Height resolution	1km/1.5km
Time resolution	60/90min
Height coverage	30-65km
Wind accuracies	~5 m/s @60km
Technical specifications of the subsystems	
LASER	
Type	Pulsed Nd:YAG with injection seeding
Wavelength of operation	532nm
Line width	~0.0045cm^{-1} (~ 135MHz or ~36m/s)
Pulse length	~7ns
Repetition rate	~20Hz
Energy per pulse	~600mJ
Beam divergence	0.1 mrad (after 10X beam expanding)
Beam size	8mm
Frequency stability	~2MHz/hour (iodine cell based)
ETALON	
Molecular line widths FWHM(GHz) 1/e width (GHz)	2.5 1.5
Plate Reflectivity	0.7
Free Spectral Range (GHz)	6.0
Zero Doppler Offset (GHz)	1.84
Etalon FWHM (GHz)	1.77
Reflective Finesse	8.76
Etalon spacing (cm)	2.5
LOS Dynamic range (m/s)	470
Aperture Finesse	7
TELESCOPE	
Type	Newtonian
Diameter (mm)	750
Field of View	1mrad
F ratio	~3.16
DETECTOR	
Quantum efficiency (APD)	~60%

3 SUMMARY

Details of the ongoing development of Rayleigh Doppler lidar are described with performance simulations and system specifications, which are aimed at measuring middle atmosphere winds.

4 REFERENCES

1. Anandan VK," Atmospheric Data Processor-Technical and user reference manual"

2. Balamuralidhar P ,"Data Processing techniques and software for MST Radar", Lecture notes , Second winter school on Indian MST Radar, 1995

3. Bhavani Kumar Y, Raghunath K ,Siva Kumar V, Rao PB, Jain AR, Kohei Mizutani, Tetsuo Aoki, Motoaki Yasui, Toshikazu Itabe, 'Indo-Japanese Lidar: System description and data processing' in *Proceedings of International Radar symposium IRSI-99,* Dec.1999

4.Chanin M L, Garnier A, Hauchecorne A, Porteneuve J, ' A Doppler Lidar for measuring winds in the middle atmosphere', *Geophysical Research Letters*, Vol 16, No.11, 1273-1276, Nov 1989

5. McGill Matthew J , Wilbert R Skinner and Todd D Irgang, 'Analysis techniques for the recovery of winds and backscatter coefficients from a multiple-channel incoherent Doppler lidar' *Applied Optics*, Vol.36, No.6, 20 February 1997/

6. Mc Gill MJ , JD Spinhirne,' Comparison of two direct detection Doppler lidar techniques', *Optical. Engineering,* 37(10), 2675-2686, October 1998

7. McKay Jack A , 'Modeling of direct detection Doppler wind lidar. I The Edge technique', *Applied Optics,* Vol.37 No.27, 20 September 1998

8. McKay Jack A , 'Modeling of direct detection Doppler wind lidar. II the fringe imaging technique', *Applied Optics*, Vol.37 No.27, 20 September 1998

9.Mizutani K, Itabe Toshikazu, Yasui Motoaki, Aoki Tetsuo, Ishi Shoken, Sasano Masahiko, Murayama Yasuhiro, Richard L Collins, ' Lidar instruments for the observations of arctic atmosphere in Alaska project', *Journal of the Communications Research Laboratory*, Vol. 49, No.2, 2002

10. Souprayen C, Anne Garnier, Albert Hertzog, Alain Hauchecorne, Jacques Porteneuve, 'Rayleigh-Mie Doppler wind lidar for atmospheric measurements. I Instrumental setup, validation and first climatological results',, *Applied Optics*, Vol 38, No.12 20 April 1999

11 . Tepley C A, Stoyan I Sargoytchev, Roberto Rojas, 'The Doppler Rayleigh Lidar System at Arecibo', *IEEE Trans. on Geoscience and Remote sensing*, Vol. 31, No.1 Jan 1993

12. von Zahn, von Cossart G, Fiedler J, Fricke KH, Nelke G, Baumgarten G, Rees D, Hauchecorne A, Adolfsen K," The ALOMAR Rayleigh/Mie/Raman lidar: Objectives, Configuration and Performance", *Annales Geophysicae*, 18, 815-833, 2000