Simultaneous measurements of wind speed at multiple distances without range ambiguity

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1. Introduction

The Frequency Stepped Pulse Train (FSPT) modulated lidar has previously been suggested as a means to achieve range resolved measurements of atmospheric wind speeds while maintaining a high duty cycle compared to other pulsed lidar systems. Earlier measurements have demonstrated the advantages of the technique on a moving hard target[1]. In this paper we show for the first time range resolved measurements of actual wind speed performed with this technique.

A FSPT consists of a sequence of laser pulses each temporally and spectrally separated from each other by a fixed time and frequency. This separation allows for an unambiguous mapping of spatial range cells into well defined slots in the measured spectrum. The temporal separation should be kept as small as possible to ensure a quasi-CW optical output and thereby a high duty cycle. On one hand the spectral separation should be larger than the highest Doppler shift to be measured to avoid range ambiguities. On the other hand it must be small enough to stay within the detector bandwidth.

This paper explains the basic concept of the FSPT modulated lidar as well as a method for generating a suitable train of pulses. Finally the first range resolved wind speed measurements produced by a FSPT modulated lidar are presented.

2. Method

The FSPT modulated lidar emits optical trains of pulses where each pulse in a train is equidistantly shifted in frequency by Δf and thereby a linear sweep is obtained. Each pulse has a pulse duration of T_{pulse} and the inter-pulse duration is given by T_{inter}. A Local Oscillator (LO) is generated as a copy of the transmitted FSPT. In this configuration the beating between the received scattered light and the LO generate peaks in separate frequency slots defined by Δf through

$$f_i = \left(i - \tfrac{3}{2}\right)\Delta f, \qquad (1)$$

$$f_i' = \left(i - \tfrac{1}{2}\right)\Delta f, \qquad (2)$$

where the i^{th} slot stretches from f_i to f_i'. Spatially each frequency slot corresponds to a given range cell because of the delay between light scattered in the atmosphere and the LO. This means, e.g. that light scattered in the second range cell will beat against an LO that is shifted by Δf, and by making sure Δf is larger than the induced Doppler shift, f_D, a unique mapping of the range cell into the frequency slot is achieved. The i^{th} range cell extending from x_i to x'_i is described by

$$x_i = \left((i-2)T_{pulse} + (i-1)T_{inter}\right)\frac{c}{2}, \qquad (3)$$

$$x_i' = \left(i \cdot T_{pulse} + (i-1)T_{inter}\right)\frac{c}{2}, \qquad (4)$$

where c is the speed of light. The concept behind the FSPT modulated lidar is illustrated in Figure 1.

As shown in Figure 1 range cells partly overlap if $T_{pulse} > T_{inter}$, and the centre of the first range cell will be situated at a distance of 0 m. The range cell positions can be changed by introducing a time delay to the LO and if sufficiently large the cropping of the first range cell is avoided[1].

The wind signal generated in the i^{th} range cell is defined by

$$f_{wind,i} = f_D(x_i : x_i') + (i-1)\Delta f, \qquad (5)$$

and the line-of-sight speed in range cell i is thereby given as

$$V_{LOS,i} = \frac{\lambda}{2}\left(f_{wind,i} - (i-1)\Delta f\right). \qquad (6)$$

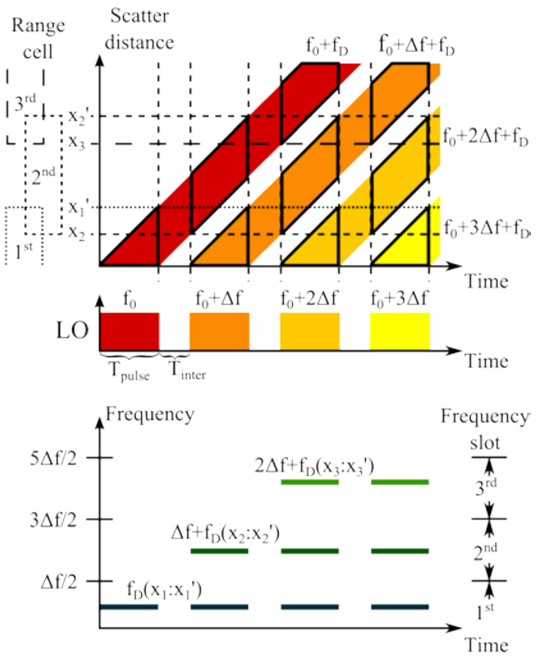

Figure 1: Top panel: Time-space representation of the received scatter from an FSPT modulated lidar. The proportionality between the scatter distance and the time of reception is determined by half of the speed of light accordingly to the optical path being twice the length of the scatter distance. Range cells are defined by the interaction time between LO pulses and scattered pulses governed by the pulse duration T_{pulse} and inter-pulse duration T_{inter}. Middle panel: Representation of LO in same time frame as the time-space representation. Bottom panel: Time-frequency representation of the heterodyne signal generated by a photo detector. The Frequency slot i defined from f_i = (i-3/2)Δf to f_i' = (i-½)Δf contains Doppler shifted frequencies from range cell i plus a frequency shift (i-1)Δf.

In this configuration the first frequency slot lacks the capability of determining the sign on the measured velocity. This may be avoided if a frequency offset is introduced to the LO. The offset should be larger than Δf/2 to avoid any velocity ambiguities.

It is noted that the FSPT should contain enough pulses such that, the received backscattered light from the last pulses in a FSPT beating with the first pulses from the subsequent LO FSPT generates frequencies outside the measured frequency range. Note that from the n^{th} LO pulse only n range cells contribute to the measurement. By using FSPT consisting of several pulses the lack of signal from higher order range cells in the initial pulses may be neglected.

3. FSPT modulated Lidar system design

A focused CW lidar system based on an all fiber setup was modified for the use as a FSPT modulated lidar. The layout of the used system can be seen in Figure 2. As the FSPT generator an Lightwave Synthesized Frequency Sweeper (LSFS)[2,3] was used. Due to the low power output of this the FSPT was amplified by an external Erbium doped fibre amplifier (EDFA) to an average power of 30 dBm. The amplified FSPT was coupled into the telescope through a circulator and focused into the atmosphere. The telescope was build with a lens diameter of 7 cm, and an adjustable focus length. A reflection from the end facet of the circulator fiber generated the non delayed, non offset LO. The backscattered light was collected through the telescope and together with the LO mixed onto an AC coupled photodiode via the circulator. The heterodyne signal generated by the photo detector was sampled at 400 MHz by a digitizer and digitally processed in a computer.

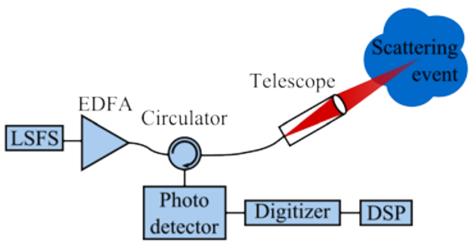

Figure 2: Illustration of the FSPT modulated lidar. The FSPT was generated by the LSFS and amplified by the EDFA. The amplified FSPT was sent into a telescope through a circulator and transmitted into the atmosphere. A weak reflection at the circulators fiber end facet simultaneously generated the LO. The backscattered light was received by the same telescope and transmitted together with the LO to a photo detector through the circulator. The heterodyne signal from the photo detector was sampled by a digitizer and processed by a Digital Signal Processor (DSP).

Sections of the sampled signal corresponding to the top of the LO pulses were cut out and processed individually and then averaged to form a signal spectrum. Each pulse was fitted with a 5. order polynomial which was subsequently subtracted in order to avoid spectral components originating from the pulse envelope. The spectral signal of each pulse was then obtained by a Fourier transformation.

The configuration of the LSFS used as the FSPT generator is illustrated in Figure 3. The loop was seeded by a 7 mW fiber laser at a wavelength of 1548 nm. One seed pulse for every FSPT was generated by an acousto-optic modulator (AOM) with an extinction ratio of 63 dB. In addition to generation of the seed pulse, the AOM induced a frequency shift of 40 MHz to the carrier frequency of the light. The seed pulse was coupled into the loop through a 50/50 coupler and from there into an EDFA of which the gain was set to match the loop loss. From the EDFA the pulse then loops through a Band Pass Filter (BPF), an AOM, a single mode transmission fiber, a polarization controller, and back into the 50/50 coupler where half the pulse power was coupled out of the ring and the other half back into the ring, thereby generating the FSPT.

The BPF was used to reduce the ASE noise generated by the EDFA[4], and the polarization controller was used to compensate for the polarization change through the ring. The loop AOM was identical to the seed AOM such that it shifts the frequency of the light by Δf = 40 MHz for each time the pulse circulates the loop.

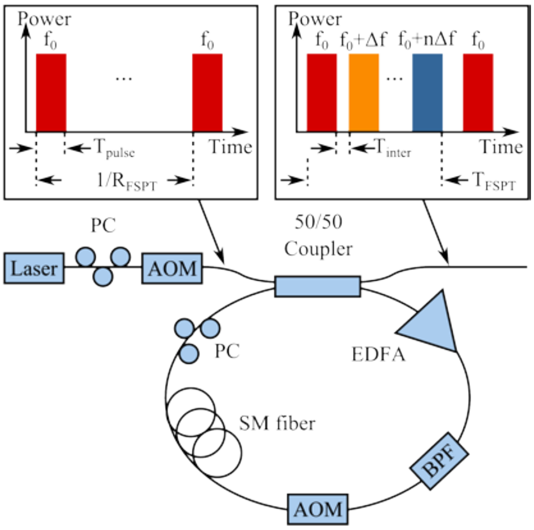

Figure 3: Illustration of the LSFS setup. A seed pulse of duration T_{pulse} was generated by modulation of the cw laser light by the seed AOM at a rate R_{FSPT}. Half of the seed pulse was coupled into the loop by a 50/50 coupler and half was coupled out of the LSFS as the first pulse in the FSPT. The pulse then circulated the ring and each time generated the next pulse in the FSPT delayed by T_{inter} compared to the previous pulse and frequency shifted Δf. The loop AOM induce d the frequency shift as well as controlled the FSPT duration. The EDFA compensated for loop loss and the BPF minimizes noise growth. The pulse to pulse time T_{pulse} + T_{inter} was governed by the loop length adjustable by the length of the Single Mode (SM) transmission fiber. The Polarization Controller (PC) was used to compensate for the polarization change through the ring.

In this configuration the seed AOM determines the pulse duration T_{pulse} and the repetition rate of the FSPT R_{FSPT}. The loop length, which is adjustable through the length of the transmission fiber, defines the pulse to pulse duration T_{pulse} + T_{inter}, and the loop AOM governs the FSPT duration T_{FSPT}.

4. Wind speed measurements

The first atmospheric wind speed measurements performed with the method described above were obtained with the following parameters: T_{pulse} = 0.55 µs, T_{inter} = 0.03 µs, T_{FSPT} = 14.3 µs, R_{FSPT} = 65.5 kHz and a frequency shift Δf of 40 MHz. With these parameters the duty cycle was 89% and wind speeds up to 15 m/s were measureable without range ambiguity. For wind speeds above 15 m/s the signal would appear in the neighboring frequency slot and hence appear to be measured in the neighboring range cell and with an opposite direction. An external directional measurement of the wind would increase the maximum measureable wind speed by a factor of two before range and speed ambiguity would occur.

Each range cell extended over 165 m and due to the low inter-pulse duration compared to the pulse duration a large overlap between consecutive range cells occurred. The range cells span from 0 - 82.5 m, 4.5 - 169.5 m, 91.5 - 256.5 m and 178.5 - 343.5 m for the first, second, third and fourth range cell respectively. The corresponding frequency slots extended from 0 – 20 MHz, 20 – 60 MHz, 60 – 100 MHz and 100 – 140 MHz, respectively.

Plots of measurements taken at a focus length of 84 m, 168 m and 26 m, which nearly corresponds to the centers of the second, third and fourth range cells, are shown in Figure 4. These measurements were achieved in high-scattering conditions and wind speeds between 5 m/s and 6 m/s were measured. The results in Figure 4 b) shows wind speeds that differ by 1 m/s in two consecutive range cells. This illustrates that the FSPT modulated lidar removes the range ambiguity and is capable of measuring wind speeds at multiple distances.

From Figure 4 a) and b) the noise floor is seen to have a dip at 40 MHz. This originates from the frequency noise generated by leakage of the AOM in the LSFS[5]. This effect is also seen at higher orders of frequency shifts i.e. 80 MHz and 120 MHz though much less pronounced. This leakage noise influences measurements at low wind speeds since signal and noise would not be distinguishable. The AOM leakage in the LSFS should therefore be reduced to a minimum.

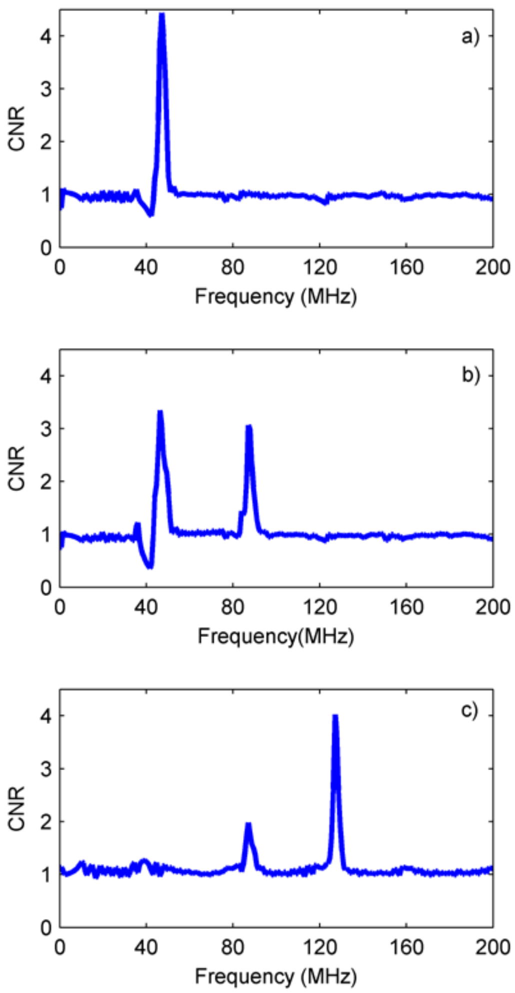

Figure 4: Spectral measurements of atmospheric wind speed by the FSPT modulated lidar at a telescope focus length of 84 m, 168 m and 261 m plotted in figure a), b) and c) respectively.

5. Conclusion

In conclusion, wind speed measurements in multiple range cells were successfully measured using a FSPT modulated lidar. The measurements showed that range ambiguities were avoided while maintaining a high duty cycle of 89%.

6. Acknowledgements

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7. References

1. P. Lindelöw "Velocity sensing FSPT-modulated coherent lidar" in proceedings of the 14th Coherent Laser Radar Conference
2. T. G. HODGKINSON, P. COPPIN, "Pulsed operation of an optical feedback frequency synthesizer," ELECTRONICS LETTERS, Vol. 26 No. 15 pages 1155-1157, (1990)
3. K. Shimizu, T. Horiguchi, Y. Koyamada, "Frequency translation of light waves by propagation around an optical ring circuit containing a frequency shifter: 1. Experiment," Appl. Opt., Vol. 32 No. 33 pages 6718-6726, (1993)
4. K. Takano, K. Nakagawa, H. Ito, "Influence of optical filters on pulse circulation in fiber rings with a frequency shifter and EDFA," Optics Express, Vol. 14, No. 22, pp. 10313-10323, (2006)
5. A. T. Pedersen, P. Lindelöw-Marsden, "Investigation of noise in Lightwave Synthesized Frequency Sweeper seeded LIDAR anemometers from leakage through Acousto Optic Modulators", in proceedings of the 15th Coherent Laser Radar Conference (2009)