# Pulsed fibre lidar for wake vortex monitoring

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## Abstract

A pulsed fibre lidar has been designed for wake vortex monitoring on airport sites. It is based on 1,5 µm fibre technology and expoits the unique capabilities of fibre sources: a MOFPA laser, designed and built at Onera, enables to tune the spectral content, the waveform and the power level as three independent parameters, a major asset for lidar performance optimization. An overview of SWAN lidar and its laser source designs are presented as well as the first field tests results obtained at Orly airport in 2007.

## 1. Introduction

Detecting atmospheric hazards such as wake vortices, wind shear, and clear air turbulence has been a major preoccupation of the european community since the past twenty years. In order to increase the operation capacity of the air transport system, it is of interest to minimize the separations between aircraft during take off and landing. Previous developments have already demonstrated that lidars offer a practical and efficient tool to monitor and characterize windfields in general and wake vortices in particular. Various systems have been developed using $CO_2$ and HoTm:Yag sources . The telecommunication developments of critical components have led us to build a lidar based on a pulsed high energy 1.5 µm fibre laser.

For 10 years, fiber lasers have been offering a new effective and high visibility technology to lidar community, allowing new instruments to be designed. The advent of the double clad fiber, along with advances in semiconductor pump diode sources, have allowed rapid power scaling of both pulsed and CW fiber sources . The unique capabilities of fiber sources, coupled with significant commercial and academic progress in implementation have driven fiber technology to enter active remote sensing markets as signal sources and amplification stages for direct detection lidars and coherent lidars as well . The fibre laser technology offers a high level of robustness, flexibility, high efficiency, eye safety, is scalable in performance and utilizes mainstream sub-components, low unit and life cycle cost.

Coherent lidars use heterodyne detection by mixing (i.e. interfering) the laser light scattered from a remote target with a reference local coherent laser oscillator. This technique offers high sensitivity as well as providing detailed phase and velocity information. Heterodyne detection outputs an electrical RF beat note, proving information on the complex amplitude of the signal field. Reflectivity is calculated from signal strength, range from time of flight and speed from frequency or phase shift. In the case of wake vortex characterization, aerosols are used as wind tracers to measure local air speed.

Coherent lidars need both a low power continuous wave (CW) laser as a local oscillator (LO), and a main powerful CW or pulsed laser for transmitting energy to the target. The choice between pulsed and CW operation is a trade off on spatial and speed resolutions, range and size of the volume of air to be probed. Pulsed operation is well suited to long range air speed measurements whereas CW lidars are used when very fine spatial analysis is required.

In this paper we will focus on a novel 1.5 µm pulsed fiber lidar, SWAN, and the first field tests results obtained at Orly airport. This lidar is the first of its kind for Wake vortex characterization and our technological choices are exposed hereafter.

## 2 SWAN Lidar design

Coherent lidars require the LO and the signal laser to have a stable frequency relationship to ensure narrow band detection. Often, part of the LO is used as a seeder for the main laser. In fibered architectures, the best architecture comprises a CW low power as LO which is also used as master oscillator of a fibered power amplifier in single path. Fibered amplifiers have a very large bandwidth (>3THz at 1550nm) and large gain, allowing various waveforms to be amplified (CW, modulated, pulsed).

### 2.1 lidar wavelength

For lidar applications, laser lines must be chosen in atmospheric windows and be compatible with outdoors firing . In the near infrared band (NIR or band I, 0.8- 2.5µm), spectral absorption is mainly due to water vapour. There exists several absorption lines in band I, where commercial Yb, Er-Yb and respectively Tm silica fiber lasers and amplifiers can be found: Ytterbium lasers (1.0-1.06µm), Erbium lasers (1.48-1.62µm) and Thulium lasers (1.8-2.1µm). However, in the 2µm spectral band the laser must be tuned very accurately between absorption lines and must remain stable.

Critical lidar components are available around 1.5µm because of telecom applications. High bandwidth detectors, couplers, circulators, acousto-optic or electro-optic modulators, single mode fibers are widely developed around the world. At other wavelengths, 1µm and 2µm, custom components can be developed but remain expensive.

Eye safety may be an issue for atmospheric lidars. Above 1.4 µm, the maximum permitted exposure (MPE) is 3 orders of magnitude higher than for shorter wavelengths and an eye-safe operation is possible even with multi-watt lasers. Following the standards, the Ytterbium laser is considered as a dangerous laser even at long range operation while Erbium and Thulium lasers are safe lasers. Yb fiber lasers are not eye-safe and Tm fiber lasers are not as mature as Er-Yb fiber lasers. This is why our choice was Er-Yb laser.

Erbium-Ytterbium codoped fibers have 3 different gain peaks (1535, 1545, 1565nm). In the three sub-bands, thanks to laser tunability, spectral atmospheric windows can be found with good transmission. Commercial components (oscillators, filters) are developed specially at these wavelengths, reducing the cost of lidar development.

Available oscillators in this spectral band are DFB diodes and fiber lasers. Laser diodes are more powerful than fiber lasers and offer better wavelength tunability with temperature: typically 0.09nm/° for laser diode and 0.01 nm/° for fiber laser.

### 2.2 Laser source design

In order to provide the LO and fullfill the spectral and spatial beam quality required for coherent detection, the MOPA configuration (Master Oscillator Power Amplifier) was chosen. The MOPFA (Master Oscillator Power Fiber Amplifier) architecture includes an oscillator, delivering a CW polarized low power single mode beam, having requested spectral linewidth and stability, a modulator that perfoms the pulse shape and the spectral shift or chirp, and then one or several cascaded fiber amplifiers. Using MOPFA lasers enables to optimize the spectral content, the waveform and the power level as three independent parameters: as a result, fiber lasers are suitable sources for coherent lidars.

The MOPFA configuration using Erbium-Ytterbium doped fibers is well adapted for 1.5µm high energy pulse generation. The peak power is however limited by Stimulated Brillouin Scattering because of the narrow signal linewidth. To overcome this limitation, large-mode-area (LMA) fibers are required with mode diameters beyond 30 µm. These fibers must also have low core NA to avoid multimode operation. Onera has studied the influence of the MOPFA architecture on the performances **.** At Onera, we have recently developed a 3 stages all fibered amplifier (see Figure 1) with 60 µJ pulses and 250 ns pulse duration. The high peak power (>240 W) requires large core diameters.

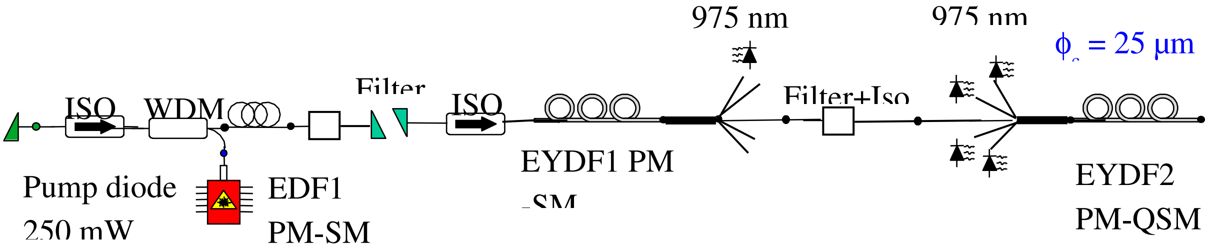
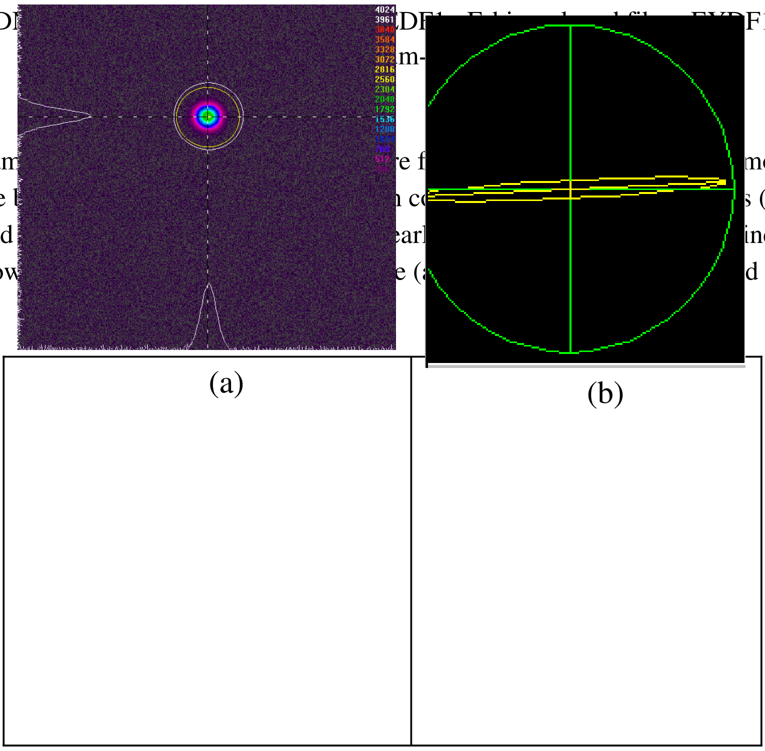


Figure 1: Set-up of the laser source

ISO : isolator; WD DF1 F1 : Erbium-Ytterbium
m-

The third stage of am e f modes groups. Thanks to
a proper packaging, the n c s (the beam quality
factor M² was measured ear inear polarization better
than 98%. Figure 2 show e ( d (b).



(a)

(b)

Figure 2: laser beam profile in far field (a) and polarisation ellipsoid (b).

## 2.3 Optical architecture and modelling

The original SWAN lidar optical architecture (see Figure 3) is based on collimated beams, and can be used with different fiber lasers, even with slightly multimode fibers, since the laser output is collimated in free space. A compact circulator, based on Brewster and quarter wave plates has been specially designed, with both robustness and very good optical isolation (60 dB). A refractive afocal telescope shapes the output beam with an effective Gaussian diameter of 50mm (at 1/e², with $M^2$=1.4), allowing a focus range up to 300m.

The received beam is reflected by the Brewster plate and focused on a single mode PM fiber before being mixed with the fibered Local Oscillator. The oscillator beam is frequency shifted by 70MHz before being amplified by the EDFA, allowing the sign of the Doppler shift to be measured.

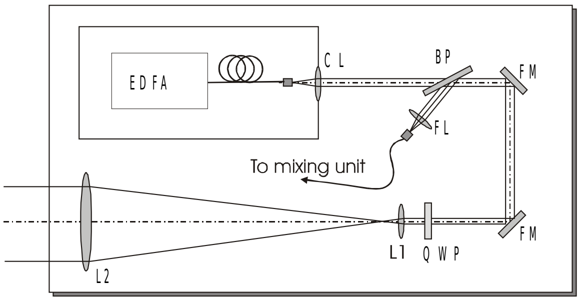


Figure 3: SWAN Lidar setup

EDFA : Fiber Doped Power Amplifier; CL : collimating lens; BP : Brewster plate; FM: folding mirror; QWP: Quarter Wave Plate; L1-L2 : afocal telescope; FL: Focusing lens

Taking into account the geometric and energetic lidar parameters, as well as atmospheric parameters, CNR and velocity resolution profiles can be derived from propagation models.

Figure 4 compares the theoretical CNR profile and the actual profile. The backscattering coefficient is here assumed to be $\beta_\pi$=3.5 $10^{-7}$ $m^{-1}$ $sr^{-1}$.

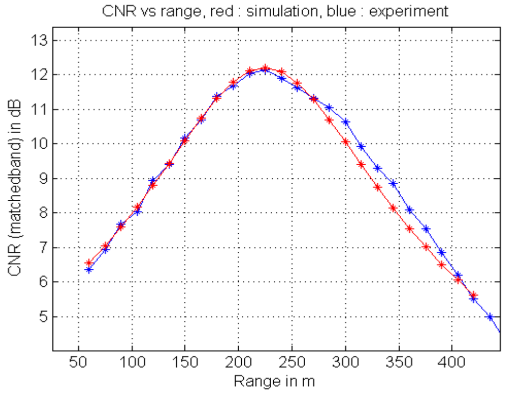


Figure 4: Theoretical and experimental CNR profile

The agreement between theory and experiment is good. These end-to-end models, developed at Onera are currently used for the lidar and laser design.

## 2.4 Signal processing

The lidar signal retrieves the wake vortex radial velocities projected along the beam. The temporal signal spectrum contains the velocity information (see Figure 5). Thanks to the pulsed signal option, there is no need for triangulation any more, as was the case for previous wake vortex campaigns in Tarbes or Munich airports .

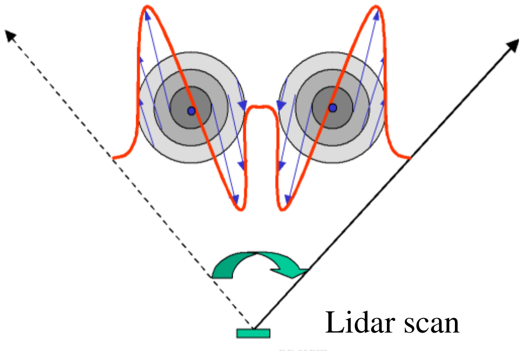


Figure 5: lidar scanning the wake vortex

The signal is sampled and processed in real time by a DSP board. It is then analysed by 64 points FFT, giving a basic range resolution of 37.5 meters, and a velocity resolution of 3 m/s. 60 samples overlap between successive FFTs gives a measurement spectrum every 2.4 m. With a 15 kHz PRF, 100 spectra averaging and 15°/s scan speed , an angular resolution as good as 0.1 ° is obtained ( 35 cm at 200m). The averaged spectra are then stored for high level processing .

In order to display the wake vortices measurements in real time, three maps are computed, having range and angle as main axes. These maps are calculated with the three first moments of the spectra, delivering respectively the CNR, the velocity centroid, and the velocity dispersion maps. The CNR map is useful for the lidar alignment setting and focus adjustment. The velocity map gives the position and trajectory of the vortex cores. The dispersion map informs on wind turbulence.

Two signal processing methods are used for wake vortex analysis, giving the vortex position and the vortex circulation as a function of time. One is based on parametric estimation , and the other one is a direct method , which we both plan to use for the data analysis.

## 3 Field testing

The SWAN lidar was installed in Onera mobile lab, Bemol (see Figure 6), and field testing was conducted at Orly airport in January 07.

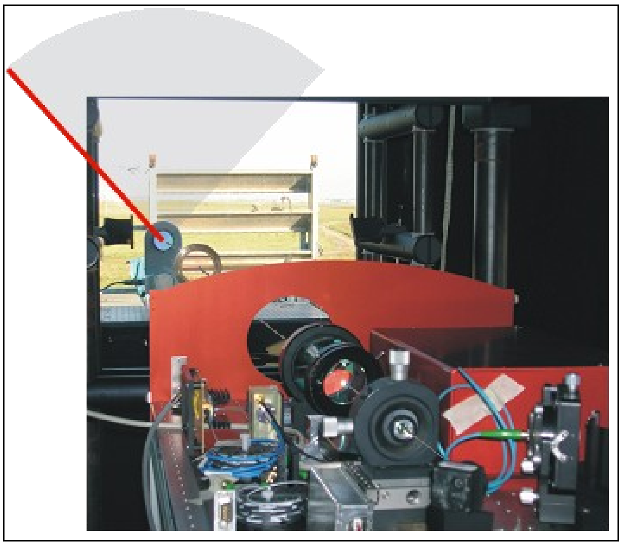


Figure 6: SWAN lidar inside Bemol

The scanning plane was vertical and was located at the end of runway 06/24 at 200 meters from the end of the runway (see Figure 7 ). Several take off and landing planes wake vortices were captured with an acceptable CNR.

Figure 7: Orly tests layout

Another field campaign took place in April at Francfort airport in the framework of the European project CREDOS. Extensive recording of aircrafts wake vortices was performed with SWAN, along with NASA and DLR 2 μm lidars. Detailed results will be presented elsewhere . Figure 8 shows the velocity map of a wake vortex pair captured 325 m away from the Lidar. The color scale gives the velocity information (spectrum centroid value) on each point of the scan plane. The display does not inform about the maximum velocity component in the spectra, related to the wake vortex circulation. However, the presence and position of a wake vortex is clearly visible on the velocity map: wake vortex has a characteristic signature which allows the operator to stop recording when the vortex has disappeared.

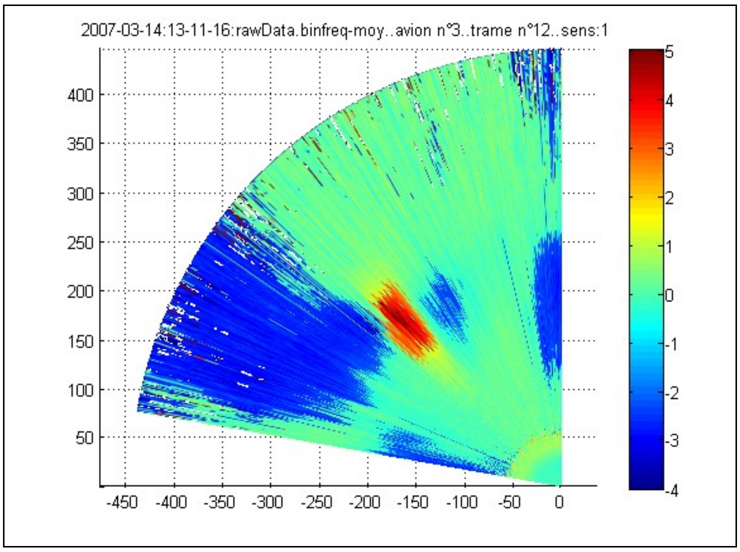


Figure 8 : Velocity map of a Boeing 747 vortex pair at Francfort airport, March 07 (raw data).

## 4 Conclusion

This paper illustrates the preliminary results obtained with a pulsed lidar based on MOPFA 1.5µm laser, for detection and monitoring of wake vortices on airport fields. Operational ranges longer than 400m have been demonstrated, with a 60µJ, 15kHz, 250ns pulse fiber doped Er laser. Wake profiles, positions and circulations can be derived from recorded data. In the near future, a compact and rugged version of the lidar should be built by Leosphere. Meanwhile, a more powerful laser source has been built at Onera in the framework of the European project FIDELIO. The SWAN lidar upgraded with this new laser source is expected to allow wake vortex characterization at ranges longer than 1 km.

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