Teramobile: a Nonlinear Femtosecond Terawatt Lidar

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ABSTRACT

We present a novel approach to characterize the atmosphere by Lidar, based on the non-linear propagation of ultrashort and ultra-intense laser pulses. For this, we built the first mobile femtosecond Terawatt Lidar system, the "Teramobile". While propagating in the atmosphere these ultra-intense laser pulses are self-guided in stable superstructures (filaments) and generate coherent superbroadband emission from the UV to the IR. Applications cover simultaneous multipollutant Lidar detection, longer range NIR-MIR Lidar, self-guiding through turbulence and clouds, and remote analysis of aerosols size and composition.

Keywords: Lidar, Ultrashort laser, White-light Supercontinuum, Aerosols

1. INTRODUCTION

For many years, the Lidar technique[1] has proven to be a powerful technique in atmospheric research. The main advantage of Lidar over other remote sensing techniques – such as DOAS[2], FTIR[3] or satellite based spectroscopy[4] – is the high range resolution over long distances, which is achieved by the use of pulsed lasers (typically a few nanoseconds or less) and fast electronics to record the signal of the light backscattered by molecules and aerosols. However, the number of the detectable species is limited by the availability of narrowband pulsed laser sources at suitable wavelengths, especially in the IR. Moreover, since the laser has to be tuned on an absorption band of the species to be measured, only one molecular species can be measured at a time by differential absorption, and interference between molecules having overlapping spectra are difficult to correct.
Other techniques such as DOAS or FTIR overcome this limitation using a wide spectral range, but at the cost of a range-integrated measurement. An other approach, to combine the advantages of both DOAS and Lidar is the use of a very broadband laser, leading to a multispectral lidar. A good candidate for that purpose is the white light supercontinuum[5] generated *in situ* by high-power, ultrashort laser pulses propagating nonlinearly in the atmosphere, as was first demonstrated by Rairoux *et al.* [6]. On the basis of these preliminary results, we developed the first mobile femtosecond-terawatt Lidar: the Teramobile.
In this paper, we show how ultrashort (100 fs), high-power (some TW) laser pulses propagating non-linearly in the atmosphere have the potential to significantly improve the information obtained by the Lidar technique. After a brief presentation of the non-linear propagation of ultrashort pulses in transparent media (Section 2), Section 3 is dedicated to

new white-light lidar results with ultrabroadband emission, including in the infrared, where many pollutants of interest have absorption bands. In section 4, we show that besides the supercontinuum-based multispectral measurements, ultrashort pulses could permit a selective detection of specific classes of atmospheric aerosols by inducing non-linear effects in the particles themselves.

2. PROPAGATION OF HIGH-POWER LASER PULSES IN THE ATMOSPHERE

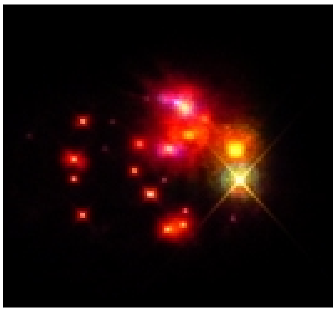

Figure 1. Picture of multiple filamentation occurring in the laser beam cross-section

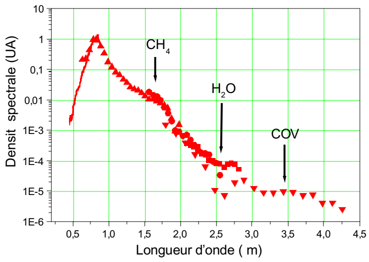

Figure 3. Spectrum of the white-light continuum produced by an ultrashort laser pulse in the air

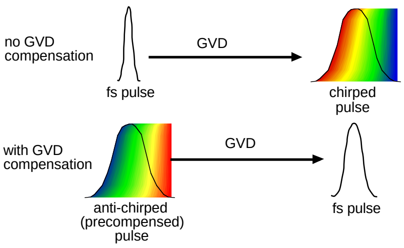

Figure 4. Principle of GVD compensation

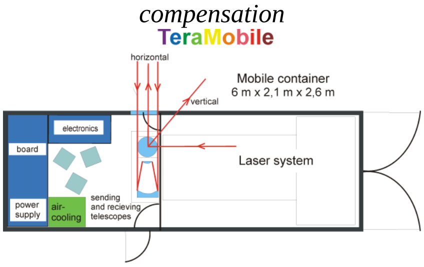

Figure 5. General layout of the Teramobile system

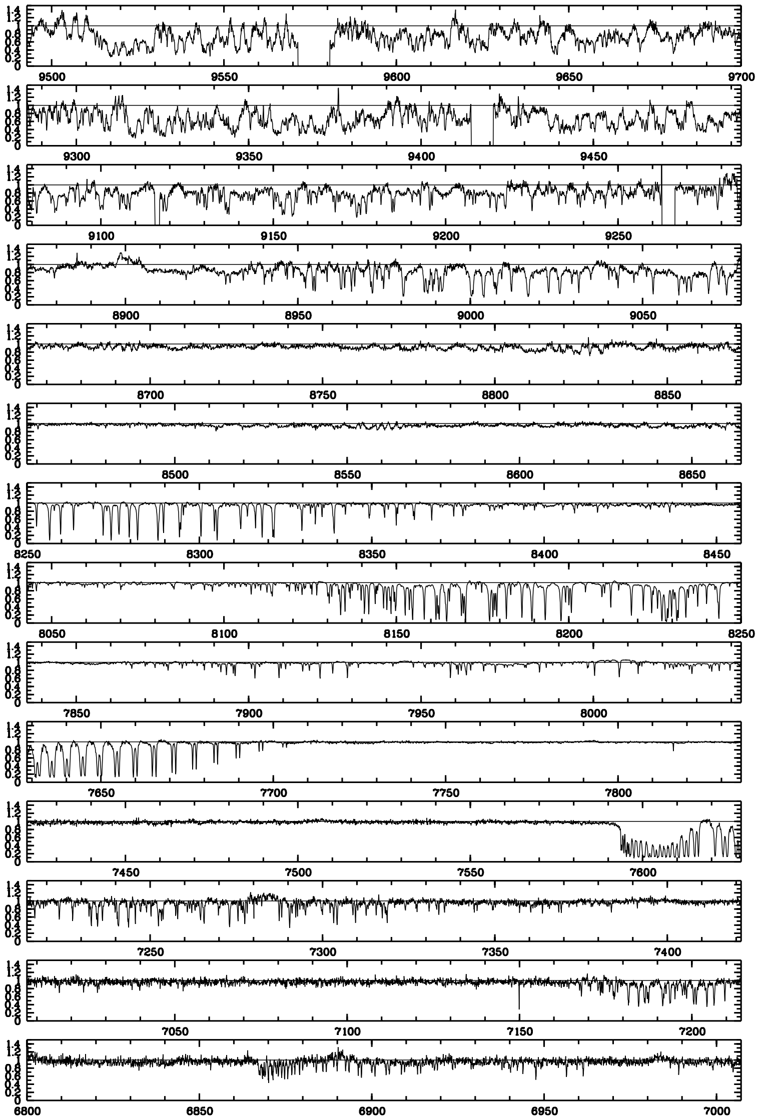

Figure 2. White-light atmospheric absorption spectrum

The interest in nonlinear laser pulse propagation has been significantly renewed since 1985, when the development of the chirped pulse amplification (CPA) technique[7], permitted to produce ultra-short laser pulses, which now reach powers in excess of 10^{14} W. At those power levels, nonlinear phenomena dominate pulse propagation even in diluted media such as atmospheric pressure gases, opening the way to applications in atmospheric applications. One of the most spectacular processes under such conditions is filamentation, which mechanism is described *e.g.* in[8]. The dynamical equilibrium between Kerr-lens self-focusing and defocusing due to plasma production results in a self-trapping of the beam for distances of at least several hundreds of meters, much longer than the Rayleigh length[9],[10] (*Figure 1*). In those thin filaments (around 100 µm[11], [12] in diameter), the intensity reaches 10^{13} - 10^{14} W/cm^2 [13], sufficient to generate significant self-phase modulation (SPM), yielding a bright white light supercontinuum[5]. In recent measurements, we could demonstrate that this supercontinuum extends from the UV to the mid-infrared up to 4 µm[14] (*Figure 3*), which covers the absorption bands of many important pollutants, such as volatile organic compounds (VOCs). Moreover, it has been shown that the white-light is a coherent radiation[15] and is emitted forward as a collimated beam as well as in the backward direction, *i.e.* more supercontinuum is emitted towards the lidar detection system than would be by elastic backscattering[16]. This leads to a highly enhanced lidar signal.

Another feature to be taken into account in the propagation of ultrashort pulses in the atmosphere is group velocity dispersion (GVD). Due to the Heisenberg principle, ultrashort pulses are broadband, eg typically 10 nm for a 100 fs pulse at 800 nm. Hence, GVD in the air results in a "chirp", which increases the pulse length after propagating some distance in the atmosphere, e.g. 1 ps per km propagation for our 100 fs pulse. However, it was shown[6,17] that by detuning the last stage of the laser amplification chain, *i.e.* the compressor, it was possible to give an "antichirp" to the pulse (see *Figure 4*). Hence GVD in air temporally recompresses *in situ* the pulse back to an ultrashort pulse at a selected distance that can be tuned by adjusting the antichirp. This technique therefore permits to control the distance at which filamentation leading to supercontinuum is started.

3. WHITE-LIGHT LIDAR

In order to study the potential of a non-linear lidar and perform field campaigns, we developed and constructed the "Teramobile" system, the first mobile fs-TW lidar system (*Figure 5*) This system has been extensively described elsewhere[18]. Briefly, the system is based on a reduced-sized CPA laser integrated in a standard 20" sea container equipped as a standalone optics laboratory. The laser provides 5 TW (350 mJ in 70 fs) pulses at 800 nm, and 10 Hz repetition rate. This mobile laboratory provides the necessary infrastructure for the laser system as well as sending and receiving optics and detection electronics for Lidar measurements. The Teramobile system has recently been installed at the Thüringer Landessternwarte in Tautenburg, Germany, an observatory with a 2 m diameter telescope. In the Coudé configuration, the telescope was connected to an Echelle spectrometer that allows recording of spectra over wide spectral regions at a 0.1 Å resolution. The telescope was aimed vertically and the white light produced was analyzed from backscattering at 4 km altitude. With this setup, we were able to record, for the first time to our knowledge, a broadband transmission spectrum of the atmosphere between 680 and 920 nm on a single lidar signal. After correction by the instrument function, the spectra were normalized to the spectral envelope of the laser-produced supercontinuum. *Figure 2* shows such a column-integrated spectrum obtained with 10 min integration time. This kind of measurements open the way to actual multicomponent Lidar measurements.

Since infrared is of major interest for white-light Lidar measurements, we specifically investigated this part of the spectrum. For this purpose, we directly coupled a photomultiphier tube (Hamamatsu R5509-72) on the telescope. The PMT has a cut-off between 1.65 and 1.7 µm and was equipped with a 1.5 µm high-pass filter. In this configuration, we were able to detect the IR Lidar signal between 1.5 and 1.7 µm scattered from 7 km high clouds, and even to resolve layered clouds. Although provisional, these results show that the white-light Lidar may be further extended and lead to useful improvements in the amount of information yielded by the Lidar, adding multicomponent resolution to the three-dimensional range resolution of classical Lidar.

4. INTERACTION OF FS-PULSES WITH AEROSOL PARTICLES

A major application of Teramobile is aerosol characterization, either by using the supercontinuum as an ultrabroadband source for the multispectral analysis of extinction coefficients, or by inducing non-linear effects in the aerosol particles themselves. In this respect, very attractive laboratory experiments showed that multi-photon excited fluorescence

(MPEF) from microdroplets is strongly enhanced in the backward direction[19], thus maximizing signal collection in Lidar set-ups. Moreover, by using dual pulse pump-probe schemes, sizing could be performed through the measurement of ballistic trajectories within the microdroplets[20]. Direct application could be simultaneous size and composition measurement of fogs, clouds and bioaerosols. Finally, to access chemical composition analysis without a-priori assumptions (unlike MPEF) it has been recently shown that a nanoplasma could be generated in the particles, from which emission lines could help identifying its constituents[21]

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