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LIDAR as an alternative to passive collectors to measure pesticide spray drift

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Abstract

Pesticide spray drift entails a series of risks and costs in terms of human, animal and environmental well-being. A proper understanding of this phenomenon is essential to minimize these risks. However, most conventional methods used in drift measurement are based on point collectors which are unable to obtain information concerning the temporal or spatial evolution of the pesticide cloud. Such methods are also costly, labour-intensive, and require a considerable amount of time. The aim of this paper is to propose a method to measure the spray drift based on lidar (Light Detection And Ranging) and to prove that it can be an alternative to passive collectors. An analytical model is proposed to relate the measurements obtained through passive collectors and those obtained with lidar systems considering several spray application and meteorological parameters. The model was tested through an experimental campaign involving multiple ground spray tests. A lidar system and two types of passive collectors (nylon strings and water-sensitive paper) were used simultaneously to measure the drift. The results showed for each test a high coefficient of determination ($R^2 \approx 0.90$) between the lidar signal and the tracer mass captured by the nylon strings. This coefficient decreased ($R^2 = 0.77$) when all tests were considered together. Lidar measurements were also used to study the evolution of the pesticide cloud with high range (1.5 m) and temporal resolution (1 s) and to estimate its velocity. Furthermore, a very satisfactory adjustment ($R^2 = 0.89$) was observed between the tracer mass collected by the nylon lines and the coverage on water-sensitive paper sheets. These results are in accordance with the proposed analytical model and allow the conclusion that

the application and meteorological parameters can be considered spatially invariant for a given test but are not invariant for different tests.

Keywords:

Light detection and ranging, Remote sensing, Sprayer, Droplet, Tracer, Agriculture.

1. Introduction

Pesticides are usually applied by equipment that distributes water droplets containing the active ingredients over a targeted vegetation. However, a fraction of the spray liquid does not reach its intended target. Part of the spray liquid is lost on falling to the ground and another part is scattered in the atmosphere. Spray drift is defined by the standard ISO 22866 (2005) as the quantity of plant protection product that is carried out of the sprayed (treated) area by the action of the air currents during the application process. The drift itself can be in the form of droplets, as dry particles or vapours (Gil and Sinfort, 2005).

Spray drift is one of the biggest sources of pollution as a result of the application of pesticide products and entails a risk for both human health and the environment (EPA, 1999). Losses due to spray drift can amount up to 30-50% of the applied product (Van den Berg et al., 1999). Spray drift clouds can damage crops close to the treated area, contaminate surface water, reach residential areas, etc. It has even been shown that the pesticides can travel thousands of kilometres via air currents, ending up in areas as remote as the polar regions (Unsworth et al., 1999).

The mechanisms that govern the pesticide drift need to be fully understood to enable optimization of the loss prevention and reduction strategies currently in use (Felsot et al., 2011). Drift related data must be included for official registration of any new pesticide formulations. The assessment of spray drift is normally carried out through field tests based on the use of point collectors located close to the area where the treatment is being applied which intercept the generated aerosol plume (ISO 22866). There are some serious drawbacks to this method, of which some of the most important are listed below (Gregorio et al., 2011):

- Information on the pesticide cloud is not time resolved. Conventional collectors only provide integrated parameters over the whole observation period.
- Two- (surface) or three-dimensional (volume) imaging of the plume is not possible. Collectors only display specific sample points of the plume, therefore ignoring the remaining drift volume.
- The results are largely influenced by the prevailing micro-meteorological conditions during the trial.
- A comparatively large amount of personnel and time resources is required; thus limiting the number of trials that can be carried out in practice.

The application of light detection and ranging (lidar) technique to airborne spray drift monitoring can overcome the above limitations. Lidar is an active range-resolving optical remote measurement technique commonly used to study the atmosphere for meteorological

or environmental purposes (Rocadenbosch, 2003). The lidar technique, which is also known as laser radar, benefits from the relatively strong interaction between the electromagnetic radiation at optical wavelengths and the aerosol/molecular atmospheric constituents (Measures, 1992).

Lidar systems, principally the elastic type ones, have been used in a number of studies for pesticide drift monitoring in both aerial (Hoff et al., 1989; Mickle, 1994; Mickle, 1996; Stoughton et al., 1997; Miller and Stoughton, 2000) and, though to a lesser extent, ground spray treatments (Huddleston et al., 1996; Miller et al., 2003). In most cases the lidar was used to study the movement and dispersion of the pesticide plumes at a qualitative level. However, key questions such as the application of the lidar to quantify droplet concentration in the pesticide clouds or determine spray drift flux (performance of mass balance) have scarcely been addressed (Hiscox et al., 2006; Khot et al., 2011). In this work, an analytical and experimental study is undertaken on the relationship between spray drift measurements obtained with an elastic-backscatter lidar system and those made using passive collectors, in this case nylon strings and water-sensitive paper sheets. The goal of this work is to determine whether the lidar technique may be an alternative to collectors conventionally used for measuring spray drift.

This paper is organised into five sections. Section 1 comprises this introduction. A theoretical model is proposed in Section 2 which relates the information obtained with the passive collectors and the lidar signal. This model takes into account the meteorological and spray application conditions. Section 3 offers a description of the materials and methods employed during the experimental campaign. Section 4 presents and compares the results with the theoretical model. Finally, the conclusions are given in Section 5.

2. Model development

A model is firstly proposed in this section which relates the lidar signal to the parameters of the monitored drift plume. Secondly, a model is considered which relates the collector measurements to the spray drift. Finally, based on the two aforementioned models, the relationship that exists between the measurements of the two sensor types is established.

2.1. Spray drift retrieval model of data obtained from a lidar sensor

Lidar measurements are based on the well-known single-scattering form of the elastic lidar equation (Collis and Russell, 1976). The return power component $P(R)$ [W] received by the lidar and due to a spray drift cloud located at a range R [m] is computed as

$$P(R) = \frac{E_0 A_r c}{2} \frac{\beta(R)}{R^2} \exp \left[-2 \int_0^R \alpha(r) dr \right], \quad (1)$$

where E_0 [J] is the energy emitted per laser pulse, A_r [m²] is the telescope effective receiving area, c [ms⁻²] is the speed of light, $\beta(R)$ [m⁻¹sr⁻¹] is the total atmospheric volume

backscattering coefficient and $\alpha(r)$ [m^{-1}] is the total atmospheric volume extinction coefficient.

The received backscattered signal [V] is given by

$$V(R) = R_i G_r P(R) \xi_{\zeta_0}, \quad (2)$$

where R_i [A/W] is the photodetector current responsivity, G_r [Ω] is the receiver transimpedance gain, and ξ_{ζ_0} is the total transmission factor of the receiving optics. A full overlap factor $\xi(R) = 1$ has been assumed.

Substituting Eq. (1) into (2), the range-corrected signal $S(R)$ [Vm^2] is obtained, given by

$$S(R) = R^2 V(R) \approx K \beta(R), \quad (3)$$

where K [Vm^3] is a constant characteristic of the system given by

$$K = \frac{R_i G_r E_0 A_r c \xi_{\zeta_0}}{2}, \quad (4)$$

and $\beta(R)$ is the total atmospheric volume backscattering coefficient, given by Eq. (5). For greater simplicity, atmospheric extinction has been disregarded in the calculation of Eq. (3). This approximation is valid under reduced optical depths as is the case here (near-field clouds with transmittance values close to unity).

$$\beta(\lambda, m, R) = \int_0^\infty \sigma_B(r_p, \lambda, m, R) N_p(r_p, R) dr_p, \quad (5)$$

where $\sigma_B(r_p, \lambda, m, R)$ [$\text{m}^2/\text{particle}$] is the backscattering cross-section of a particle of radius r_p [m] and complex refractive index m when illuminated by light of wavelength λ . $N_p(r_p, R)$ [particles/ m^3] is the particle number concentration, defined as the number of particles per unit volume with radius between r_p and $r_p + dr_p$. In what follows the dependency of the backscatter coefficient on λ and m will be disregarded for notational simplicity. The backscattering cross-section can be written as

$$\sigma_B(r_p, \lambda, m, R) = \pi r_p^2 Q_B(x, m, R), \quad (6)$$

where $Q_B(x, m, R)$ is the backscattering efficiency, defined as the ratio of particulate backscattering cross-section to the geometric cross-section, and x is the size parameter, defined as

$$x = 2\pi r_p / \lambda. \quad (7)$$

The volumetric mean diameter (VMD) of the droplets that make up the drift clouds depends on the meteorological and spray application conditions (spray composition, nozzle, pressure, air flow, etc.). Considering the studies of several authors (Elliot and Wilson, 1983; Bache and Johnstone, 1992; Miller, 1993) a range between 10 and 150 μm is assumed. So, applying Eq. (7) and considering a wavelength of 355 nm (corresponding to

the lidar system used in these tests), it is found that x takes values ranging between 88 and 1327. For these size parameters the backscattering efficiency of the water displays highly oscillatory behaviour. This behaviour is because the imaginary component of the water refractive index has a very low value (Deirmendjian, 1969; Segelstein, 1981).

Equation (8) below is obtained from Eqs. (5-7). In this equation, the total atmospheric volume backscattering coefficient is expressed as a function of particle size. It is also considered that the lidar emits at a specific wavelength and it is assumed that, for each test, the drift droplets have similar refractive index values.

$$\beta(R) \approx \pi \int_0^{\infty} r_p^2 Q_B(r_p, R) N_p'(r_p, R) dr_p. \quad (8)$$

So, the range-corrected lidar signal will be given by

$$S(R) \approx \pi K \int_0^{\infty} r_p^2 Q_B(r_p, R) N_p'(r_p, R) dr_p. \quad (9)$$

Equation (9) can be expressed as

$$S(R) \approx \frac{K}{4} a_e(R), \quad (10)$$

where $a_e(R)$ is the modified surface area concentration [m^2/m^3], defined as

$$a_e(R) = 4\pi \int_0^{\infty} r_p^2 Q_B(r_p, R) N_p'(r_p, R) dr_p. \quad (11)$$

The term “modified” accounts for inclusion of the backscattering efficiency, $Q_B(r_p, R)$ in Eq. (11), which is in contrast to the classic definition of the “effective surface area concentration” in the literature (Ansmann and Müller, 2005).

In order to compare the lidar measurements with those obtained from the passive collectors, it is necessary to add together the signals received by the lidar system during the time interval t_{int} over the course of which the drift cloud is detected. The range-corrected and time-integrated lidar signal $IS(R)$ is calculated as

$$IS(R) \approx \sum_{i=1}^N S_i(R), \quad (12)$$

where $S_i(R)$ is the range-corrected signal corresponding to the measurement i and N is the total number of lidar measurements made during the time interval t_{int} , given by

$$N = \frac{t_{\text{int}}}{T_f}, \quad (13)$$

where T_f [s] is the pulse-repetition period of the lidar system. Through Eqs. (10), (12) and (13), the following expression for the time-integrated lidar signal is obtained,

$$IS(R) \approx \frac{t_{\text{int}}}{T_f} \frac{K}{4} \overline{a_e}(R), \quad (14)$$

where $\overline{a_e}(R)$ is the time-average modified surface area concentration during the integration time, t_{int} .

2.2. Spray drift retrieval model from passive tracer collectors

The spray liquid volume [m^3 spray liquid] collected by a nylon string (passive collector) located at a range R can be expressed as

$$V_d(R) = V_{\text{air}}(R) \overline{\rho_d}(R), \quad (15)$$

where $V_{\text{air}}(R)$ [m^3 air] is the effective air volume sampled by that collector segment and $\overline{\rho_d}(R)$ [m^3 spray liquid/ m^3 air] is the average total volume concentration of spray liquid during the integration time. An upper bar indicates “averaged” over the integration time. The total volume concentration ρ_d is defined by Ansmann and Müller (2005) as

$$\rho_d(R) = \frac{4\pi}{3} \int_0^\infty r_p^3 N_p(r_p, R) dr_p. \quad (16)$$

The effective air volume sampled by the collector segment (Fig. 1) is given by

$$V_{\text{air}}(R) = A_c \overline{w_p} \eta_c t_{\text{int}}, \quad (17)$$

where A_c [m^2] is the projected area of the collector segment, $\overline{w_p}$ [m/s] is the average speed of the plume or the average speed at which the droplets reach the collector, η_c is the collector efficiency during the test and t_{int} has been previously presented.

Substituting Eq. (17) in (15), the following expression is obtained for the spray liquid volume $V_d(R)$ [m^3 spray liquid drift] captured by a collector segment

$$V_d(R) = A_c \overline{w_p} \eta_c t_{\text{int}} \overline{\rho_d}(R). \quad (18)$$

Equation (18) indicates that the spray liquid volume captured over a time t_{int} by each string collector segment is determined by the average volume concentration $\overline{\rho_d}(R)$ of airborne spray liquid over this time.

2.3. Relationship between lidar signal and deposition on linear passive collectors

The modified effective radius r_{eff} (surface-area-weighted mean radius) at a given range R from the lidar is defined as

$$r_{\text{eff}}(R) = \frac{\int_0^{\infty} r_p^3 N_p(r_p, R) dr_p}{\int_0^{\infty} r_p^2 Q_B(r_p, R) N_p(r_p, R) dr_p} = 3 \frac{\rho_d(R)}{a_e(R)}. \quad (19)$$

This definition differs from the classical definition of Ansmann and Müller (2005) in that the backscatter efficiency $Q_B(r_p, R)$ is included in the denominator. Main advantage of this redefinition is that allows for the formulation of a lidar-to-passive collector relationship.

Dividing Eqs. (18) and (14) and carrying out the operation, we obtain

$$V_d(R) = \frac{4T_f A_c}{3K} \overline{w_p} \eta_c \overline{r_{\text{eff}}} IS(R). \quad (20)$$

In order to simplify the above expression, the constant C is defined as

$$C = \frac{4T_f A_c}{3K}, \quad (21)$$

from which the following equation is obtained

$$V_d(R) = C \overline{w_p} \eta_c \overline{r_{\text{eff}}} IS(R). \quad (22)$$

The spray liquid volume deposited on a collector segment is related to the tracer mass m_t [kg] captured by this collector segment by

$$m_t(R) = V_d(R) \overline{\rho_{m,f}}, \quad (23)$$

where $\overline{\rho_{m,f}}$ [kg/m³] is the mean tracer concentration in the droplets which are deposited on the collector.

Considering an integration time t_{int} in the test and substituting Eq. (22) in (23) the following relationship is obtained

$$m_t(R) = C \overline{w_p} \eta_c \overline{\rho_{m,f}} \overline{r_{\text{eff}}} IS(R). \quad (24)$$

Equation (24) is presented as a theoretical model which allows the prediction of the tracer mass deposited on the nylon strings from the backscattered lidar signal integrated over a time t_{int} ($IS(R)$) and the physical parameters ($\overline{w_p}, \eta_c, \overline{\rho_{m,f}}, \overline{r_{\text{eff}}}$) which define the drift cloud when it reaches the sampling point.

3. Materials and methods

3.1. General description of field tests

Ten spray tests were performed between September 18 and 21, 2009, at a field owned by the Institut de Recerca i Tecnologia Agroalimentàries (IRTA) in Gimènells (lat. 41°39'11''N, long. 0°23'28''E, elev. 259 m) located 25 km from Lleida, Spain. Fig. 2 shows a map of the field as well as the position of the instruments and machinery used

during the trials. The field is flat and lies next to a dirt road. At the time of the trials, there was no crop on the field.

The spray was generated by a cross-flow air-assisted sprayer (Ilemo Arrow F-1000, Ilemo/Hardi SA, Lleida, Spain) operating at 1 MPa. Three nozzle types were tested: 1) hollow cone (Albuz ATR Orange, Saint-Gobain, Evreux, France), 2) air injected anti-drift (Albuz TVI 80 02, Yellow), and 3) disc-core full cone nozzles (Teejet D3DC35, Spraying Systems Co., Wheaton, Illinois, USA). The use in each trial of different types and number of nozzles aims to increase the variability of application conditions. The sprayer was kept in a static position. The position of the sprayer was modified in the various tests depending on the wind direction in order to ensure that the plume drift would reach the collectors. The spray liquid comprised an aqueous solution of brilliant sulphoflavine (BSF, Biovalley, Marne La Vallée, France). This tracer was chosen because of its low solar degradation, high recovery rate, and its earlier successful use in previous experimental studies (Ganzelmeier et al., 1995; Solanelles et al., 2001).

Table 1 details the conditions of application of all the tests. For each test, the date the test was performed, the start time, the duration t_a of the spraying, the position of the air-assisted sprayer, the nozzle model employed, the number of open nozzles, the individual nozzle flow rate at a pressure of 1 MPa and the initial concentration, $\rho_{m,i}$, of BSF in the spray liquid, determined by fluorimetry of a sample taken from the tank are shown. The position of the sprayer is expressed with the terms d_a and d_b [m] which, as can be seen in Fig. 2, refer to the distances between the sprayer outlet and the posts A and B holding up a nylon string. $d_{\perp}$ [m] is, as it can be seen in Fig. 2, the orthogonal distance between sprayer and string and is calculated from d_a and d_b .

3.2. Passive collectors

Two types of collectors were used in each test: 2 mm diameter nylon string (reference drift collection system in ISO 22866 (2005)) 25.5 m long and 16 water-sensitive paper sheets 26×76 mm (Water-Sensitive Paper, Spraying Systems Co.). The nylon string was positioned horizontally 1.7 m above the ground and was held up at its two ends by posts which remained in the same position throughout all the tests (A and B in Fig. 2). The water-sensitive paper sheets were attached to the nylon string with pegs (Fig. 3 (a)), at a distance from each other of 1.5 m (Fig. 3 (b)) matching the range resolution of the lidar system (Table 2).

3.3. Lidar measurements

A 355-nm 16-mJ elastic-backscatter lidar system (ALS 300, Leosphere, Orsay, France) was used for pesticide spray drift monitoring. Lidar system specifications (Leosphere, 2009) are listed in Table 2.

The lidar system was positioned in the southeast corner of the field 225.5 m away from post A (Fig. 2). This distance ensured there would be no energy loss due to partial overlap

between the laser emission and the telescope field-of-view of the lidar (i.e., overlap factor $\xi(R) < 1$, refer to Eq. (2) comments). The range of full overlap was configured around 80 metres). As it can be seen in Fig. 2 and Fig. 4, the lidar system was pointed horizontally with its laser beam aligned with the nylon string. This was done to enable comparison of the measurements obtained by both sensors. It should be mentioned that in all the tests the separation between the laser beam and the nylon string was less than 30 cm.

3.4. Meteorological measurements

A portable weather station equipped with a temperature and humidity sensor (EE20 Series, E+E Elektronik Ges.m.b.H., Engerwitzdorf, Austria) and a pyranometer (SKS 1110, Skye, Powys, UK) was used. The station was positioned at a height of 4 m and took a measurement every minute. The streamwise (u), cross-stream (v) and vertical (w) wind components were measured by a 3-axis ultrasonic anemometer (WindMaster, Gill Instruments Ltd, Lymington, UK) at an output rate of 10 Hz. The anemometer was also positioned at a height of 4 m.

Table 3 shows the prevailing micrometeorological conditions during the performance of the tests. Temperature, relative humidity and solar radiation measurements were provided by the portable weather station and correspond to the minute in which the spraying was carried out. The wind speed U was calculated from the three orthogonal components provided by the sonic anemometer and by averaging the resulting vector during the 60 s after the start of the spraying operation. A 60 s averaging period was chosen bearing in mind that the lidar system did not detect a signal after this time in any of the tests due to drift. The parallel $U_{\parallel}$ and cross $U_{\perp}$ wind components with respect to the nylon string, whose orientation during the tests was known, were calculated from the averaged wind speed and direction values.

3.5. Estimation of drift deposition on passive collectors

Nylon strings

After each spraying, once the nylon string dried, it was cut in 1.5 m long segments, corresponding to the range resolution of the lidar system used (Table 2). Each segment was introduced in a plastic bag for its transfer to the laboratory where 50 ml of deionised water were added to each bag for tracer (BSF) extraction. Determination of BSF concentration in the water extracts was carried out directly from the bags using a fluorescence spectrophotometer (LS 30 Luminescence Spectrometer, Perkin Elmer, Waltham, Massachusetts, USA) at a wavelength of 425 nm for excitation and 510 nm for emission. The total BSF mass deposited on each 1.5 m long collector segment was calculated by using that

$$m_i = \rho_i V_w, \quad (25)$$

where m_i [g] is the BSF mass on each collector segment, ρ_i [g/l] is the concentration of BSF in the water extract and V_w is the water volume used in the extraction (0.05 l).

Water-sensitive papers

Water-sensitive papers (*WSP*) were photographed at the laboratory and these images were analysed with specific software (Matrox Inspector, version 2.2, MatroxTM, Dorval, Canada) following the methodology described by Chueca et al. (2010). The images were taken with 20 pixels/mm resolution. Objects in the image comprising one single pixel were considered as noise and thus removed. Therefore, impacts less than $2.5 \cdot 10^{-3} \text{ mm}^2$ were not detected. In each image, the program measured coverage (percentage of surface covered by all the objects present in the image), the area of all the impacts produced by the deposited droplets and the average diameter.

Because *WSP* are much easier to handle and analyse than nylon strings, it is also important to assess whether they can be used as appropriate collectors in field experiments. For this reason, the relationship between total BSF-deposited mass, m_i , and coverage (%) of water-sensitive papers (WSP_{cov}) was studied using Simple Linear Regression Analysis (SRA).

3.6. Estimation of the mean cross-plume velocity

Lidar data were used to obtain range-time intensity plots (RTI) of the pesticide plume and to calculate the time-integrated lidar signal. To generate RTI plots, lidar data were range-corrected and background subtracted. To obtain the background signal, time-averaged measurements were used in each test taken a few seconds before the start of the spraying operation (pre-calibration measurements). All the measurements have a time resolution of 1 s (Table 2).

Estimation of the mean cross-plume velocity, $\overline{w_p}$, was carried out from RTI plots. $\overline{w_p}$ is an estimation of the component of the speed of the pesticide cloud orthogonal to the direction of the nylon string (Fig. 2). For each RTI plot the time t_m [s] corresponding to the mid-point of the cloud is calculated and it is assumed that at this time half of the spraying has been performed. The value of t_m is given by

$$t_m = t_i + \frac{t_f - t_i}{2}, \quad (26)$$

where t_i [s] is the time elapsed between the start of the spraying operation and the moment when the plume begins to be detected by the lidar and t_f [s] is the time elapsed between the start of the spraying and the time instant when the plume ceases to be detected by the lidar.

The mean cross-plume velocity $\overline{w_p}$ is computed as

$$\overline{w_p} = \frac{d_{\perp}}{t_m - \frac{t_a}{2}}, \quad (27)$$

where $d_{\perp}$ [m] (Fig. 2) is the orthogonal distance between sprayer and nylon string and t_a [s] is the duration of the application. Substituting Eq. (26) in (27) gives

$$\overline{w_p} = \frac{2 \cdot d_{\perp}}{t_i + t_f - t_a}. \quad (28)$$

The values of the orthogonal distance $d_{\perp}$ and the duration of the spray application t_a are shown in Table 1, while t_i and t_f are determined from the RTI plots (Table 5).

3.7. Lidar data analysis

The time-integrated lidar signal $IS(R)$ was calculated adding together the range-corrected background subtracted lidar data throughout all the measurement period. The accumulated (not averaged) lidar signal is obtained with distance resolution, suitable for comparison with passive collector data.

The model proposed in Eq. (24) was studied using the test results. SRA was applied to analyse whether there exists a linear relationship between the time-integrated lidar signal, IS , and the BSF mass, m_i , deposited on each nylon string segment. All lidar signal processing was performed using numerical computing software (Matlab[®] version 7.3, MathWorks Inc., Natick, Massachusetts, USA) and commercial statistical software (JMP[®] 10.0.0, SAS Institute Inc., Cary, North Carolina, USA).

4. Results and discussion

4.1. Relationship between nylon string and WSP measurements

In this section a comparison is made of the data obtained with both passive collector types. It should be remembered that the nylon strings provide information about the amount of spray liquid (tracer) that reaches them while the water-sensitive paper sheets offer descriptive information about how this spray liquid was deposited. Moreover, since the nylon string catches 1.5 m of the spray plume and the WSP only represents a very small point along this length, it is expected that the nylon string will obtain more drift information than the WSP. Given the above, Eq. (29) describes the relationship between tracer mass, m_i [μg], collected for each nylon string segment and the coverage on water-sensitive paper sheets WSP_{cov} (percentage of the total surface covered by the strikes), with a coefficient of determination $R^2 = 0.89$.

$$m_i = 0.923 + 1.772 WSP_{cov}. \quad (29)$$

Figure 5 shows that the relationship between both variables can be considered linear. The model shows a strong dependency between WSP and nylon string data and admits the possibility of substituting nylon strings with simpler to handle and analyse WSP collectors in future field works. It should be noted that this model (Table 4) presents a statistically significant intercept ($p\text{-value} < 0.05$). This agrees with the fact that WSP has very low collection efficiency for small diameter droplets.

4.2. Range-time evolution of the spray drift

Figure 6 shows the RTI plots of the pesticide plumes corresponding to four of the tests that were performed (E2, E4, E7 and E10). The backscattered lidar signal is represented for each test.

Table 5 shows the values obtained for the plume velocity, as well as the detection start and end times with the lidar. It can be seen that in almost all the tests, $\overline{w_p}$ differs from the orthogonal wind component $U_{\perp}$ (Table 3). It is considered that this is because, on the one hand, the plume velocity is not only dependant on the wind speed but it is also influenced by the sprayer fan, the droplet output velocity, the size of the droplets, the friction between these and the air, etc., and on the other hand because, due to atmospheric turbulence and the short duration of the tests, wind speed measurement at the anemometer position may not coincide with the real values in the position of the drift cloud.

4.3. Consistency of the proposed model

This section aims to validate the Eq. (24) model. A comparison is made in Fig. 7 for the same tests as in Fig. 6 of the backscattered signal received by the lidar system with the measurements taken with the passive collectors. The left-hand column shows as a function of range the lidar signal integrated in time IS , the tracer mass m_i deposited on the nylon string and the percentage of coverage, WSP_{cov} , of the water-sensitive paper sheets. Passive collectors and lidar-based measurements clearly follow a similar trend. It should be remembered that the passive collectors only measured the drift for distances ranging between 225.5 and 251 m, which is where the support posts were positioned (Fig. 2). This entails a disadvantage with respect to the lidar system which enables monitoring of the whole pesticide plume. This can be clearly seen in Fig. 7(d), where the passive collectors are only able to detect a small fraction of the plume while the peak of the plume is detected at around 220 m by the lidar system.

The right-hand column of Fig. 7 shows for each test the measurement of the tracer mass m_i deposited on each nylon string segment (1.5 m) versus the time-integrated lidar signal IS corresponding to the same segment. A high coefficient of determination can be observed in all the tests between both variables ($R^2 \approx 0.90$) in accordance with the linear formulation – in first approximation – proposed by the model of Eq. (24). In the remaining tests, not represented in Fig. 7, similar results have been obtained. The theoretical relationship between passive collector captured tracer mass and the integrated lidar signal is, according to Eq. (24), a function of 4 parameters ($\overline{w_p}, \eta_c, \overline{\rho_{m,f}}, \overline{r_{eff}}$) which depend on the weather and spray application conditions. For a given test, the average meteorological conditions to which the drift droplets which reach the different collector segments are subjected to will be very similar, while the spray application conditions are the same.

Therefore, the spray drift radii distribution $\overline{r_{eff}}$, the mean cross-plume velocity $\overline{w_p}$, the final concentration of tracer $\overline{\rho_{m,f}}$ and the collector efficiency η_c are spatially and time invariant on a given test experiment. So, Eq. (24) can be rewritten in a simplified form as

$$m_i(R) = CK_i IS(R), \quad (30)$$

where K_i is the characteristic constant of the test given by the meteorological and application conditions of that test and is defined as

$$K_i = \overline{w_p} \eta_c \overline{\rho_{m,f}} \overline{r_{eff}}. \quad (31)$$

From Eq. (30) it follows that for a given test there exists a linear relationship between the tracer mass deposited on the different nylon string segments and the corresponding time-integrated lidar measurements. This theoretical relationship is in agreement with the test results shown in Fig. 7 (right).

Considering the results of all the tests together, the relationship between the deposited tracer mass, m_i [μg], and the time-integrated lidar signal, IS [a.u.], is given by

$$m_i = -1.108 + 2.256 \cdot 10^{-4} IS. \quad (32)$$

The intercept of Eq. (32) is not statistically significant ($p\text{-value} > 0.05$), as shown in Table 6. Therefore, a regression analysis through the origin is carried out, yielding

$$m_i = 2.099 \cdot 10^{-4} IS. \quad (33)$$

Fig. 8 shows both regressions, with and without intercept. As shown in Table 6, the adjustment between m_i and the time-integrated lidar signal, IS , is better for the regression through the origin ($R^2 = 0.77$) than for the regression with intercept ($R^2 = 0.67$). This result is in agreement with model of Eq. (24), where there is no intercept.

5. Conclusions

The results of the experimental campaign revealed for each of the tests a strong linear relationship ($R^2 \approx 0.90$) between the backscattered time-integrated elastic lidar signal and the measurements obtained via the passive collectors. This has led to the conclusion that the application and meteorological parameters of the model presented in Eq. (24) are spatially invariant for a given test.

The coefficients of determination obtained in this work are significantly higher than those calculated by Khot et al. (2011), who also compared drift measurements with those taken by in situ collectors. This discrepancy may be because in their study these authors did not calculate the correlation for each of the tests separately. In any case, our model has shown a similar predictive capacity ($R^2 = 0.77$) when all the measurements are considered simultaneously. These results allow the conclusion that for different tests the application and meteorological parameters are not spatially invariant and, therefore, the relationship between the lidar signal and the measurements of the passive collectors cannot be

considered linear. As a result, it follows that calibration of the lidar signal using cooperative sensors is valid for a given test, but that this calibration cannot be extrapolated to different tests.

In this work, the advantages of the lidar system have been highlighted in terms of their monitoring capacity (range and time-resolved information in RTI plots) and the lower amount of time required for measurements. Additionally, the lidar system enables estimation of the plume speed, and its comparison with the anemometer measured wind speed. It is concluded that lidar is an appropriate technique for measuring the pesticide drift as it has been possible to relate the lidar measurements to those obtained via conventional sampling techniques.

Currently, the authors are developing a new eye-safe microlidar system specifically aimed at monitoring pesticide spray drift. Future work will include a complete validation of the model presented. For doing this, a greater number of tests will be required, under contrasting conditions and measuring all the variables ($\overline{w_p}, \eta_c, \overline{\rho_{m,f}}, \overline{r_{eff}}$) that affect the model.

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Fig. 1. Volume of air sampled by a collector segment of cross-section A_c and efficiency η_c over an integration time t_{int} and considering a plume speed $\bar{w}_p$.

Fig. 2. Experimental field with sensor and operation locations. U is the wind speed and $U_{\perp}$ and $U_{\parallel}$ are, respectively, the wind components that are orthogonal and parallel to the nylon string. w_p is the component of the plume drift speed orthogonal to the nylon string.

(a)

(b)

Fig. 3. (a) Detail of a water-sensitive paper sheet attached by peg to the nylon string. (b) Nylon string with water-sensitive sheets attached each 1.5 m.

Fig. 4. Relative position of the lidar system (foreground), posts holding up the nylon string (right-hand side background) and the air-assisted sprayer (left-hand side background).

Fig. 5. Tracer mass, m_t [μg], versus coverage on water-sensitive papers WSP_{cov} [%], Eq. (29).

Fig. 6. Range-corrected background-subtracted lidar signal (arbitrary units). (a) Test E2. (b) Test E4. (c) Test E7. (d) Test E10. Temporal resolution is 1 s and range resolution is 1.5 m.

Fig. 7. (left) Range profiles of time-integrated lidar signals, tracer mass captured by nylon strings and spray coverage on the water-sensitive papers. All units are arbitrary and plots are scaled for representation purposes. (right) Tracer mass [μg] deposited on each nylon string segment vs time-integrated lidar signal. (a) Test E2. (b) Test E4. (c) Test E7. (d) Test E10.

Fig. 8. Tracer mass, m_i [μg], versus time-integrated lidar signal, IS [a.u.], Eq. (32-33).

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Table 1

Description of the experiments.

Test	Date	Pulverization start time	t_a [s]	Sprayer position			Nozzles		Flow rate [l/min/nozzle] ^b	$\rho_{m,i}$ [g/l]
				d_a^a [m]	d_b^a [m]	$d_{\perp}^a$ [m]	Model	Number		
E1	9/18/09	14:44:40	40	26.85	37.45	26.84	Albuz ATR Orange	10	1.39	0.897
E2	9/18/09	16:01:10	34	26.85	37.45	26.84	Albuz ATR Orange	5	1.39	0.897
E3	9/20/09	13:29:30	30	27.95	32.95	27.12	Teejet D3DC35	10	2.0	0.907
E4	9/20/09	14:57:40	30	27.95	32.95	27.12	Teejet D3DC35	5	2.0	0.907
E5	9/20/09	16:21:30	30	27.95	32.95	27.12	Albuz TVI 80° Yellow	10	1.46	0.907
E6	9/21/09	11:36:40	30	26.30	37.55	26.27	Albuz TVI 80° Yellow	5	1.46	0.93
E7	9/21/09	14:50:07	30	26.30	37.55	26.27	Albuz ATR Orange	10	1.39	1
E8	9/21/09	15:08:44	30	26.30	37.55	26.27	Albuz TVI 80° Yellow	10	1.46	1
E9	9/21/09	16:47:11	33	22.90	44.70	16.24	Albuz ATR Orange	10	1.39	1
E10	9/21/09	17:06:13	31	22.90	44.70	16.24	Albuz ATR Orange	10	1.39	1

^a d_a , d_b and $d_{\perp}$ refer to distances in Fig. 2.

^b Individual nozzle flow rate at an operating pressure of 1 MPa.

Table 2

Lidar system specifications.

Wavelength, λ	354.7 nm (tripled Nd:YAG)
Pulse-repetition frequency, PRF	20 Hz
Pulse energy, E_o	16 mJ ($\pm 5\%$ pulse by pulse)
Laser emission divergence	< 0.25 mrad
Receiving diameter, d_o	150 mm
Interference filter width, $\Delta\lambda$	0.3 nm
Detector	Photomultiplier (PMT)
Range resolution, ΔR	1.5 m
Temporal Resolution	1 s (used in these tests)

Table 3
Meteorological conditions during the tests.

Test	Temperature [°C]	Relative Humidity [%]	Solar radiation [W/m ²]	$U_{\parallel}$ [m/s]*	$U_{\perp}$ [m/s]*	U [m/s]*
E1	16.5	75	199	2.235	2.427	3.299
E2	17.7	65	183	0.919	1.430	1.700
E3	22.4	45	714	1.022	1.494	1.810
E4	23.5	45	452	0.191	0.967	0.986
E5	24.2	44	166	-0.558	0.863	1.028
E6	21.5	54	690	0.540	2.495	2.553
E7	25	39	529	N/A	N/A	N/A
E8	24.9	36	457	N/A	N/A	N/A
E9	25.1	36	142	1.821	0.762	1.974
E10	24.8	39	71	1.083	1.177	1.599

* $U_{\parallel}$ is the wind component parallel to the nylon string (positive when it moves away from the lidar system), $U_{\perp}$ is the wind component perpendicular to the nylon string, and U is the wind speed modulus. N/A stands for not available.

Table 4
Statistical analysis of simple linear regression model for tracer mass m_i as a function of the coverage on WSP.

Model significance	R^2	RMSE	Parameter	Estimate (standard error)	p – value
<0.001	0.89	3.301	Intercept	0.923 (0.311)	0.0034
			WSP_{cov}	1.772 (0.051)	<0.0001

Table 5
Cloud detection start time t_i , cloud detection end time t_f and mean cross-plume velocity $\overline{w_p}$ during the tests.

Test	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
t_i [s]	8	10	N/A	24	17	6	13	22	11	8
t_f [s]	67	51	N/A	57	41	37	53	49	53	52
$\overline{w_p}$ [m/s]	1.534	1.988	N/A	1.064	1.937	4.042	1.459	1.281	1.048	1.120

N/A stands for not available.

Table 6
Statistical analysis of simple linear regression model for tracer mass, m_i , as a function of time-integrated lidar signal, IS .

Model significance	R^2	RMSE	Parameter	Estimate (standard error)	p – value
With intercept					
<0.001	0.67	5.649	Intercept	-1.108 (0.630)	0.0807
			IS	$2.256 \cdot 10^{-4}$ ($1.275 \cdot 10^{-5}$)	<0.0001
Without intercept					
<0.001	0.77	5.686	IS	$2.099 \cdot 10^{-4}$ ($9.151 \cdot 10^{-6}$)	<0.0001