Review. Airborne spray drift measurement using passive collectors and lidar systems

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Abstract

Minimization of the risk associated with spray applications requires a proper understanding of the spray drift phenomenon. This fact has led over the years to the development of several techniques to measure the deposition on horizontal surfaces as well as the airborne spray profiles. Assessment of airborne spray drift is particularly difficult because this phenomenon is subject to variable micrometeorological conditions. However the monitoring of airborne drift has a great importance since it can be carried over long distances from its source. This paper reviews main sampling techniques currently used to asses the airborne spray drift, based on passive collectors and tracers. Theoretical principles that determine the efficiency of passive samplers are studied as well as the performance of different types of tracers. It also provides an overview of the recently established standards for monitoring the spray drift. On the other hand, this paper shows new airborne spray drift assessment techniques based on lidar (radar laser) technology, reviewing its principle of operation as well as its practical application in several spray drift trials. It is concluded that the lidar technique has significant advantages over conventional methods, especially in terms of time consumption and monitoring capabilities. However, the future adoption of lidar technology for airborne spray drift studies will be subjected to the development of lidar instruments really adapted to this application.

Additional key words: agriculture emission measurement, pesticide application, remote sensing, spray drift legislation, tracer.

Abbreviations used: LIDAR (light detection and ranging).

Introduction

According to the ISO 22866 standard spray drift is defined as the quantity of plant protection product that is carried out of the sprayed (treated) area by the action of air currents during the application process. The spray fraction that can cause drift in a spray application is considered to be the one that is made up of all the droplets of a diameter smaller than 100 µm (Elliott and Wilson, 1983). Nevertheless, the values are different depending on the authors. In this way Miller (1993), quoting different studies, places the median volume diameter (VMD) of the spray droplets that produce the spray drift fraction within a wide range between 18 and 93 µm. Other authors increase the limit of spray drift hazard up to 150 µm (Bache and Johnstone, 1992). However, the behaviour of a single droplet will be determined both by its size and the relative importance of the turbulence and sedimentation process. Thus, Miller (1993) states that the turbulent sedimentation dominates when the falling velocity of a droplet is higher than 3 times the air friction velocity.

Therefore, the measurement of the airborne spray drift caused by a spray application can be explained, to some extent, as the measurement of the concentration in an air flow of the droplets in the aerosol size range. A summary of the different techniques used to measure the atmospheric spray drift flux in the spray applications can be found in the same work of Miller (1993) –the measurement of the spray drift deposit close to the treatment zone being another possibility. These techniques include the sampling of the airborne spray drift flux using collectors and tracers and remote sensing lidar systems, which depending on their complexity can provide range information and quantitative parameters (such and its reflectivity or mass concentration) on the spray drift cloud. An updated review of the different methods follows.

Collectors for the measurement of airborne spray drift

Airborne spray drift collectors can be classified in volumetric air samplers (isokinetic or not), rotary samplers and passive collectors.

The isokinetic collectors are devices designed so that the air velocity inside the collector is the same as the air velocity outside and its axis can be oriented in the wind direction. In some cases they can be designed to classify the droplets according to their size (cascade impactors). The rotary samplers are powered by an engine, so that the rotational speed of the collector board is kept constant during the measurement process. A glass plate coated with magnesium oxide (Cooper *et al.*, 1996) can be used as a collector. One problem of this system is the disturbance of the air flow that is caused by the rotation of the device.

Approximate location of Fig. 1

The sampling techniques more commonly used in the experimental work are those based on passive collectors, even though sometimes their precision can be hindered by the difficulties of knowing their efficiency with accuracy. The current use of plastic lines with a diameter of 2 mm (Fig. 1) is based on the high efficiency that this kind of collectors are said to have.

Spray drift collector efficiency

The efficiency of a collector is defined as the ratio between the number of droplets that deposit on the collector surface and the number of droplets that would deposit provided that the air flow lines did not deviate in the surroundings of the collector (Johnstone *et al*., 1977). The behaviour of a spray droplet when it goes past a collector is determined by the value of the Stokes number, which, according to Crowe *et al*. (1998), is defined as

$$St = \frac{T_V}{T_F}, \qquad [1]$$

where T_V is the response time of the droplet velocity, which is defined as the time that it takes for a droplet, which is released with no velocity in the air flow, to reach 63% of the air flow velocity, and T_F is a temporal characteristic of the flow. In the case of the air flow around the spray collectors T_F is defined as l/u, where l is a dimensional characteristic of the collector, -i.e. in the case of a cylindrical collector the diameter (D) - and u is the air velocity.

When $St << 1$, the response time of the droplet is much lower than the characteristic time of the flow near to the collector. Therefore, droplets will have time enough to adjust to the air velocity changes and it is not likely that they can impact on the collector. On the other hand, if $St >> 1$, it is the opposite situation and the probability of impact is much higher, increasing the collector efficiency

May and Clifford (1966) determined in an experimental way the efficiency of passive collectors with defined geometrical shapes –cylinders, spheres, discs, ... – and they related empirically the efficiency of a given collector with the expression for the Stokes number, which, from Eq. [1], can be shown that takes the form

$$St = \frac{ud^2\rho_g}{18\eta D}, \qquad [2]$$

where d is the droplet diameter, ρ_g is the droplet density and η is the dynamic viscosity of the air. This relationship is fulfilled for laminar flow conditions, when the Reynolds number of the droplet ($\mathrm{Re}_g = ud\rho_c/\eta$, ρ_c being the air density) is lower than 0.5. For higher values, corrections based on the stopping distance of the droplet have to be made. This is the distance that a droplet will travel when released in still air with an initial velocity u. When the flow complies with the Stokes law, in other words, for low Reynolds numbers, it can be shown that this distance is

$$l = \frac{ud^2 \rho_g}{18\eta} \quad [3]$$

The relationship between the Eq. [2] and the efficiency is different for each kind of collector and the characteristics of the air flow (laminar or turbulent) but, in general, the higher the value of St, the higher the collector efficiency. Therefore, the smallest droplets, which are carried by a lower air flow velocity are the ones that will have more difficulty in depositing on the collector. On the other hand, the collector efficiency increases as the collector diameter decreases.

The efficiency of the spray drift collectors based on Eq. [2] has been used in different studies. Specifically, Johnstone *et al*. (1977) measured the spray drift with different kinds of collectors in an ultralow volume spray application, making corrections in the amount of spray deposit accoding to the above-mentioned relationship. It has also been used to model the aerial transport of spores of fungi, as in the work of Legg and Powell (1979), followed and extended by Aylor (1982), in order to forecast its deposition on plant surfaces.

In the domain of the modelisation of the spraying process, the work of Walklate (1992) was based on the same expression in order to determine the probably of the spray droplet deposition on the collectors in a spray drift simulation for a spray application with an air-assisted fruit crop sprayer. In this case the following expression for the Stokes number was used:

$$St = \frac{2W_f u}{gD} \quad [4]$$

where W_f is the terminal falling velocity of a droplet ($W_f = gT_V / f$), g is the gravitational acceleration and f is the resistance coefficient that depends on the Reynolds' number.

The Eq. [4] is similar to the relationship proposed by Ankilov *et al*. (1981) for the determination of the collection efficiency by the vegetation of aerosols particles with a diameter d, with an air velocity u inside the same vegetation.

$$E = k\left(W_f u\right)^{0.65} \quad [5]$$

where k is a coefficient that depends on the vegetation density.

The measurement of the efficiency of different collectors is usually a preliminary task of the experimental work on spray drift measurement, although one can find some publications focussed only on this subject, e.g., Miller *et al*. (1989) who conclude that collector efficiency in field conditions will be 50% or less and that passive drift collectors should not be used in local wind speeds of less than 2 m/s. Herbst (1994) shows that the more useful collectors for airborne spray drift measurements are the cylindrical collectors of a diameter of 2 mm. Walklate (1994) carried out a comparison of the efficiency of cylindrical collectors for drift measurement in a wind tunnel and concluded that the plastic lines of a diameter of 2 mm are more efficient only up to wind velocities lower than 10 m/s, as long as the spray saturation flow for this kind of collectors (2 µl/mm^2) is not surpassed.

Among other works carried out in wind tunnels, Parkin and Young (2000) showed that the deposition of droplets in the size range of aerosols on cylindrical collectors of diameters between 1 and 10 mm did not follow the May and Clifford's model. The authors say that the reason for this result was the surface properties of the collector plastic material and the chemical composition of the aerosol. Fox *et al.* (2004) measured the efficiency of a nylon fiber mesh and presented some possible reasons to obtain higher efficiency values than those expected according to the above-mentioned model. Finally, Gil *et al*. (2005) showed that the efficiency of 2-mm PVC plastic lines was higher than 77% with wind velocities lower than 3.5 m/s. In this case, the different droplet sizes that were tested (VMD from 146 to 255) did not cause significant differences in the collector efficiency.

Tracers

The measurement of the spray distribution in a spray application was firstly carried out with the use of the same plant protection products used against the pests and diseases of the crops. Later on, different chemical compounds were used as substitutes of the plant protection products. They were selected so that, without their disadvantages –i.e., the toxicity or the complexity of the analytical techniques involved-, they could provide accurate information on the spray liquid distribution. It has to be stated, however, that most of these products are not registered for agricultural use. This has to be taken into account, if necessary, at the moment of harvesting.

Cooke and Hislop (1993) carried out an assessment of the different kinds of chemical compounds used as tracers for spray application measurements. According to this review, the most commonly used products are visible and fluorescent dyes and metals and their salts, even though some experimental works have made use of radioactive isotopes and immuno-assay techniques.

The mostly used visible dyes are those authorised as food dyes. Among those that are more often found in the literature, the following ones can be mentioned: tartrazine, brilliant black, green S, and amarant. Bor (1991b) makes an assessment of the ability of some of them to be used as tracers. The analytical determination is made by means of spectrometric techniques, working at a wavelength corresponding to the maximum absorption of the dye. In general, they are not very sensitive to light degradation in field conditions, although in some conditions they can be taken up by the crop leaves. This makes them not very suitable for use when a long time period between application and sampling is expected (Cross *et al.*, 1997). Some of these dyes and others like nigrosine make also possible to carry out a visual assessment or an image analysis of the spray deposit on the application target.

The fluorescent dyes are a group of chemical compounds that when they are excited with light of a given wavelength, they emit light of a higher wavelength. Some examples of the use of these products as tracers are already found in Sharp (1955) and Yates and Akesson (1963). In this way, Yates and Akesson (1963) list as advantages for the use of these products, among others: high sensitivity and the possibility of measuring concentrations down to 10 µg/l, simplicity of analysis, solubility, few incompatibilities with the different collectors and low toxicity.

Different groups of products can be found among the fluorescent dyes. There is the group of those that are water soluble like, for instance, fluorescein, brilliant sulphoflavine, rodamine or Tinopal. Another group is made up by the ones that are only soluble in organic solvents, like Helios (Uvitex) and finally the pigments, like Saturn Yellow, where the dye is found on a base of ground resin, which makes it more stable.

Bor (1991a) also makes a comprehensive review of the chemical properties of the different fluorescent dyes that can be used as tracers. One important characteristic of some of these products is the ability to show fluorescence once the solvent has evaporated. This makes possible the direct observation of the spray deposit on the leaves after the spray applications, as it is the case of Tinopal CBS-X, used by Holownicki *et al.* (2005).

Among the products that have been often used in previous works, two can be highlighted, fluorescein and brilliant sulphoflavine (BSF). The most important problem of the use of fluorecein is the quick degradation in sunlight. On the other hand, BSF shows a better stability and a good recovery in comparison with plan protection products, when they both were applied at the same time (Smelt *et al.*, 1993), but it losses most of the fluorescence when it has dried up (Byass, 1969). It has been successfully used in many experimental works to measure the spray distribution both on the crop and on artificial collectors. Among them Ganzelmeier *et al*. (1995), Solanelles *et al*. (1996, 1997, 2001) and Planas *et al*. (1998) can be referenced as examples.

It is likely that the use of metals as tracers began with the use of plant protection products based on Cu (Large, 1940). The colour of the deposits on the crop made a visual assessment possible. Cu by-products were also used for a quantitative determination of the spray distribution (Planas and Fillat, 1988; Fillat *et al.*, 1993; Gil, 2001). The use of these products and other metallic compounds has come possible thanks to the availability of quick an accurate analysis techniques based on atomic absorption spectroscopy.

A very interesting technique is the one that uses two or more metal chelates in consecutive application on the same crop zone or the same collectors (Fig. 2). If a given metal is related to a spray application of the same trial, important time savings can be achieved.

Approximate location of Fig. 2

This strategy has also been used with other kind of tracers. Johnstone (1977) used two water-insoluble, visible dyes, whereas Hayden *et al*. (1990) two water-soluble dyes and Goering and Butler (1974) two fluorescent dyes. A problem that usually arises with this kind of tracers is the absorption of the other dye at the working wavelength of the dye to be measured. On these grounds, the use of this methodology is not advised when the concentration rate of the two dyes in the sample solution is lower than 10 to 1. This is often the case in the spray distribution tests (Cross *et al*., 1997). In relation to the metals, the independent measurement of different elements in the same sample is easily achieved without interferences, as it was shown by Travis *et al*. (1987a, 1987b) in field tests in an apple orchard. Later on, Murray *et al*. (2000) made a thorough assessment of the methodology showing which are the most suitable metals and the advisable procedure for a right use. This methodology has also been used to test different application conditions in fruit orchards, like the effects of spray liquid flow rate (Cross *et al*., 2001a), the spray quality (Cross *et al*., 2001b) or the air flow rate (Cross *et al*., 2003). It has also been used to assess the performance of sprayer prototypes with variable application systems, based either on ultrasonic sensors (Solanelles *et al.*, 2006; Gil *et al*., 2007) or on lidar (Escolà *et al*., 2007). A setback in relation to the fluorescent dyes is that the detection limit is higher and, therefore, the measurement of small amounts of spray deposit may be hindered.

Lidar sensing of airborne spray drift

Fundamentals of lidar technology for airborne spray drift monitoring

Collector-based spray drift assessment techniques have significant limitations, among which the following ones can be pointed out:

- 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.
- Their efficiency is 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 remote sensing LIDAR (LIght Detection And Ranging) techniques to airborne spray drift monitoring can overcome these limitations. The lidar technique, which is also known as laser radar, is commonly used in atmospheric studies and benefits from the relatively strong interaction between the electromagnetic radiation at optical wavelengths and the aerosol/molecular atmospheric constituents (Measures, 1992).

Approximate location of Fig. 3

The elastic backscatter lidar technique (Fig. 3) is the most commonly used. Its principle of operation is usually based on the emission of an extremely short laser pulse (e.g., in the nano-second range) and the detection of the backscattered radiation at the same wavelength (elastic interaction). The delay between the emitted pulse and the plume-backscattered received signal (time-of-flight delay) enables to compute the distance to the scattering particles (e.g. aerosols/droplets in the application under study) (Collis and Russell, 1976) as

$$R = \frac{ct}{2}, \quad [6]$$

where R is the distance along the line of sight from which the returns are received, c is the velocity of light and t is the time-of-flight delay. The factor 2 arises because the total distance traveled by the laser pulse takes into account the round-trip travel to the scatterers in suspension.

Pulsed elastic lidars provide an "optical echo" or received signal consisting on a range-resolved intensity profile as a result of the interaction between the emitted laser pulse and the propagation medium under study (the atmosphere in this case). Under the hypothesis of simple scattering, this intensity profile follows the lidar equation, which expresses the received power as (Collis and Russell, 1976),

$$P(\lambda, R) = P_0\left(\frac{c\tau_l}{2}\right)\beta(\lambda, R)\frac{A_r}{R^2}\exp\left[-2\int_0^R \alpha(\lambda, r)dr\right]\xi(\lambda)\xi(R), \quad [7]$$

where $P(\lambda,R)$ is the received power, R is the distance, λ is the wavelength, P_0 is the transmitted peak power, c is the velocity of light, τ_l is the duration of the laser pulse in transmission, $\beta(\lambda,R)$ is the volumetric backscattering coefficient (equivalently, the backscattering cross section per volume and solid angle unit) at the wavelength λ, A_r is the effective area of the telescope (i.e., the "optical antenna") in reception, $\alpha(\lambda,R)$ is the volume extinction coefficient (equivalently, atmospheric attenuation), $\xi(\lambda)$ is the spectral transmissivity factor of emission-reception optical system and $\xi(R)$ is the overlap factor between the transmitted laser beam and the field of view in reception (the overlap factor models the fraction of illuminated cross section in the medium that is "viewed" by the receiving telescope (Measures, 1992)).

In reception, a spectrally selective optical element (in the simplest case, an optical interference filter) selects the optical wavelength of interest from the backscattered radiation (which includes a background component, e.g. solar) and an optoelectronic receiver transduces the received optical power (Eq. [7]) into a voltage. After that, a signal acquisition system (either analog or photon-counting based), acquires and digitizes the return signal for disk storage and subsequent processing.

As in Eq. [6], for a lidar system that, in emission, uses laser pulses of duration τ_l and, in reception, a temporal detection window τ_d, the spatial resolution of the system is given by (Measures, 1992)

$$\Delta R = \frac{c(\tau_l + \tau_d)}{2} \approx \frac{c\tau_s}{2}, \qquad \tau_l << \tau_s . \qquad [8]$$

In the case of analog signal acquisition by using an acquisition card sampling at a frequency f_s, $\tau_d = 1/f_s$ in Eq. [7], while in the case of photon counting acquisition, τ_d is directly the bin time. Obviously, when the duration of the laser pulses in emission is comparatively much lower than the detection window, $\tau_l << \tau_d$, and Eq. [7] reduces to $\Delta R \approx c\tau_d / 2$.

Excellent reviews of the different lidar techniques and their operating principles can be found in several monographs (Measures, 1992; Kovalev and Eichinger, 2004; Weitkamp, 2005).

Review of lidar systems applied on spray drift studies

The first works on the use of lidar technology for pesticide spray drift monitoring were conducted during the summers of 1966 and 1967 by the Stanford Research Institute in collaboration with the U.S. Forest Service (Collis, 1968). In these studies two pulsed elastic backscatter lidars were used (Mark I and Mark V) for monitoring the insecticide clouds generated in aerial treatments over several forests. Although these lidars had a very low pulse repetition frequency limited to a few pulses per minute (Table 1), first images of the vertical cross section of the insecticide clouds were obtained from the backscattered lidar intensity.

Another outstanding study was carried out by Zalay *et al.* (1980), which assessed the feasibility of using a mobile atmospheric laser Doppler velocimeter (LDV) for monitoring the spray plume generated in aerial applications. The relative intensities measured by the LDV agreed with the concentration obtained by terrestrial collectors and Kromekote cards. Note that unlike the elastic lidars, the LDV allows to determine the velocity of the droplets from the Doppler frequency of the backscattered radiation, being this last system much more complex.

Despite these previous works, it was not until the late 80s, with the development the ARAL lidar system (Table 1) by the Atmospheric Environment Service (AES) of Canada, when it began more frequent elastic-backscatter lidar measurements of spray drifts. The

ARAL system (Hoff *et al*., 1989) is an elastic-backscatter lidar that allows for rapid scans of the cross section of the pesticide plume, obtaining near real-time maps of relative intensities in correspondence with airborne droplet concentration. This instrument was used in several works (Mickle, 1994; Mickle, 1996) for studying the dynamics of the aerial emitted pesticides and specially, the influence over them of the aircraft wing-tip vortices. Range-resolved lidar data showed the evolution of these vortices, demonstrating that under crosswind conditions, the upwind vortex rapidly reaches the surface while the downwind vortex remains suspended in the air generating spray drift until large distances (Mickle, 1996).

Approximate location of Table 1

The high temporal and spatial resolution of lidar systems (Table 1) makes them an ideal tool to validate theoretical spray-transport models. By this way, researchers from the University of Connecticut (Stoughton *et al*., 1997) used an elastic backscatter lidar system (Table 1) to scan vertical and horizontal planes of pesticide plumes generated in aerial applications over a forest. The comparison of these results with those obtained from theoretical models showed that the lidar is capable of detecting airborne spray drift until distances of several kilometers. Mickle (1999) reports another comparison between lidar measurements and spray-transport models in an insecticide efficacy study conducted in Florida.

Lidar systems have also been used to assess the influence of atmospheric stability over the spray drift movement and dispersion. Miller and Stoughton (2000) made several horizontal and vertical scans of an aerially applied pesticide plume, observing that under stable conditions, the cloud spreads more slowly than under unstable conditions. This information is very useful to timely schedule the spray operations.

Remote quantification of the spray drift plume concentration by means of lidar has been carried out by Hiscox *et al*. (2006) in field trials under stable atmospheric conditions. The authors proposed a new methodology to obtain the absolute concentration of the pesticide cloud from the backscattered lidar signal. Thus, given the application rate of the nozzles and the initial drop size distribution, evaporation and deposition theoretical models were applied to simulate the temporal evolution of the quantity of product suspended in the atmosphere. Both the lidar-measured backscatter signal and the model-derived product quantity were divided by the volume of the pesticide plume, which in turn was estimated from the lidar images. Good correlation in the concentrations estimated from these two independent methods was observed, which yield the calibration factor between the lidar measurements and the sought-after product concentration.

Most of the lidar systems used in previous works are not eye-safe and have opto-mechanical configurations inherited from atmospheric applications (i.e., best adapted for remote sensing in the far field), which has hampered their application in terrestrial spray drift studies. In spite of this fact, some works with lidars have been carried out in fruit orchards (Huddleston *et al*., 1996). In another study (Miller *et al*., 2003), the lidar measurements allowed the generation of tri-dimensional images of the spray drift plume over an orange orchard, detecting the cloud until heights of 18 meters above the canopy. It was also possible to visualize the alignment between the plume and the wind direction above the canopy and between the plume and the rows below the canopy top. Moreover, it was shown how in unstable atmospheric conditions a higher fraction of pesticide drifts above the vegetation. In the same line, researchers from the University of Washington in Seattle (Tsai, 2007), have used an ultraviolet lidar (Table 1) for monitoring the pesticide plume over an apple orchard. The lidar measurements were compared with those obtained with a spray simulation model (OSDM: Orchard Spray Drift Model) showing significant discrepancies between both results. This fact highlights the potential of lidar instruments to contribute to the improvement of these transport models.

Future Trends

Most of the airborne spray drift measurements carried out today are still made using collectors and tracers. The use of this methodology is costly and time-consuming. Besides, because the great variety of crop and meteorological conditions it is difficult to make an accurate assessment of the real spray drift hazard related with each application technique. This fact has increased the interest for alternative methodologies, which can be carried out either in the laboratory, using wind tunnels, or in the field. In this case, the use of optical systems like the lidar is the most feasible option nowadays.

This review shows that lidar systems allow real-time monitoring of airborne spray drift obtaining range-resolved images of the spray plume with a more reduced personnel and time consumption. Considering these obvious advantages, the use of lidar systems in future airborne spray drift studies should be promoted and correlation relationships between results from conventional sampling techniques and spray transport models should be investigated.

However, despite the advantages of lidar systems for airborne spray drift monitoring, they have been used on a limited way. This is because currently available lidar systems inherit their architecture design from atmospheric monitoring applications (high energy, low pulse-repetition-frequency systems), which make them expensive and requiring trained personnel for their operation. In addition, many of these instruments are not eye-safe, which hinders their practical application particularly in terrestrial spray drift studies (quasi-horizontal sounding). Recent developments in the last years on efficient low-energy high-PRF lasers (typically 1-100 μJ and 1-10 kHz repetition rates) and photodetectors with reasonable costs in the eye-safe bands (1.5 and 2.1 μm) will allow the development of affordable lidars better adapted to airborne spray drift monitoring with a high spatial and temporal resolutions.

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Figure 1. (left) Position of the masts to measure the airborne spray drift. (right) Detail of the plastic vertical lines used as collectors.

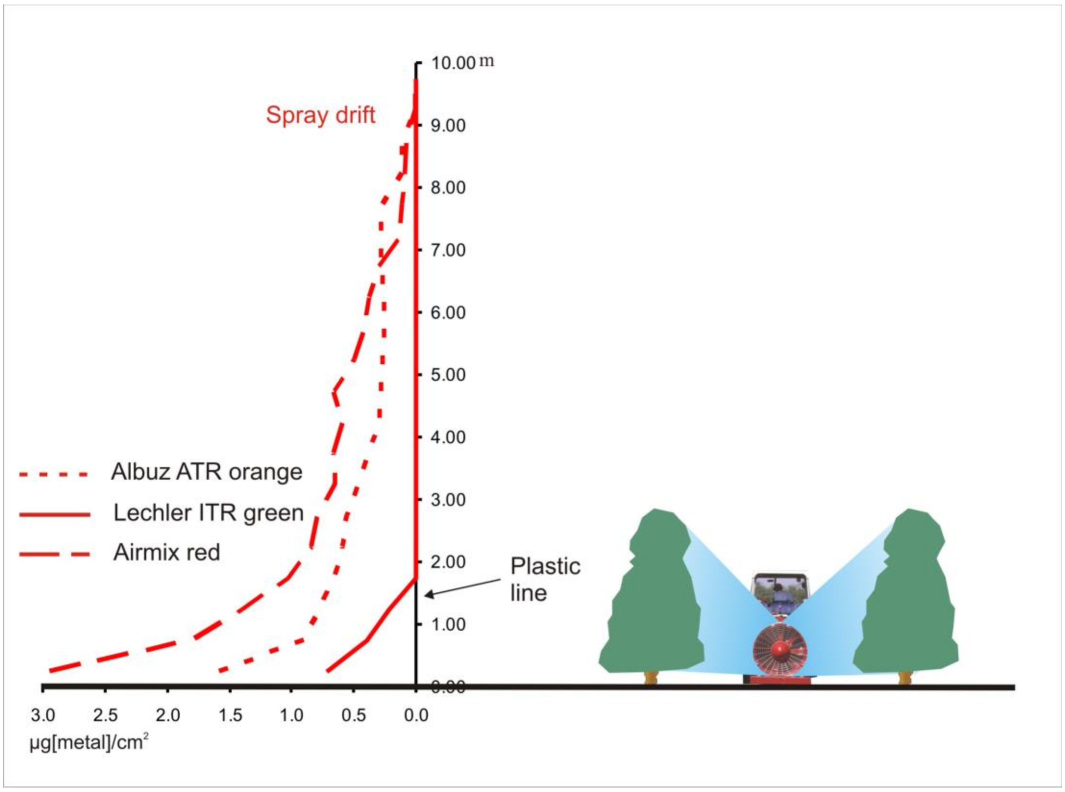

Figure 2. Airborne spray drift measured on the same collectors using a different metal chelate for each spray nozzle.

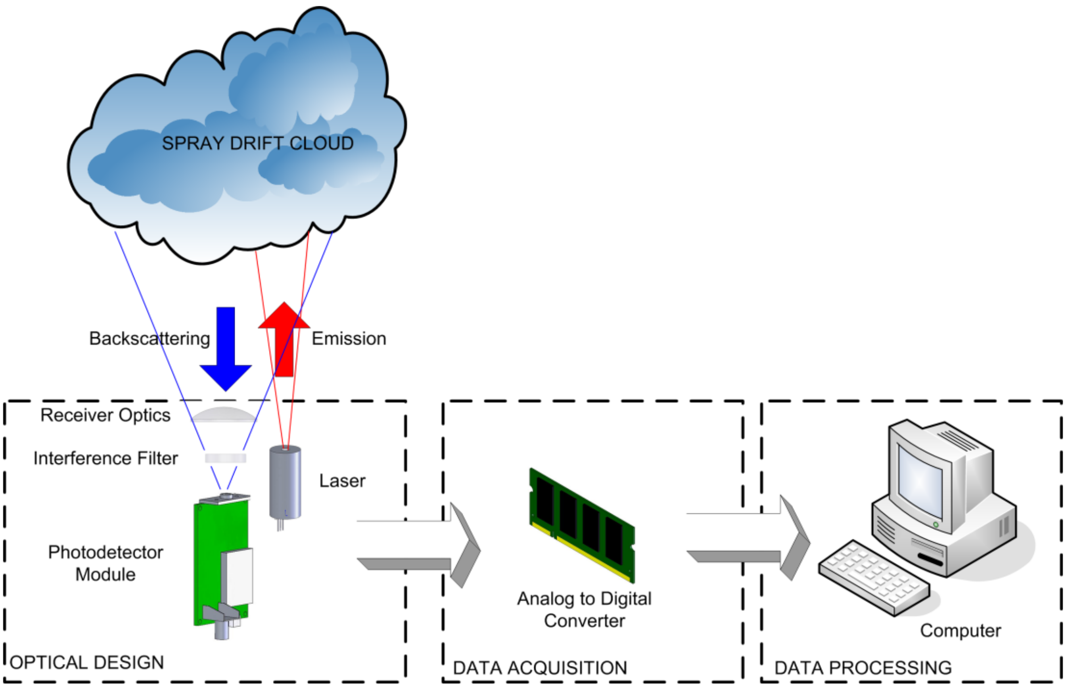

Figure 3. Set-up of a typical lidar system.

Table 1. Specifications of pulsed elastic backscatter lidar systems used for spray drift monitoring.

Lidar System	Wavelength	Output Energy[1] (Peak power)	Pulse Length	Pulse Repetition Frequency	Receiving Diameter	Range Resolution
Mark I (Collis, 1968)	694.3 nm	≈240 mJ (10 MW)	24 ns	1-2 pulses per minute	101.6 mm	N/A[2]
Mark V (Collis, 1968)	1060 nm	≈600 mJ (50 MW)	12 ns	1-2 pulses per minute (1966) 12 pulses per minute (1967)	152.6 mm	N/A
ARAL (Hoff *et al*., 1989)	1064 nm	50 mJ (≈5.6 MW)	9 ns	10 Hz	355.4 mm	N/A
UConn lidar (Stoughton *et al*., 1997)	1064 nm	125 mJ (≈8.3 MW)	<15 ns	50 Hz	254 mm	2.55 m
UW lidar (Tsai, 2007)	355 nm	8 mJ (≈2 MW)	3-5 ns	10 Hz	N/A	0.6 m

[1]Output energy (per pulse). [2]N/A: Not Available.