AN APPLICATION OF BACKSCATTER LIDAR TO MODEL THE ODOUR NUISANCE ARISING FROM AIRCRAFT TYRE SMOKE

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ABSTRACT
A Rapid-Scanning Lidar system (RASCAL) has been deployed for field trials at Heathrow and Manchester Airports to collect backscatter data from aerosols and particulates in the wakes of several hundred flights. The principal aim of these measurements was to characterize the dispersion of the engine exhausts, but it was found that tyre smoke was also visible, giving a signal an order of magnitude greater than that from the engines. Although Lidar measures the backscatter from airborne particulate, the dispersion of pollutant gases can also be inferred. We discuss here how an odour perception model may be applied to the time series of Lidar cross-sections to estimate the nuisance arising from the tyre smoke.

INTRODUCTION AND CONTEXT
Aviation has become an integral part of the social and global economy, and the expansion of the air transport industry is expected to continue. This growth, coupled with the ever increasing urbanization around airports, has resulted in increasing concerns regarding airport air quality.

Odour nuisance is a subjective problem that rarely receives attention as an airport air quality issue. Nevertheless, odours often represent a significant source of anxiety and concern to local residents. Noxious odours from kerosene and from burning tyres, arising from the aircraft landing and take-off cycle, can appreciably reduce the quality of life of the local population.

While no direct measurements of the composition of tyre smoke from landing aircraft have been reported, it is known that when tyres are burnt a wide variety of decomposition products is generated. Many of these decomposition products have been characterized in test burns and include: sulphur compounds (CS_2, SO_2, H_2S, thiols etc.), polycyclic aromatic hydrocarbons, aromatic, naphthenic and paraffinic oils, oxides of carbon and nitrogen, various light-end aromatic hydrocarbons (toluene, xylene, benzene etc), and a large number of particulates. These decomposition products are extensive and varied depending on a variety of factors including tyre type, burn rate, ambient temperature, and humidity (*New Zealand Ministry for the Environment, 2004*). Consequently in the assessment of air quality in the vicinity of airports, the measurement of decomposition products and odour nuisance from burning aircraft tyres is an air quality issue that perhaps should be afforded greater attention than it has so far received.

Within the aviation industry, Lidar has previously been used in many applications including: studies of wing tip vortices (*Holzäpfel, F, et al., 2003*), contrail formation and dispersion (*Sussmann, R, and K. Gierens, 2001*), and particulate emissions and dispersion (*DeCoursey, R, et al., 1997*). Lidar has also been used for the study of exhaust dispersion from rocket engines (*Dao, D and A.Dentamaro, 1999*). Very little has been reported on the use of Lidar for determining aircraft exhaust plume dynamics (*Wayson, R, et al., 2004*).

To the authors' knowledge there are no reports of the use of Lidar to investigate the dispersion of aircraft tyre smoke in the literature, though the importance of such emissions for air quality in the vicinity of airports has been clearly identified (*Curran, R, 2005, Morris, K, 2007, UK Department for Transport*, 2006). For a given plume the intensity of the backscattered Lidar signal is (to a first approximation) directly proportional to the concentration of scatterers in the plume. The concentration of other volatiles and gaseous components in the plume can thus be inferred, where the emittents are uniformly mixed. Hence Lidar may be used as a tool to map out indirectly the spatial and temporal distribution of the tyre smoke odorants. It is a particularly useful means to visualize concentration fluctuations within the plume. Such fluctuations re-awaken the nose and brain to the presence of odour. Accordingly, given a mathematical model of odour perception, we can use the concentration time series derived from our Lidar measurements to model the perceived nuisance of an emission over the whole of the scanned coss-section.

EXPERIMENT

The RASCAL system is mounted on a commercial vehicle with onboard power generation and is thus fully autonomous and mobile. The system was originally developed by the Central Electricity Generating Board for studies of dispersion from power stations (*Bennett, M, et al., 1992*), but is now resident at MMU's Centre for Air Transport and the Environment. Details of the optics, control and data acquisition systems can be found elsewhere (*Christie, S, et al., 2006*).

RASCAL was deployed at Heathrow and Manchester airports for 6 weeks during 2005-06 to map the dispersion of aerosols and particulates from aircraft in the wakes of several hundred flights. Most of the measurements were directed at engine emissions, but a subset of scans was directed at the tyre smoke emissions on landing: most landing aircraft (particularly the larger ones) provided a measurable signal (Figure 1). This sequence shows the dispersion of the aircraft tyre smoke, with a time resolution between scans of 4 s. The maximum backscatter shown is more than 3 times the backscatter from the clear air: this was easily visible to the naked eye.

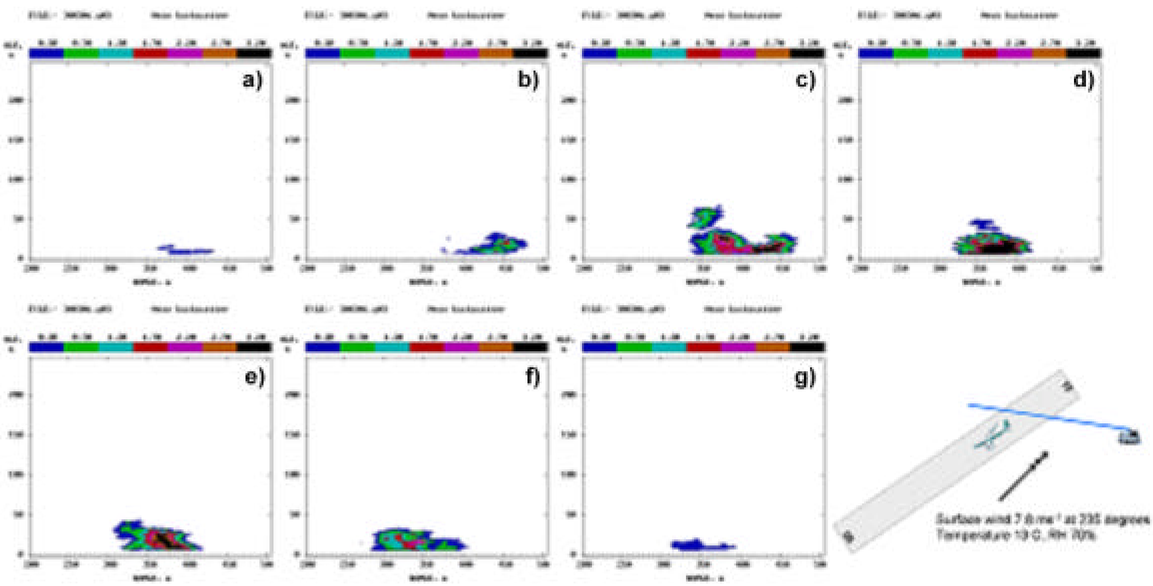

Fig. 1; A series of vertical Lidar scans through a tyre smoke plume for a landing Boeing 777 aircraft (azimuth 277.4^o). Time increases by 4 s between successive scans. The Lidar beam intersects the runway (24) at an angle of 37^o. Surface wind 7.8 m s^{-1} at 235^o, temperature 13^{o}C, relative humidity 70%.

The dataset covers a variety of aircraft types and classes. Most observations were made with the beam swept in the vertical and oriented at several different azimuths to the runway. A limited number of observations with the beam being swept in azimuth at a low angle of elevation were also made. There is data coverage in conditions ranging from near calm to 10 m s^{-1} wind speed; neutral to moderately unstable; relative humidity from 40 – 100%; and air temperatures of 4° - 19° C. An onboard meteorological station with an extendable mast mounted on the RASCAL vehicle logs wind speed, wind direction, temperature, humidity, and shortwave insolation at 10 s intervals. These measurements are used as an aid in the interpretation of the dispersion data.

MODEL OF ODOUR

The highly non-linear sensitivity of the human noise allows the detection of even small concentrations of an unfamiliar odour. The nose and brain perceive the initial arrival of a puff of pollutant but habituate to it physiologically and cognitively over a period of a few seconds, unless their sensitivity is cleared by a period of clean air.

To a first approximation, tyre smoke produced by an aircraft's landing gear may be considered as an instantaneous point source of odour. As the smoke is advected by the wind to a recipient, fluctuations in odour concentrations and intermittency inevitably occur. These intermittencies re-awaken nose and brain to the presence of the odour. *Kishiuchi, K and D.J. Wilson* (2005) have constructed a model, which interprets such fluctuations in terms of a perceived odour nuisance. We may follow a similar approach in interpreting our Lidar measurements.

Firstly, we rescale the physically measured concentration, C (for which the measured backscatter is a surrogate) in terms of perceived odour intensity, I. This is conventionally done using Steven's power-law model, $I = kC^n$. Values of k and n have been tabulated for many odorants, though not for 'tyre smoke' *per se*. We note however, that burning rubber can be confused with skunk odour, whose principal component is 2-butene-1-thiol, for which n = 0.26 (*Patte, F et al., 1975*). Clearly, it is advantageous to the skunk to have a stench whose offensiveness varies only weakly with concentration: for H_2S the slope is steeper, n = 0.51. While k is also known for these substances, it is not useful in this case since the Lidar does not provide us with an absolute value of C. Instead we may note that when the tyre smoke advects directly towards the Lidar, a strong smell is perceived when it arrives: this provides a semi-quantitative value of k relevant to this experimental arrangement.

Secondly, we note that the nose tires when subjected to a continuous odour but is refreshed by clean air. We may interpret this in terms of a simple adsorption model, where we introduce an olfactory sensitivity, S, being the proportion of receptors not blocked by a given odour at a given moment. Thus the perceivable odour is given by $I' = S.I$ with $0 = S = 1$. The rate at which receptors are lost through blocking is $-S\,C / (C_0\, t_b)$ and the rate at which they then clear is given by $(1-S) / t_c$. It appears that the timescale for clearing, t_c is about 5 s, (*Wang, L et al., 2002*) and that S does indeed rise more quickly from a lower base.

In steady state, we then have $S = (1 + C\, t_c / (C_0\, t_b))^{-1}$. 'Perceivable', of course, is not the same as 'perceived'. Although the nose may still be physiologically capable of reporting a steady concentration, the brain rapidly becomes bored: in general only rapid increases in I' are perceived. Crudely, we could model this by saying that perception is proportional to $t_p\, d(I')/dt$. At high odorant concentrations it is the ratio of this rate of change to I' which is perceived; at low concentrations, it is the ratio to some background level I_o'. *Wang, L et al.* (2002) estimated a psychometric response time t_p of order 2.5 s.

Finally, *Kishiuchi, K and D.J. Wilson* (2005) suggest applying a running mean over (say) 30 min to the psychometric response so as to estimate the annoyance caused.

We have programmed such a mathematical model into our Lidar analysis software so as to generate maps which might give some qualitative indication of the nuisance arising from tyre smoke.

RESULTS AND DISCUSSION

As discussed, Figure 1 shows a typical time sequence of Lidar scans following the dispersion of a tyre smoke event. The aircraft touched down on the runway centre line approximately 450 m from the Lidar. The observed plume is entirely due to tyre smoke: brakes are not usually applied until after the aircraft landing sequence has been brought under control. The aerosol in this young plume is relatively concentrated, being well above ambient levels. The Lidar scanning direction was maintained throughout the image sequence, so that the series illustrates typical behaviour of the tyre smoke as it was advected relatively briskly through the scanning plane. Such plumes could be followed downwind with the Lidar for more than 500 m – the odour was also easily perceptible at this distance.

The effect of the dynamic response of the perception system is to flatten the perceived nuisance relative to the mean concentration experienced. On the puff centreline, a large concentration arrives, habituates the perceptual response, and then leaves. Indeed applying our model we found that the ratio of the peak centreline value to the threshold of ambient noise roughly halved as between the mean backscatter over the series in Figure 1 and the inferred odour nuisance.

On the edges of the puff, the situation is more subtle. Wisps of odorant may evoke a multiple responses, but can only do so when they are above the perceptual threshold relative to background odour. Depending upon the parameters chosen, the predicted nuisance may cover an area significantly smaller than that over which the plume has been detected with the Lidar.

CONCLUSIONS

Lidar has long been proven as a fast and efficient remote sensing technique. The size range of the particulates and aerosols emitted in the tyre smoke from the aircraft is well matched to the scattering of UV radiation at 355 nm wavelength. Aerosols and particulates associated with tyre smoke were observed for up to 90 s after emission. In light wind conditions the smell of burning rubber would persist for several minutes.

Although the results from such an analysis of our Lidar measurements can be suggestive, it is clear that the mathematical model we are using relies upon parameters some of which are very poorly characterized. Even if we could identify the essential component of the odour, the Stevens parameters k and n refer only to a particular exposure protocol. In our formulation we additionally need several dynamic response parameters - t_c, $C_0 t_b$ and t_c. We have values for t_c and t_c for isoamyl acetate from *Wang, L et al.* (2002) but nothing for $C_0 t_b$ and certainly nothing for the likely principal odorants in tyre smoke. Many more studies of the dynamic olfactory response to practical odorants are thus urgently required. Note further that in a real situation it is not the value of k measured in an olfactory laboratory that is relevant, but, rather, its ratio to the response to background odours. It would also be helpful to scan the

Lidar rather more rapidly, so as to exceed the probable rate at which the nose initially habituates.

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