Anthropogenic Effects on Observing Conditions at Paranal. I: Aviation

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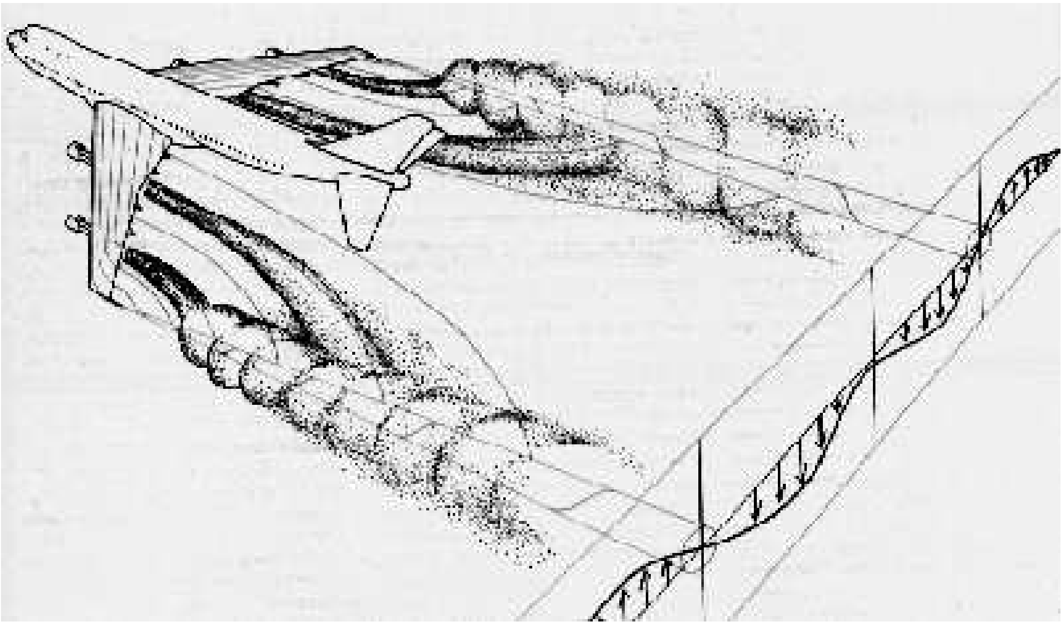
May 7, 1997



From Chigier (1974)

1 Summary

Although Paranal has been selected, among other virtues, for its remoteness from major urban centers, some anthropogenic effects will nevertheless be felt during observations with the VLT. These can be light from local site traffic, scattered light over industrial centers, general aviation, and artificial Earth satellites.

In this report, the effects of aviation will be discussed and ways will be suggested how to further study and possibly eliminate or circumvent the problem. A later report may deal with artificial Earth satellites.

2 Possible Effects of Aviation

The passage of aircraft over an astronomical observatory can influence observing conditions in a number of ways. Visual and infrared photometry, as well as imaging and spectroscopic data can be affected. Some of the effects are small, and will hardly present a problem. In other instances can serious misinterpretation result.

For Paranal, the most obvious effects are caused by condensating jet exhaust plumes (contrails). These may block much of the optical radiation coming from the astronomical source, and will, under moon-lit conditions add background light. Also non-condensed plumes must be detectable to some distance behind the aircraft, due to their elevated temperature, which causes degradation of astronomical 'seeing'. Furthermore, the exhaust contains gases and particles, which in theory may contaminate data.

3 Aviation near Paranal

Several air-ways pass is the vicinity of Paranal, carrying domestic, as well as international traffic. This is described in a report by de Castro (1997), from which we quote:

- International flights on the route Santiago-Lima-Santiago use the Upper Air Corridor within lines UL 302 and UL 312. This corridor passes over the Pacific, some 250 kilometers West of Paranal.

- Flights on the route Santiago-La Paz-Santiago use the UL 309 or the UG 425 Upper Air Corridors. At the moment this route is served by 6 daily flights, 3 going and 3 coming. According to present flight schedules these are all day flights.

- The Upper Air Corridors UL 300 and UW 200 (30 miles wide, 25,000-45,000 feet) pass slightly West of Paranal. They carry mostly day-time traffic between Santiago and Iquique (12 flights daily). Also some occasional other commercial and private planes use these air-ways.

- Other Chilean, domestic traffic use the Lower Air Corridors G-679 and W-200 (14,500-24,500 feet) exclusively during day-time; the frequency is very low.

- A total of 70-80 aircraft arrive daily to Antofagasta from either North or South. This traffic is limited to the time interval 07:00 - 00:30. (The airport is open at night-time to serve small fishing company planes). Some planes use approximation routes from the South and take-off routes to the North, which pass slightly West of Paranal, right over the coast line. One daily flight (round trip) by the planes (from company) ALTA tends to pass towards the East of Paranal.

- When Santiago airports are closed, all flights coming from the North are diverted to Antofagasta.

We remark that recent navigation aids ("Area Navigational System") have removed the need to pass vertically over radio beacons.

3.1 The 1988 observations from La Silla

During the period May 17 - September 26, 1987 all casually observed aircraft were registered (Pedersen, 1988). The records include time, direction, and formation of contrail, and can be summarized in tabular form:

Propulsion	Number	Direction			Contrail		
		N	S	unknown	yes	no	unknown
Jet	48	21	23	3	21	17	10
Propeller	16	7	2	7			
Unknown	1	1					
Total	65						

It appears that contrails were formed in 43 percent of the sightings. An observational bias cannot be excluded.

3.2 Contrail drift

Nearly all traffic near La Silla and Paranal is North-South. Since high altitude winds preferentially blow from West to East, at typical speeds of 20 m s^{-1}, the contrails will move Eastwards at 0.15 $^{o}s^{-1}$ (in zenith). A five-minute old trail, from an aircraft which passed overhead, will have swept 40^{o} eastward. At the same time, the aircraft is already close to the horizon. Accordingly, a very large part of the observable sky can be influenced by a single, young trail.

4 Jet engine exhaust

At a short distance behind two- or four-engine jets, the exhausts merge on the left and right side, to form only one vortex pair, separated by approximately the wing-span. The generation of this vortex pair is directly associated with the aerodynamic process creating the lift of the aircraft.

In the wake of the aircraft, the exhaust sinks; the vertical speed is about 2.4 m s^{-1}, corresponding to the inclination $\sim 1/100$. This has been confirmed up to a distance of 12 km behind a B747-200.

The vortexes are remarkably stable. They are found to be most stable under calm conditions over the ocean, and disintegrate far more rapidly over a mountainous region. Chigier (1974) observed vortexes to persist with little change up to 25 km [15 miles] behind a Boing 747. The diameter of the tightly bound vortex core is roughly 3 percent of the wingspan. This motion, and the enclosed hot air, carries much of the energy resulting from the aircraft propulsion. The center of the vortex moves forward by about one tenth of the aircraft velocity.

Schumann (1994) measured the width of contrails as function of distance behind a B747-200 jet. At the largest distance, 7.2 km, the average diameter of the left and right contrail was 12 meters. This measurement was conducted over Southern Germany.

Eventually the vortexes become unstable. “The dispersion regime begins when the organized motion of the trailing vortex pair breaks up into turbulent motions and ends when this turbulence has decayed. Thereafter a so-called diffusion regime follows in which atmospheric motions control further dispersion. In the dispersion and diffusion regimes at time-scales of minutes to several hours, the resultant plume of exhaust emissions spreads laterally from a few hectometers to a few kilometers mainly by atmospheric turbulence and shear in the ambient air. ... It can take time, of an order of a day, before all the plumes resulting from typical air traffic get homogeneously mixed within the flight corridor” (Schumann et al., 1995).

The energy dissipation along the flight path is highly complex and no satisfactory theory exists, which describes the decrease of temperature and turbulent velocity. From very rough estimates, it appears that stable vortex cores may hold air, which remain several degrees warmer than ambient air, up to 10 - 20 km behind a large aircraft. Even in the more rarified atmosphere of normal flight altitudes, this is sufficient to severely affect ’seeing’ conditions.

5 The Contrail Phenomenon

Due to its possible climatic effects, the physics of aircraft exhaust and contrail formation is a well studied subject dating back to 1919. Quoting literally from Schumann (1996): “The clouds often visible to be formed in the wake of aircraft are called condensation trains [...] or contrails [...]. Contrails form for various reasons but the most important is the emission of water vapour. In order to form contrails, the air must be cold, typically colder than -40^{o}C, but the precise threshold depends pressure, ambient humidity, the amounts of heat and water vapour released by the aircraft, and on the details of the mixing and particle formation processes in the aircraft wake. These details are not yet fully understood.”

The contrails usually form 10 - 30 m behind each engine, i.e. before the exhaust reaches the aircraft tail. At the start of the contrail, its diameter is

3 -4 m. It will often sublimate when mixed to diameters of more than 30 m.

In a study of contrail formation over California Schumann (1966) found that flights above 10.7 km caused contrails in more than 50 % of the cases.

The final diameter of dissipating contrails is the larger the higher the external humidity. "Contrails are short-lived, when getting mixed with sufficiently dry ambient air. Persistent trails, which do not evaporate when mixed with the environment, on the other hand form when the ambient air is supersaturated with respect to ice, i.e. for frost saturation. Such conditions are not uncommon for the upper troposphere. Here, aircraft locally induce ice particles, presumably via the liquid phase, which then form the freezing nuclei necessary to trigger the formation of wide spreading ice cirrus layers often visible ... Such contrails may also develop into long-lasting subvisible cirrus cloud layers." (Schumann, 1966)

6 Aircraft exhaust chemistry

During the operation of a jet engine at cruising altitude, the main process of the combustion is the formation of water and carbon dioxide:

$$C_aH_b + (a+\frac{b}{4})\ O_2 = \frac{b}{2}\ H_2O + a\ CO_2$$

Standard jet fuel consist of 80 % (volume) paraffins, 18 percent aromatics, and 2 % olefins. For paraffins, a=i, b=2i+2 (i = 1,2,3..) and for benzene (an aromatics), a=b. For the present purpose, we can assume b=4a. This implies that 16 g jet fuel combine with 64 g oxygen to form 36 g water vapour and 44 g carbon dioxide.

At cruising speed each engine consumes approximately 12 gram of jet fuel. The resulting deposition of water vapour is 27 g m^{-1}, and that of carbon dioxide 33 g m^{-1}.

Emission of soot and non-consumed fuel was common in earlier engines, but seems now to have been very much reduced. Soot may however play a role as nucleation agent for the contrail formation process.

- Water: The deposition of 36 g of water vapour per meter per jet engine increases the line-of-sight integral of water by an amount, which depends upon to spread of the aircraft exhaust as function of time. At the moment when the exhaust has reached the width of a VLT mirror, 8 meters (1 - 5 km behind the aircraft), the average thickness of the induced precipitable water vapor will be $\sim$0.5 μm. As long as the water remains in the vapor state, this amount is negligible, compared to the best conditions at Paranal, $\sim$1 mm precipitable water.

- Carbon dioxide: If spread uniformly over a width of 8 meters, the exhaust of CO_2 amounts to 0.4 10^{-3} g m^{-2} per engine. This is small compared to the mass of CO_2 above Paranal, $\sim$0.36 g cm^{-2}.

  The CO$-$2 molecule absorbs heavily in the infrared, in particular at the 2.8, 4.3 and 15 μm bands.

- Nitric Oxides: Nitric oxide, NO, and nitrogen dioxide NO_2, is formed in a variable mixing ratio, for which reason the mixture is usually referred to as NO_x. The creation of NO_x increases strongly with engine temperature, implying that modern jet engines produce more than older. For Boeing 747, DC10 and L1011, the output of NO_x at cruising altitude is about 14-16 g per kg of jet fuel, while for Boeing 707 and DC8 the corresponding figure is 6 g (Anonymous 1975, p.71). The NO_x production can thus be estimated at 0.18 g m^{-1} m per jet engine.

- Sulphur dioxide: The degree to which sulphur dioxide is emitted depends directly upon the sulphur content of the jet fuel. Here, sulphur is considered a contaminant, and low-sulphur fuel is nowadays used at most airports. The world average is estimated at 0.05 weight percent (Anonymous, p.265). This means that each engine emits about 6 mg sulphur per flown meter.

7 The Possible Cures

To lessen the influence of aviation on observing conditions at Paranal, several actions can be thought of. An Eastward shift of the most damaging air-corridors is the most obvious solution, and the only one, which is fully adequate to astronomy. However, ways of achieving this is beyond the scope of the present report. An second solution would involve the use of such jet-fuel additives, which are known to leave contrails almost invisible. A third solution would be to 'live' with the problem, avoiding critical observations when aircraft or aircraft exhaust plumes are predicted to pass the field-of-view of a given VLT unit telescope.

7.1 Contrail suppression

Means exist of suppressing the contrail visibility, by the formation of droplets much small than the wavelength of visible light. This can happen "by the injection of clorosulphonic acid, $HClSO_3$, chlo-fluoro-sulphonic acid, or detergents formed from water solutions containing monohydric or polyhydric alcohols, possibly in combination with inorganic nucleating salts such as silver iodide into the hot jet exhaust." (Schumann, 1996). These agents should cause formation of particles less than 0.06 μm, leading to optical thickness below 0.02. The exhaust will then appear a blue haze.

These additives are, as pointed out by Schumann, certainly unsuited for aviation in general.

7.2 Wake Avoidance

Alternatively to contrail suppression, evasive action may be taken when an exhaust plume is about to pass through the FOV of a given telescope. This procedure can be programmed to function autonomously within the telescope scheduling software, provided that basic data are present, such as: aircraft position, velocity vector, and high-altitude wind-pattern. Further meteorological data may serve to predict whether or not a visible contrail is likely to be formed.

8 Conclusion and Proposed Field Tests

It appears that spectroscopic effects from H_2O, CO_2 and other exhaust gases are negligible. The main problems caused by aviation are therefore increased seeing, extinction, and sky background. All these effects are short-lasting, with typical time scale 1 s, and may cause severe problems in particular for time-resolved astronomy.

To assess the predictability of contrail formation over Paranal, including its diurnal and seasonal variability, it is proposed to undertake a field investigation.

For each aircraft, records will be taken of the airplane's minimum angular distance, the formation of contrail, and its development with time. For a set of more well developed contrails, photographic records will be made using a wide-angle camera pointing vertically upwards.

Subsequent analysis will correlate this material with data (to be) supplied by the Chilean civil aviation authority. This should allow identification of most observed aircraft according to type, altitude, and flight corridor.

Contrail drift rates will be deduced from the photographs. These drift rates will be correlated with wind speed data, both actual and forecast.

As to the seasonal variability, it will be fully sufficient to limit the records to one week each month, centered on full Moon. Except for the initial set-up and training, all field measurements can be done by two local assistants, working in shifts.

9 References

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