P13A.4

THE AIR FRANCE 358 INCIDENT OF 2 AUGUST 2005 AT TORONTO INTERNATIONAL AIRPORT

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1. Introduction

On Aug 2, 2005, Air France flight number 358, an Airbus 340, touch downed about halfway down runway 24L at 20:01:55 UTC (4:01:55 pm LT) and slid off the end of the runway into a gully at 20:02:25 UTC. AF358 carried 309 passengers and crew. Severe thunderstorms were in the area for the past four hours and rain was raining heavily on the runway at the time of landing. The plane burst into flames and eventually was completely destroyed. There were no fatalities and only about a dozen injuries.

Of particular concern are:

1. What hazardous features were present in the thunderstorm that might have affected the pilot decision making or aircraft performance?
2. In particular, was there a wind shear situation? What was the nature of the wind shear – microburst, downburst, gust front?
3. What precipitation was the aircraft experiencing on approach?
4. What was the precipitation situation on the runway?

2. Incident Overview

Pearson airport is located about 7 km north of Lake Ontario, northwest of the city of Toronto. The runway used by AF358 was 24L which is the southern-most runway available at Pearson. The runway has a 227^{o} orientation from true north. There are several "weather" surface stations operated by different agencies at the airport. Fig. 1 shows a map of the general layout of the airport.

Figure 1: Image showing the runway orientation of the Lester B. Pearson Airport (YYZ) and the critical times as the plane approached from the upper right of the figure.

2. General Weather Synopsis

The surface weather map shows that there was a high pressure system to the south of Lake Erie, a quasi-stationary front lay well to the northwest. So, Pearson International Airport (YYZ) was in the warm sector of a frontal system. Thunderstorms in the warm sector are initiated by a variety of small scale weather features such as atmospheric convergence lines, thunderstorm outflow boundaries and lake breezes.

The vertical sounding shows that the air mass could support deep convection. The low level air mass was warm and moist and soundings indicated a dry layer aloft which promotes the development intense thunderstorms with strong outflows.

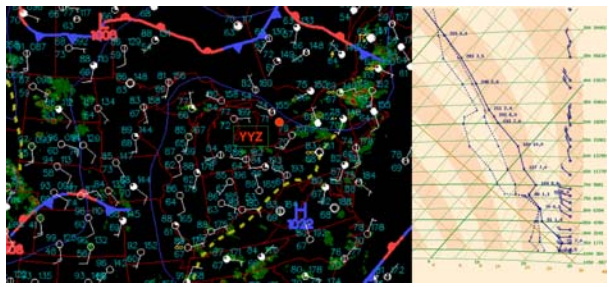

Figure 2: Surface weather map (left) for Aug 3 0Z which shows that Pearson Airport (red dot) lay in a warm air mass. Upper air sounding (right) from Buffalo Aug 2 0Z shows an air mass capable of supporting thunderstorm development with strong outflows.

Aug 2, 2005 was characterized by many small isolated thunderstorms (~5km in diameter) with lightning, forming outflow boundaries that originate from thunderstorm downdrafts. Fig. 3 shows a sequence of radar images illustrating the nature of the thunderstorms in the hour leading up to 2000Z UTC.

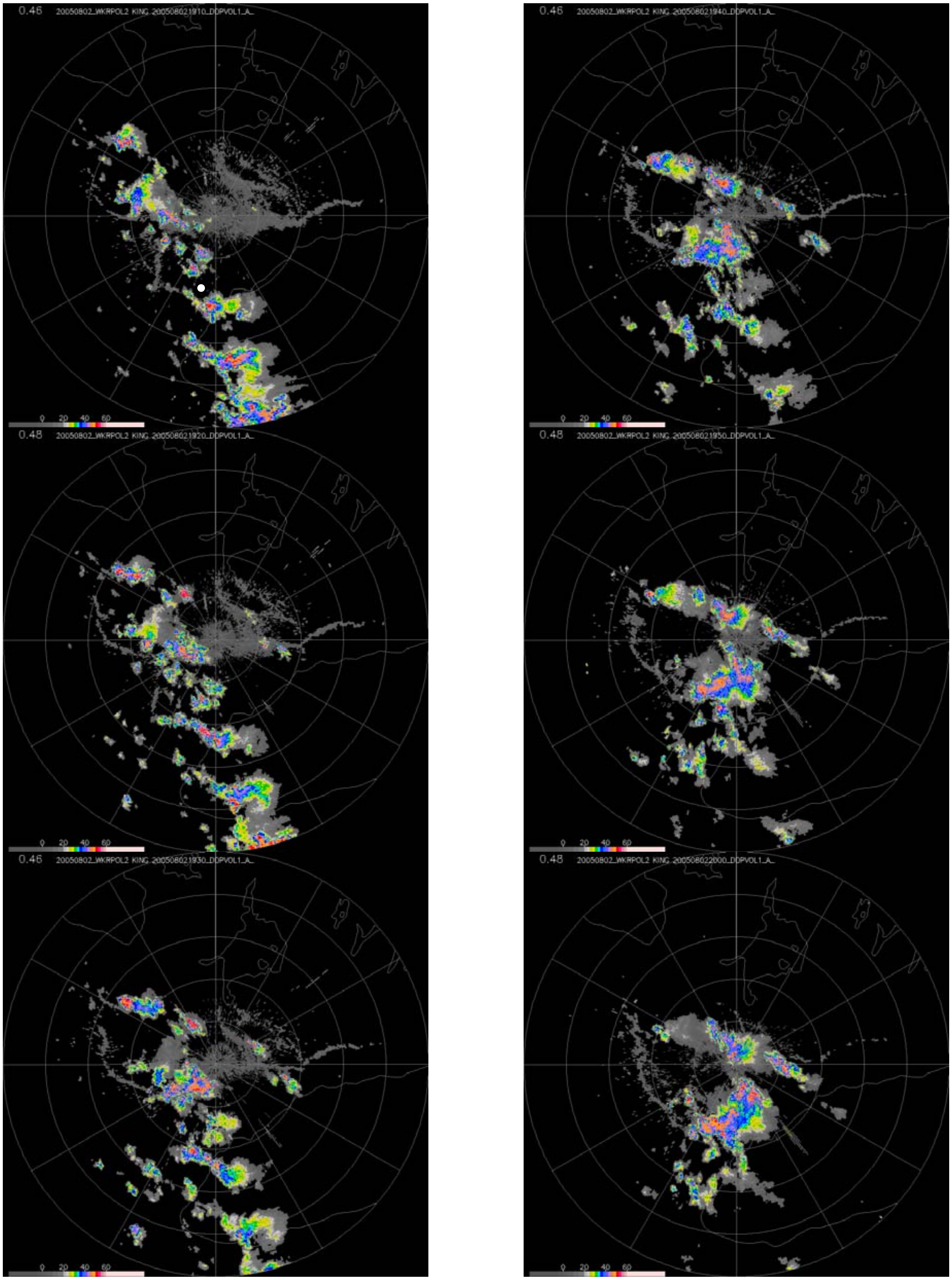

Figure 3: Sequence of 0.5^o reflectivity radar images from King City radar showing the time evolution of thunderstorms in the period 1910-2000UTC, every 10 minutes. The sequence starts in the upper left and goes down the page and then across to the second column. The very large thunderstorm in the last picture forms from the merger of many smaller ones. Lines of low reflectivity echo show location and evolution of thunderstorm outflow boundaries and the lake breeze. White dot in upper left figure is the airport location.

4. Synopsis of the Thunderstorms and Outflows

On this day, the storm cells moved from north to south. Cells are identified on weather radar as contiguous areas of high radar reflectivity. In the early afternoon, the cells were very short lived, forming and dieing in about 20 minutes. New storms were forming on the outflows of earlier cells. Then the individual small cells merged to form a single very large (20-30 km) and longer lived storm complex at the boundary of the Lake Breeze, coinciding with the location of the airport at about 20Z when AF358 was landing.

Small downbursts were observed in many storms through out the day – both before and after the AF358 incident. Between 19 and 20Z, the small outflows merged to form a large outflow boundary or gust front. Also, shortly before 20Z, a very large and long lived downburst developed in conjunction with the merging storms. It started northwest of the airport and it reached its full intensity over the airport, just after the AF358 incident occurred. This leading edge of the downburst also merged with the existing gust front.

The storm, the gust front and the downburst were moving and evolving. The airport and the aircraft would first experience the effect of the gust front, then the downburst which was then followed by intense precipitation.

5. Radar Analysis – Thunderstorm Overview

The following three images (Fig. 4-6) show reflectivity and radial velocity images at three times bracketing the incident to illustrate the evolution of the thunderstorms. These times are chosen because they best illustrate the various wind features identified.

At 1920Z, the storms (left image) are relatively small, somewhat scattered and disorganized. The gust front is first clearly identified in the Doppler data at this time. By 2010Z, these storms grew, decayed and eventually merged into a very large storm over the airport which is marked by a cyan dot at 33 km range and 180^{o} azimuth. A well defined downburst is observed. At 2100Z, the storms continued to persist and continued to show small downburst signatures illustrating the spectrum of wind features on this day.

The images on the right are radial velocity images. At 1920Z, there is a linear feature at about 20 km range southwest of the radar indicative of the divergent winds of a gust fronts. Other gust fronts are observed as linear low reflectivity features. These wind features emanate from individual small storms. They combine into a large single gust front associated with the large storm at 2010Z. At this latter time, a large downburst signature can also be observed.

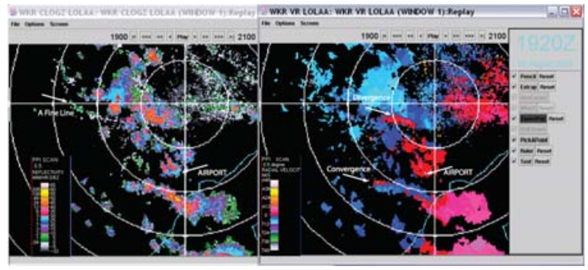

Figure 4 Reflectivity (left) and radial velocity (right) image of storms at a nominal time of 1920Z, about 40 min before the incident. Range rings are every 20 km. The white arrows marked A and D show separate gust fronts identified in different ways. 'A' is by the low reflectivity 'fine' line and 'D' is by looking for a linear divergence feature in the radial velocity data. The white arrow marked 'B' shows a convergence line and there is an arrow marking the location of the cyan square which is the airport.

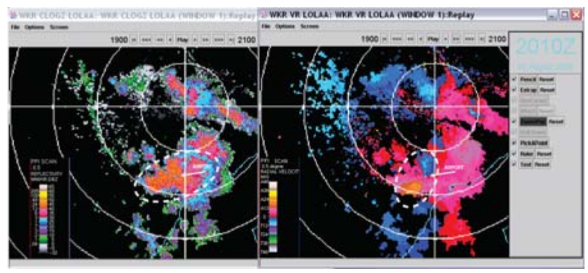

Figure 5. The white arrow marks a well defined gust front in the reflectivity data. The many scattered small thunderstorms have now merged into a single very large storm over the airport (dashed ellipse). The ellipse on the radial velocity image shows a well defined large downburst signature over the airport (cyan marker and arrow). The gust front is only subtlely evident in this image (see subsequent figures).

To complete the overview, Fig. 6, depicts a much later time 2100Z, almost 60 min, after the incident, to illustrate both the evolution of the large main storm over the airport but also the continued development of storms in the vicinity that had small downburst signatures that continued through the day.

6. Gust Front and Downburst Detail

Fig. 7 shows a detailed zoomed-in image of the downburst that occurred near the airport when the incident occurred. The velocity data has a Nyquist velocity of 16 m/s and is shown with a colour scale that has a 1 m/s gradation. The data is slightly aliased but the de-aliasing is straightforward as the data is contiguous (see caption). The time of the data is 20:04:34, which is about 3 minutes after the plane touched down. The elevation angle of the data is 0.3^{o}. The meteorological wind features will not have changed significantly from the time of the incident except that it will be shifted in space to the north.

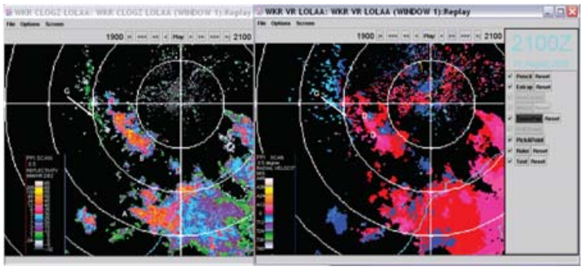

Figure 6: Reflectivity (left) and radial velocity (right) image of storms at nominal time of 2100Z, about 60 min after the incident. Range rings are every 20 km. The large storm (A) that was over the airport is still evident but has veered to the right, following the lake breeze (not shown). Other storms (B) continue to develop and track towards the airport. The previously analyzed gust front is no longer evident in the data because the radar beam increases in height with range and is too high, overshooting the gust front. Another gust front is developing at about 40 km west of the radar (G). In this case, the gust front can be seen in both reflectivity and radial velocity. Small downbursts (D) can also be seen.

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The downburst signature is seen as closed areas of away and toward radial velocities aligned along a radar azimuth. From examining the sequence of detailed radial velocity images (not shown), the downburst was moving from the north-northwest towards the airport. At this time, the downburst is still to the northwest of the airport. The airport would be just beginning to experience northwest wind from the downburst. AF358 had already touched down and was already off the runway 24L (the southwest-most runway) at this point in time.

The gust front is identified, in the radar data, by a combination of a line of strong radial winds and a line of fine low intensity lines in the reflectivity data. At this time, the gust fronts from several individual storms have merged and have already passed over the airport from a northerly direction (true). So the airport experienced northerly winds as the gust front passed over. Subsequent detailed analysis (of radar and anemometer data) indicates that the incident happened just after the gust front passage over the airport.

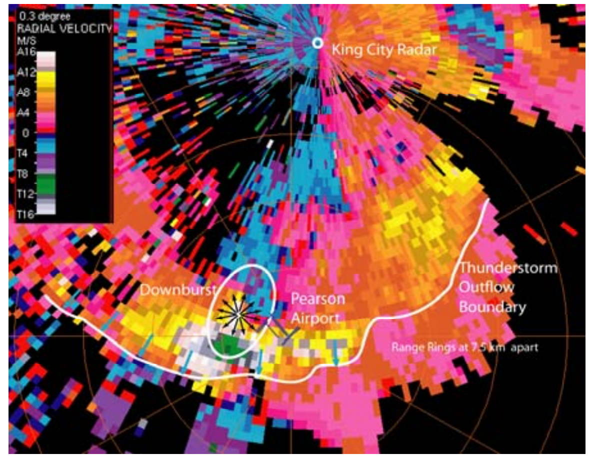

Figure 7: A zoomed in image of the 0.3° elevation angle radial velocity data at 20:04:34. Each change in shade is a 1 m/s change in radial velocity. The airport runways are marked by dark grey lines. The radiating arrows and the ellipse indicates the location of downburst. The white line denotes the edge of strong radial winds and interpreted as the gust front. The patch of green (toward) velocities, in the south west of the downburst are aliased and are actually away velocities of about 20 m/s.

Fig. 8 shows a manual analysis of the location of the downburst and the gust front for several time steps (nominal times of 1930Z to 2020Z, actual times of 19:34:45 to 19:34:45). The gust front at 20:04:36 was about 4 km south of the airport. It moved about 7 km in 10 minutes from the north and therefore it passed over the airport at about 5 minutes earlier at about 19:59:30. So AF358 was in the northerly gust front air on final approach.

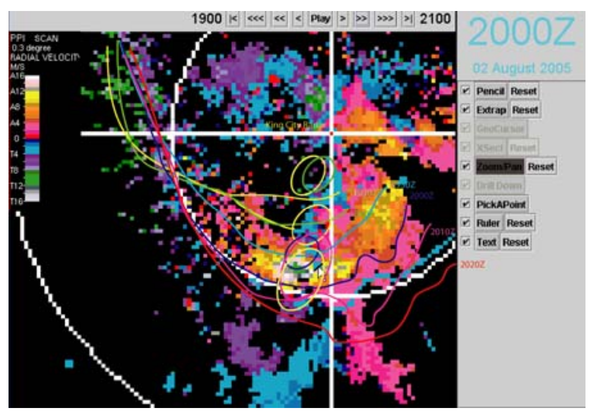

Figure 8: The radial velocity image is the same as shown in the previous figure but with the analyzed position of the the downburst and gust front from nominal times of 1930z-2020Z (add ~00:04:30 for the actual time). Runway 24L is marked as short dark line with a white arrow.

8. Gust Front and Downburst Statistics

The following table (Table 1) shows the strength of the gust front (maximum velocity) and of the downburst (maximum velocity difference) with time. The maximum velocity of the gust front is estimated by searching for the maximum Doppler radial velocity data along the front. At any given point along the gust front, the actual velocity may be different. The maximum velocity is presented here to estimate the maximum potential impact of the gust front.

The strength of the downburst is estimated by searching for the maximum radial velocity differential, the corresponding distance between the radial velocity couplet and computing the radial shear.

Note that the maximum intensity occurs after the time of the incident and after it passed over the airport. Between 19:54:30 and 20:04:30, when the leading edge of the gust front was passing over the airport, its strength was estimated between 13-16 m/s or between 26-32 knots. The gust front wind was from the north and so the along-runway component of 19-23 knots (tailwind) and a cross-runway component of 17-21 knots (cross wind from the right).

Table 1: Analysis of the strength of the Gust Front and Downburst

Time Stamp	Time	Gust	Downburst		Diameter	Orientation	Max Delta	Shear
			towards	away	max to max			
UTC	UTC	m/s	m/s	m/s	km	deg	m/s	m/s/km
1930	1934	7	24	11	10	29	35	3.5
1940	1944	9	16	13	12	14	29	2.4
1950	1954	16	8	16	12	35	24	2.0
2000	2004	13	6	23	9	21	29	3.2
2010	2014	25	6	25	15	24	31	2.1
2020	2024	20	8	21	16	12	29	1.8

9. Wind Analysis

Surface Wind

The radar analysis was corroborated by the sruface anemometers at the airport (Fig. 9). GTAA South is an anemometer that is located about the mid-point of 24L. Not all the sensors were functional throughout the event. However there is sufficient consistency in the data that relevant comments can be made.

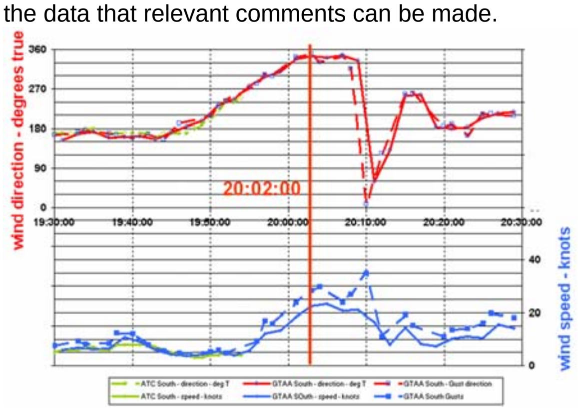

Figure 9: Anemometer measurements for various locations around the airport. The bottom set of plots are the wind speed (right ordinate) and the top set of plots are wind direction (left ordinate). The touch down time is marked.

There are phases to the wind data:

- An initial south wind to about 19:47
- A wind shift from south to north from about 19:47 to about 20:00
- A north wind from about 20:00 to about 20:10
- A rapid wind shift from north clockwise to west from about 20:10 to 20:19
- A return to the initial south wind at about 20:19 and beyond

The air from the south is the environmental air ahead of the gust front. This air had a speed of 5-10 knots.

The Gust Front Wind

The wind direction linearly shifted from 180^o (from the south) to 360^o (from the north) in the period from 19:45 to 20:06. The wind speed began increasing almost linearly beginning about 10 minutes later (~19:55) and peaked at about 20:05. The northerly winds extend to about 20:10. The anemometer marked ATC North, is at the north end of the airport and report an earlier shift at about 19:40. This wind shift is an indication of the gust front passage.

Radar Wind and Anemometer

The anemometer analysis corresponds very nicely with the radar analysis. Like the radar, the surface anemometer shows a north wind between 20:00 and 20:10, during the time of the incident. The wind strengths are between 15 and 23 knots, a little less than the winds from the radar. Again, this indicates that AF358 was in the northerly gust front air during the touchdown phase of its flight and results in a tailwind component of about 19-23 knots.

Tail/Cross Wind Components

In the previous analysis, we estimated the wind speed and direction from various sensors and technology. Now we analyze the maximum Doppler wind measured (Table 1) and estimate the runway component for Doppler winds of different magnitudes and direction to examine the sensitivity of the tail and cross winds to a variation in the actual wind speed and direction.

The yellow highlights a range of most likely wind speeds and their runway components derived from the radar and anemometer analysis. Conservatively, the tailwind component of the surface wind would therefore be at least 20 knots.

Table 6: Sensitivity of the Tailwind Component to the Wind Estimate

Wind Direction	Wind Speed	Runway Direction	Component
	knots	227	knots
360	20	227	14.6
360	21	227	15.4
360	22	227	16.1
360	23	227	16.8
360	24	227	17.6
360	25	227	18.3
360	26	227	19.0
360	27	227	19.7
360	28	227	20.5
360	29	227	21.2
360	30	227	21.9
360	31	227	22.7
360	32	227	23.4
360	33	227	24.1
360	34	227	24.9
360	35	227	25.6
360	36	227	26.3
360	37	227	27.1
360	38	227	27.8
360	39	227	28.5
360	40	227	29.3
360	41	227	30.0
360	42	227	30.7
360	43	227	31.4
360	44	227	32.2
360	45	227	32.9

10. Vertical Structure of the Gust Front

In Fig. 10, a radial velocity vertical cross-section is created through the core of the storm and perpendicular to the gust front at 2010Z. This line is chosen in order to best examine the vertical structure of the horizontal velocity. Along this path, the tangential wind components are negligible since the radial wind is approximately aligned with the true wind.

The gust front is moving left to right in the plane of the image, the radar is well to the left of the figure (not marked) the leading edge is located around the 30 km mark and it is about 1 to 1.5 km in height. The blue colors (between 35 and 50 km) indicate motion moving towards the radar. This is undercut by air moving away from the radar (red colors). The 'head' of the gust front can be seen at the 30 km mark. There is a strong vertical couplet of radial velocity (marked with R) which indicates a rotor, with the air flowing in a horizontal cylindrical motion. The alternating color patterns of warm and cool colors (marked with W) indicate a buoyancy wave.

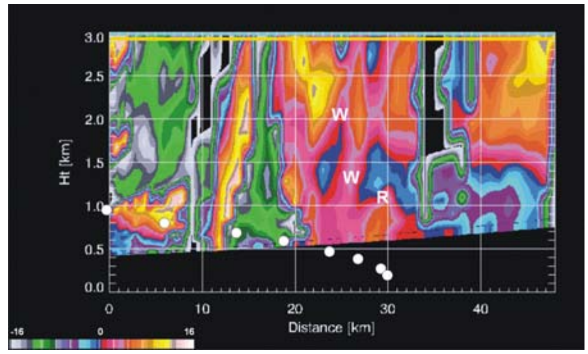

Figure 10: Radial velocity cross-section through the gust front. The data in green is aliased. Ignore data to the left of 20 km mark, it is not pertinent for this discussion. The gust front pattern can be seen in the area around the 30 km mark. The red/yellow are velocities away from the radar which is on the left. The blue and purple are velocity toward the radar and flow over the head of the gust front. The white dots indicate the location of the aircraft relative to the gust front.

11. Flight Path of AF358 With Respect to the Gust Front

We want to determine the location of the aircraft relative to the gust front. Both the aircraft and the gust front were moving. In this analysis, we assume that the gust front structure is "frozen" during the last few minutes of the flight but moving. We assume that the gust front structure is given by Fig. 10.

The gust front was moving from the north at 12 m/s or 24 knots. We have the three-dimensional trajectory and time information from the Flight Data Recorder and we reference the location and timing of the maximum wind in the gust front to the location of the center of runway 24L. From this, we can estimate where, in the gust front that, AF358 landed.

The analysis is approximate and accurate to about a kilometer or so. The white dots in Fig. 10, indicate where AF358 was located relative to the gust front. in order to estimate whether the aircraft encountered the wave like structure lying on top of the gust front. Due to the relative nature of the aircraft motion and gust front, the dots indicate the aircraft position as a projection onto the vertical plane of the cross-section.

A wavelike structure at 20-30 km distance and 1.0-2.5 km in height is shown by the alternating sequence of orange and blue colors and so it is above flight track of AF358. Also, it is very reasonable to expect that there would be vertical motions associated with the rotor (downward motion on the left and upward motion on the right). In both cases, it appears that the aircraft was below the regions where the vertical motions would be expected to be strong (Fig. 11).

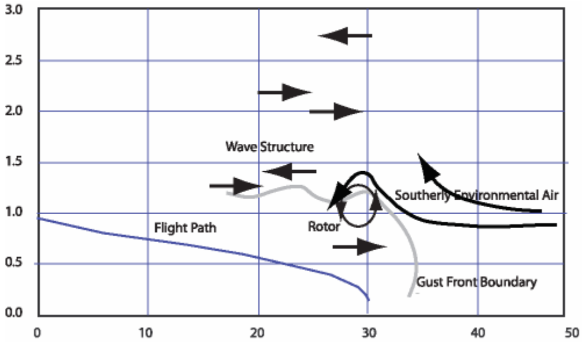

Figure 11: Schematic of the previous figure with flight path, rotor, gust front boundary and airflow. The arrows mark the centre of areas of local maxima or minima of radial velocity and indicate a wave like pattern.

From other published cases, the vertical speeds would be expected to be of the order of 5-6 m/s. AF358 may have encountered this downward air at ~20:01:00 but it was most likely weaker than that since it was close to the ground.

12. Runway Precipitation Analysis

In Fig. 12, radar derived precipitation rates at various runway locations are presented. In addition, tipping bucket results are presented for comparison. There may be timing issues with the TBRG data due to a variety of factors (paper insertion into mechanical device, drum motion, paper stretching).

The figure shows the tipping bucket rain gauge results (marked TB) and four radar derived rain intensity results computed at the tipping bucket location, the east end, the west end and the middle of runway 24L which are marked TB0, PAE, PAW, PA0, respectively. The radar data have been scaled to the tipping bucket data.

From the figure (except for the timing issue), the pattern of the TB and TB0 results are very similar leading to confidence regarding the information. The radar uses a network time and expected to be accurate to be much less than a second.

The analysis shows that the precipitation intensity was rapidly increasing at the airport in the time period from 19:55 to about 20:10. The maximum intensities at 20:10 were 150 mm/h or more. The best estimate of the intensities at 20:02 when AF358 was on final approach indicates the rain fall intensity to be 20 to 60 mm/h. The precipitation was most intense at the ends of the runways than at the center of the runway. This is due to the spatial rainfall pattern (see following sections on the radar analysis of the rainfall). There is a 5 minute difference when the maximum intensity was reached at the ends of the runway compared to the center of the runway.

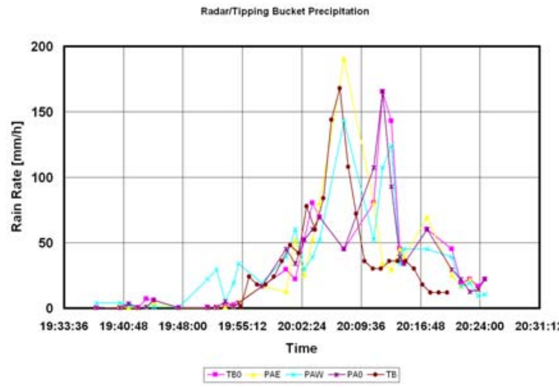

Figure 12: Rainfall intensity analysis for various locations along runway 24L and at the tipping bucket site. TB is the tipping bucket. TB0, PAE, PAW and PA0 are the radar derived precipitation rates at the tipping bucket site, the east, west and center of runway 24L. There is likely a timing error with the tipping bucket data.

To resolve the timing issues, Runway Visual Range (RVR) data were examined from a nearby runway (not shown). RVR measures the visibility and it can be influenced by precipitation and other factors. In this case, precipitation was the dominant factor. The temporal variation in the rain pattern shown by the radar at the various 24L runway locations is supported by the RVR data and we conclude that the TBRG timing is off by 6-7 minutes. Note that it is not expected to this precise.

13. Aircraft Precipitation

This rainfall pattern (intensity and timing variation) is verified by examining the time sequence of radar images. In Fig. 13, the situation at 20:01:36 is depicted. The colors indicate the radial velocity data, the contours indicate the precipitation data and the line indicates the aircraft track, the marker indicates the aircraft location at the time the data was collected.

Fig. 14, shows the radar estimated derived precipitation rate that the airplane experienced. The precipitation rate is estimated from volume scans bracketing the time of the incident. It shows how rapidly the weather was changing.

In particular, the data in Fig. 13 show that in the last minute of the flight, the aircraft experienced very heavy precipitation (marked with letter A) then “popped out” into relatively light precipitation (B) at the threshold of runway 24L and then very heavy precipitation after touch down (C).

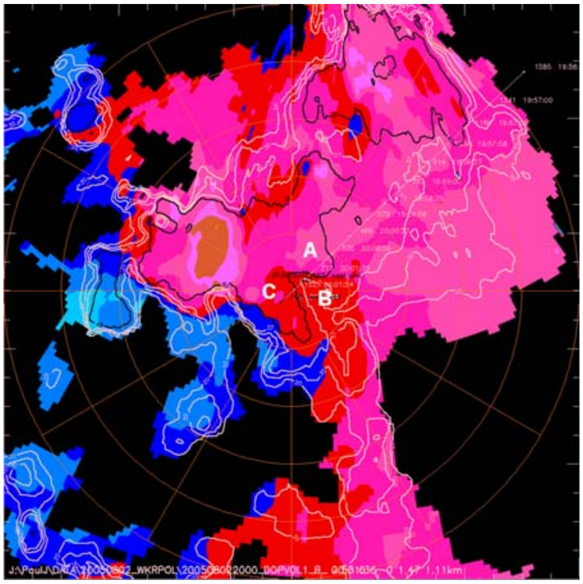

Figure 13: The rainfall intensity pattern is shown for 20:01:36 as contours of 0.5, 2.5 and 7.5 mm/h (white) and for 45 dBZ (black). These contour values correspond to various thresholds and standards in common use to indicate light, moderate or heavy precipitation or thunderstorm cores. The flight track is in white and the runway is marked in black. The marker indicates the aircraft location at the time of the data. At this time, the aircraft has just through very heavy rain and is now in a relatively clear or very light rain region and about to encounter another very area of rain after landing. The underlying image is the radial velocity image showing the downburst to the northwest of the airport at this time. See text for meaning of A, B and C.

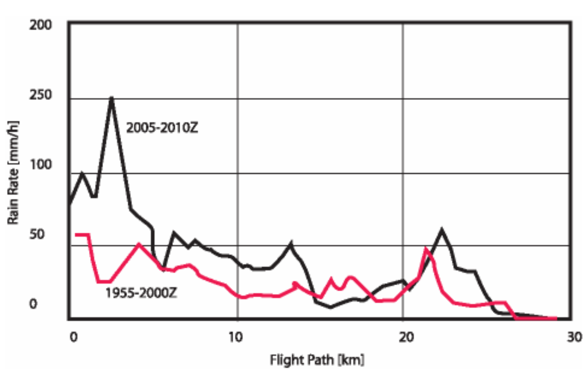

Figure 14: Radar estimated rain rates encountered along the flight path. The estimates were generated from the volume scans bracketing the time of the incident. This shows how rapidly the weather was changing but also the intense rates (250 mmh^{-1}) that were present in the thunderstorm for short time periods.

14. Summary

AF358 encountered an intense thunderstorm on final approach onto runway 24L at ~2000Z on 2 August 2005. The structure of various thunderstorm features was examined in this radar analysis that involved a detailed look at small scale spatial features and a finely resolved time analysis of the data.

The radar used for the study was the King City radar which is located about 33.2 km from the center of runway 24L. Other radars are too far away to detect the low level features of the thunderstorm (>280 m). At 33.2 km, many of the critical thunderstorm features can be directly detected due to beam propagation refraction and Earth curvature effects, the radar does not detect right to ground level at this distance. The radar is used for general weather surveillance and not for specific terminal airport protection.

In the hours previous to and after the touchdown time of AF358, scattered thunderstorms were observed in an area north of Pearson International airport. These thunderstorms were intense and relatively short lived (20-30 minutes). They produced strong downdrafts resulting in small gust fronts or thunderstorm outflows. Small short lived thunderstorms then formed on these individual outflows.

Approaching 20:00, the individual thunderstorm outflow merged into a large gust front. At about the same time, the small individual thunderstorms merged to form a very large intense thunderstorm which produced a large and long lived downburst. Over time, this downburst merged with the gust front. First, the gust front propagated over the airport creating a northerly wind, then the thunderstorm went over the airport producing heavy rain, low visibility and then the downburst passed over the airport.

The gust front laid approximately east-west and approached the airport from the north. The analysis showed that the leading edge of the gust front went through the airport at 19:59:30. So, at touchdown time (20:01:54), the gust front had already passed 24L by about two and half minutes. The northerly winds from the gust front were estimated to be 26-32 knots which produced 19-23 knot tailwind. Anemometer data showed a wind of 20 gusting to 32 knots from the north corroborating the radar wind analysis. In the radar analysis, the maximum radial velocity observed anywhere along the gust front was used as the representative value for its intensity and so it is an overestimate. It is remarkable that the radar analysis and the FDR winds agree so closely in time, direction and magnitude.

Analysis of the trajectory of the aircraft combined with Doppler radial velocity vertical cross-sections of the gust front showed that the aircraft was landing just as the gust front was passing over the runway. A wave pattern could be observed at the top of the gust front at a height of 1 to 1.5 km above the ground. The trajectory analysis showed that AF358 passed underneath this feature.

Radar plan views of the thunderstorm showed several protuberances of heavy precipitation. Analysis showed that the aircraft flew through a patch of heavy rain before reaching the runway threshold and then was in very light rain until touching down into very heavy rain. At the time and location of touchdown, precipitation rates were of the order of 50 mm/h or more. The most intense part of the storm reached over 150 mm/h but occurred at about 20:05:00, after the incident was over. At the touchdown time, about 5 mm of rain had accumulated on the runway.

The downburst was long lived and was most pronounced at about 20:10 which was after the incident. Analysis showed that the downburst pass right around the airport. At the touchdown time, the center of the downburst was more than 7 km northwest of the runway 24L and the winds from the downburst did not affect the aircraft. This was supported by the anemometer data.