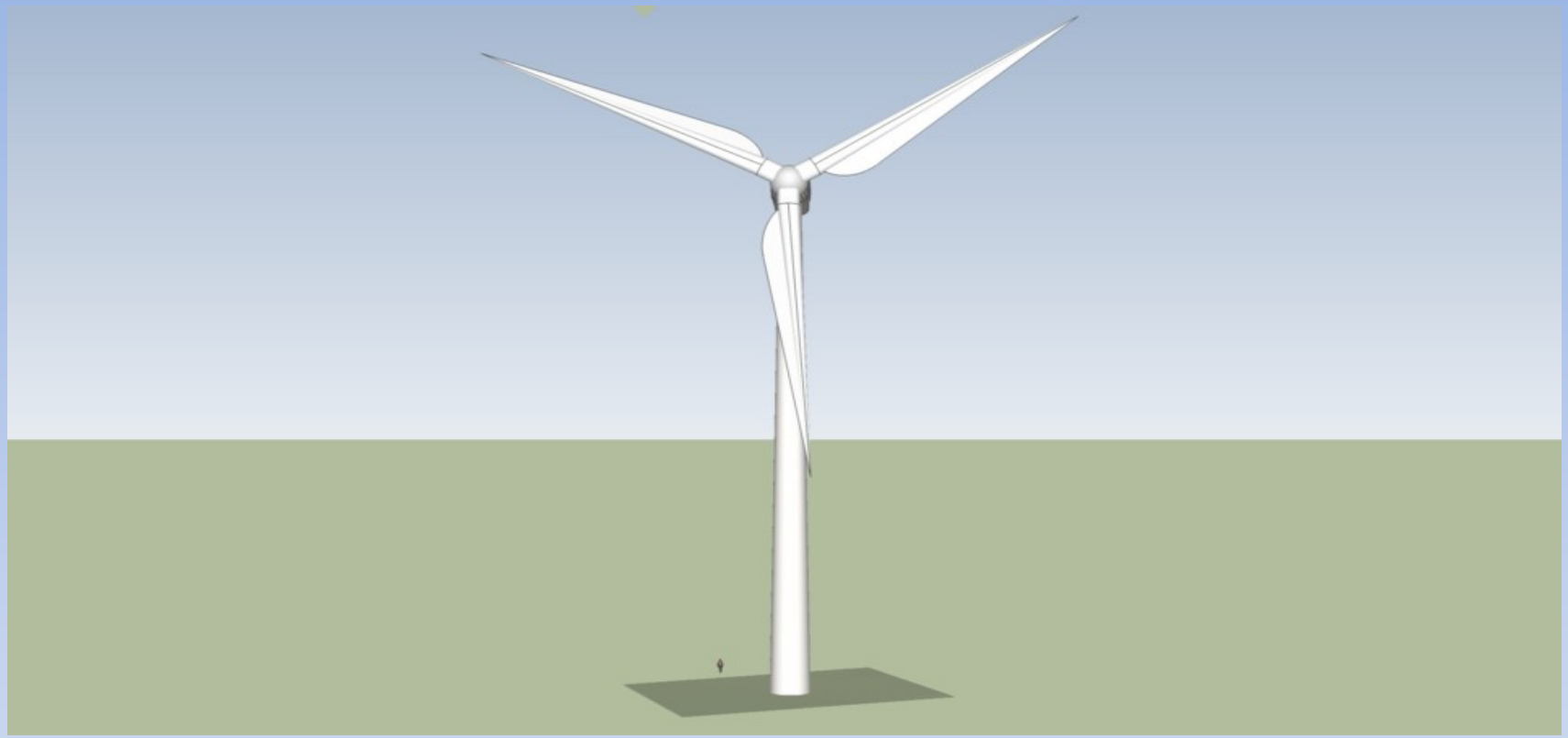


Section 1: Wind Turbines
Section 2: Crookwell Aerodrome

By Ralph Holland, B Sc., Dip Ed., Dip. Com. Sc., ACT Australia. Nov 2009

Section I

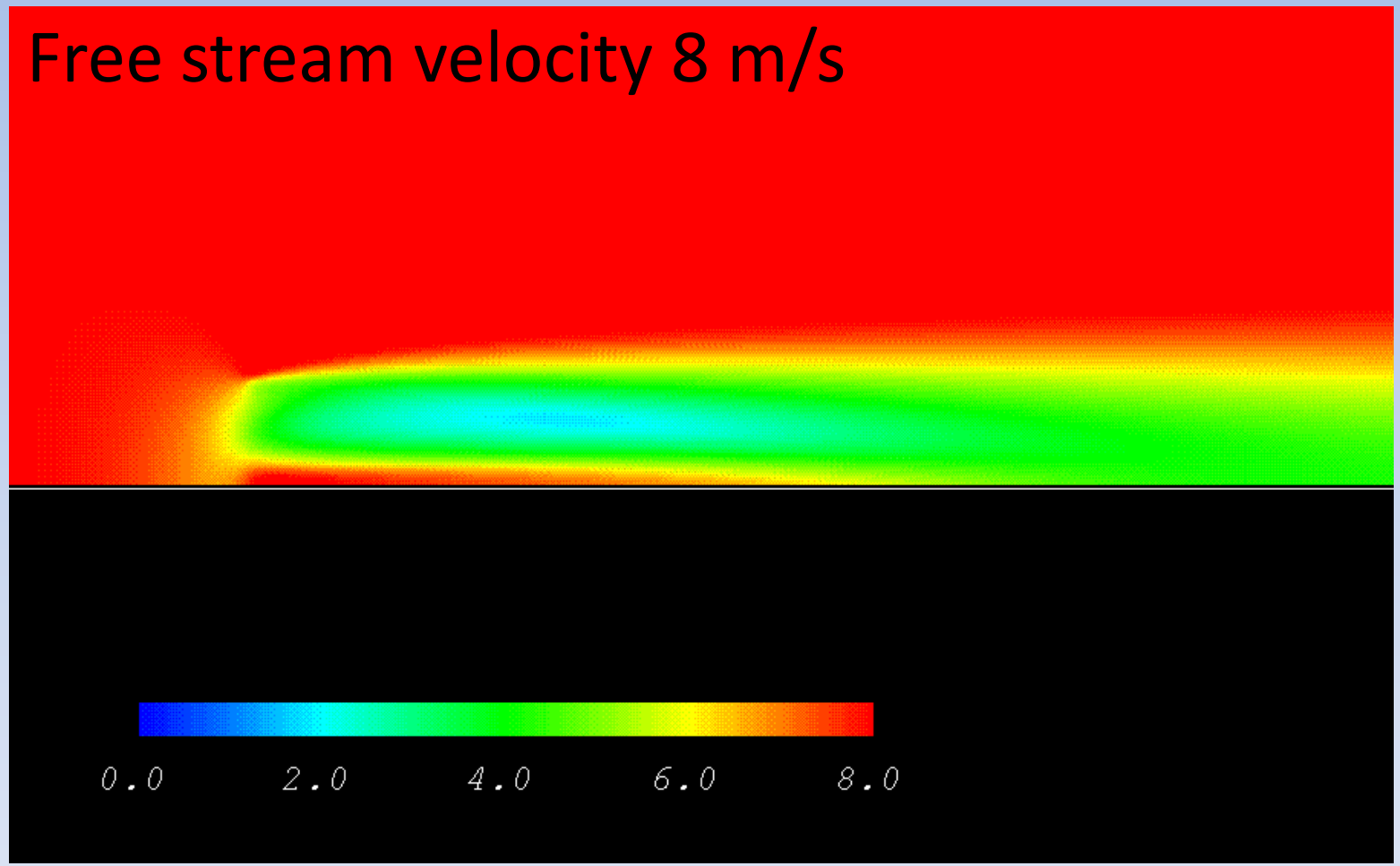
Covers Turbine Wake

- pressure changes
- velocity deficit
- turbulence
- and visual evidence

Parameters and assumptions

Blade Diameter m	Total height m	Max RPM	max tip speed kph	Max tip speed knots	tip speed ratio	wind speed at max tip speed Knots	wind speed at max tip speed m/s	16 * blade diam. m
93	126.5	17	298.0	160.9	6.0	26.8	13.8	1488
120	195	17	384.5	207.6	6.0	34.6	17.8	1920

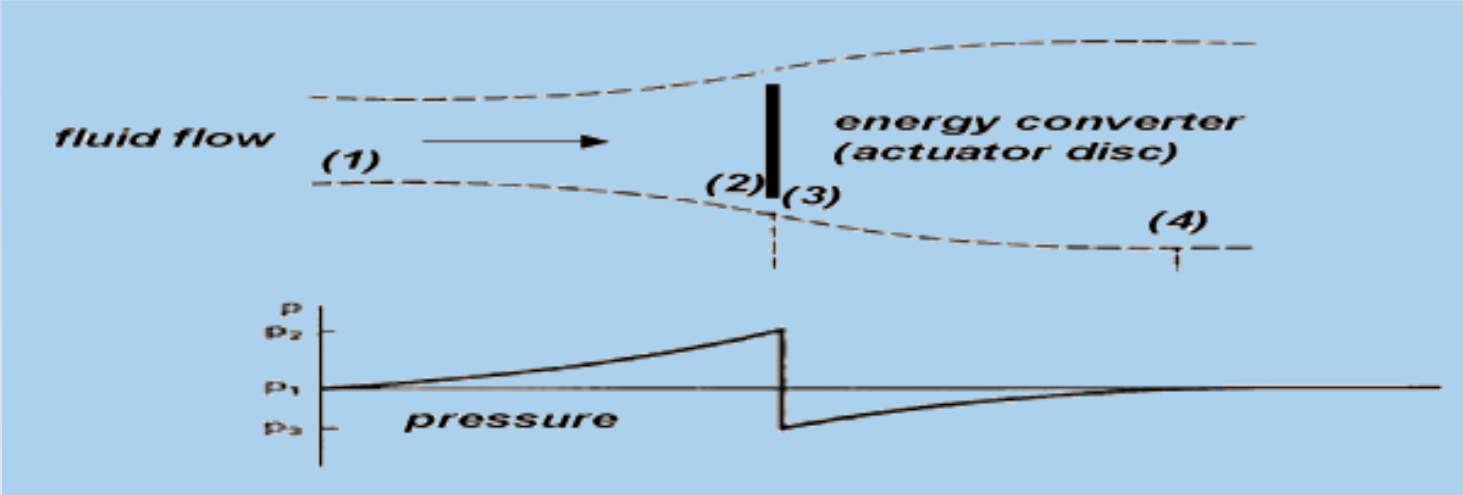
Turbine Wake



From M Pawlka and F Richert – ref. 1

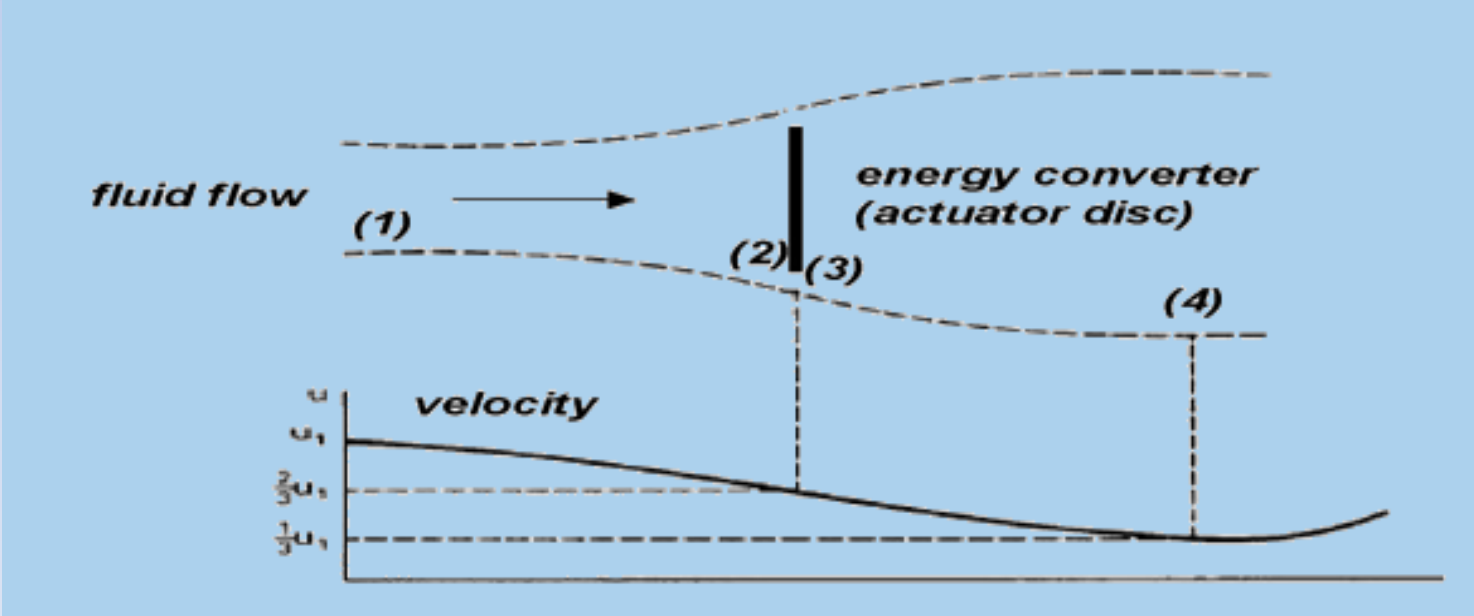
Pressure Differential

- Severe pressure differential crossing the blade/disk
- pressure differential represents a bio hazard to air-borne mammals crossing the disk.
- blade tip velocities of the order of 160 Kts (298 kph) for 93 m diameter turbines.



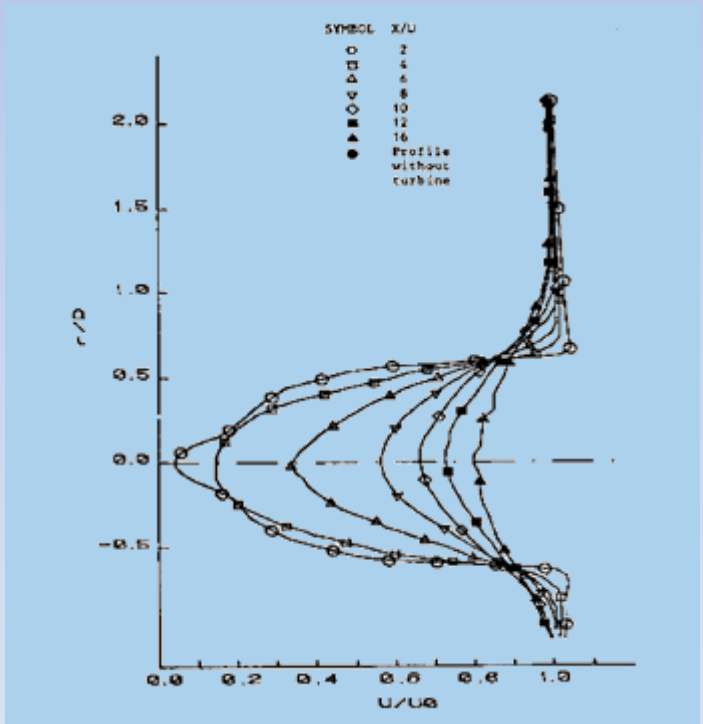
Velocity deficit

- airspeed reduced to 2/3 of free flow velocity in front
- airspeed reduced to 1/3 of free flow velocity behind
- airspeed deficit 37% at 16 blade/disk diameters downstream
- how far downstream does it return to normal?



Gary L Johnson – Ref 3

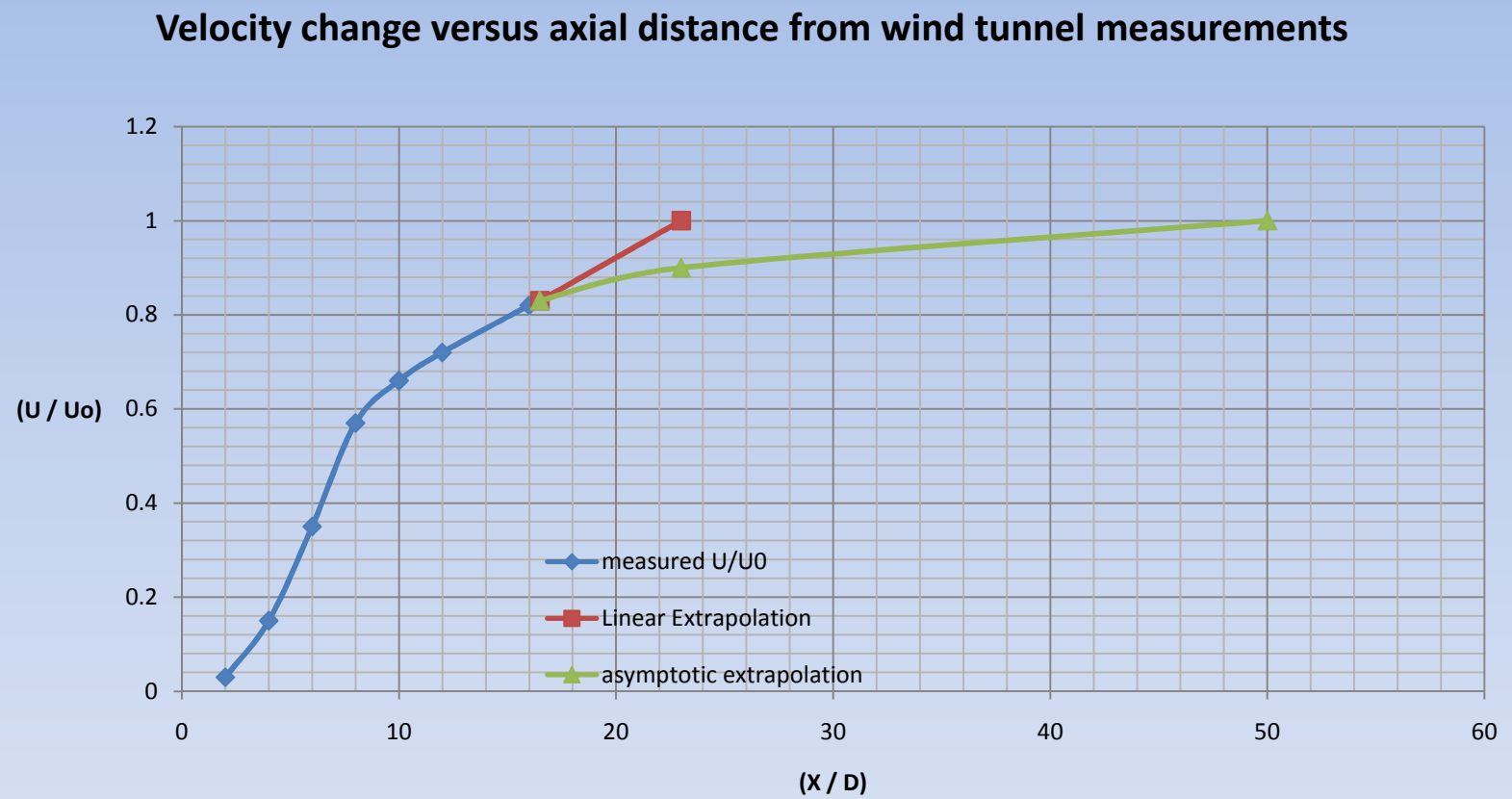
Profile of Velocity Deficit



- A plume, almost contained within the diameter of the blades, extends downstream behind the turbine
- velocity is 0.33 times free stream velocity at 6 blade diameters (558/600 m) downstream
- velocity is 0.55 times free stream velocity at 10 blade diameters (930/1200 m) downstream
- velocity is 0.63 times free stream velocity at 16 blade diameters (1488/1920 m) downstream

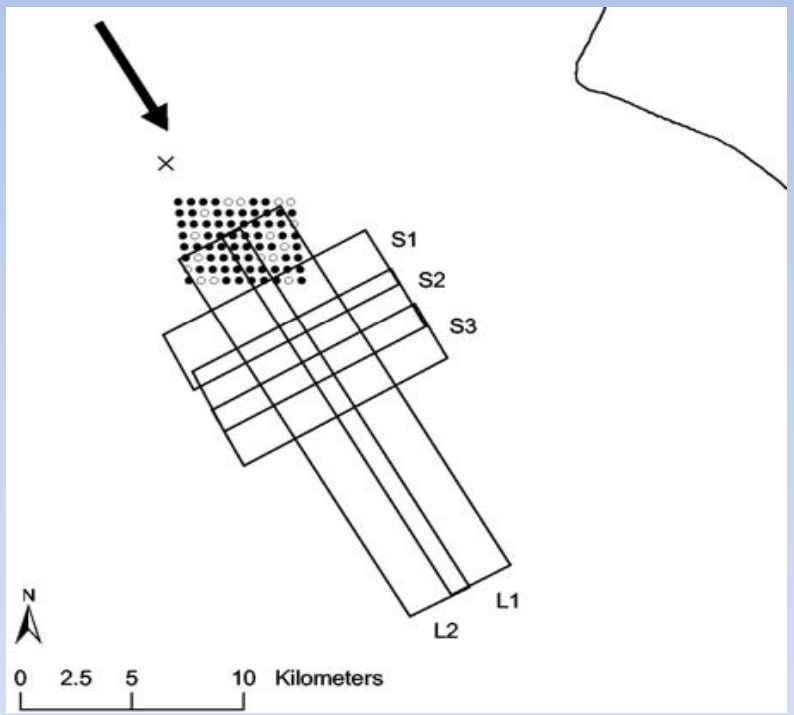
Hand M et al – Ref 4.

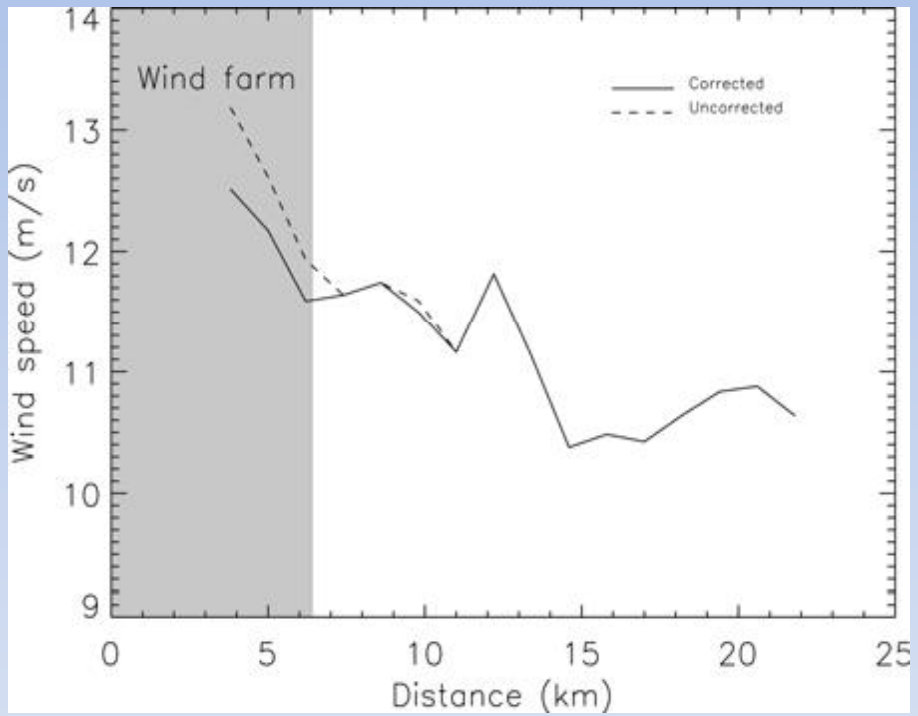
How far does the deficit extend?



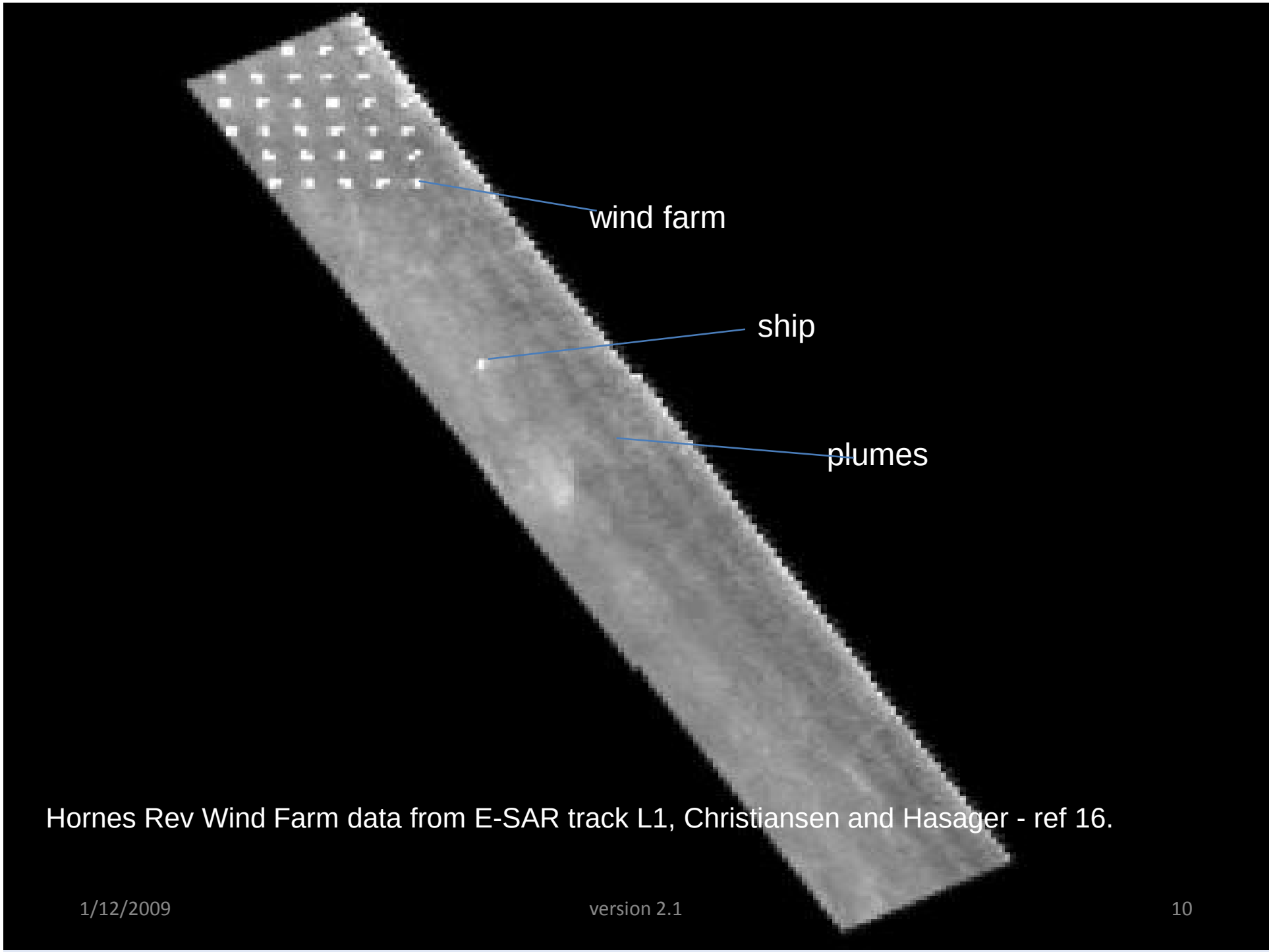
- Blue line obtained from data on the Profile graph
- Red and green lines are extrapolations

Hornes Rev Wind Farm Denmark



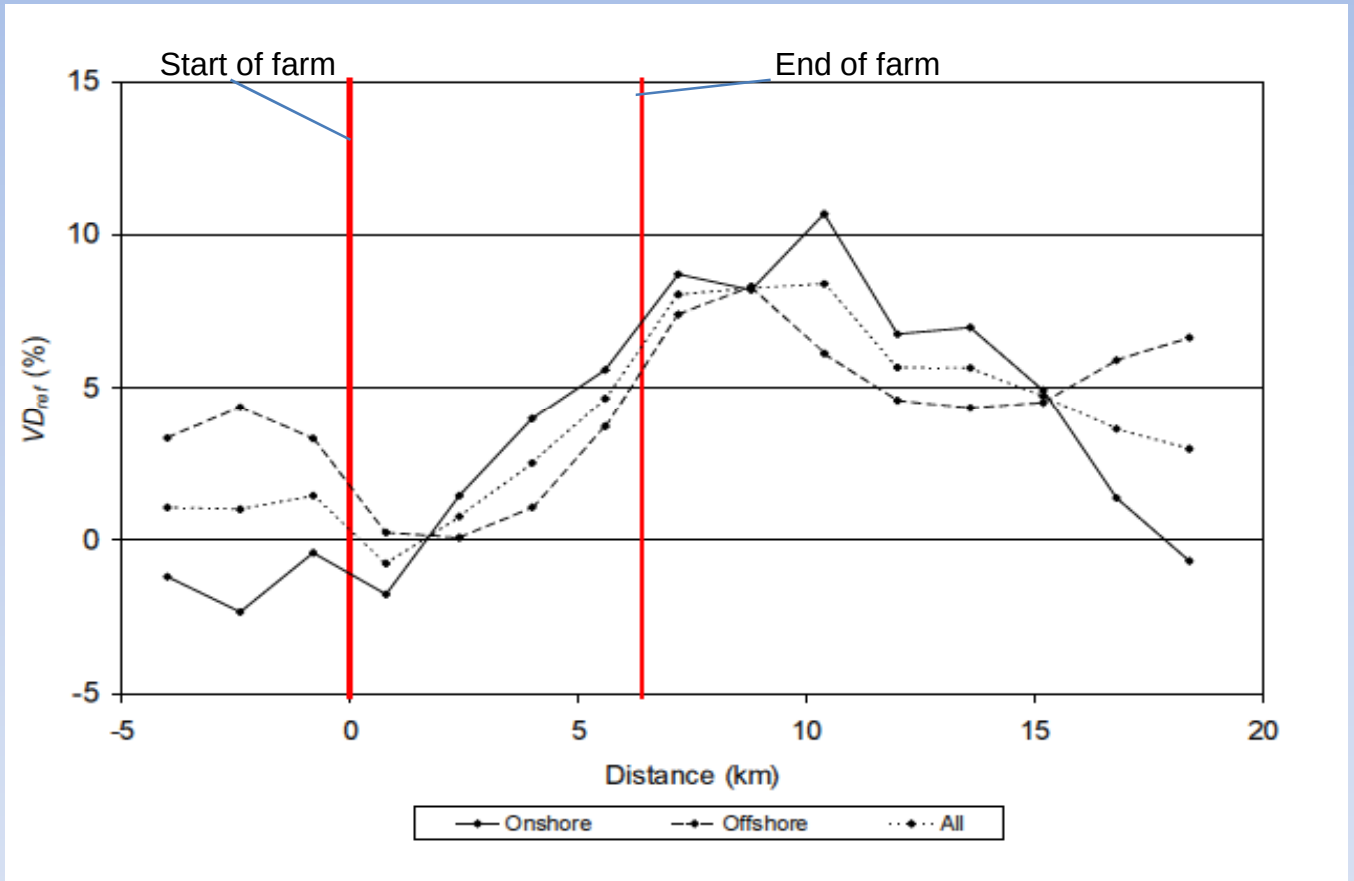


Measurements made via Dromader Aircraft equipped with Synthetic Aperture Radar, Christiansen and Hasager – Ref 16



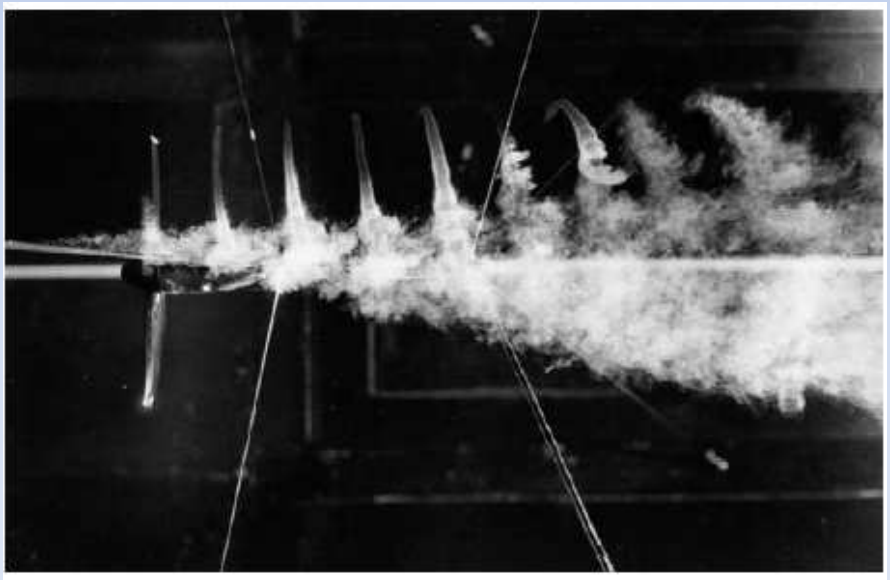
Hornes Rev Wind Farm data from E-SAR track L1, Christiansen and Hasager - ref 16.

ERS-2 SAR and ENVISAT ASAR satellite data



Velocity deficit as a percentage versus distance, Christiansen and Hasager - ref 16

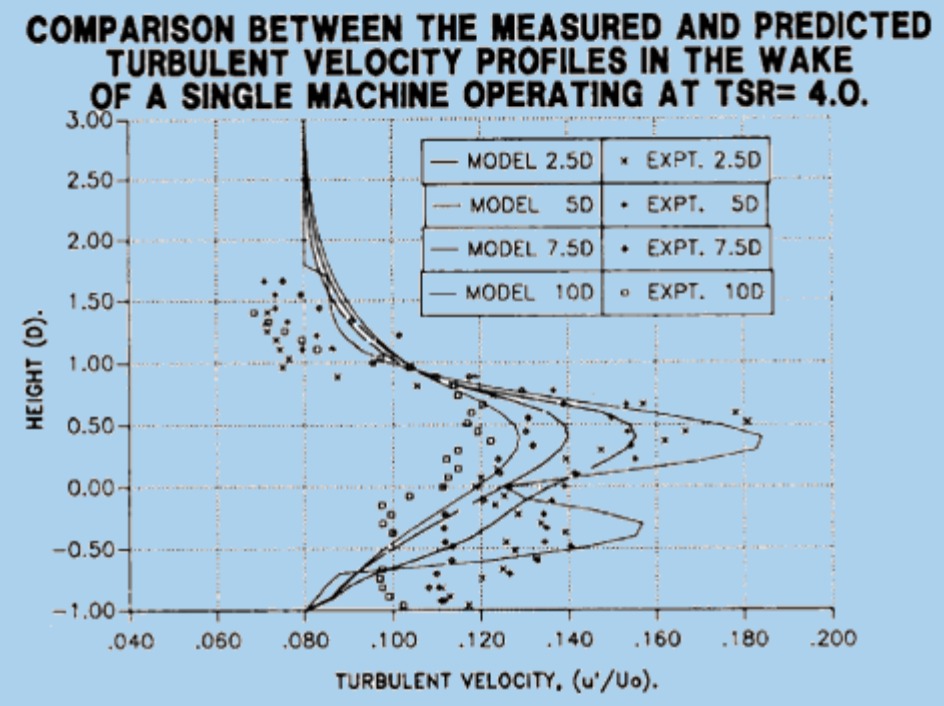
Tip Vortices and Turbulence



Alfredson P-H, Dahlberg J-A. - Ref 2

Turbulence

- The wake turbulence is generated as a side-effect of the rotation and power.
- The wake turbulence at 10 blade diameters downstream is 12% of the velocity at that point (variation of 12% in wind speed @ 930/1200 m)



Hand M et al. – Ref 4

Power

Assumptions:

- 3.3MW generated with turbine operating at Betz limit
- with blade tip speed of 6
- 17 rpm with wind velocity of 13.8 m/s
- blade disk diameter 93 metres

$P = T\ 2\pi\ rpm / 60$

$T = P * 60 / (2\pi\ rpm)$

$= 3300000 * 60 / (6.283 * 17)$

$= 1853686.9$ Kg m

$F = T / d$

= 39,864 kg force at blade tips (approx 39.9 metric tonnes)

(Ref. 5)

Vortices from the tips

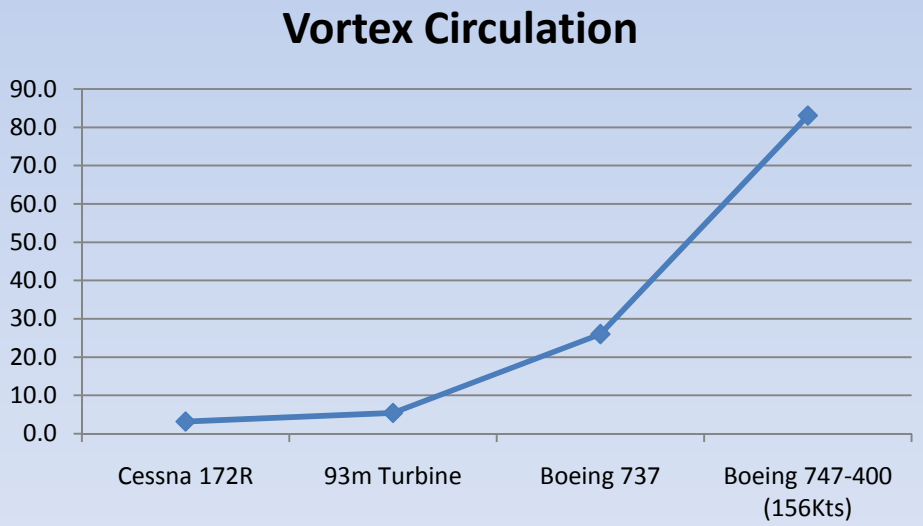
Vortex Circulation = 4L/(πρbV)

(Ref. 6)

where

- L = lift (kg)
- ρ = air density (kg / m^3)
- b = wingspan (m)
- V = speed (m/s)

Examples	Vortex Circulation
Cessna 172R	3.1
93m Turbine	5.4
Boeing 737	26.0
Boeing 747-400 (156Kts)	83.0



Windmills in the Mist

Please view the video at this point to see:

- the danger of the blade-tips hidden by cloud,
- the downstream void in the cloud, and
- the turbulence effects in that cloud, around

Cullerin Wind Farm situated 33.4 km SSW of Crookwell Aerodrome.

Windmills in the Mist

Summary

- By direct wind tunnel measurements the velocity deficit in the **wake** is 37% at 16 blade diameters (**1,488** /1920) metres.
- The wake extends more than 16 blade/disk diameters downstream (**1488**/1920 m) , and by asymptotic extrapolation the wake could extend **50 blade diameters** (**4,650**/11,112m) or more.
- Airborne Synthetic Aperture Radar measurements of offshore wind farms show the velocity deficit extending more than **15 km** (**>100D**), from turbine clusters with a total height of only 110 m.
- The velocity deficit is coupled with **turbulence** being 12% of the free stream velocity at **10D** 930 (1200) metres downstream, and by accounts extends further than the velocity deficit.
- The wake interacts with terrain and airflow as it flows downstream.
- The wake represents **wind-sheer**, which is dangerous to passing aircraft.
- Light aircraft **taking off** and landing are at substantial risk.
- Ultra-light aircraft with little momentum are more at risk.
- In aviation terms, the volume behind a turbine is a **no-go zone** for an aircraft (ref 15).

Section II

Covers:

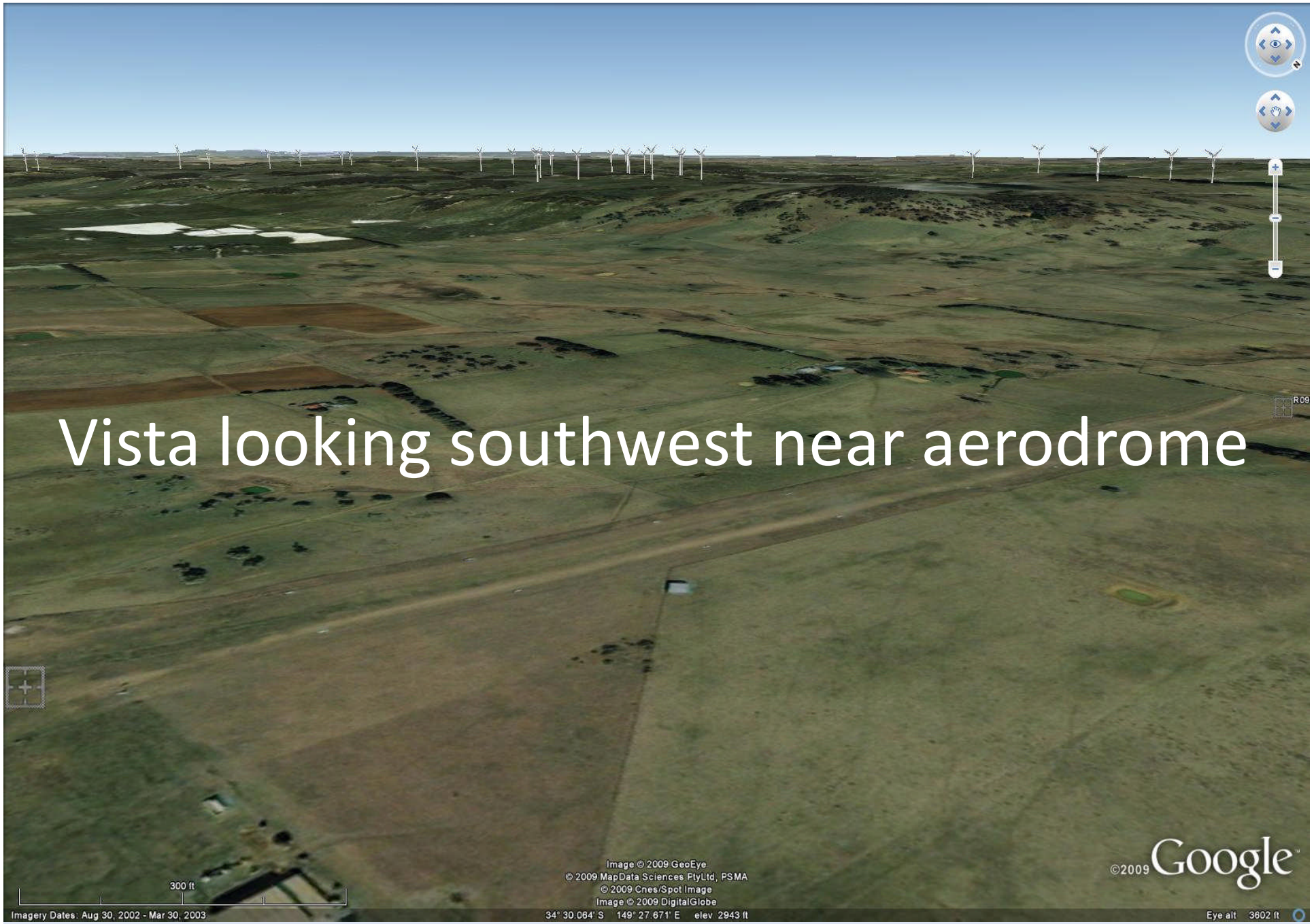
- Turbine locations
- Simulated vista from Crookwell Aerodrome
- Flight path after take off from R27
- Standards
- Operational airspace extent and buffer zones

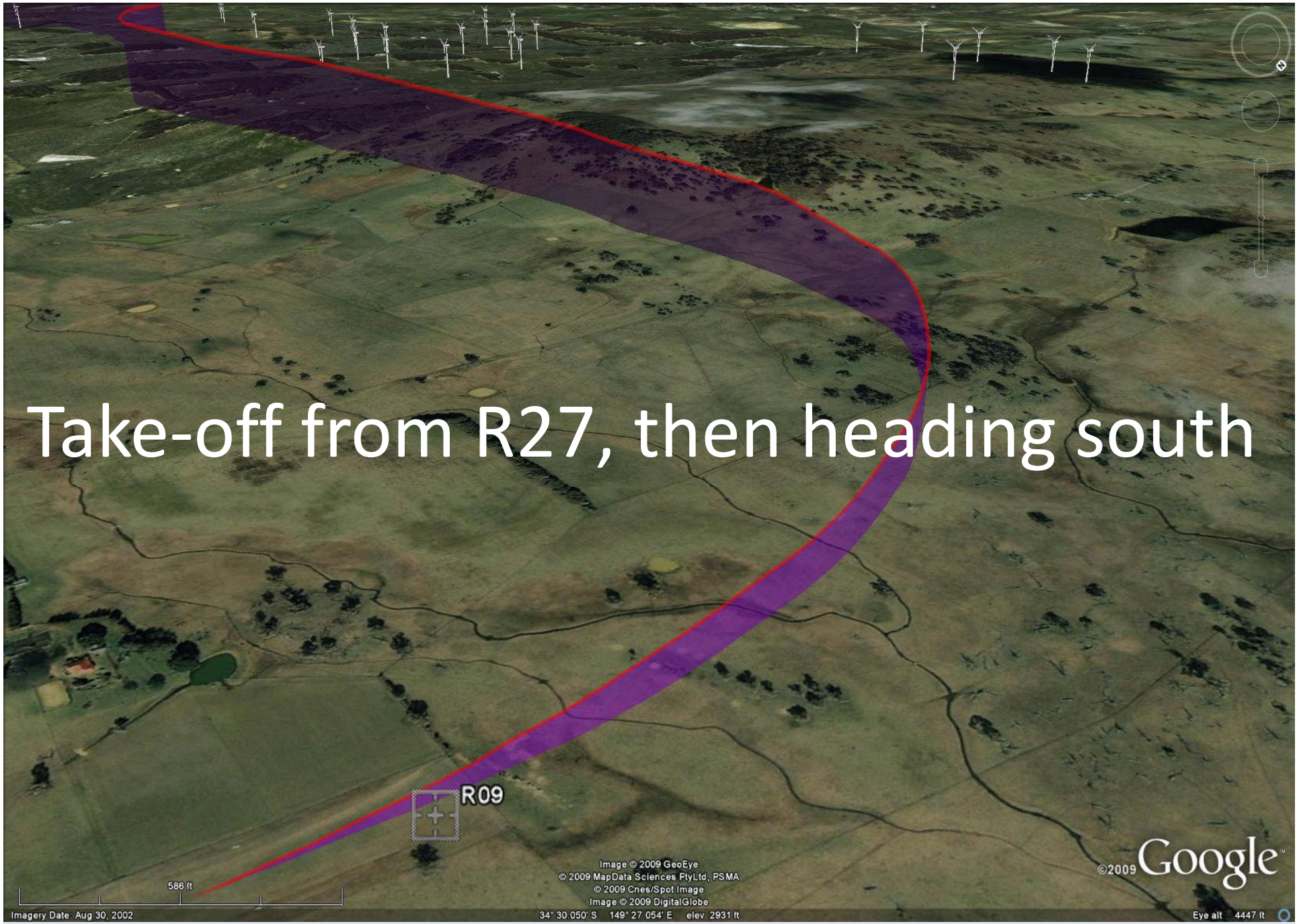
Turbine locations

Turbine Name	Easting	Northing	Lat	Lon
KIA_05	722477	6178958	-34 ° 30 ' 25.27282 “	149 ° 25 ' 24.07198 "
KIA_04	722293	6178775	-34 ° 30 ' 31.3517 "	149 ° 25 ' 17.03418 "
KIA_06	722744	6178681	-34 ° 30 ' 34.04990 "	149 ° 25 ' 34.79421 "
KIA_03	722267	6178510	-34 ° 30 ' 39.96754 "	149 ° 25 ' 16.26416 "
KIA_02	722171	6178251	-34 ° 30 ' 48.44313 "	149 ° 25 ' 12.74549 "
KIA_01	722125	6177964	-34 ° 30 ' 57.78809 "	149 ° 25 ' 11.21224 "
KIA_14	723709	6177613	-34 ° 31 ' 7.93843 "	149 ° 26 ' 13.61523 "
KIA_07	723379	6177555	-34 ° 31 ' 10.07770 ''	149 ° 26 ' 0.73806 ''
KIA_08	723227	6177336	-34 ° 31 ' 17.29988 ''	149 ° 25 ' 54.98805 ''
KIA_10	723918	6177304	-34 ° 31 ' 17.79753 ''	149 ° 26 ' 22.09777 ''
KIA_11	723623	6177203	-34 ° 31 ' 21.30443 ''	149 ° 26 ' 10.63250 ''
KIA_09	723200	6177054	-34 ° 31 ' 26.46792 ''	149 ° 25 ' 54.19592 ''
BAN_01	722828	6177027	-34 ° 31 ' 27.63386 ''	149 ° 25 ' 39.64260 ''
KIA_12	723560	6176950	-34 ° 31 ' 29.55998 ''	149 ° 26 ' 8.40260 ''

Turbine locations supplied by Epuron (Ref. 9) as GDA zone 55 Northing and Eastings. The position data were sorted by Northings and converted to WGS84 Latitude and Longitude for entry into Google Earth.

A 93 metre height turbine tower model was chosen from the Google Sketchup 3D Warehouse and used to place turbines at each way-point for visualisation, note the proposed Crookwell turbines will be taller.

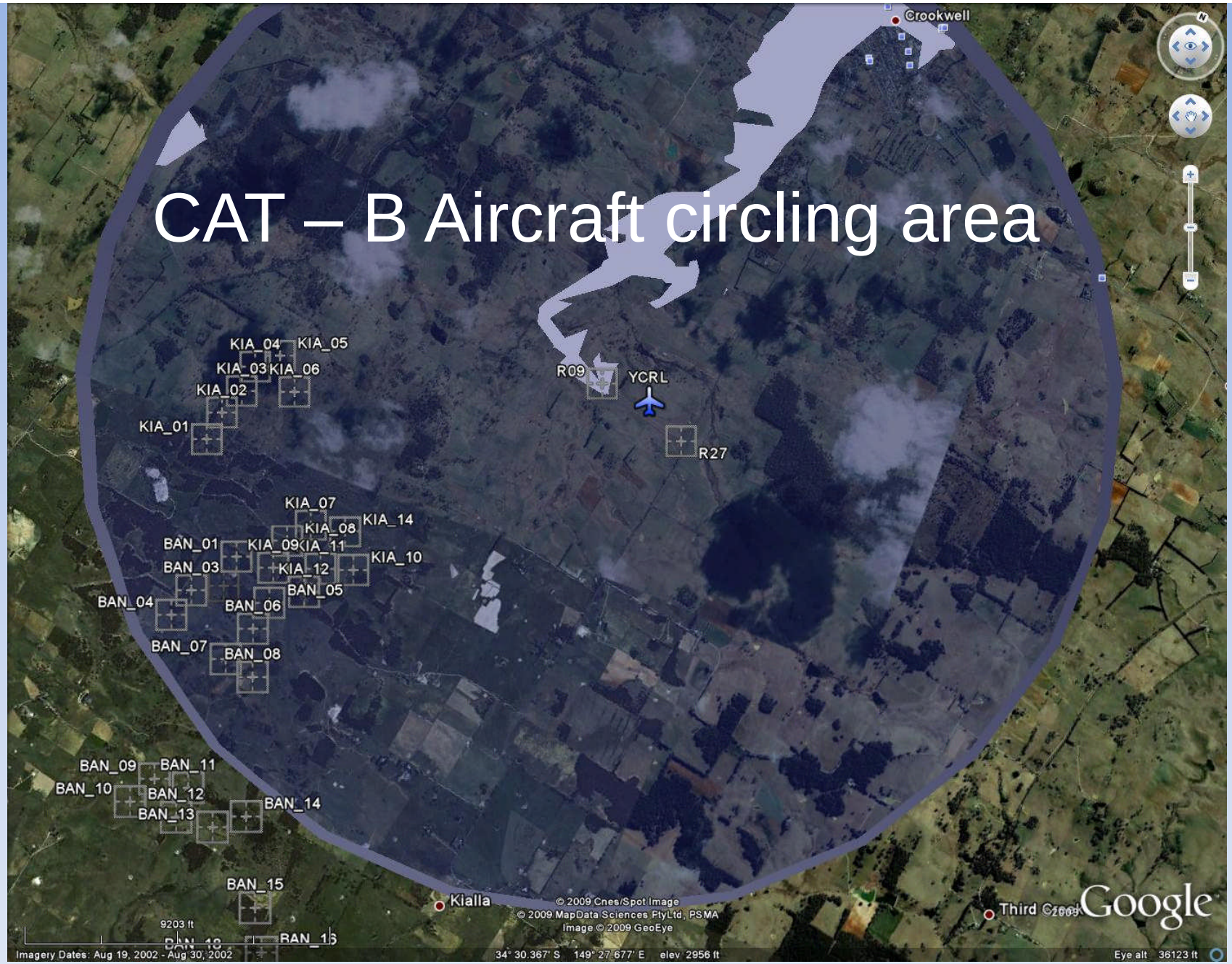

Vista looking southwest near aerodrome
300 ft
Imagery Dates: Aug 30, 2002 - Mar 30, 2003
Image © 2009 GeoEye
© 2009 MapData Sciences PtyLtd, PSMA
© 2009 Cnes/Spot Image
Image © 2009 DigitalGlobe
34° 30.064' S 149° 27.671' E elev 2943 ft
©2009 Google
Eye alt 3602 ft

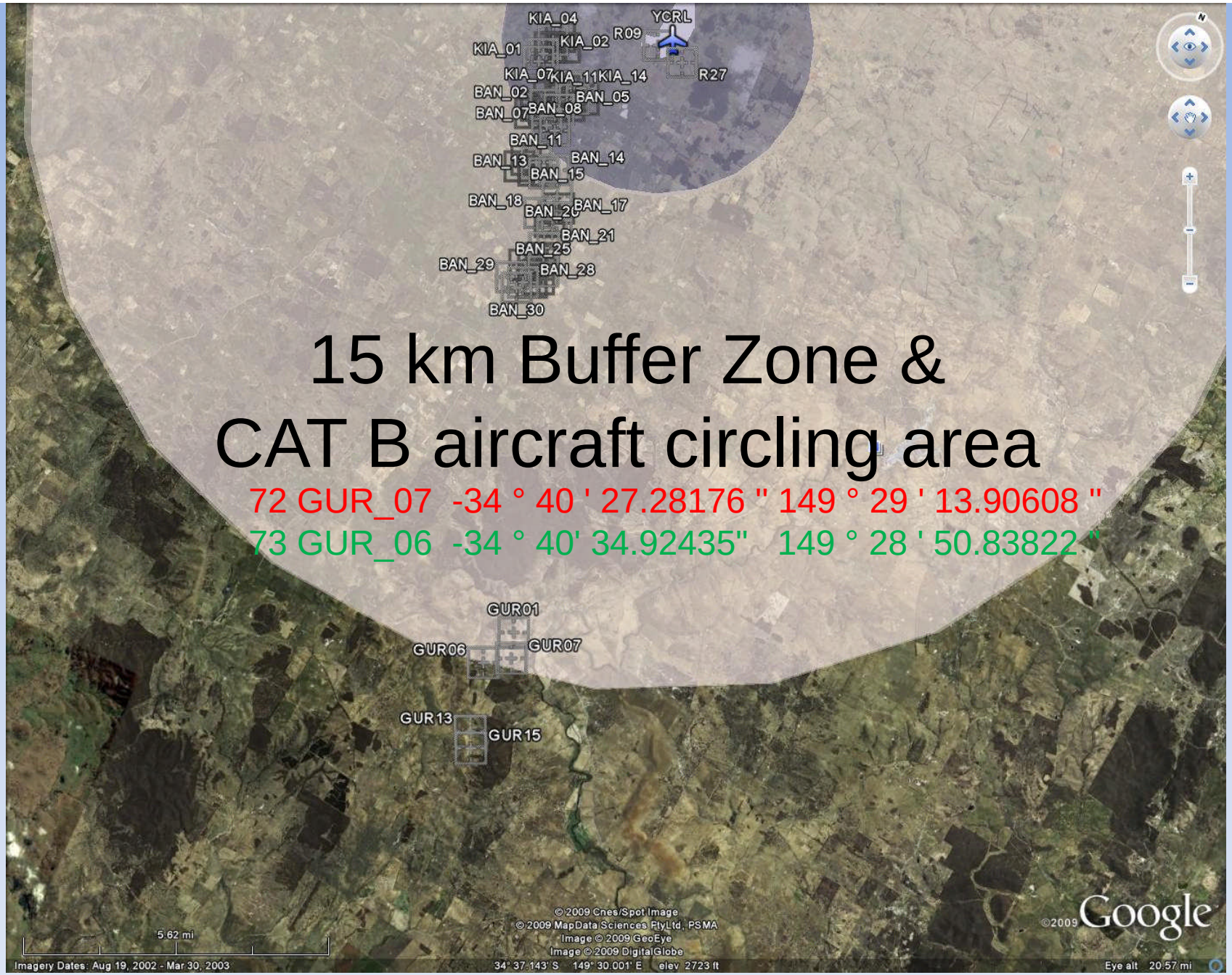

Take-off from R27, then heading south
R09
586 ft
Image © 2009 GeoEye
© 2009 MapData Sciences PtyLtd, PSMA
© 2009 Cnes/Spot Image
Image © 2009 DigitalGlobe
34° 30.050' S 149° 27.054' E elev 2931 ft
Imagery Date: Aug 30, 2002
©2009 Google
Eye alt 4447 ft

Instructions to Pilots

- MOS Part 139 - Cat 1 aerodrome 2.5 km arc.
- MOS Part 139 - Cat 2 aerodrome 3.0 km arc.
- AIP ENR 1.5 Cat A aircraft 3.111 km arc,
- ... Cat B aircraft 2.66 nm (4.926 km) arc.
- Old ICAO rules 3 nm (5.556 km) from aerodrome reference point (i.e. a circle).

CAT – B Aircraft circling area




KIA_04
YCRL
R09
KIA_02
KIA_01
KIA_07
KIA_11
KIA_14
R27
BAN_02
BAN_05
BAN_07
BAN_08
BAN_11
BAN_13
BAN_14
BAN_15
BAN_18
BAN_17
BAN_20
BAN_21
BAN_25
BAN_29
BAN_28
BAN_30
15 km Buffer Zone &
CAT B aircraft circling area
72 GUR_07 -34 ° 40 ' 27.28176 " 149 ° 29 ' 13.90608 "
73 GUR_06 -34 ° 40' 34.92435" 149 ° 28 ' 50.83822 "
GUR01
GUR06
GUR07
GUR13
GUR15
© 2009 Cnes/Spot Image
© 2009 MapData Sciences Pty Ltd, PSMA
Image © 2009 GeoEye
Image © 2009 DigitalGlobe
©2009 Google
5.62 mi
Imagery Dates: Aug 19, 2002 - Mar 30, 2003
34° 37.143' S 149° 30.001' E elev 2723 ft
Eye alt 20.57 mi

Summary

- Wind Turbines are dynamic obstructions that generate a plume in their wake, by measurements extends more than **16 blade diameters** (**1488**/1920 m) down stream, and by extrapolation we can expect the plume to extend to **30 blade diameters** (**2790**/3600m) or more downstream, airborne SAR evidence shows it extending > **15 kms** downstream for offshore wind farm clusters.
- The wake plume contains **turbulence** energy.
- This wake and turbulence plume cannot be seen directly, and is a **void** to flight.
- Pilots should **avoid** flying behind the turbine blades, because the velocity deficit extends downstream in the plume like a tube for a few kilometres. Note there is also an upstream velocity deficit close in front of the turbine.
- A suitable **buffer zone is required** around any aerodrome to permit safe operations of aircraft.
- To ensure pilots can avoid the wake, the turbines should be **set-back** so it is not possible for the wake plume to affect expected aerodrome traffic and operational areas.

Safety Considerations

1. The NSW Rural fire services requires the aerodrome to support Category B Aircraft (ref-14), namely the twins: Cessna 310, Piper Cheiftain, Beechcraft Baron, and the Partenavia P86.
2. That Category-B circling requirements and areas be used because they match the category of aircraft operating into the aerodrome.
3. That consideration be given to the extent of the turbine wake plumes when determining set-back of turbines to ensure that the wake does not infringe on the operational areas of any aircraft using the aerodrome and associated operational areas.

References and Credits

1. New Model for Calculating the Intensities of Turbulence in the Wake of Wind-Turbines. M Pawlka, F Richert.
2. A preliminary wind tunnel study of windmill wake dispersion in various flow conditions. Technical Note AI-1499, Part 7, FFA, Stockholm, Sweden, September 1979. Alfredson P-H, Dahlberg J-A.
3. Wind Energy Systems. Gary L Johnson.
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8. AIP ENR 1.5 http://www.airservicesaustralia.com/publications/pending/aip/enr/1_5_1-5.pdf
9. Turbine locations supplied by Epuron www.epuron.com.au and converted from GDA84 to WGS84.
10. GDA84 to WGS84 conversions via calculator from GeoSciences website http://www.ga.gov.au/geodesy/datums/redfearn_grid_to_geo.jsp.
11. Google Sketchup tool http://sketchup.google.com/ and turbine model from the Sketchup Warehouse.
12. Google Keyhole markup file containing Turbine waypoints etc supplied by Ralph Holland.
13. **Google Earth and Maps (c) copyright by Google and Google providers, used under fair use for academic and for environmental report reasons as per the terms on www.earthgoogle.com.** All the maps views in this presentation can be reproduced entirely from the CrookwellAerodrome.kmz data file by importing into the Google Earth application.
14. Letter from Alan Lawrance, the Director of Works and Operations, Upper Lachlan Shire Council, regarding NSW Fire Service aircraft. Tabled Thursday 15 October 2009.
15. Email from Richard Thompson, regarding Wind Turbine affect on the flight of an Aero Commander 680E aeroplane.
16. Wake Studies around a large offshore wind farm using Satellite and Airborne SAR, Christiansen and Hasager http://www.isprs.org/publications/related/ISRSE/html/papers/272.pdf

Revision History

2.1	01 Dec 09 –Airborne SAR data shows 29% deficit at 15 km so included that as buffer zone with Cat B aircraft circling area, removed unnecessary slides.
2.0	24 Nov 09 – reduced summary to > 10 km for SAR data.
1.9	22 Nov 09 – Included 3 slides and reference 16 on SAR measurements of the velocity deficit plumes for the Hornes Rev 80 turbine offshore wind farm, Denmark.
1.8	21 Nov 09 – Page 5 understated the length of the blade., though the tip velocity was correct.
1.7	12 Nov 09 – Twin aircraft included in Category B due to 1.3 times stall speed.
1.6	09 Nov 09 – Updated Section I and Section II Summary. Included safety considerations in Section II and the references 14 and 15.
1.5	08 Nov 09 – corrected the placement of KIA_14.
1.4	05 Nov 09 – corrected turbulence statement to 12% of free stream velocity at 10D.
1.3	05 Nov 09 – Included Google Map with distance arc for ICAO Cat B aircraft, which operate into Crookwell for fire-fighting.
1.2	04 Nov 09 - Corrected GDM to GDA and included statement on Google Maps use. Included statement on aerodrome arcs instead of the simple circles employed in the Google Sketchup models, included additional references and mark-up to that effect, and some minor typographical edits. Corrected placement of several turbines and updated Google Map diagrams.
1.1	04 Nov 09 - Included extrapolation of wake plume distance.
1.0	03 Nov 09 - Initial writing.