

Effects of En-route Wake Vortex on RPAS Operations

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Outline

- 1 Introduction
- 2 Problem statement
- 3 Vortex generation
- 4 Vortex severity
- 5 Impact on separation
- 6 Conclusions & further work

En-route vortex encounters¹

- Simulation of wake vortex trajectories for 24 days of historical surveillance data (over 400,000 flights).
- Probability of an en-route wake vortex encounter above FL285:
 - RMC: *Roll Moment Coefficient*
 - When $RMC > 0.07 \rightarrow$ severe encounter

Induced RMC	Encounter frequency	Wake Vortex Encounters
Any RMC	3.3×10^{-5} per flight	1 every 2 days
$RMC > 0.03$	1.5×10^{-5} per flight	1 every 4 days
$RMC > 0.07$	1.6×10^{-6} per flight	1 every 38 days

¹Hoogstraten, Mike, et al. "Improved Understanding of En Route Wake-Vortex Encounters." *Journal of Aircraft* (2014)

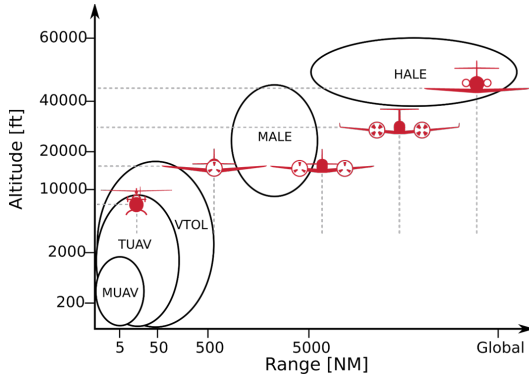
Wake Vortex background²

- ICAO wake vortex categories:
 - Light, Medium, Heavy, and A380
- RECAT-EU wake vortex categories (light, lower medium, upper medium, lower, heavy, upper heavy, super heavy).
- RECAT2-EU: Pairwise separation. Wake Vortex Encounter (WVE) severity metric depends on generator and follower aircraft parameters, namely:
 - Generator mass.
 - Generator airspeed.
 - Generator wingspan.
 - Generator altitude.
 - Follower speed.
 - Follower wingspan.
 - Follower aspect ratio.

²Trewe, Vincent, and Frederic Rooseleer **RECAT-EU proposal, validation and consultation** WakeNet Europe 2014 Workshop. 2014.

Impact on ATM processes

- Shared airspace scenario: MALE and HALE RPAS will interact with jet/turboprop airliners.

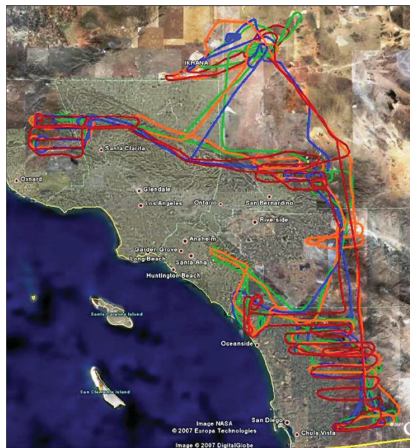
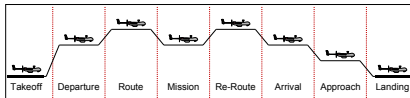
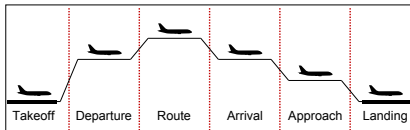


Performance issues



Performance Parameter	RPAS	Manned Aircraft
Cruise airspeed	↓↓↓	↑↑↑
Rate of climb	↓↓↓	↑↑↑
Cruise altitude	≈	≈
Endurance	↑↑↑	↓↓↓

Mission particularities



Problem statement

- MQ9 Reaper:
 - $b = 20.1 \text{ m}$
 - $AR = 17$
 - $TAS = 170 \text{ kt}$
- RQ4A Global Hawk
 - $b = 39.9 \text{ m}$
 - $AR = 25$
 - $TAS = 300 \text{ kt}$
- A320:
 - $b = 35.80 \text{ m}$
 - $AR = 10.33$
 - $TAS = 450 \text{ kt}$

NORTHROP GRUMMAN
RQ-4 GLOBAL HAWK



Problem statement

Do current separation standards preserve the RPAS from wake vortex encounters?



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Vortex intensity³

- Definition of the Roll Moment Coefficient (RMC):

$$RMC(t) = \frac{\Gamma_{tot}(t)}{V_f b_f} \frac{AR_f}{AR_f + 4} F\left(\frac{b_l}{b_f}\right) \quad (1)$$

$$F\left(\frac{b_l}{b_f}\right) = 1 - 2\left(2r_c \frac{b_l}{b_f}\right) \left(\sqrt{1 + \left(2r_c \frac{b_l}{b_f}\right)^2} - \left(2r_c \frac{b_l}{b_f}\right) \right) \quad (2)$$

- Where:

- Γ_{tot} is the vortex circulation [m^2/s].
- V_f is the follower speed [m/s].
- b_f is the follower span [m].
- b_l is the generator span [m].
- AR_f is the follower wing aspect ratio.
- r_c is the core parameter ($r_c = 0.035$).

³De Visscher et al. **A simple Wake Vortex Encounter Severity Metric**,
11th ATM Seminar, Lisbon Portugal (2015)

Vortex initial value & vertical position

- $\Gamma_0 = \Gamma_{tot}(t = 0)$ can be computed as follows:

$$\Gamma_0 = \frac{W}{\rho V L_v} \quad (3)$$

Where:

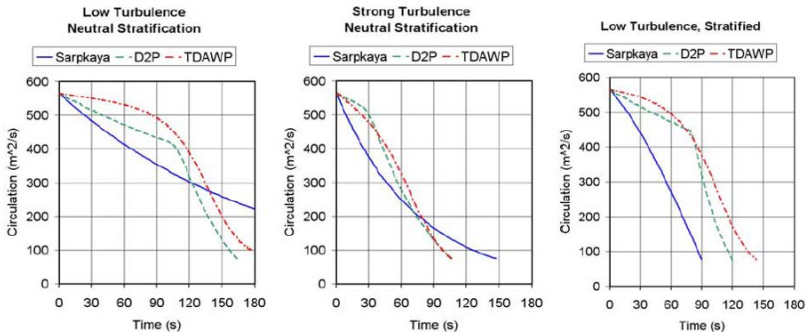
- W is the weight of the generator [N].
 - ρ is the density of air [kg/m³].
 - V is the airspeed of the generating aircraft.
- Downwash velocity:

$$w = \frac{\Gamma_0}{2\pi L_v} \quad (4)$$

Where:

- w is the downwash velocity [m/s].
- Γ_0 is the vortex circulation [m²/s].
- L_v is the span between vortex axes.

Vortex decay⁴



$$\Gamma_{tot} = \Gamma(t) = \Gamma_0 + a \cdot \exp^{(b \cdot t)} + c \cdot \exp^{(d \cdot t)} \quad (5)$$

⁴Proctor F. et al **Thee-Phased Wake Vortex Decay** AIAA Atmospheric and Space Environments Conference, 2010 Toronto (Canada)

RMC of control⁵

- RMC of control: Amount of roll moment that the control system of the following aircraft can generate.

$$RMC_{ctrl} = -RMC_p \left(\frac{pb}{2U_0} \right) \quad (6)$$

Where:

- RMC_p is the roll damping coefficient [-].
- $\left(\frac{pb}{2U_0} \right) = 0.07$ is the roll rate [-].
- The roll damping coefficient:

$$RMC_p = -\frac{C_{L_\alpha} [1 + 3\lambda]}{12 [1 + \lambda]} \quad (7)$$

⁵**Economon T.** *Effects of wake vortices on commercial aircraft* 46th AIAA Aerospace Sciences Meeting and Exhibit, 2008 Reno, Nevada

Impact ratio

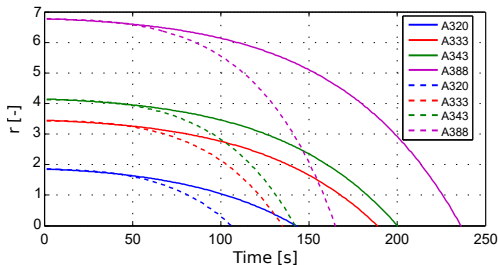
- Define r as the ratio between RMC and RMC_{ctrl} :

$$r = \frac{RMC}{RMC_{ctrl}} \quad (8)$$

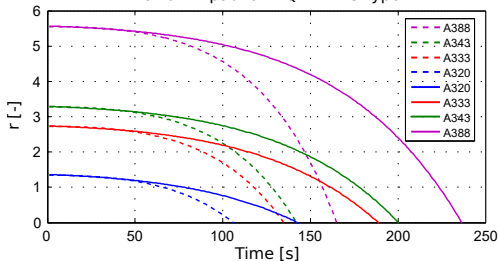
- If $r > 0$ the follower is not able to compensate the moment generated by the wake vortex.
- If $r < 0$ the follower is able to compensate the moment generated by the wake vortex.

Impact ratio (r) computation for different circumstances

Vortex impact on MQ-9 RPAS-type



Vortex impact on RQ-4 RPAS-type

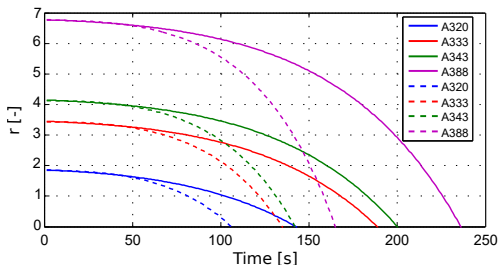


■ Dependency with:

- Generating aircraft type.
- Follower aircraft type.
- Atmosphere.

Impact ratio (r) computation for different circumstances

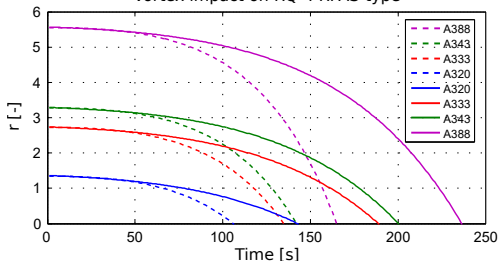
Vortex impact on MQ-9 RPAS-type



Airliner model	t_e^{th}
A320	80 - 100 s
A333	120 - 170 s
A343	130 - 180 s
A388	160 - 220 s

■ $t_e^{th} = \text{Time } (r = 1)$

Vortex impact on RQ-4 RPAS-type



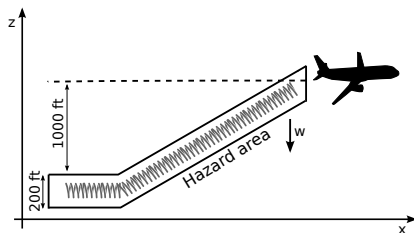
Airliner model	t_e^{th}
A320	60 - 80 s
A333	120 - 160 s
A343	130 - 170 s
A388	160 - 220 s

Impact on separation minima: Vertical separation

- Current vertical separation (RVSM airspace): 1,000 ft
- Recall downwash velocity:

$$\omega = \frac{\Gamma_0}{2\pi L_v} \quad (9)$$

- When vortex gets stabilized (t_s), is it strong enough to negatively impact on the RPAS airworthiness?



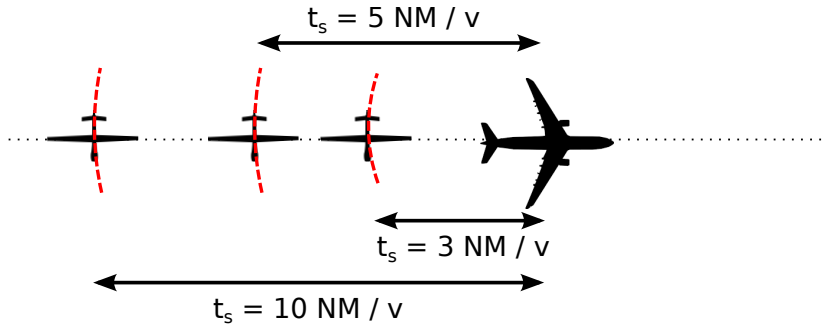
Impact on separation minima: Vertical separation

Model	A320	A333	A343	A388
ω [ft/min]	586	737	880	1303
t_s [s]	102.4	81.4	68.2	46
t_e^{th} (MQ-9A) [s]	80 - 100 ✓	120 - 170 X	130 - 180 X	160 - 220 X
t_e^{th} (RQ-4A) [s]	60 - 80 ✓	120 - 160 X	130 - 170 X	160 - 220 X

- Wake vortex is sufficiently attenuated before reaching its stabilization altitude when the generator is an A320 for both MQ-9A and RQ-4A RPAS models regardless considered atmosphere.
- When the generator aircraft is bigger the wake vortex is not sufficiently attenuated regardless considered RPAS models.

Impact on separation minima: Horizontal separation

- Typical radar separation minimas: 3 NM, 5 NM, 10 NM
- Is the wake vortex still strong enough to negatively impact on the RPAS airworthiness?



Impact on separation minima: Horizontal separation

Model Minima	A320	A333	A343	A388
t_e^{th} (MQ-9A) [s]	80-100	120-170	130-180	160-220
3 NM	24 s X	23 s X	23 s X	22 s X
5 NM	39 s X	39 s X	38 s X	37 s X
10 NM	79 s X	77 s X	77 s X	74 s X

- For the MQ-9 RPAS even for separation minimas of 10 NM the vortex is not enough attenuated to not negatively affect to the RPAS.

Impact on separation minima: Horizontal separation

Model Minima	A320	A333	A343	A388
t_e^{th} (RQ-4A) [s]	60-80	120-160	130-170	160-220
3 NM	24 s X	23 s X	23 s X	22 s X
5 NM	39 s X	39 s X	38 s X	37 s X
10 NM	79 s ✓	77 s X	77 s X	74 s X

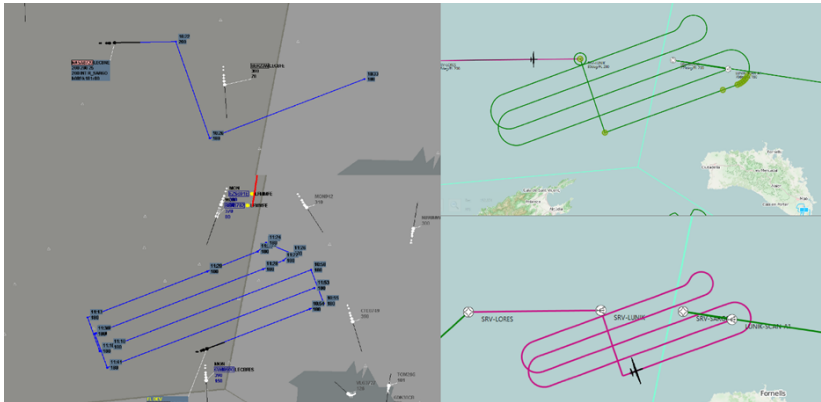
- For the RQ-4A case, only for the smallest considered generator aircraft the vortex is sufficiently attenuated, when the separation minima is set to 10 NM.

Conclusions

- The introduction of new airspace users such as MALE/HALE RPAS may pose additional risks on en-route wake vortex encounters.
- A danger threshold has been specified above which RPAS may compromise their airworthiness.
- The current stasis of separation minima has been reviewed. Results showed:
 - Vertically: Both considered RPAS were well separated from the smallest considered airliner.
 - Horizontally: In general radar separation is not big enough.

Further work

- Review the sensitivity of the vortex generation model.
- Apply the methodology to detect vortex encounters in simulated non-segregated RPAS operations.



Thank you for your attention!!