Wake Vortices

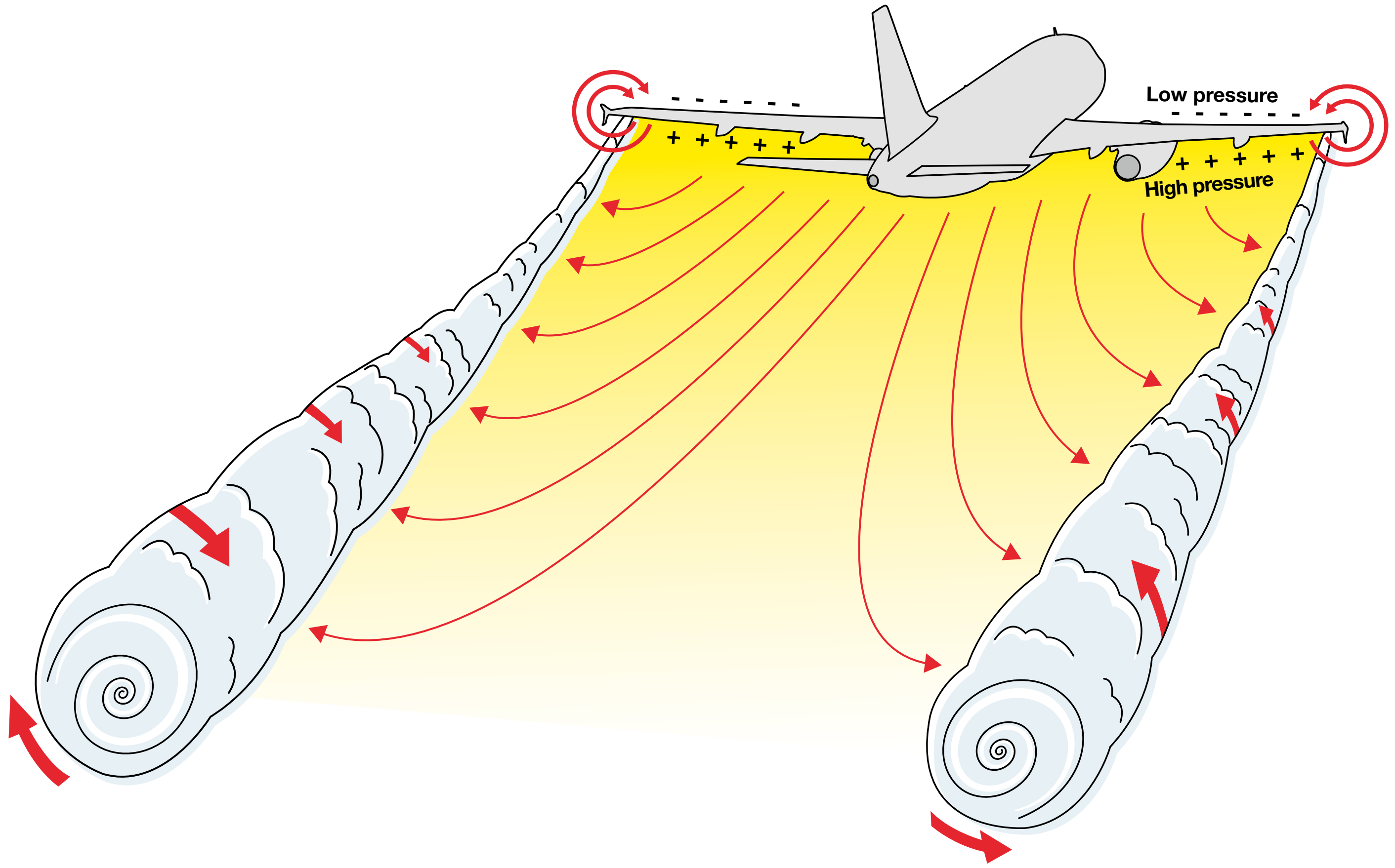
All aircraft generate wake vortices, also known as wake turbulence, which continue to be evident far behind the generating aircraft. Another aircraft crossing this wake may feel a sharp and brief turbulence which can be strong under some circumstances. Let's review the specific characteristics of wake vortices' and how pilots should react in case of an encounter to ensure the safety of the flight.

CLAUDE LELAIE
Former Head
of Flight Test

Where do Wake Vortices come from?

All aircraft generate wake vortices, also known as wake turbulence. When an aircraft is flying, there is an increase in pressure below the wing and a depression on the top of the aerofoil. Therefore, at the tip of the wing, there is a differential pressure that triggers the roll up of the airflow aft of the wing. Limited swirls exist also for the same reason at the tips of the flaps. Behind the aircraft all these small vortices mix together and roll up into two main vortices turning in opposite directions, clockwise behind the left wing (seen from behind) and anti-clockwise behind the right one **(fig.1)**.

(fig.1)
Development of wingtip vortices



What are the characteristics of wake vortices?

Size: The active part of a vortex has a very small radius, not more than a few meters. However, there is a lot of energy due to the high rotation speed of the air.

Descent rate: In calm air, a wake vortex descends slowly. As an order of magnitude, in cruise, it could be 1000 ft below and behind the generating aircraft at a range of around 15 NM. Then, when far away from the generator, the rate of descent becomes very small. In approach, the descent is usually limited to around 700 ft.

> The decay is much faster in ground effect.

> Calm weather creates the most critical situation as the strength decreases slowly and the vortex effect may be felt far behind the vortex generating aircraft.

However, depending on weather conditions the descent rate may vary significantly and may even be very small. One of the key factors affecting this descent is the variation of the temperature with the altitude. A temperature inversion limits the rate of descent.

Decay rate: One important parameter of a wake vortex is the decay of its strength with time. The decay rate varies slightly from one aircraft type to another. Unfortunately, in calm air, due to low external interference, it is rather low and this is why the separation between aircraft needs to be so large.

Ground effect: When the aircraft is close to the ground, less than a wingspan, the two vortices tend to drift out from the centre line, each towards its own side, at a speed of around 2 to 3 kt. It is this phenomenon, when associated with a light crosswind component that tends to "hold" the "into wind" vortex roughly on the centreline, whilst the "downwind" vortex moves away.

Due to this phenomenon, the decay is much faster in ground effect.

Parameters affecting the wake vortex

Aircraft weight: Wake vortex strength increases with the weight of the aircraft. This is why today the ICAO aircraft classification is based on the MTOW. However, such an approach is a simplification as other parameters also affect the strength at the separation distance.

Wing characteristics: The wing shape and the load distribution affect the wake vortex characteristics, mainly through the decay rate.

A smaller wing span increases the decay rate. Therefore, for a given "vortex generator" or "leader" aircraft weight and at the same distance, vortex encounters are less severe behind an aircraft having a smaller wingspan.

It has also been demonstrated that aircraft having a high inboard loading (higher deflection of the flaps close to the fuselage as an example) have a faster decay of their vortices.

Weather conditions: The weather conditions play a major role in wake vortex development and decay. In the case of heavy turbulence, a vortex will dissipate very quickly and there is no risk for the "follower" aircraft. Strong winds are associated with turbulence and will also contribute to a rapid dissipation.

Calm weather creates the most critical situation as the strength decreases slowly and the vortex effect may be felt far behind the vortex generating aircraft. Today, in order to be safe, all separations assume that the aircraft are flying in perfectly calm conditions.

Encountering a wake vortex

DEFINITIONS

When an aircraft enters in the vortex of another aircraft, the "manoeuvre" is called an encounter. The aircraft emitting the vortex is called the generator and the one experiencing it, the follower.

How likely is an encounter?

It is not possible to implement navigation procedures such that the probability of an encounter is zero. To give an example, during the Airbus wake vortex flight tests, in cruise, A319 vortices were identified at a range of 42 NM, thanks to the contrails. An encounter with such a vortex is obviously very weak but it exists and it would have been a bit stronger behind a Heavy. It is also common to have, in the initial approach phase, encounters at distances well above the ICAO minimum separations. The ICAO separations have not been set to avoid all encounters but to prevent unsafe encounters. Avoiding all encounters would require very significant separations and dramatically limit the traffic on all airports and airways without significantly improving safety. It is also to be noted that statistics show that the probability of injury to passengers and crew is about five times greater in turbulence due to weather, than with a wake vortex encounter.

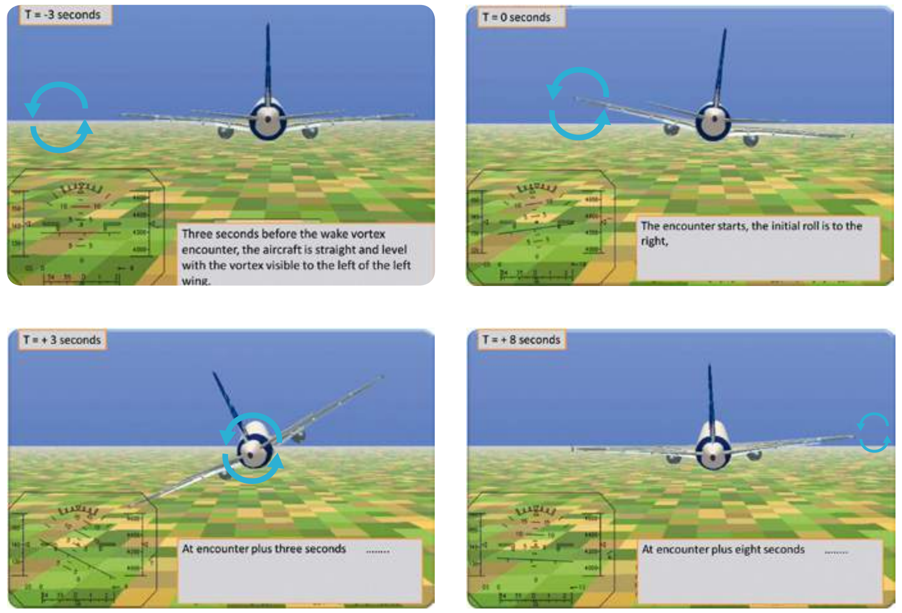
> The ICAO separations have not been set to avoid all encounters but to prevent unsafe encounters.

How does it feel to encounter a wake vortex?

In most cases the effect of the vortex is mainly felt in roll. We will consider here the case of an aircraft entering laterally in a vortex, which is the most frequent situation. Let's assume that a follower aircraft is entering the right vortex of the leader aircraft from its right side. Seen from behind, this vortex is rotating anti-clockwise. When the left wing of the follower first enters the vortex, there is on this wing a local angle of attack increase and therefore the lift becomes higher than on the right wing. The initial roll motion is therefore to the right. Then, when the aircraft is in the middle of the vortex, it will be subjected to the full strength of the vortex and roll in the same direction as the vortex, to the left **(fig.2).** This is the main rolling motion that creates the strongest roll acceleration.

As a conclusion, the typical signature of a severe encounter is an initial small roll in one direction followed by a much more significant roll in the other sense.

When in cruise, this roll motion may be associated with significant load factor variations.



(fig.2)
Aircraft behaviour in a wake vortex encounter (The aircraft bank angle is voluntarily exagerated on the figure)

> The typical signature of a severe encounter is an initial small roll in one direction followed by a much more significant roll in the other sense.

Effect on the trajectory of the follower

To experience a severe roll encounter, it is necessary for the follower to have a trajectory with a small closing angle with the vortex. However, if this angle is too small, the aircraft will be smoothly "ejected" from the vortex (due to the initial roll in the example above). When perpendicular, there will be no rotation, and any encounter will be a very brief but sharp turbulence effect. To experience a severe encounter, the most critical angle between the trajectory of the follower and the vortex is around 10 degrees.

Severity of the encounters

The authorized separations are such that the severity of the encounters does not create an unsafe control situation. When the aircraft is not in ground effect, the order of magnitude of the bank angle for a severe encounter on the approach is around 20°. But when in ground effect, as explained above, the decay is much faster and the worldwide experience during many years shows that the bank angle achieved is much lower and does not lead to a risk of touching the ground with the wingtip.

Duration of an encounter

A severe encounter, as described above, where the trajectories of both aircraft have an angle around 10 degrees, typically lasts around 4 to 6 seconds.

It is not possible to remain for a long time in a severe vortex as the rotating airflow on the wing and on the fin, eject the aircraft from the vortex. In line with the flight mechanics equations, it has been demonstrated during Airbus flight tests that the stabilization of a large aircraft inside a vortex can only be obtained by voluntarily establishing a large sideslip angle. As airliners do not and should not fly with large sideslip angles, they cannot remain in a vortex. Therefore, a vortex cannot be the cause of long duration turbulence.

Operational procedures

General procedure increases

Considering the way the vortex is acting on the aircraft as explained previously, if the pilot reacts at the first roll motion, to the right in the example given, he will correct by rolling to the left. When in the core of the vortex, the main roll motion to the left will then be amplified by this initial piloting action. The result will be a final bank angle greater than if the pilot would not have moved the controls.

This has also been demonstrated during the Airbus flight tests. Most of the encounters have been performed stick free, but several hundred were carried out with the pilot trying to minimize the bank angle. The results clearly show that pilot action does not improve the situation.

In addition, in-flight incidents have demonstrated that the pilot inputs may exacerbate the unusual attitude situation with rapid roll control reversals carried out in an "out of phase" manner.

In the case of a severe encounter the autopilot may disconnect automatically, but in all other cases, it will be able to counter properly the roll and pitch motions generated by the vortex.

For these reasons, the best procedure in case of encounter is:

RELEASE THE CONTROLS

Do not voluntarily disconnect the autopilot
If the autopilot is disconnected, before any reaction, wait for a reasonable stabilization of the aircraft, then:
- Roll wings level.
- Re-establish the initial cruise level or the standard climb or descent trajectory.

Use of rudder warning

A large deflection of the rudder creates a very important lateral acceleration that may well surprise the pilot. It could lead to a reaction with a deflection to the other side. This could then give rise to very large forces on the fin that may exceed the structural resistance. An accident has already occurred for this reason. Some recent aircraft types are protected thanks to their fly-by-wire systems, but anyway, any use of the rudder does not reduce the severity of the encounter nor does it improve the ease of recovery. Therefore:

DO NOT USE THE RUDDER

Lateral offset

If two aircraft are flying exactly on the same track, one being 1000 ft below the other, in the same or opposite direction, and if there is no cross wind, there is a risk of encounter with a vortex for the lower aircraft. In this case, it is possible to reduce the risk by using a lateral offset.

However, most of the time, it is difficult to know whether the other aircraft is flying with or without a small relative offset due to the lack of angular precision of the TCAS. Therefore, this offset is not a guarantee that an encounter will be avoided (except if the vortices are clearly visible by contrails).

In case of cross wind, if the two aircraft are flying exactly on the same track, the wind will move the vortices out of the track of the lower aircraft whilst they are descending. In this situation, if a lateral offset is decided for other reasons than wake vortex avoidance, an offset upwind by the follower is to be preferred, since a downwind one may potentially create an encounter.

Final approach

During the final approach, it has sometimes been suggested to maintain a trajectory slightly above the glide slope. This is not a satisfactory procedure for transport aircraft for several reasons:

- When established in descent on the standard approach slope, as the vortex is descending, there is little risk of encountering the vortices of the previous aircraft, except possibly when reaching the area of the ground effect. However, this possibility has not led to an unsafe situation (no accident in ground effect recorded on transport aircraft with standard separations).

- If the aircraft is flown too high above the threshold to avoid a possible encounter, it will lead to a long landing and therefore significantly increase the risk of runway excursion. It is well known that runway excursion is already, today, the main cause of accidents and such a technique would only increase that risk.

As a conclusion, a transport aircraft should not deviate from the standard approach slope to avoid a risk of encounter. However, for light aircraft, with low approach speed, approaching on a long runway, it is an acceptable procedure to perform a high approach and a long landing, targeting a touch down point after that of the previous aircraft.

It is to be noted that, when on an approach, there is no risk of encounter with the vortices of an aircraft taking-off on the same runway as a vortex will only move backward due to the wind effect. Such a vortex will have a very limited strength, and in the case of a strong headwind may even be dissipated completely. However, with crossing runways, depending on their geometry, and with inappropriate procedures, it may be possible that, very close to the ground, a landing aircraft enters the vortex of an aircraft which took-off on another runway. Pilots on the approach need to maintain a general vigilance and awareness, especially with calm wind conditions.

Departure

During the take-off phase, other than time separation, no avoidance procedure is applicable as the manoeuvre is dictated by characteristic speeds V1, Vr, V2, determined by the weight, the weather conditions and the runway. The time separations given for some aircraft types ensure that possible encounters after take-off remain controllable. When no time separation is given by ICAO rules, the separation is decided by the ATC to obtain a minimum radar separation, depending on the departure trajectory and long experience has demonstrated an acceptable level of safety.

For a light aircraft taking-off from a long runway behind a transport aircraft, it is recommended to choose the departure point in order to achieve a trajectory well above the preceding aircraft.

Separations

ICAO rules

Almost everywhere in the world the separations comply with the ICAO rules.

Classifications: Three categories of aircraft are defined according to the MTOW:
Heavy (H): above 136 tons.
Medium (M): between 7 and 136 tons.
Light (L): below 7 tons.

In addition, despite being classified as Heavy, the A380 is known as Super (S), and subjected to increased separations in approach, behind.

Cruise: In cruise, the separations are identical for all aircraft types:
Horizontally: 5 NM.
Vertically: 1000 ft.

Approach: On approach, the separations depend on the leader and the follower classification. The table below gives the separations for the various pairs on the same runway. They apply also to operations on different parallel runways if they are separated laterally by less than 760 m. To be noted that the A380 separations are not in the ICAO recommendations (PANS-ATM), but in a provisional State Letter published by ICAO in 2008.

		Follower			
		S	H	M	L
Leader	S		6 NM	7 NM	8 NM
	H		4 NM	5 NM	6 NM
	M				5 NM
	L				

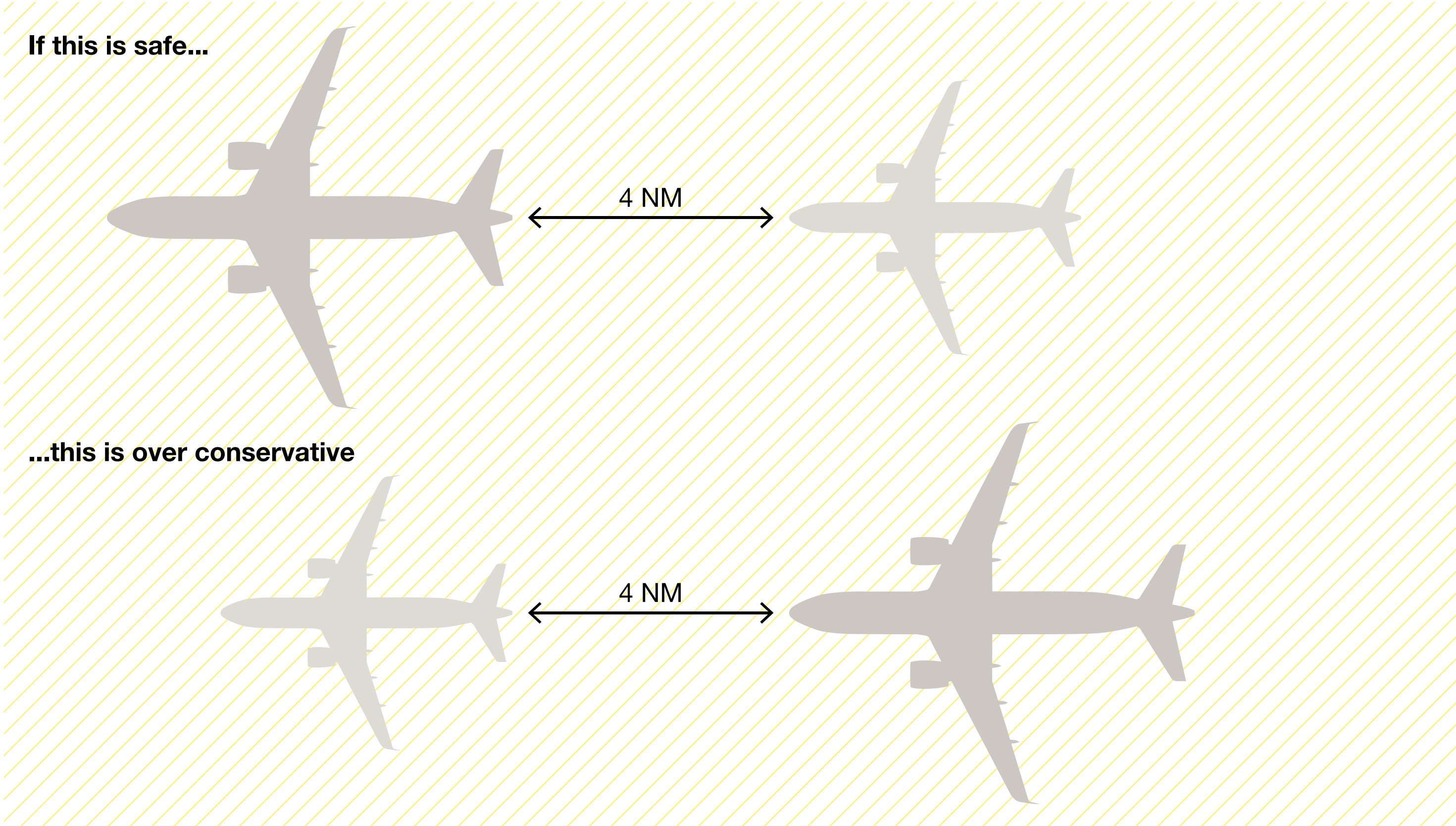
Other rules: The ICAO rules are used worldwide except in two Countries, USA and UK. These two Countries apply a different classification with different weight limits and separations.

RECAT (Re-categorization).

Principles of the re-categorization: The target of the re-categorization is to reduce the separations on approach and for departure between some aircraft pairs, without degradation of the safety levels, in order to improve the landing capacity of a given runway or runway couple.

The first step is called RECAT 1. All the aircraft are placed in 6 categories from A to F, A being the larger aircraft category. The principle is to divide the Heavies and the Medium each in 2 categories. As an example, today, the separations between Heavies are established for the worst case that is the smaller Heavy behind the bigger. However, if this bigger Heavy follows the smallest, common sense indicates that a reduction of separation is possible without any impact on the safety level **(fig.3).** Similarly, the separation may be reduced between two big Heavies or two small Heavies. The same principles apply to the Medium category. The target is that no situation should be worse than that which exists today with ICAO separations.

(fig.3)
Toward a reduction of aircraft separation minima to aircraft categories



RECAT 1 FAA: The FAA decided to reclassify the aircraft by MTOW and wingspan. The RECAT FAA is implemented on several US airports.

RECAT 1 EU: It appeared that the RECAT FAA approach was giving few benefits to the European airports due to the differences in the airlines fleets on both sides of the Atlantic. A RECAT EU was therefore developed. It takes into consideration not only the strength of the wake vortex of the leader aircraft, but also the resistance of the follower. The encounter tests performed by Airbus allowed validating some models used for the computations.

The RECAT 1 EU has also 6 categories:

A - Super Heavy: Including A380 and An124.
B - Upper Heavy: MTOW above 100 tons and wingspan between 52 m and 72 m.
C - Lower Heavy: MTOW above 100 tons and wingspan below 52 m
D - Upper Medium: MTOW between 15 and 100 tons and wingspan above 32 m.
E - Lower Medium: MTOW between 15 and 100 tons and wing span below 32 m
F - Light: MTOW below 15 tons.

The separations are as follows:

		Follower					
		Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
Leader	Super Heavy	3 NM	4 NM	5 NM	5 NM	6 NM	8 NM
	Upper Heavy		3 NM	4 NM	4 NM	5 NM	7 NM
	Lower Heavy			3 NM	3 NM	4 NM	6 NM
	Upper Medium						5 NM
	Lower Medium						4 NM
	Light						3 NM

The RECAT EU was approved by EASA end 2014. The implementation is planned at Paris-Charles-de-Gaulle airport in February 2016 and it will also be implemented in some airports worldwide.

It is to be noted that this implementation is not intended to be mandatory and only the most important European airports will use it, the other ones will keep the ICAO separations.

RECAT 2 and RECAT 3: The RECAT 2 is also called “pair-wise”, with a separation that takes into consideration the leader and the follower types, possibly by groups of aircraft. It will be implemented in the coming years.

The separations are not meant to avoid all encounters but to prevent unsafe ones. In very calm air, wake vortices encounters may lead to strong turbulence with significant bank angle and possibly some load factor when at high altitude.

Remember: Release the Controls and DO NOT use Rudder.