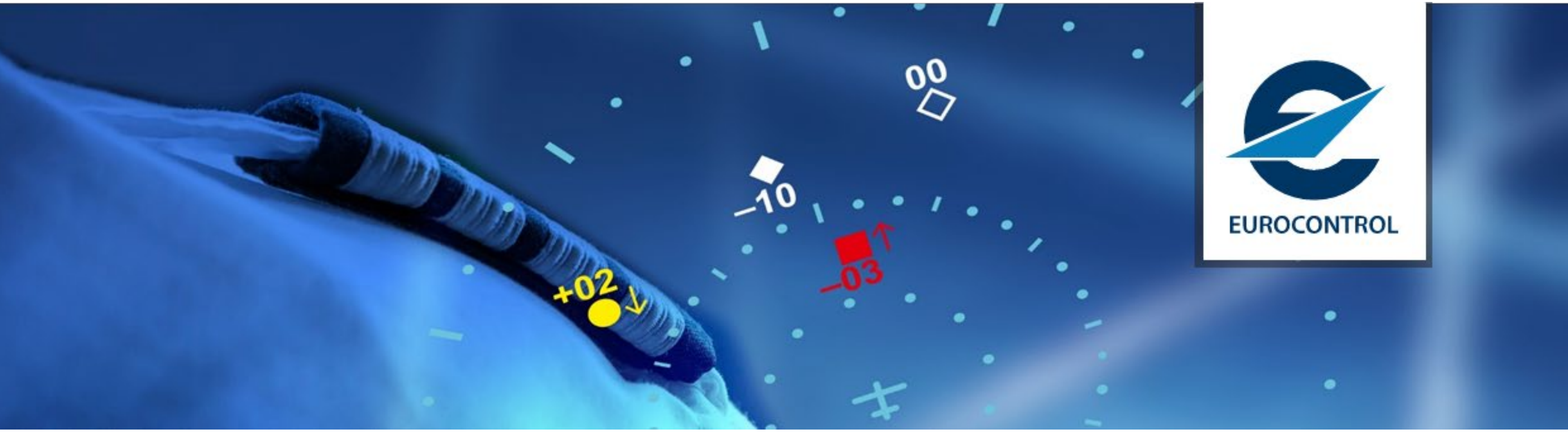


Technical information paper

TCAS II RAs during parallel approaches due to *tau*–cap mechanism

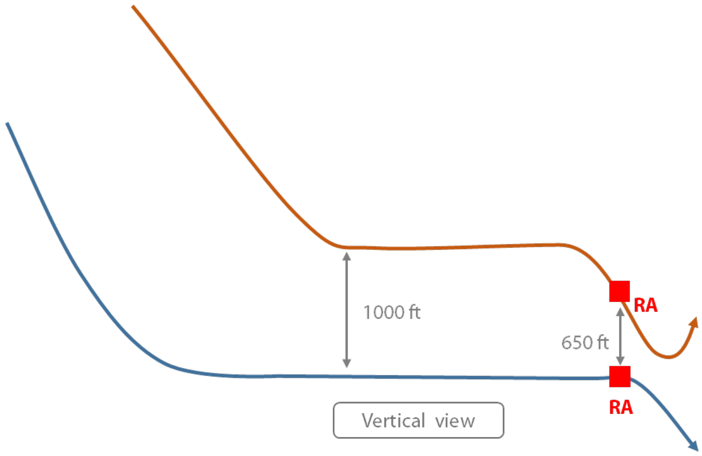
June 2023

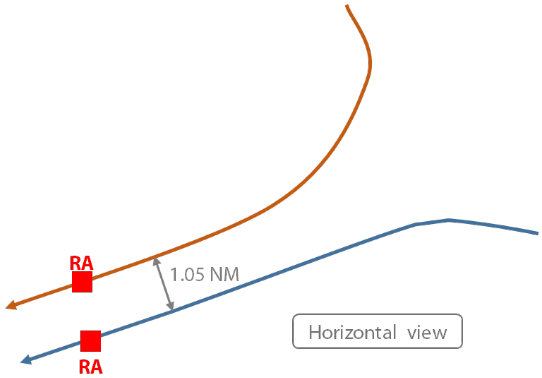
Background information

Reports of operationally unnecessary TCAS RAs have been received from a number of European airports as well as some airports outside Europe. Examples of horizontal and vertical trajectories are shown in the adjacent graphs.

In the reported cases, the aircraft were separated vertically by approximately 600 feet and horizontally by approximately 1 NM when they received coordinated TCAS II RAs, in some cases resulting in a missed approach by one of the aircraft.

This paper explains why, in certain conditions, TCAS II may generate operationally unnecessary RAs between two aircraft established on the final approach and performing independent parallel approaches.





***Tau*-cap mechanism**

TCAS II tracks nearby aircraft in order to protect against the risk of midair collision. This it does by issuing Resolution Advisories (RAs) when it diagnoses a risk of an imminent collision on the basis of an estimated time to collision (i.e., assuming the worst case scenario) and whether this falls below a certain time threshold. In order to be robust and remain independent of the means of separation provision, this estimate (known as *tau*) is based on a simple calculation derived only from the tracked range of the potential threat.

A consequence of the algebra of this simple calculation is that if there is a significant miss distance at closest approach ("significant" from a collision avoidance perspective can be much closer than from a separation provision perspective) the estimated time to collision can rise to arbitrarily large values while the aircraft are still converging.

If the TCAS II algorithms ignored this effect then an RA could be delayed or even prevented (depending on the altitude profiles) if the aircraft pass close to each other but remain on a straight course. However, if in this scenario one or other of the aircraft execute a late manoeuvre there will be insufficient time remaining before a potential collision for a timely and effective RA to be issued.

To overcome this deficiency the value of tau is "capped" (i.e., not allowed to increase) in encounters in which the aircraft are projected to pass close (from a collision avoidance perspective) to each other.

The *tau*-cap mechanism ensures that in close encounters in which there is a late manoeuvre a timely and effective RA can be issued. The drawback is that in instances of planned proximity (like parallel approaches) an RA can be issued even though there is not a late manoeuvre.

The *tau*-cap mechanism has been present in all operational versions of TCAS II logic, from version 6.02 (now obsolete), through version 7.1 (the version currently mandated in Europe).

Threat detection

The TCAS II threat detection algorithms onboard own aircraft declare an alert if an intruder simultaneously satisfies two criteria referred to as passing the Range Test and passing the Altitude Test.

The Range Test passes if, on the basis of tracked range and range-rate, the intruder is:

- currently close; or
- is projected to be close within some given time threshold.

The Altitude Test passes if, on the basis of tracked altitude and altitude-rate, the intruder is:

- currently close in altitude;
- or is projected to be close in altitude within some given time window.

In the Range Test 'close' (current or projected) means that the slant range between own aircraft and the intruder falls below a distance parameter (known as 'DMOD' – distance modifier – and which depends on altitude ranging from 0.2 NM near the ground to 1.1 NM en-route). The time threshold, *T*, also depends on altitude ranging from 15 seconds near the ground to 35 seconds en-route. The projected time to closest approach is known as *tau*, and when the aircraft are not on a collision course (i.e., there is projected to be a significant separation, in collision avoidance terms, at closest approach) this will be an overestimate.

The ostensibly surprising aspect of some of the alerts that occur on parallel approaches is that analysis of flight data recordings and/or diagnostics in simulated encounters reveals that they occur when the range is greater than the appropriate value of DMOD and the calculated value of *tau* is greater than the appropriate value of the time threshold *T*. The reason that in some circumstances the Range Test passes (and consequently, subject to the Altitude Test, an alert may be generated) is that the value of *tau* used in the Range Test has been 'capped' to a smaller value that was calculated earlier in the encounter. This capping is a consequence of the way in which a feature known as the Nuisance Alarm Filter (NAF) is implemented in the TCAS algorithms (explained in more detail in the Appendix) and occurs whenever the separation of the two aircraft is less than a parameter known as 'NAFRANGE' which has the value 1.7 NM.

When *tau* is capped below the alert time threshold, the Range Test passes on every cycle, and it is only the behaviour of the Altitude Test that determines whether and when an alert will be generated. This will only occur in some cases of parallel approaches when the aircraft trajectories will be within the parameter window in which the *tau*-cap mechanism is triggered, and RAs are generated. The majority of aircraft on parallel approaches will not experience this phenomenon.

Pilot and controller actions

Pilots cannot and should not attempt to assess in real time whether the RA is operationally needed. It can be done reliably in hindsight only through data analysis. In the event of an RA, the pilot must respond immediately by following the RA unless doing so would jeopardise the safety of the aircraft.

Air traffic controllers and pilots are advised not to undertake any actions in an attempt to prevent the occurrence of these RAs, as the combination of factors that triggers them (altitude, distance, closing speed) are complex and impossible to correctly predict at the ATC radar display or TCAS traffic display.

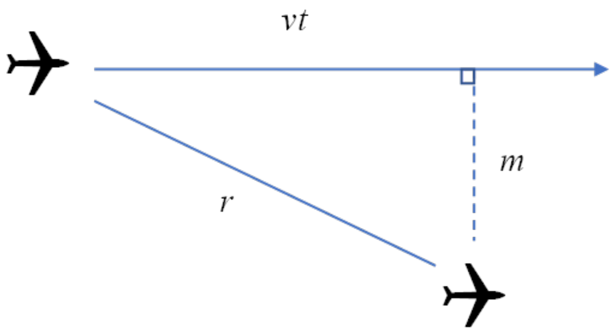
It should not be assumed that all RAs occurring during parallel approaches can be attributed to the *tau*-cap mechanism. The majority of aircraft on parallel approaches will not experience this phenomenon. Only very few parallel approaches will result in these operationally unnecessary RAs when the trajectories of the aircraft by coincidence fall within the narrow window in which the *tau*-cap mechanism RAs are generated. Each event needs to be investigated individually in order for conclusions to be drawn.

Conclusions

- Operationally unnecessary RAs occasionally observed during parallel approaches may be caused by the *tau*-cap mechanism in the TCAS II logic.
- Only very few parallel approaches will result in these operationally unnecessary RAs when the trajectories of the aircraft by coincidence fall within the narrow window in which the *tau*-cap mechanism RAs are generated.
- Not every RA during a parallel approach will be caused by the *tau*-cap mechanism.
- Pilots should follow all RAs even if they believe they are operationally unnecessary as that cannot be determined in real time.

Appendix

The simplest encounters to analyse algebraically are so-called 'linear encounters': encounters in which two aircraft travel, each with a constant velocity (i.e., fixed heading, speed, and vertical rate). The relative velocity in such encounters will be constant (equal to the vector difference of the individual velocities) with a fixed magnitude, *v*. The slant range between the two aircraft, *r*, will be a function of time and will have a minimum value, *m* (the 'miss distance'), at the instant of closest approach. Without loss of generality we can measure time relative to the instant of closest approach ($t = 0$), so that before closest approach, while the aircraft are converging (i.e., the range is decreasing), time is negative[1].



The geometry of a linear encounter is illustrated above[2]. From Pythagoras' Theorem we can write the slant-range as a function of time as

$$r(t) = \sqrt{(vt)^2 + m^2}$$

It is convenient to write this in the following form

$$r^2 = v^2t^2 + m^2$$

and differentiating both sides with respect to time and removing a factor of two, we have

$$r\dot{r} = v^2t$$

where $\dot{r}$ is the rate at which the range is changing with respect to time.

At any instant an estimate of the time remaining until closest approach, τ, can be formed from the ratio of the current range and the instantaneous rate at which this range is being eroded (i.e., a linear extrapolation to zero range)

$$\tau = -\left(\frac{r}{\dot{r}}\right) = -\left(\frac{r^2}{r\dot{r}}\right)$$

Note that because the range is decreasing, $\dot{r}$ is a negative quantity and the minus sign ensures that τ is a positive quantity. Substituting both parts of the fraction using the expressions above we get

$$\tau = -\left(\frac{v^2t^2 + m^2}{v^2t}\right) = -\left(t + \left(\frac{m}{v}\right)^2 \frac{1}{t}\right)$$

Note that this is only a reliable estimate (i.e., $\tau \approx -t$) when the miss distance is negligible (the aircraft are on a collision course), or the closing speed is very high, or the time remaining until closest approach is very large – otherwise it is an overestimate.

This expression for τ as a function of time is a hyperbola and goes through a minimum value before increasing to arbitrarily large values as the aircraft converge on closest approach ($t \to 0$). The critical time, t_{crit}, at which this minimum occurs can be found by differentiating the expression for τ with respect to time

$$\dot{\tau} = -\left(1 - \left(\frac{m}{v}\right)^2 \frac{1}{t^2}\right)$$

and setting it to zero

$$\dot{\tau} = 0 \Rightarrow -\left(1 - \left(\frac{m}{v}\right)^2 \frac{1}{t_{\text{crit}}^2}\right) = 0$$

The expression for the time of minimum τ is therefore found as

$$t_{\text{crit}} = -\frac{m}{v}$$

Substituting this value into the expression for range as a function of time we find that, in linear encounters, the estimated time to closest approach starts to increase when the range has decreased to a critical value r_{crit} given by

$$r_{\text{crit}} = \sqrt{2}m$$

Alerts in encounters in which the two aircraft ultimately pass with a significant separation are a nuisance. TCAS eliminates many of such alerts through a feature in the threat detection algorithms known as the Nuisance Alarm

[1] Naturally, in a real encounter we cannot be certain of the timing of closest approach before it occurs, but in this analysis we will eventually eliminate the variable *t*.

[2] The illustration is specific to a slow overtake encounter such as when two aircraft are following the same airway or are on approach to parallel runways. More generally the headings of the two aircraft would not necessarily be aligned with the relative velocity.

Filter (NAF)[3]. In collision avoidance terms a significant separation, *d*, is taken to be the magnitude of the horizontal offset that could conceivably be eroded in the event that one aircraft manoeuvred, thus rendering the encounter non-linear. Commercial aircraft rarely perform horizontal manoeuvres in excess of ⅓ *g*, and so the parameter *d* is set to be the distance resulting from such an acceleration throughout a period corresponding to the length of the time threshold *T*.

In TCAS this corresponds to the preset values of DMOD which are rounded to the nearest 0.05 NM.

The Nuisance Alarm Filter exploits the features of linear encounters by suppressing alerts in which the τ value is rising (which is symptomatic of an encounter with a finite miss distance). However, it is undesirable to suppress alerts in which this miss distance will be less than DMOD. This is achieved by capping the calculated τ value (so that it does not increase) if the current range is less than a given value, NAFRANGE, that indicates that the miss distance will be less than DMOD[4]. This corresponds to the situation in which we calculated the critical range r_{crit} above. The value of NAFRANGE is therefore set to be 10% greater than √2 times the maximum value of DMOD, or 110% × √2 × 1.1 NM = 1.7 NM[5].

[3] The Nuisance Alarm Filter is distinct from another, more sophisticated, feature known as the horizontal Miss Distance Filter.

[4] The Nuisance Alarm Filter is implemented via a *tau*-cap, rather than more direct means, because the filter was introduced during TCAS development after the Range Test and it was desired not to amend the latter's verified code.

[5] NAFRANGE is established as a single parameter because when the filter was introduced it was again desirable not to modify existing code with the introduction of another altitude dependent parameter.

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