Impact of Autoflight Vertical Modes on TCAS RAs

Capt. Martin Vecko
CSA–Czech Airlines

Contents

Description of TCAS Algorithm and Cockpit Indication

The use of TCAS (traffic alert and collision avoidance system) is to provide information and avoidance guidance for pilots in situations of mid-air collisions or near mid-air collisions between aircraft. Currently used TCAS II version 7.0 complies with ICAO standard for ACAS II (airborne collision avoidance system).

Its main features are:

- An airborne equipment that interrogates adjacent SSR transponders (intruders)
- It works independently of all other airborne and ground systems (aircraft navigation, FMS, ATC ground systems and clearance, pilot intention or autopilot inputs, aircraft performance degradation).
- Two types of alerts can be provided:

- TA (traffic alert) provides visual and aural warning of the conflicting traffic.
- RA (resolution advisory) is provided in case the intruder is equipped with C or S transponder mode. It offers a visual and aural guidance for vertical avoidance maneuver, i.e., establishment of safe vertical separation (300–700 ft). If both aircraft are equipped with transponder S mode, the maneuver is mutually coordinated (RA direction only).

- Collision criterion is based on CPA (closest point of approach) calculation, satisfying both horizontal and vertical test limits. The size of the protected volume depends on the altitude, speed and heading of the aircraft involved in the encounter.
- Alerts (TA, RA) are provided on the basis of time-to-go to the CPA (not range).
    - For TA 20–48 sec.
    - For RA 15–35 sec.
- These time scales are shorter at lower altitudes (where aircraft fly slower).
- Horizontal situation (i.e., relative bearing and distance of intruder) is visually provided on a modified VSI (vertical speed indicator) display or ND (navigation display). Azimuthal position is relatively inaccurate, with an error of up to 5 deg. Vertical limits of displayed intruders are typically +/- 2700 ft of relative altitude, with a possibility to extend this range in one direction up to 9900 ft (above / below function).
- Vertical RA guidance is visually provided on :
    - Dedicated instantaneous VSI (round dial), displaying the avoided / required VS area with red / green arc, respectively.
    - Vertical speed tape on PFD (primary flight display), displaying the avoided / required VS area with red / green band respectively.

- Using pitch cue, i.e., red trapezoid area on ADI (attitude director indicator) on PFD. Pitches to be avoided, corresponding to the VS to be avoided, are in the red trapezoid or double trapezoid area.

- The RA on the PFD vertical speed tape is sometimes reported to be difficult to interpret, being less intuitive than the pitch cue, namely in certain lighting conditions.

TCAS RA Statistics

The following data are based on CSA pilot reports and FDM program in the last three years (2006–2008). Within this period approximately 250,000 flights were performed. The majority of them were on European routes using Boeing 737-400 and -500 and Airbus 320 family. A total of 64 TCAS RA events were recorded and analyzed.

For a brief comparison, Eurocontrol data from the Eurocontrol ATM Safety Database are used [EVAIR Safety Bulletin, April 2008].

RAs were classified according to the Harmonization for European Incident Definition Initiative for ATM (HEIDI) taxonomy:

- **Useful RA** — events when TCAS generated an advisory in accordance with its technical specification in a situation where there was or could have been a risk of collision between the aircraft.

  In the CSA data sample these include pilot or ATC errors, encounter with military traffic and a corrective RA instruction to a previous RA that was not properly handled.

- **Unnecessary RA** — events when TCAS generated an advisory in accordance with its technical specification in a situation where there was not, nor could have been, a risk of collision.

  In the CSA data sample these events are all 1000 ft level-off maneuvers with a high vertical speed of the CSA or other traffic when approaching their cleared level.

- **Unclassifiable RA** —events when the reason for the RA could not be classified. In the CSA data sample these events include technical failures of TCAS equipment.

Results are shown in Figs. 1 and 2 for Eurocontrol and CSA data, respectively. For CSA events distribution per phase of flight, current flight level and geographic location is shown in Figs. 3, 4 and 5. Detailed analysis of these events show that all unnecessary RAs were caused by high vertical speed before level-off by one or both participating aircraft in the TCAS RA. In 31 percent of all RA events high vertical speed was used by CSA traffic, and in 20 percent it was the other traffic. Being conservative, this latter part of RAs is labeled as "probably unnecessary" in Fig. 2. Spectrum of RA commands issued in the category of unnecessary and all RAs are shown in Figs. 6a and 6b, respectively.

Eurocontrol recommendation is to reduce the vertical speed to less than 1000 fpm in the last 1000 ft to level-off. ICAO discussed a proposal for a recommendation to reduce the vertical rates to less than 1500 fpm in the last 1000 ft before level-off and its inclusion in Annex 6.

Had the traffic participating in these RA events followed these recommendations, the unnecessary RAs would not have occurred and the probably unnecessary RAs would probably not have occurred (Fig. 2).

Fig. 7 shows a single level-off encounter. Assuming a 30-sec time threshold to RA (at lower altitudes) and a climb rate of 3400 fpm (i.e., vertical closure rate of 3400 fpm), RA is generated approximately 700 ft prior to level-off.

Autoflight Vertical Modes

Following is a simplified review of most common vertical autoflight modes used for climb or descend.

Airbus 320 family (and similar):

- CLB (Climb) … managed mode using max. climb thrust with speed provided by FMGS or selected by a pilot

- OP CLB (Open Climb) … selected mode using max. climb thrust with speed provided by FMGS or selected by a pilot
- DES (Descend) … managed mode using thrust setting (idle thrust or higher) based on relative position to calculated vertical flight path; speed varying in a range calculated by FMGS or selected by a pilot
- OP DES (Open Descend) … selected mode using idle thrust with speed provided by FMGS or selected by a pilot
- VS … selected mode maintaining selected value of vertical speed in climb or descend (if performance in climb permits)

Boeing 737 (and similar):

- VNAV PTH (VNAV Path) for climb … max. climb thrust used with speed provided by FMS
- LVL CHG (Level Change) for climb … max. climb thrust used with speed selected by a pilot
- VNAV PTH (VNAV Path) for descend … thrust setting (idle thrust or higher) based on relative position to calculated vertical flight path with speed provided by FMS
- LVL CHG (Level Change) for descend … idle thrust used with speed selected by a pilot
- VS … mode maintaining selected value of vertical speed in climb or descend (if climb performance permits)

With the exception of VS, DES and VNAV PTH (for descend) these vertical modes optimize the climb or descend performance by using max. climb thrust or idle, respectively, and maintaining FMS-calculated or pilot-selected airspeed. They provide high vertical rates of climb or descend until altitude capture phase.

FDM (Flight Data Monitoring Program) Data

In this chapter we will display vertical rates throughout climb, descend and altitude capture phase using some of the autoflight vertical modes reviewed in previous chapter.

The following data come from an A319 flight with a MTOW (max. takeoff weight) of 68 tons. Figs. 8 and 9 represent climb to FL 280 and FL 360, respectively (with an actual takeoff weight of 50.5 tons), Fig. 10 climb to FL 390 (with an actual takeoff weight of 58 tons). Fig. 11 shows descend to FL 240. Climb is performed using CLB mode, descend is performed with OP DES mode. Diamonds are explicit values of recorded vertical speed at given level, and the solid line is a smooth line drawn through these values.

Final climb (approx. last two levels) to FL 280 and FL 360 is performed with vertical speed around or above 2000 fpm. Final climb to FL 390 used rates of less than 1500 fpm with a local increase to vertical speed of 1700 fpm approximately 500 ft before level-off.

Descend rates to FL 240 range from 3000 to 4500 fpm. Altitude capture with this rate occurs approximately 1000 ft prior to assigned level, i.e. at 24,992 ft.

The vertical speed values presented in these figures obviously depend on the actual takeoff weight. The A319 flight is presented for the possibility of using a more enhanced analysis software, AirFase, within CSA FDM program. Data from 737 operations would not be significantly different.

At a vertical separation of 1000 ft from the assigned level the vertical rates are significantly higher than the recommended values of max. 1000 fpm.

The above-used common autoflight vertical modes and altitude capture laws are optimized for an efficient climb or descend and a smooth altitude capture. But their vertical profiles do not comply with the recommended vertical speed rates during leveling off.

Negative Aspects of Unnecessary RAs

Execution of a TCAS RA maneuver might create some additional problems or inconvenience for the aircraft involved or for other traffic, originally not involved.

This could include:

- Inaccurate or erroneous manual aircraft handling throughout the RA maneuver. Standard operating procedures in case of a TCAS RA call for autopilot disconnection and manual flying. Disconnection of autothrust is required on some aircraft types. Explicit examples from FDM analysis show:
  - After correctly performing a TCAS RA (Descend) maneuver at 32,200 ft a 737 crew engaged the autopilot but forgot to re-engage the autothrust. Airspeed decreased from 265 to 224 kt with an activation of stick shaker.
  - An A320 crew received a TCAS RA (Climb) at level flight at FL 110. Their manual input was rough, resulting in a bank angle of 41 deg and vertical load ranging from 1.88 to 0.53 g.
- Opposite pilot responses to TCAS RAs were occasionally reported. Studies show that 4 percent of initial responses were wrong or opposite to the instructions provided by RA. A lecture dealing with analysis of such events was presented at the Air Europa's 2nd International Aviation Safety Conference (Jeff Bayless, United Airlines, Madrid, 2008). The opposite reactions might range from delayed response to confusion or conscious disregard of RA instruction. A tragic example of the latter is the 2002 accident over Uberlingen, Germany, where a TU-154 and Boeing 757 collided.
- Threat of reducing vertical separation with traffic not involved in the primary encounter when responding to RA. Assuming the situation in Fig. 7, the traffic at FL 110 could receive an RA instruction to climb to solve the primary conflict. This could create a secondary "chain" conflict with opposite traffic at FL 120.

The impact of the above-listed problems or difficulties (which is obviously not a complete list) is fully justified in case of a useful RA. On the other hand, even though these situations might not be numerous, it is worthwhile to reduce their impact in the case of unnecessary RAs.

How? Simply by reducing the number of unnecessary RAs.

Reduction of the Number of Unnecessary RAs

As shown above, most (if not all) of the unnecessary RAs are caused by high vertical rates during leveling off. Systematic adherence to the recommended reduction of vertical speed at level-off could reduce the number of unnecessary RAs which create a significant part of all RAs.

From the point of view of autoflight modes this can be achieved in two ways:

1. Systematic implementation of operational procedures requiring pilots to reduce vertical speed by their input or change the vertical mode of autoflight system. The most common way is the engagement of VS mode and a selection of reduced value of vertical rate (1000 fpm). It is a matter of great concern to perform this procedure well in advance.

   Fig. 12 displays an A320 climbing to FL 230 with vertical speed above 2500 fpm. Approximately at FL 215 the crew observed opposite traffic at FL 240 at a distance of approx. 12 NM. They engaged VS mode and selected vertical rate of 1200 fpm. Anyway, this reduction came too late and a TCAS RA (at 22,310 ft with vertical speed of 1800 fpm) was generated. In hindsight it was evaluated as unnecessary. Airbus A320 FDM data show that the autoflight system of the A320 family requires approximately 1000 ft for the reduction of intermediate vertical rate of 2500 fpm (in CLB mode) to a shallow climb of 1000 ft (after change of CLB mode to VS mode). In case of a reduction from a high rate of climb of 3500 fpm to a shallow climb of 1000 fpm, this altitude requirement is approximately 2000 ft.

   Using the situation in Fig. 7, this means that the transition from CLB mode to VS mode (with selection of a rate of 1000 fpm) has to be started approximately at FL 70. This shows that pilot input into the autoflight system has to be well in advance of level-off.

2. The second option is a modification of current autoflight vertical modes and altitude capture laws. This is a lengthy and challenging process, but could provide a robust solution to this problem.

Other solutions not involving the autoflight system are:

- Redesign of TCAS logic and algorithms using the information of selected altitude by participating traffic. This, on the other hand, would mean restricting the independent function of TCAS.
- Redesign of ATC routes (SID, STAR) to avoid the simultaneous horizontal and vertical convergence of aircraft.

Conclusion

TCAS is a powerful warning system providing a last-resort safety barrier to mid-air or near mid-air collision. This statement is valid if TCAS is properly used. Regardless of any discussed classification of RAs, the instructions of TCAS must be always followed by a pilot. Any evaluation has to be done in hindsight.

Significant improvement of TCAS use will be achieved by RA autoflight mode. This mode provides either FD guidance or automated flight throughout the RA maneuver. Using the terminology of risk management, this is a reactive approach, i.e., solving an existing conflict.

As stated above, TCAS is a warning system. Being proactive, we should aim at reducing the number of its activations, namely, in situations where this warning was evaluated as unnecessary. As up to approximately 50 percent of all RAs (CSA data) are unnecessary events caused by high vertical speed, this reduction can be achieved by limiting vertical speed during leveling off.

From the point of view of autoflight system this means:

- Implementation of operational procedures requiring pilot input into the current autoflight system.
- modification of autoflight vertical modes and altitude capture laws.

The first option aims its effort at pilots, the second at aircraft manufacturers. Both options are expensive and laborious, but worth it for improving aviation safety.

Fig. 1

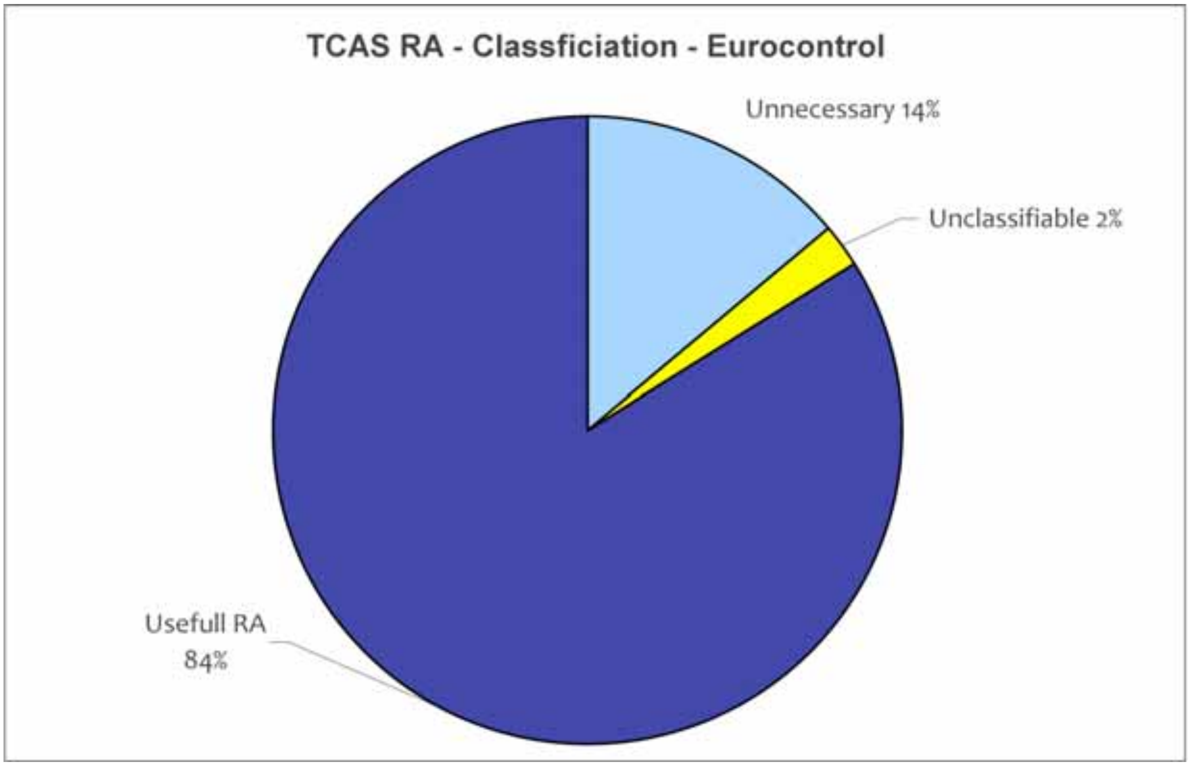

TCAS RA - Classficiation - Eurocontrol
Unnecessary 14%
Unclassifiable 2%
Usefull RA
84%

Fig. 2

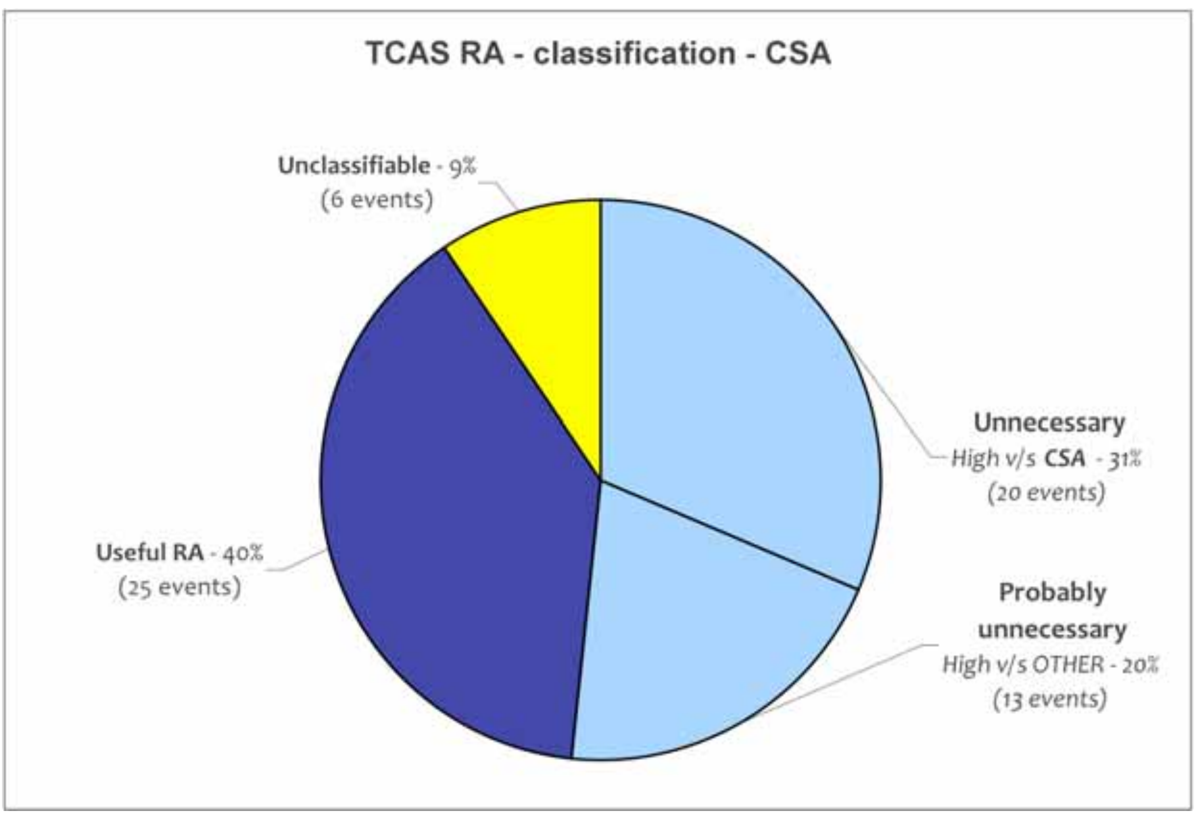

TCAS RA - classification - CSA
Unclassifiable - 9%
(6 events)
Unnecessary
High v/s CSA - 31%
(20 events)
Useful RA - 40%
(25 events)
Probably
unnecessary
High v/s OTHER - 20%
(13 events)

Fig. 3

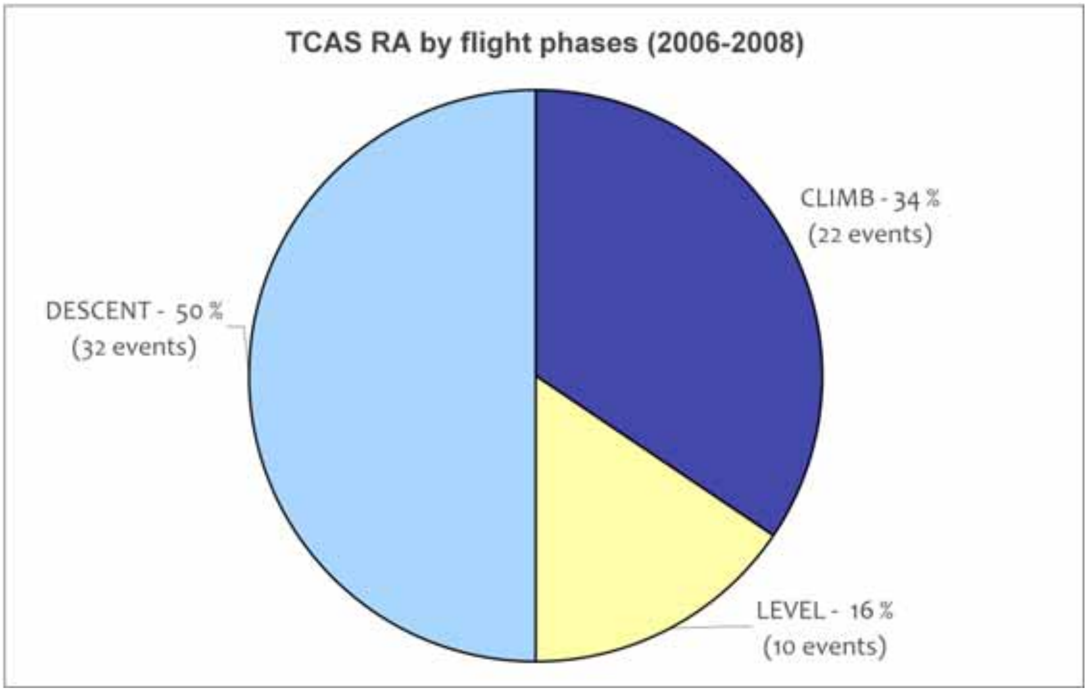

TCAS RA by flight phases (2006-2008)
CLIMB - 34 %
(22 events)
DESCENT - 50 %
(32 events)
LEVEL - 16 %
(10 events)

Fig. 4

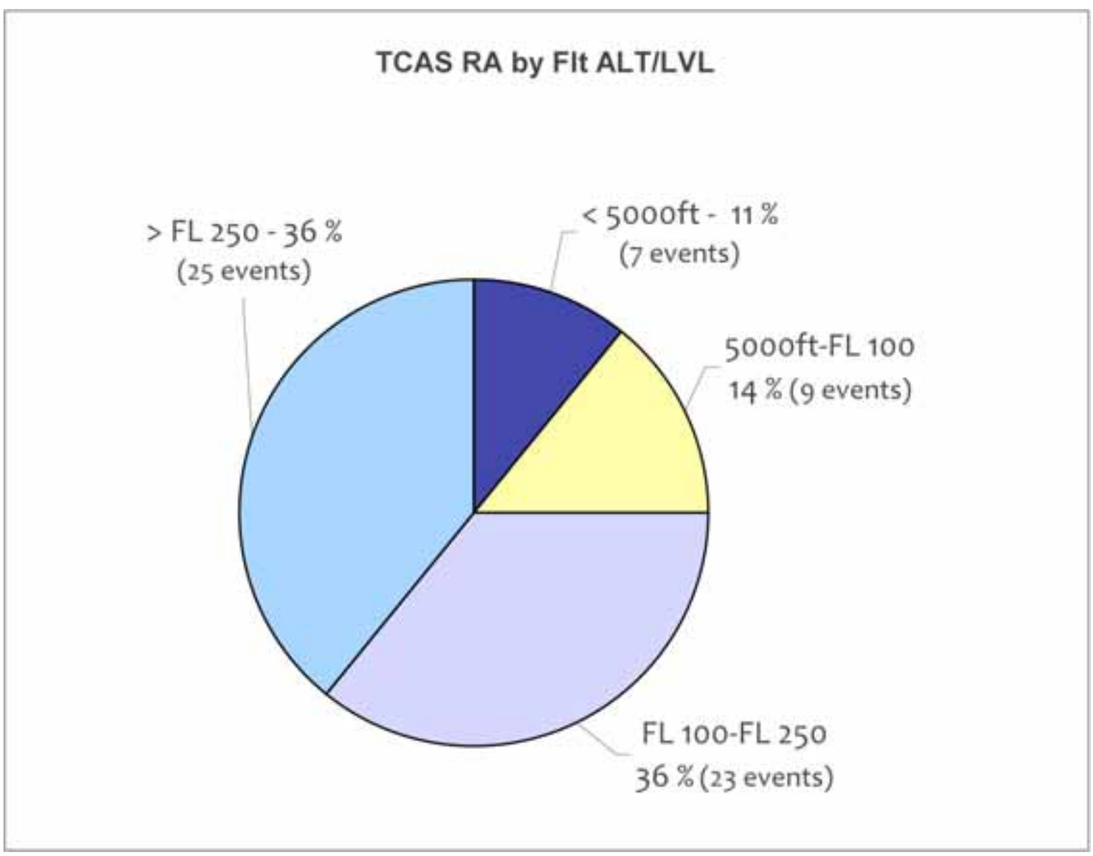
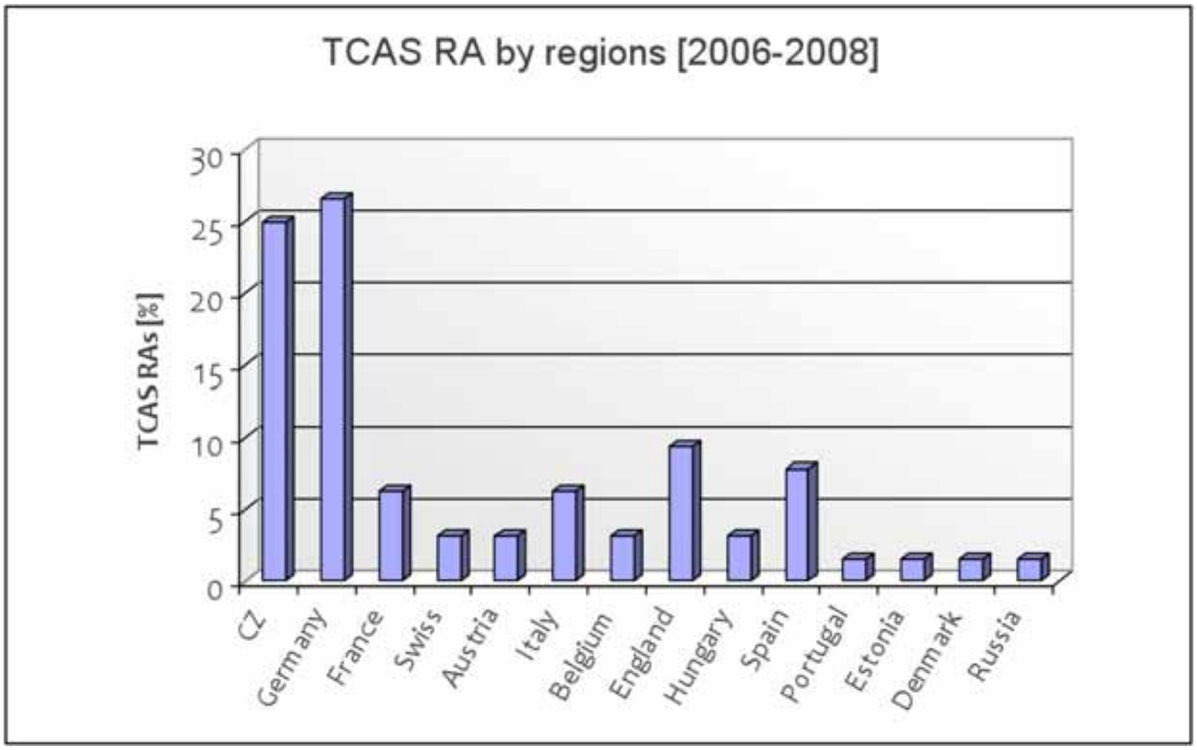

TCAS RA by Flt ALT/LVL
> FL 250 - 36 %
(25 events)
< 5000ft - 11 %
(7 events)
5000ft-FL 100
14 % (9 events)
FL 100-FL 250
36 % (23 events)

Fig. 5



TCAS RA by regions [2006-2008]
TCAS RAs [%]
30
25
20
15
10
5
0
CZ
Germany
France
Swiss
Austria
Italy
Belgium
England
Hungary
Spain
Portugal
Estonia
Denmark
Russia

Fig.6a

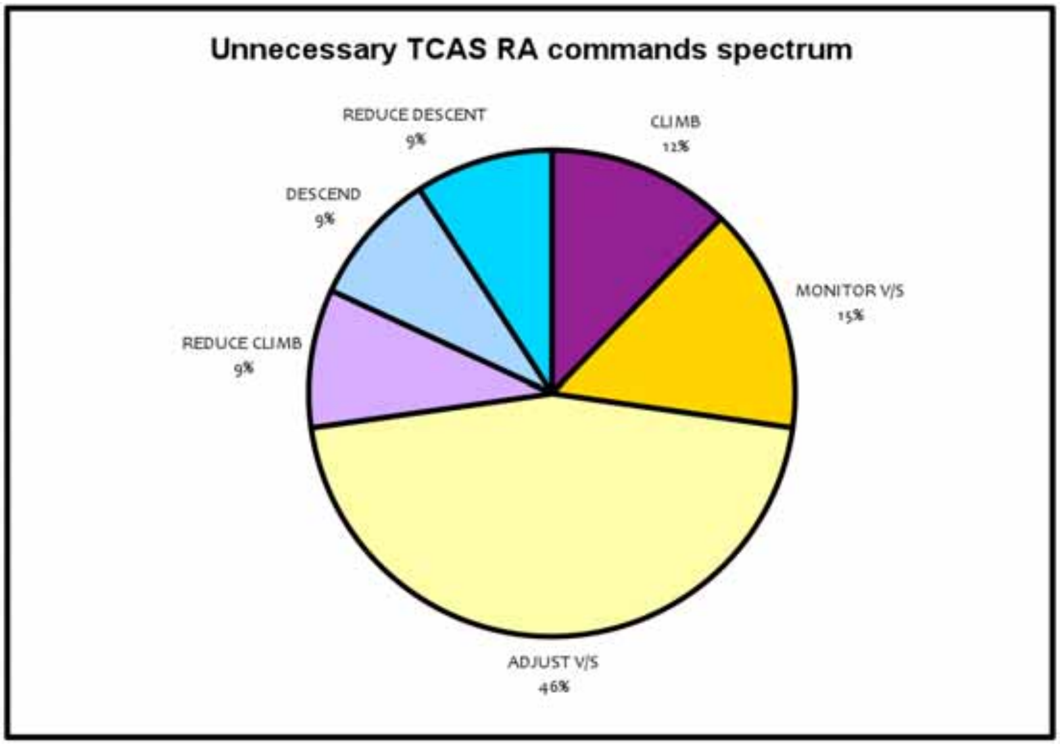

Unnecessary TCAS RA commands spectrum
REDUCE DESCENT
9%
CLIMB
12%
DESCEND
9%
MONITOR V/S
15%
REDUCE CLIMB
9%
ADJUST V/S
46%

Fig. 6b

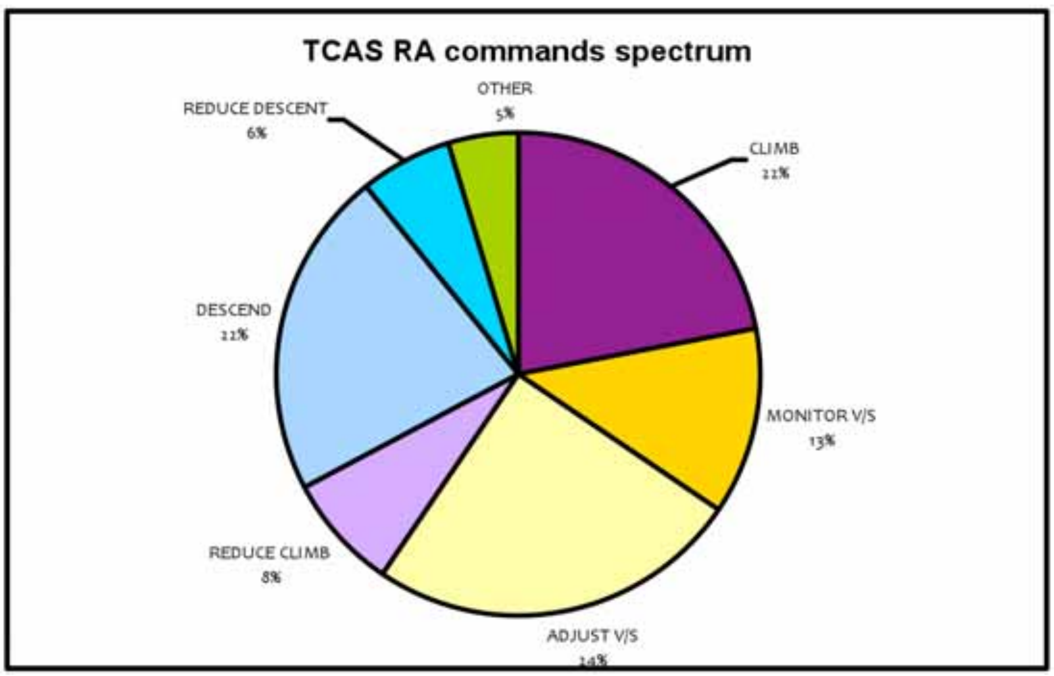

TCAS RA commands spectrum
OTHER
5%
REDUCE DESCENT
6%
CLIMB
22%
DESCEND
22%
MONITOR V/S
13%
REDUCE CLIMB
8%
ADJUST V/S

Fig. 7

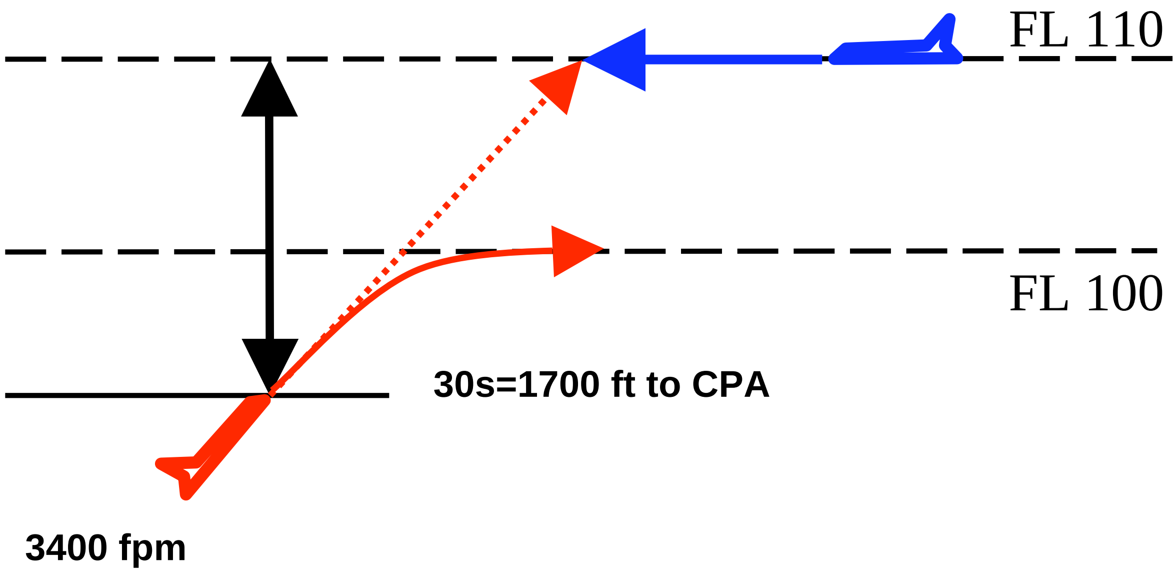


Fig. 8

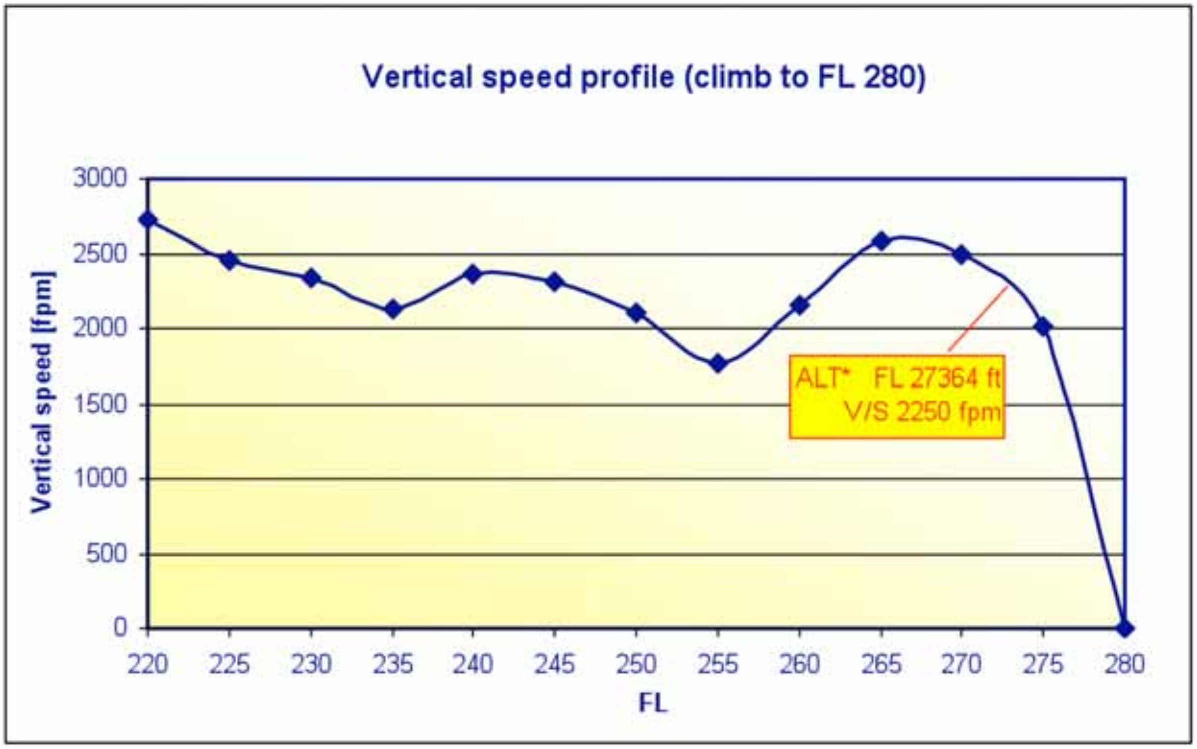

Vertical speed profile (climb to FL 280)
Vertical speed [fpm]
3000
2500
2000
1500
1000
500
0
220
225
230
235
240
245
250
255
260
265
270
275
280
FL
ALT* FL 27364 ft
V/S 2250 fpm

Fig. 9

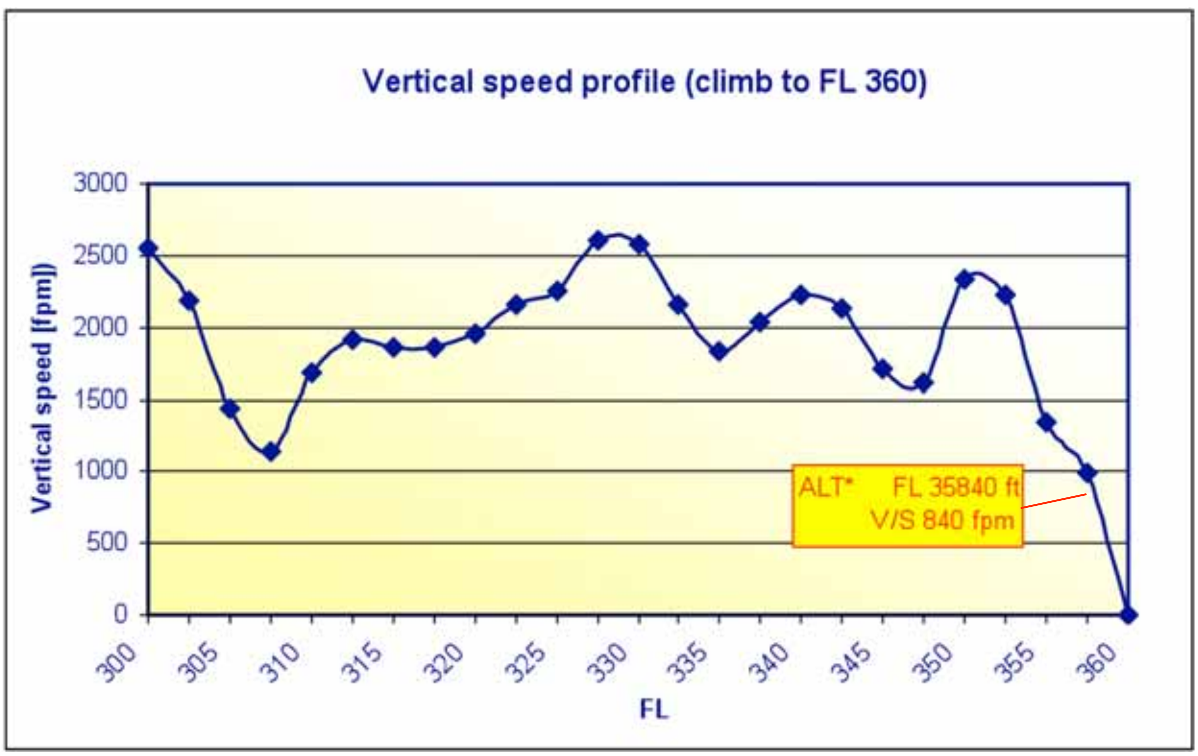

Vertical speed profile (climb to FL 360)
Vertical speed [fpm])
3000
2500
2000
1500
1000
500
0
300
305
310
315
320
325
330
335
340
345
350
355
360
FL
ALT* FL 35840 ft
V/S 840 fpm

Fig. 10

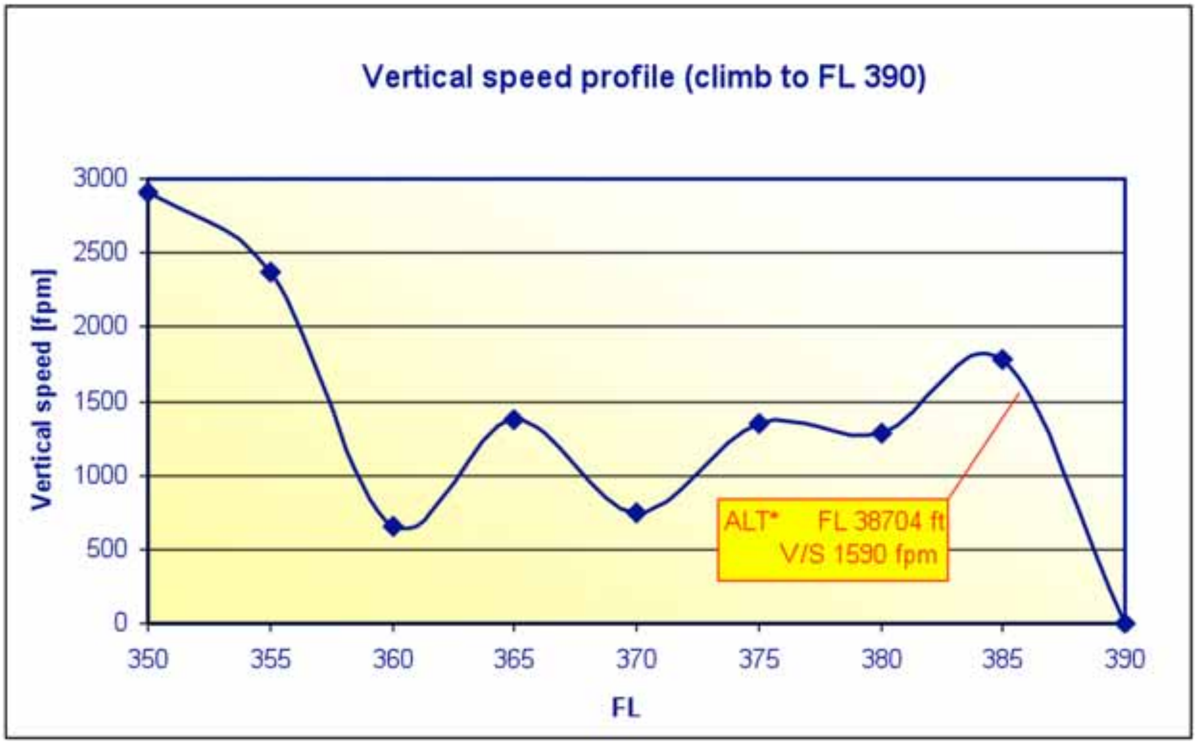

Vertical speed profile (climb to FL 390)
Vertical speed [fpm]
3000
2500
2000
1500
1000
500
0
350
355
360
365
370
375
380
385
390
FL
ALT* FL 38704 ft
V/S 1590 fpm

Fig. 11

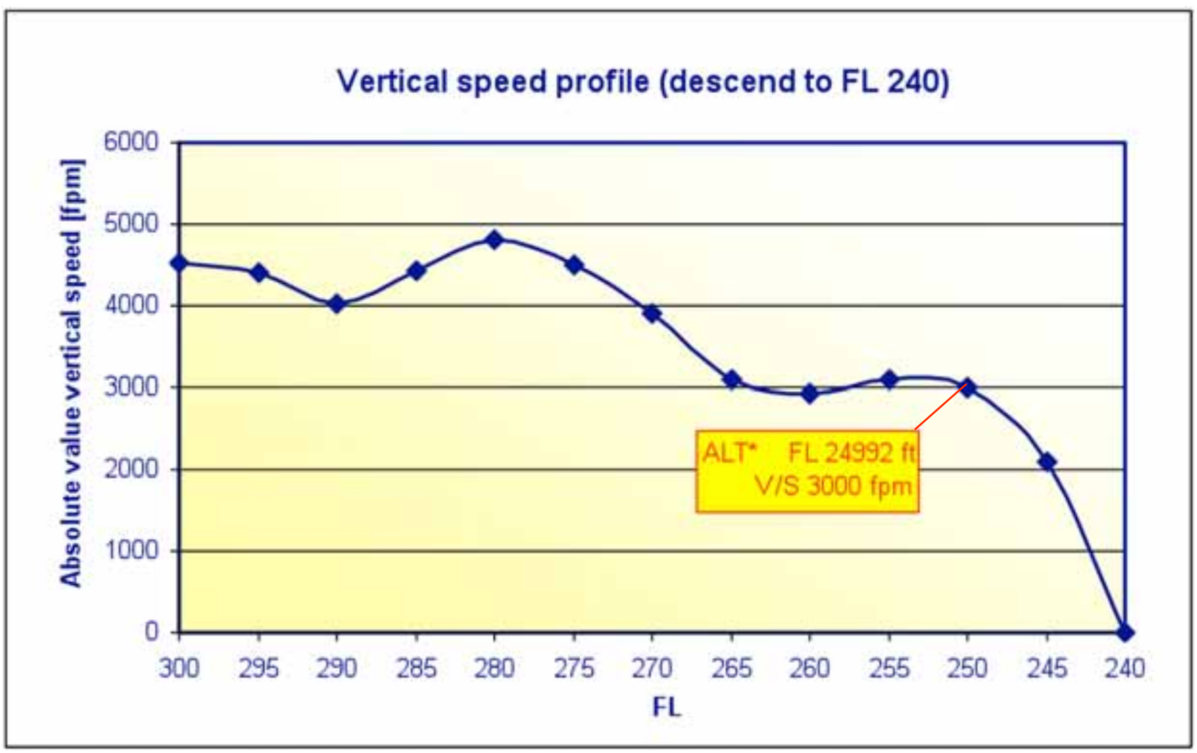
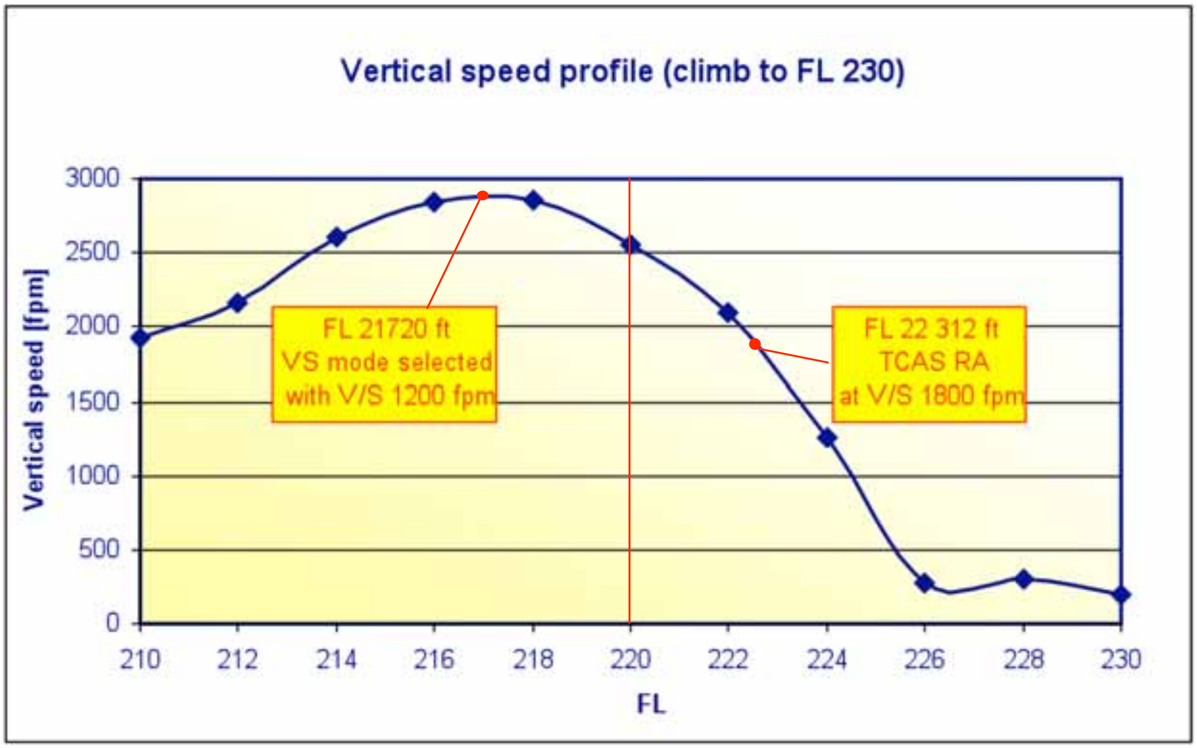

Vertical speed profile (descend to FL 240)
Absolute value vertical speed [fpm]
6000
5000
4000
3000
2000
1000
0
300
295
290
285
280
275
270
265
260
255
250
245
240
FL
ALT* FL 24992 ft
V/S 3000 fpm

Fig. 12



Vertical speed profile (climb to FL 230)
Vertical speed [fpm]
3000
2500
2000
1500
1000
500
0
210
212
214
216
218
220
222
224
226
228
230
FL
FL 21720 ft
VS mode selected
with V/S 1200 fpm
FL 22 312 ft
TCAS RA
at V/S 1800 fpm