AIRCRAFT FLIGHT TRAJECTORY DEVIATION IN THE STANDARD INSTRUMENT DEPARTURES. OPERATORS PENALTIES

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Abstract

In the recent years many problems are emerging due to the aircraft noise on the airport surrounding areas. The solution to this problem is not easy considering that the neighbourhood asks for the reduction of the number of aircraft operations and the airlines ask for a growing demand in the number of operations in the major airports. So the airport and regulatory authorities try to get a solution imposing a fine to the aircraft which its actual trajectory differs from the nominal one more than a lateral deviation. But, which is the value of this deviation?. The current situation is that many operators have to pay a lot of money for exceeding a deviation which has been established without operational criteria.

This paper presents the results of a research program which is being carried out by the authors which aims to determine the "delta" deviation to be used for this purpose. In addition it is proposed a customized method per SID and per airport to be used for determining the maximum allowed lateral deviation by which if the aircraft is within it, then none fine will be imposed.

The paper will also explain the current criteria used to design and publish the SIDs and will show the results of the performed assessment for determining the deviation of different aircraft families flying the same departure procedure in an airport aiming to define a current deviation value considering operational factors such airfield elevation, temperature, wind, SID design, etc.
And last, the method for determining the allowed lateral deviation without any penalty consists in the computation of a set of templates per aircraft family/SID/airport, in such a way that a particular deviation could be compared against the corresponding template. When the trajectory to be assessed is within the selected template limits, it will mean none penalty should be imposed..

1 SID published vs SID flown

In the design of a Standard Instrument Departure (SID) many factors are considered [1], being one of the most important the speed of the aircraft. From the flight predictability point of view, in order to avoid the over-flight of certain urban areas is the speed the most important factor. It is easy to understand that the higher speed the larger turn radii.

Generally speaking, the largest deviation between the actual and published paths are given at the turn points, in particular when the aircraft ends the turn until it tries to reassume to the next straight path segment. Due to that, the point in which the turn will be fixed is a key element for the procedure designer from the noise alleviation point of view.

Bearing in mind the standards, the operational requirements and his experience, the procedure designer will choose, the best position for fixing such a point; however, when the SID is implemented a large deviation between the actual path flown and the published one exists. But, which is the cause for such a deviation?

The answer can be found in the PANS-OPS [2]. ICAO establishes "When close conformance to an accurate track, especially for turning departures (for noise abatement/ATC constraints, etc), **statistical data** on aircraft performance can be used to determine the procedure with the average flight path". So this text says that the trajectory is published/drawn in the navigation chart considering an **average flight path.** But, which is the meaning of an average flight path?, the average for all aircraft categories, or the average for each of the category. This issue is the first cause for the not conformance between both path. If the average flight path has been computed and drawn for a Cat D, it is easy to understand that a Cat C or B aircraft will not flight on the same path exactly. This is the cornerstone of this paper: **Is it acceptable to impose a fine to an operator when a deviation between the published and the actual flown path is given?** Most of the deviations should not cause the imposition of a fine, so to know which the threshold for this imposition is, may be a good justification for this research program.

2 SID analysis per fleet

In this research project several SIDs at different airports were analysed. Due to do not to extend the text too much, only required results for conclusions justification are included.

The results shown along this chapter are aiming to quantify the lateral deviation when different aircraft fleets have flown part of a SID at Madrid-Barajas airport.

This analysis has been performed per fleet aiming to demonstrate different behaviour when same procedure is flown by different aircraft. This difference in lateral deviation could justify the use of distinct lateral deviation figures in order to impose a fine.

The following results correspond to different aircraft fleet when first segments of some of the SIDs used at Madrid-Barajas airport: PINAR 2R, RBO1R, NANDO 3R, NASOS 3R, CJN1R Y VTB 2W, actually in use in RWY 36R have been flown. All of these procedures have their first segments in common. (See figure 1).

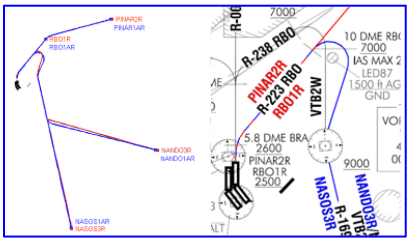

Fig. 1- First segments of analysed SIDs

The SIDs description corresponding to these first segments is as follows [3]: "Climb on heading 017º direct to 5,8 DME BRA at 2600 ft or higher, then to intercept and follow R223 RBO direct to ………"

Every trajectory analysed and showed along this paper has been obtained from data recorded from an ADS-B receiver installed at the Polytechnic University of Madrid.

The first exercise performed consisted in the analysis of the actual path flown by two aircraft (A320 and A340). Figure 2 shows the first segments. The first one was to follow a heading 017 then a 25º right turn to follow R-223 RBO. In right side of figure 2 can be observed the actual deviation of these two aircraft (A320 in red, A340 in blue) related to the nominal route (green). Without any particular consideration, it can be affirmed the difference in lateral deviation for different aircraft.

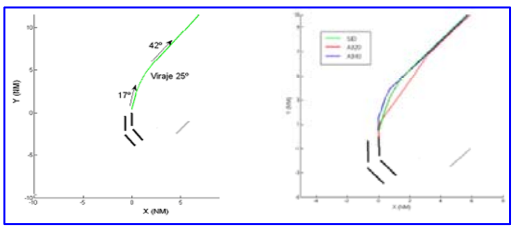

Fig. 2- Comparison between flown and published paths (A-320 y A340)

A more in dept analysis for computing lateral and vertical deviations at different distances from the End of the Runway (DER) was carried out.

These different distances were called “sections”. For this goal four sections were used in such a way that “S0”is the section at the DER; “S2”, “S4” and “S6” are the sections sited at 2, 4 and 6 nautical miles from DER respectively.

Figure 3, on its left side, shows the situation of each section and lateral deviation at these sections are shown for a set of aircraft on the right side

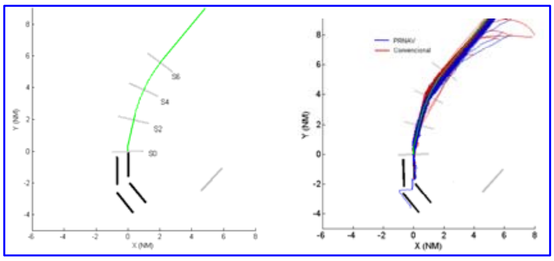

Fig. 3- Nominal path and sections (left side). Lateral dispersion for 400 aircraft (right side)

In order to know the exact value of these deviations many trajectories were analysed. The analyses were performed per type of aircraft, so the selected fleets were: A320, B738 y CRJ2.

Figure 4 shows the lateral and vertical deviations in each section for A320 family when the mentioned SID were flown by them. Blue dots (PRNAV) and red dots (Conventional navigation) represent the aircraft positions at each section for a particular flight. The boxes represent the limits of ± 1σ, ± 2σ, ± 3σ standard deviation. It is important to highlight that from the beginning (see section 2, Figure 4b) lateral deviation among aircraft trajectories of more than 600 m and 2500 ft in vertical dimension are obtained.

In figures 4, the 0 value in abscises axis correspond to the nominal route which is published in the AIP. As it is can be observed in figure 4a, at the DER, for a total of 3484 aircraft analysed, the results show a 12,4 m of mean lateral deviation on the right and a Standard deviation of ± 26,9 m. For the same fleet at section “S2” the results are highly important, the mean lateral deviation is -47,6 m (left side) and the standard deviation increases up to 86,1 m. In section 4 the mean lateral deviation is -57,1 m and the standard deviation is 194,5 m; and last, in section 6 the mean lateral deviation is 327,4 m and the standard deviation is 214,4 m. Main results for the three fleet in terms of lateral and vertical deviation are presented in tables 1,2 and 3.

Looking at figures 4a, to 4d, it can be observed how the set of points are splitting into two groups. A later analysis allowed to know that this division was due to aircraft flying under PRNAV (blue dots) or under conventional navigation (red dots). In these figures, the central histogram corresponds to both of them together and the right one was obtained computing the PRNAV and conventional independently.

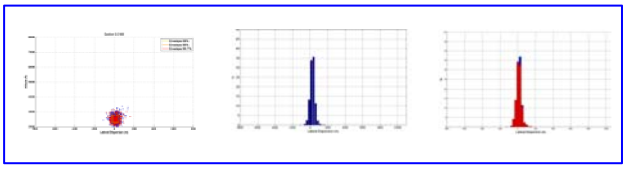

Fig. 4a- A320. Deviations at DER (Section S0)

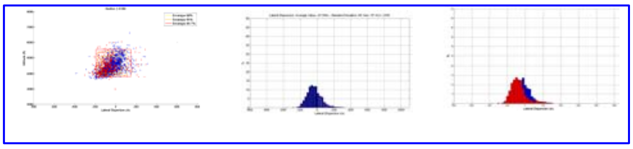

Fig. 4b- A320. Deviations at section S2 (2 nm from DER)

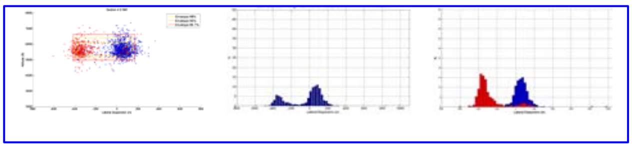

Fig. 4c- A320. Deviations at section S4 (4 nm from DER)

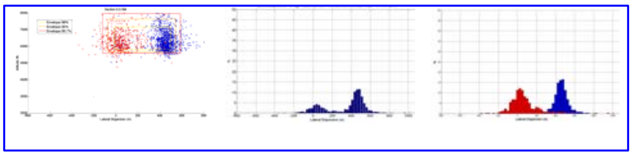

Fig. 4d- A320. Deviations at section S6 (6 nm from DER)

Tables 1, 2 and 3 show the summary of the results reached from this first analyses in terms of lateral and vertical deviation from the nominal trajectory for three different aircraft fleet (A320, B738 y CRJ2). For A320 and B738 fleet three tables for each one have been included. The data correspond to PRNAV + conventional together, only PRNAV and only conventional.

A320 fleet (Conventional + PRNAV navigation) (sample number 3484 A/Cs)																
Section (NM)	Lateral Deviation (m)								Vertical Deviation (ft)							
	Mean μ_{DL}	σ_{DL}	$\mu_{DL} \pm\sigma_{DL}$		$\mu_{DL} \pm2\sigma_{DL}$		$\mu_{DL} \pm3\sigma_{DL}$		Mean μ_{DV}	σ_{DV}	$\mu_{DV} \pm\sigma_{DV}$		$\mu_{DV} \pm2\sigma_{DV}$		$\mu_{DV} \pm3\sigma_{DV}$	
			Left	Right	Left	Right	Left	Right			Low	Up	Low	Up	Low	Up
0 (DER)	12,4	26,9	-14,5	39,3	-41,4	66,2	-68,3	93,1	2487	215	2272	2702	2057	2917	1842	3132
2	-47,6	86,1	-133,7	38,5	-219,8	124,6	-305,9	210,7	4491	453	4038	4944	3585	5397	3132	5850
4	-57,1	194,5	-251,6	137,4	-446,1	331,9	-640,6	526,4	5634	408	5226	6042	4818	6450	4410	6858
6	327,4	214,4	113	541,8	-101,4	756,2	-315,8	970,6	6347	613	5734	6960	5121	7573	4508	8186

Table 1.a- A320. (Conventional + PRNAV) Summary of deviations at the first turn (25º Right)

A320 Fleet (PRNAV only) (sample number: 2338 A/Cs)																
Section (NM)	Lateral Deviation (m)								Vertical Deviation (ft)							
	Mean μ_{DL}	σ_{DL}	$\mu_{DL} \pm\sigma_{DL}$		$\mu_{DL} \pm2\sigma_{DL}$		$\mu_{DL} \pm3\sigma_{DL}$		Mean μ_{DV}	σ_{DV}	$\mu_{DV} \pm\sigma_{DV}$		$\mu_{DV} \pm2\sigma_{DV}$		$\mu_{DV} \pm3\sigma_{DV}$	
			Left	Right	Left	Right	Left	Right			Low	Up	Low	Up	Low	Up
0 (DER)	12,7	26,0	-13,3	38,6	-39,3	64,6	-65,2	90,6	2496	218	2278	2714	2060	2932	1842	3150
2	-34,8	80,7	-115,5	45,9	-196,2	126,6	-276,9	207,3	4507	452	4055	4959	3603	5411	3151	5863
4	54,0	77,4	-23,5	131,4	-100,9	208,8	-178,4	286,3	5646	405	5241	6051	4836	6456	4431	6861
6	458,0	81,5	376,5	539,5	295,0	621,0	213,5	702,5	6348	604	5744	6952	5140	7556	4536	8160

Table 1.b- A320. (PRNAV only) Summary of deviations at the first turn (25º Right)

A320 fleet (Conventional navigation) (samples number: 1146 A/Cs)																
Section (NM)	Lateral Deviation (m)								Vertical Deviation (ft)							
	Mean μ_{DL}	σ_{DL}	$\mu_{DL} \pm\sigma_{DL}$		$\mu_{DL} \pm2\sigma_{DL}$		$\mu_{DL} \pm3\sigma_{DL}$		Mean μ_{DV}	σ_{DV}	$\mu_{DV} \pm\sigma_{DV}$		$\mu_{DV} \pm2\sigma_{DV}$		$\mu_{DV} \pm3\sigma_{DV}$	
			Left	Right	Left	Right	Left	Right			Low	Up	Low	Up	Low	Up
0 (DER)	11,7	29,4	-17,7	41,1	-47,1	70,5	-76,5	99,9	2476	207	2269	2683	2062	2890	1855	3097
2	-72,6	92	-164,6	19,4	-256,6	111,4	-348,6	203,4	4477	458	4019	4935	3561	5393	3103	5851
4	-282,8	164,9	-447,7	-117,9	-612,6	47	-777,5	211,9	5627	415	5212	6042	4797	6457	4382	6872
6	62,5	140,5	-78	203	-218,5	343,5	-359	484	6369	641	5728	7010	5087	7651	4446	8292

Table 1.c- A320. (Conventional only) Summary of deviations at the first turn (25º Right)

B738 fleet (Conventional + PRNAV navigation) (samples number: 776 A/Cs)																
Section (NM)	Lateral Deviation (m)								Vertical Deviation (ft)							
	Mean μ_{DL}	σ_{DL}	$\mu_{DL} \pm\sigma_{DL}$		$\mu_{DL} \pm2\sigma_{DL}$		$\mu_{DL} \pm3\sigma_{DL}$		Mean μ_{DV}	σ_{DV}	$\mu_{DV} \pm\sigma_{DV}$		$\mu_{DV} \pm2\sigma_{DV}$		$\mu_{DV} \pm3\sigma_{DV}$	
			Left	Right	Left	Right	Left	Right			Low	Up	Low	Up	Low	Up
0 (DER)	12	34,4	-22,4	46,4	-56,8	80,8	-91,2	115,2	2397	208	2189	2605	1981	2813	1773	3021
2	-35,5	163	-198,5	127,5	-361,5	290,5	-524,5	453,5	4239	447	3792	4686	3345	5133	2898	5580
4	-154,2	266,5	-420,7	112,3	-687,2	378,8	-953,7	645,3	5662	456	5206	6118	4750	6574	4294	7030
6	251,9	286,2	-34,3	538,1	-320,5	824,3	-606,7	1110,5	6647	707	5940	7354	5233	8061	4526	8768

Table 2.a- B738. (Conventional + PRNAV) Summary of deviations at the first turn (25º Right)

B738 fleet (PRNAV only) (samples number: 324 A/Cs)																
Section (NM)	Lateral Deviation (m)								Vertical Deviation (ft)							
	Mean μ_{DL}	σ_{DL}	$\mu_{DL} \pm\sigma_{DL}$		$\mu_{DL} \pm2\sigma_{DL}$		$\mu_{DL} \pm3\sigma_{DL}$		Mean μ_{DV}	σ_{DV}	$\mu_{DV} \pm\sigma_{DV}$		$\mu_{DV} \pm2\sigma_{DV}$		$\mu_{DV} \pm3\sigma_{DV}$	
			Left	Right	Left	Right	Left	Right			Low	Up	Low	Up	Low	Up
0 (DER)	10,6	26,9	-16,3	37,5	-43,2	64,4	-70,1	91,3	2383	211	2172	2594	1961	2805	1750	3016
2	91,3	111,3	-20	202,6	-131,3	313,9	-242,6	425,2	4227	409	3818	4636	3409	5045	3000	5454
4	91,8	88,7	3,1	180,5	-85,6	269,2	-174,3	357,9	5643	409	5234	6052	4825	6461	4416	6870
6	533,1	50,4	482,7	583,5	432,3	633,9	381,9	684,3	6571	609	5962	7180	5353	7789	4744	8398

Table 2.b- B738. (PRNAV only) Summary of deviations at the first turn (25º Right)

B738 fleet (Conventional navigation) (sample number: 452 A/Cs)																
Section (NM)	Lateral Deviation (m)								Vertical Deviation (ft)							
	Mean μ_{DL}	σ_{DL}	$\mu_{DL} \pm\sigma_{DL}$		$\mu_{DL} \pm2\sigma_{DL}$		$\mu_{DL} \pm3\sigma_{DL}$		Mean μ_{DV}	σ_{DV}	$\mu_{DV} \pm\sigma_{DV}$		$\mu_{DV} \pm2\sigma_{DV}$		$\mu_{DV} \pm3\sigma_{DV}$	
			Left	Right	Left	Right	Left	Right			Low	Up	Low	Up	Low	Up
0 (DER)	13,4	39,7	-26,3	53,1	-66	92,8	-105,7	132,5	2409	205	2204	2614	1999	2819	1794	3024
2	-126,3	130,3	-256,6	4	-386,9	134,3	-517,2	264,6	4248	473	3775	4721	3302	5194	2829	5667
4	-330,3	204,3	-534,6	-126	-738,9	78,3	-943,2	282,6	5676	487	5189	6163	4702	6650	4215	7137
6	50,6	203,4	-152,8	254	-356,2	457,4	-559,6	660,8	6702	766	5936	7468	5170	8234	4404	9000

Table 2.c- B738. (Conventional only) Summary of deviations at the first turn (25º Right)

CRJ2 Fleet (Conventional navigation) (sample number: 453 A/Cs)																
Section (NM)	Lateral Deviation (m)								Vertical Deviation (ft)							
	Mean μ_{DL}	σ_{DL}	$\mu_{DL} \pm\sigma_{DL}$		$\mu_{DL} \pm2\sigma_{DL}$		$\mu_{DL} \pm3\sigma_{DL}$		Mean μ_{DV}	σ_{DV}	$\mu_{DV} \pm\sigma_{DV}$		$\mu_{DV} \pm2\sigma_{DV}$		$\mu_{DV} \pm3\sigma_{DV}$	
			Left	Right	Left	Right	Left	Right			Low	Up	Low	Up	Low	Up
0 (DER)	39,7	40	-0,3	79,7	-40,3	119,7	-80,3	159,7	2370	198	2172	2568	1974	2766	1776	2964
2	-186,5	135,6	-322,1	-50,9	-457,7	84,7	-593,3	220,3	4329	503	3826	4832	3323	5335	2820	5838
4	-200,6	170	-370,6	-30,6	-540,6	139,4	-710,6	309,4	5767	538	5229	6305	4691	6843	4153	7381
6	-10	118,3	-128,3	108,3	-246,6	226,6	-364,9	344,9	6863	755	6108	7618	5353	8373	4598	9128

Table 3- CRJ2. Deviations at the first turn (25º Right)

2 A320 fleet analyses. Temperature and wind effects

The second activity of this research program was to analyse the effect of the Outside Air Temperature (OAT) and winds in lateral and vertical deviation in the flight of a SID. Once again, aircraft data recorded using an ADS-B receiver were used. The scenario was Madrid-Barajas airport and the selected SID was the named as "BARDI1A" [3]. Figure 5 shows this SID starting at runway 36L. On the right side of the picture the four sections selected for this study can be seen.

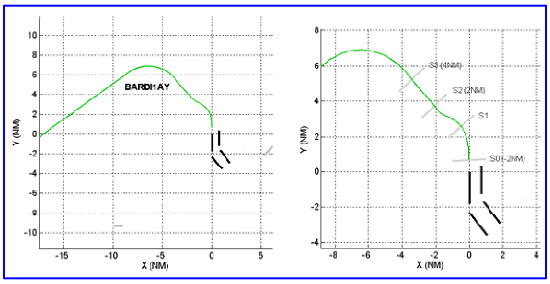

Fig. 5- SID analysed and sections considered.

The numbering of the sections is different to the previous one. In this event, the section corresponding to the turn point was numbered as S1, two nautical miles before was numbered as section S0, then S2 corresponds to a section sited 2 nautical miles forward turn point, then S4 is called the section sited 4 nautical miles forward the turn point.

Recorded data correspond to 1464 flights which were obtained since August 2011 until May 2012. All aircraft were A320 aircraft.

2.1 Outside air temperature effect analysis

In order to analyse the temperature effect, the available paths were filtered considering winds which intensity were less than 12 knots, so the number of trajectories computed was 1231. In the pictures have been drawn the trajectories until FL80.

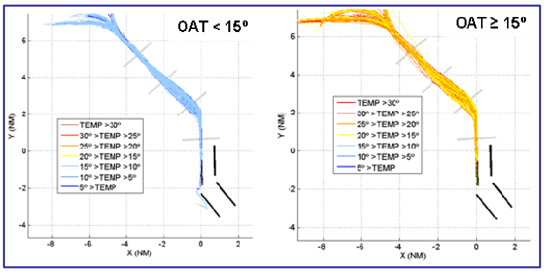

Fig. 6- Dispersion as function of OAT.

Although the analyses was done for many temperature values, in order to present a better results it was decided to represent the trajectories considering OAT lower and higher than 15º. Figure 6 shows these two groups of paths in which can be observed how the lower temperature the narrower lateral dispersion area.

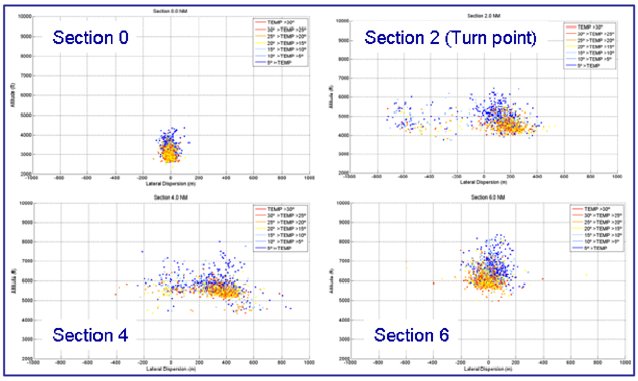

Fig. 7- Dispersion as function of OAT.

Another important and quick result can be observed in figure 7. Blue dots represent aircraft position at different sections with lower outside air temperature. So, the lower temperature the higher flight altitude.

Quantitative results are presented in table 4 in which have been included the mean lateral deviation and the standard deviation (SD) for each section and for different temperature values.

OAT (ºC)	Sections								Aircraft samples
	S0		S1		S2		S3		
	Mean (m)	SD (m)	Mean (m)	SD (m)	Mean (m)	SD (m)	Mean (m)	SD (m)	
0-5	-6	31	62	232	304	162	26	74	102
5-10	-4	34	20	247	279	170	18	77	149
10-15	-5	26	57	249	294	160	9	65	336
15-20	-6	26	132	215	320	170	-2	103	336
20-25	-9	28	126	212	324	163	-16	79	348
25-30	-2	28	137	173	326	151	-16	82	115
30-35	-12	19	144	204	376	158	12	93	76

Table 4- A320. Lateral deviation as function of outside temperature

Looking at the table 4 and figure 8 can be established that:

- The higher OAT the larger mean lateral deviation.
- After the turn point (S2) the higher OAT the larger Mean lateral deviation.
- The behaviour of the Standard deviation depends on the section. In S1 the lower OAT the larger SD, however in S4 the higher OAT the larger Standard Deviation.

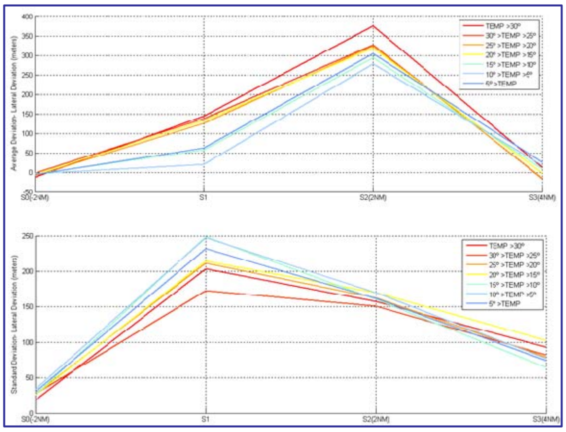

Fig. 8- Lateral deviation as function of OAT.

OAT (ºC)	Sections							
	S0		S1		S2		S3	
	Mean (ft)	SD (ft	Mean (ft)	SD (ft)	Mean (ft)	SD (ft)	Mean (ft)	SD (ft)
0-5	3257	356	4957	475	5821	498	6553	565
5-10	3311	333	5065	444	5874	445	6724	570
10-15	3125	251	4736	398	5613	412	6381	474
15-20	2992	248	4557	317	5505	282	6114	427
20-25	3025	256	4534	330	5475	336	6117	453
25-30	2940	236	4518	316	5502	315	6075	422
30-35	2942	205	4481	300	5403	299	5929	357

Table 5- A320. Vertical deviation as function of OAT

Similarly vertical deviations are shown at table 5 and figure 9. Analysing this information can be established that: The higher OAT the smaller Standard Deviation and lower mean vertical deviation.

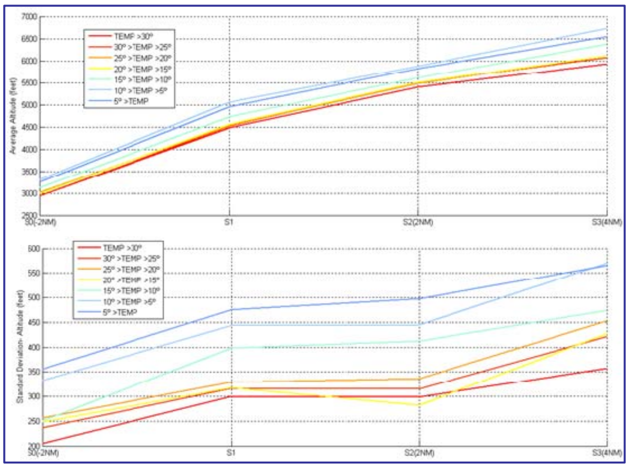

Fig. 9- Vertical deviation as function of OAT.

2.2 Wind effect analysis

In order to analyse the wind effect, the available trajectories were filtered considering OATs lower or equal 20ºC, so the trajectories computed in this part of the study were 925. In the pictures have been drawn the trajectories until FL80.

After filtering the available data in order to remove the paths with temperature higher than 20ºC, it was observed that the remaining trajectories are not representative for winds stronger than 10 Kt. Looking at table 6 can be known that there are 99 samples only with winds stronger than 10 Kt. With this issue in mind, the results for these trajectories will not be good enough. Only results for winds up to 10 knots could be accepted

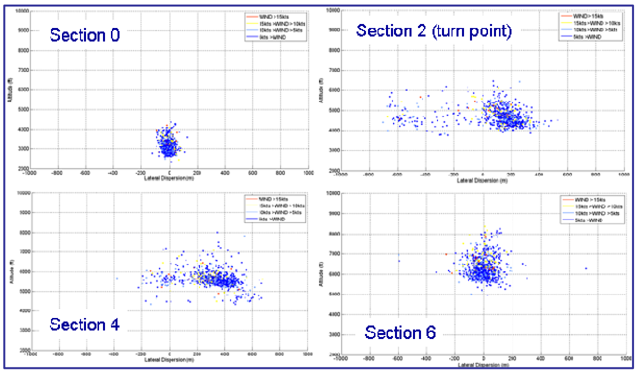

Fig. 10- Dispersion as function of wind.

Wind Intensity (Kt)	Sections								A/C
	S0		S1		S2		S3		
	Mean (m)	SD (m)	Mean (m)	SD (m)	Mean (m)	SD (m)	Mean (m)	SD (m)	
0-5	-6	29	92	226	312	159	3	84	610
5-10	-5	28	93	241	297	172	-8	83	216
10-15	0	31	107	187	268	127	-17	73	77
> 15	4	40	19	214	208	168	-17	95	22

Table 6- Lateral deviation as function of wind

Table 6 shows the figures for the mean lateral deviation and standard deviation at the corresponding sections. As it was said previously, only the data corresponding to winds up to 10 knots could be representatives. A graphical representation of these data has been achieved in figure 11.

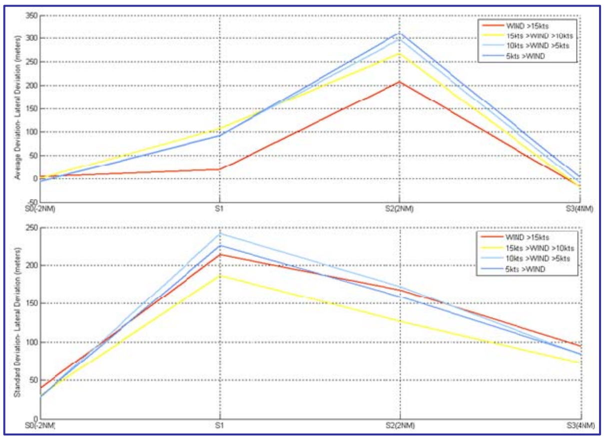

Fig. 11-Lateral Deviation as function of wind.

In figure 11 the red line corresponds to trajectories with winds stronger than 15 kt (22 samples only exist). If this group of trajectories is not considered, then a small difference in lateral deviation will be appreciated, so with winds up to 15 knots the lateral deviation is not too much important.

With the available information, it can not be found a definitive establishment in terms of lateral deviation considering the wind effect.

Table 7 and figure 12 are related to the wind effect on the vertical profile. The results obtained can be used for confirming what is expected. Considering that the wind has a head component the results show that the stronger wind the higher flight profile.

Wind Int. (Kt)	Sections							
	S0		S1		S2		S3	
	Mean (ft)	ST (ft)	Mean (ft)	ST (ft)	Mean (ft)	ST (ft)	Mean (ft)	ST (ft)
0-5	3118	322	4713	451	5624	449	6297	538
5-10	3093	289	4668	391	5562	363	6244	503
10-15	3164	320	4824	435	5719	406	6689	550
> 15	3249	386	4935	365	5676	382	6593	587

Table 7- Vertical deviation as function of wind

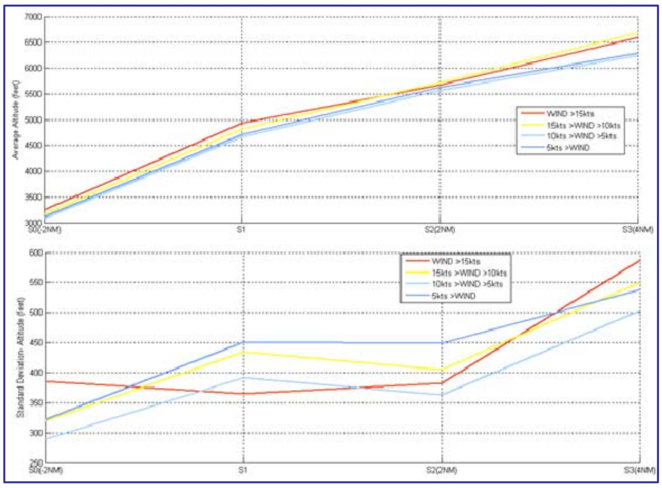

Fig. 12- Vertical deviation as function of wind.

3 Conclusions

The conclusions obtained so far are the followings:

• Different fleets flying same route have important differences in terms of lateral deviation respect to the published route and even among fleets.

• Due to SIDs are computed and published for a particular aircraft category, it may not be the best practice to use the same lateral deviation value to decide to impose a fine to the operators. Same value only could be acceptable if the deviation range is large enough to cover every category.

• PRNAV aircraft has smaller deviation than conventional navigation aircraft. When same SID is flown.

• The design criteria (RNAV or conventional) is a key factor in the deviation of the aircraft when the procedure is flown.

▪ In order to impose a fine should not be used same deviation figure for every aircraft. The deviation threshold must be customized to the aircraft family and considering external factors as temperature and wind existing at the flight time.

4 Future works

The results obtained, although are quite important are not sufficient to consider this research program as finished. So additional work should be done:

- To analyse the wind effect in order to obtain better results
- To analyse the airfield elevation in the lateral deviation,
- To determine the lateral deviation in different turning point with different track changes.
- To define the criteria for determining the acceptable threshold for considering to impose a fine in a particular SID

5…References

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