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Technical document

Triggered Transmission of Flight Data Working Group

Report

Bureau d'Enquêtes et d'Analyses
pour la sécurité de l'aviation civile
Ministère de l'écologie, de l'énergie, du développement durable et de la mer, en charge des technologies vertes et des négociations sur le climat

Foreword

The conclusions of this document are based upon work performed by the Triggered Transmission of Flight Data working group. The use of this report for any purpose other than for the prevention of future accidents could lead to erroneous interpretations.

Contents

1 – INTRODUCTION

1.1 Background

Prompted by the difficulties experienced recovering the flight data recorders of AF447, as well as other difficult sea recovery operations, in October 2009 the BEA created an international working group called "Flight Data Recovery". Its aim was to look into new technology to safeguard flight data and/or to facilitate the localization and recovery of on-board recorders. This working group met twice in Fall 2009 and areas such as flight data transmission via satellite as well as new flight recorder or ULB technology were evaluated.

In the second AF447 interim report dated 17 December 2009, the BEA issued recommendations based on the results of this working group. These results are summarized in a document available on the BEA's website:

http://www.bea.aero/en/enquetes/flight.af.447/flight.data.recovery.working.group.final.report.pdf

They were presented at the ICAO high level safety conference (HLSC) in March 2010. During this meeting[1], it was decided that "ICAO should pursue as a matter of high priority a review of SARPs[2] and guidance materials with the aim of proposing to States for consideration any amendment required to ensure that the data necessary to support investigation of accidents are available, including provisions for the recovery of data and information from flight recorders".

In this context, ICAO's Flight Recorder Panel (FLIRECP) was tasked to propose amendments to Annex 6 to ICAO's Air Navigation Commission. Amendments were discussed in June 2010 and these state that aeroplanes with a maximum certificated take-off mass of over 27 000 kg and for which:

- the type certificate is first issued on or after 1 January 2018, a means of automatically transmitting sufficient information to determine the position of an accident over water to within 4 NM shall be installed.
- the individual certificate of airworthiness is first issued on or after 1 January 2020, a means of automatically transmitting sufficient information to determine the position of an accident over water to within 4 NM shall be installed.

Note: An ELT integrated in a deployable recorder or transmission of data may be examples of means of compliance. Transmission under water is not considered acceptable as a means of compliance.

Regulation No. 996/2010 of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents states in part (29) of the preamble that:

> (29) Progress on research into both the real-time tracking of aircraft and the possibility of accessing flight-recorder information without the flight recorder being physically present should be encouraged to improve the tools available to investigators for determining the causes of accidents and to enhance capabilities for preventing recurrent incidents. Such developments would be an important step forward in aviation safety.

The "Flight Data Recovery" working group identified the transmission of flight data when an upcoming catastrophic event is detected as a solution with good potential. However it was

[1] See HLSC's report at http://www2.icao.int/en/HLSC/Lists/Advance%20Copy%20of%20the%20HLSC%202010%20Report/Attachments/1/HLSC.2010.DOC.9335.EN.pdf

[2] Standards And Recommended Practices

not recommended in the AF447 second interim report, as additional work was deemed necessary to assess the operational suitability of this solution. This is why the BEA decided to consult members of the group again and created in March 2010 the “Triggered Transmission of Flight Data” working group.

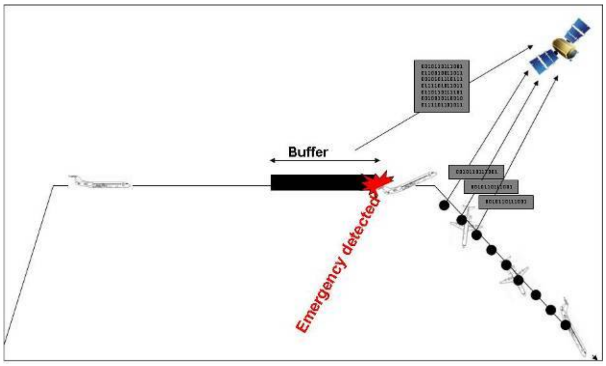
1.2 Concept of Triggered Transmission of Flight Data

Flight parameters can be analyzed in real-time by onboard equipment and the use of triggered data transmission by means of logic equation is a well established mechanism. Such systems have already been developed and deployed with airlines for maintenance and monitoring purposes. See appendix 1 for examples of existing systems.

However, no criteria for detecting an emergency situation based on flight parameters were known to the BEA.

The concept of triggering the transmission of flight data consists of:

- Detecting, using flight parameters, whether an emergency situation is upcoming. If so,
- Transmitting data automatically from the aircraft until either the emergency situation ends, or the aircraft impacts the surface. The buffered data containing the moments prior to the emergency could also be sent.



1.3 Objective of the working group

The objective was to determine if the concept of triggered transmission is feasible in order to help locate wreckage after accidents to fixed-wing aircraft over maritime or remote areas.

To do so, the group provided answers to the following questions:

1. Are there triggering criteria that meet the 2 following conditions:
    a. The probability of detection of an upcoming catastrophic event is maximum (ideally 100%)
    b. The probability of nuisance triggered transmission is reduced to the minimum (ideally 0%)?
2. Are satellite connection and transmission times compatible with the warning times provided by the emergency situation detection criteria?
3. Does the current and/or future satellite antenna technology allow for continuous transmission, even for aircraft in unusual attitudes and subject to high pitch and roll rates?

If these 3 conditions are met, the results of the working group would be the basis for safety recommendations that would be issued in the framework of the AF447 investigation.

ICAO’s Flight Recorder Panel (FLIRECP) would also use these results to propose modifications of Annex 6, during their meeting in June 2011.

Encryption and protection of data, as well as privacy rights, were not addressed by this working group. Only the technical feasibility of the triggered flight data transmission was considered. The cost/benefit analysis was already performed by the Flight Data Recovery working group and was therefore not re-evaluated in this report.

1.4 Approach

The group looked into what could be considered as reliable criteria to detect emergency situations using flight parameters and assessed the robustness of such criteria.

Members of the working group tested their criteria using a database of accident and normal flights.

The robustness of the triggering criteria was evaluated using the following metrics:

- False detection rate (or nuisance trigger rate): out of all the normal flights, how many are considered as containing an emergency situation
- Nuisance transmission time that the nuisance triggers generate
- Emergency situation detection rate: out of all the accident/incident flights, how many are considered as containing an emergency situation
- For flights with a correctly detected emergency situation, what is the warning time between the time of detection and the time of impact with the surface

It was rapidly recognized that runway excursions do not need to be detected in real-time, simply because the wreckage is always easy to locate. Transmitting data in those cases would not significantly reduce the time to recover the recorders. Therefore runway excursions are not represented in the database for this working group.

Nuisance triggers are to be expected. A way to mitigate their cost effect is to minimize the amount of data transmitted: only latitude, longitude and altitude could suffice to reach the primary objective of locating the impact position. Another way is to set up “stop transmission” criteria in order to interrupt the transmission of data if it is determined that the emergency no longer exists.

The database was also used to assess communication continuity with satellites when aircraft are in unusual attitudes.

1.5 Timeframe

Three meetings took place, 2 at the BEA in Paris in March and June 2010 and a final one at ICAO headquarters in Montreal in March 2011.

1.6 Attendees

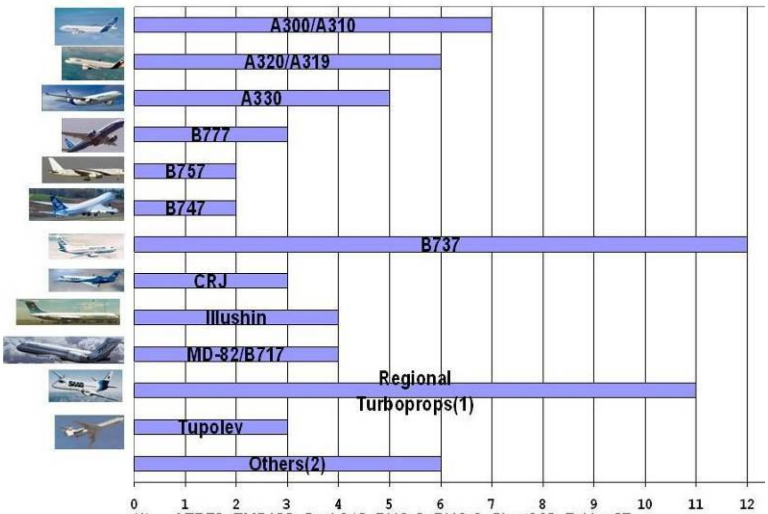
The group was composed of more than 150 members from many countries, representing a wide range of actors: investigation bodies (BEA, NTSB, AAIB, TSBC, ATSB, ASC, MAK) regulatory authorities (ICAO, EASA, FAA, DGAC…), airframe manufacturers (Airbus, Boeing), service providers, equipment and satellite manufacturers (Astrium/Star Navigation, Inmarsat, Iridium, FLYHT, DRS…), and international associations (IATA, COSPAS-SARSAT…).

2 – WORK PERFORMED

2.1 Database

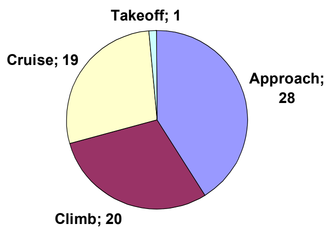
The BEA set up and managed a database of flight datasets that contains 68 real accidents and incidents[3] datasets and 621 "normal" flight datasets. These 621 normal flights represent 3,661 hours of data. Accident datasets are referenced in the database as A<*number*>, incidents as I<*number*> and normal flights as N<*number*>.

The accident datasets were provided by the official investigation authorities. The "normal" flight datasets were provided by Air France. "Normal" flights include regular uneventful commercial flights, as well as flights with minor incidents (like turbulences, slight over speed…). The datasets were de-identified, as no date or latitude/longitude parameters were provided. Information about aircraft type, phase of flight and occurrence category[4] is available for each file of the database. See appendix 2 for details. The accidents and incidents were provided by the investigation authorities[5] and involve the following aircraft types:



(1) ATR72, EMB120, Saab340, DHC-8, DHC-6, Short360, Fokker27
(2) BAe146, Tuplolev154, Concorde, F100, Illushin 18V …

The breakdown by flight phase and occurrence category is as follows:

Flight phases	Occurrence categories
	see table below

ID	Occurence Description	Number
LOC-I	Loss of Control In Flight	27
CFIT	Controlled Flight Into Terrain	13
ICE	Icing	8
SCF-NP	System/Component failure or malfunction (non-powerplant)	8
MAC	Airprox/TCAS/Loss of Separation/Mid-Air Collision	4
TURB	Turbulence Encounter	2
UNK	Unknown or undetermined	2
AMAN	Abrupt Maneuvre	1
F-NI	Fire/Smoke (Non-Impact)	1
FUEL	Fuel related	1
SCF-PP	System/Component failure or malfunction (powerplant)	1

[3] 44 accidents and 24 incidents
[4] As defined by the CAST/ICAO Common Taxonomy Team (see http://www.intlaviationstandards.org/Documents/CICTTOccurrenceCategoryDefinitions.pdf)
[5] AAIB, ASC, ATSB, BEA, MAK, NTSB and TSBC

The datasets from normal flights are composed of 212 Airbus A320 flights, 217 Airbus A330 flights and 192 Boeing B777 flights, which make a total of 621 flight and represent more than 3600 hours of data. Each file represents on average 6 hours of flight, from take-off to landing.

2.2 Emergency Detection Criteria

The group looked into what criteria would detect a maximum number of accidents and incidents with the greatest warning times, while at the same time limiting nuisance triggering for normal flights. The criteria developed by the WG use a limited set of parameters (see appendix 3 for the list of parameters). Many more parameters would be available for actual aircraft systems that might be available in the future.

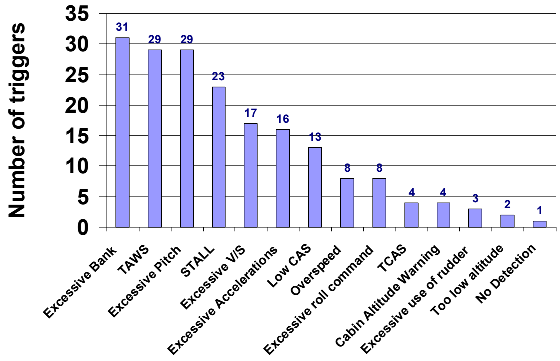
2.2.1 Binary logic approach

The BEA elaborated the following set of criteria, based on an estimation of what constitutes an emergency situation. The approach is binary in the sense that a condition is either true or false. If one condition is true, then it is considered that an emergency has started. Otherwise, if all conditions are false, then the flight is considered normal.

Criteria Type	Criteria Name	Equation	Confirmation time[6]
Unusual attitude	Excessive Bank	{|Roll|>50°} **OR** {|Roll|>45° **AND** |Roll rate|>10°/s}	2 sec
	Excessive Pitch	{Pitch>30°} **OR** {Pitch<-20°} **OR** {Pitch>20° **AND** Pitch rate>3°/s} **OR** {Pitch<-15° **AND** Pitch rate<-3°/s}	2 sec
Unusual speed	STALL	STALL Warning=TRUE	1 sec
	Low CAS	{CAS<100kt(*) **AND** Radio altitude>100 ft} *(*) 60 kt for DHC-6*	2 sec
	Excessive Vertical speed (V/S)	{|V/S|>9000 ft/min}	2 sec
	Overspeed	{IAS>400kt} **OR** {OVERSPEED Warning = TRUE **AND** Alt<15000 ft}	2 sec
Excessive accelerations	Unusual load factors	{ nz>2.6g OR nz<-1.1g } **OR** {|ny|>0.25g}	2 sec
Control command inputs	Excessive roll command	{|Captain Roll cmd|>50 **OR** |F/O Roll cmd|>50 } **AND** {IAS>80 kt}	2 sec
	Excessive use of rudder	{|Rudder position|>6° **AND** IAS>240 kt}	2 sec
Ground Proximity	TAWS warning	TAWS warning/alert = TRUE	1 sec
	Too low altitude (poor altitude gain after takeoff)	{40<Radio Altitude<100 **AND** Eng1N1>80% **AND** Eng2N1>80% }	10 sec
Others	TCAS	TCAS RA = TRUE	1 sec
	Cabin Altitude Warning	CABIN ALT WARNING = TRUE	10 sec

The number of times each criteria is true when run against the 68 accidents and incidents is as follows:

[6] Number of consecutive seconds for which the condition has to be true



The most used criteria are the ones dealing with unusual attitudes and TAWS warnings. This is in line with the accident categories in the database as close to 60% of them are either Loss of Control in flight or CFIT (Controlled Flight Into Terrain).
Only one accident could not be detected using the criteria above. This is accident A036 (see appendix 2) which is a CFIT accident. The dataset for accident A036 did not contain any TAWS parameter, which makes the event difficult to detect.

The total number of accidents/incidents detected is 67, out of 68, which makes a detection rate of 98%.

Nuisance triggers occurred for normal flights N158 and N179:

FileID	ACType	Criteria Name
N158	A320	Overspeed
N179	A320	Excessive V/S

Flight N158 did experience a slight overspeed lasting 4 seconds, which was detected using the criteria.
N179 actually had some bad data with recorded V/S going above 9000 ft/min (once for 23 seconds, and a second time for 2 seconds). These excessive V/S are not what the aircraft actually experienced, as they are inconsistent with the other parameters (pitch, airspeed, vertical acceleration…)

The nuisance trigger rate is therefore 2 out of 621 flights. In order to limit the cost impact of such nuisance triggering, the transmission should be stopped if the emergency condition no longer exits. A period of time of 250 seconds was chosen to confirm that an emergency condition had disappeared: if no criteria are true for 250 consecutive seconds, then the transmission could be stopped. The value of 250 seconds was chosen so that the transmission would not stop for any accident in the database:

The 5 accidents listed here are the only ones for which a detection occurred more than 250 seconds before impact. For all of them, there is no period greater than 250 seconds without at least one trigger condition being true. Therefore, the transmission would not be automatically interrupted before impact.

(Note: this statement is made without taking into account the communication continuity issue discussed later in the report)

FileID	Warning Times (s)
A043	266
A028	298
A013	765
A042	1618
A035	10019

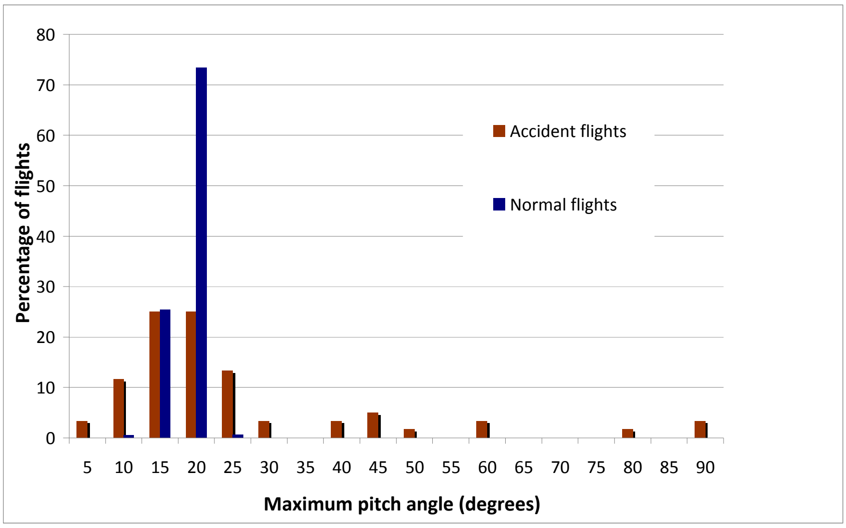
By adding 250 seconds to the times the triggering criteria are true for flights N158 and N179, the total time for nuisance transmission is 779 seconds[7]. Since the total flight time of the 621 normal flights is 3,661 hours, the nuisance transmission time represents 0.006% of flight time. It also represents one minute of nuisance transmission for every 282 hours of flight.

[7] 4 + 23 + 2 + 3x250 sec = 779 sec

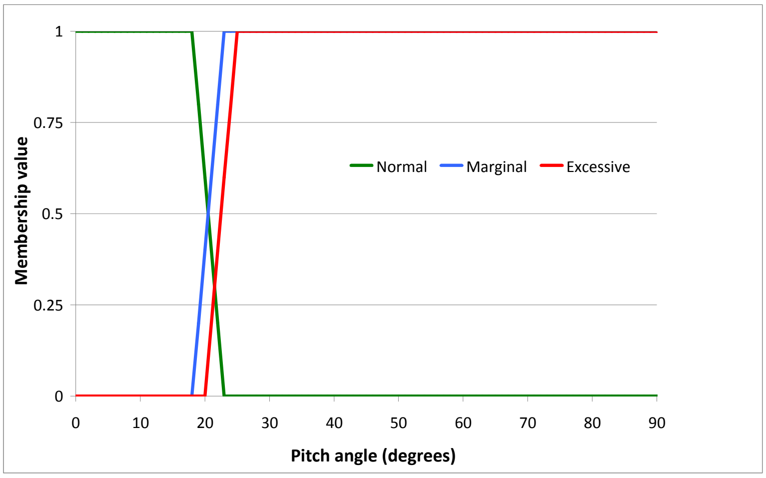
2.2.2 Fuzzy logic approach

As an alternative approach to the binary logic rules described in Section 2.2.1, a fuzzy logic approach was also developed as a 'proof of concept' by Cranfield University[8]. Fuzzy logic allows inputs to be weighted using continuous 'membership functions' rather than discrete step functions which in turn allows decisions to be made about the degree to which an output condition is true or not. In the case of triggered transmission, the output is the extent to which an accident is occurring based on a number of rules in combination.

Whilst the rules described in Section 2.2.1 formed the basis of the fuzzy system, histograms showing the distribution of maximum parameter values for all flights were used to set limits for 'normal' values, 'marginal' values and 'excessive' values. An example of a histogram and membership functions is shown for pitch angles.



This distribution of maximum values led to the following membership functions for pitch angles:



For this example, a pitch angle less than 18° is considered "normal". If it is between 18° and 23°, it is still considered "normal" but to a lesser degree. If it is greater than 23°, then it's not "normal".

In the same manner, if the pitch angle is greater than 25°, then it is "excessive". If it is between 20° and 25°, it is also "excessive", but to a lesser degree. Finally, if it is less then 20°, it is not "excessive".

The inputs employed in the fuzzy model are: pitch, roll, derived pitch rate, TAWS warning, Stall warning, cabin altitude warning, TCAS warning, Captain commanded roll, lateral acceleration, and the 'poor altitude gain after takeoff' condition described in Section 2.2.1.
In essence, there are three regimes governing the system:

[8] Cranfield University, College Road, Cranfield, Bedfordshire, MK43 0AL (United Kingdom)

Description	Logic rules
If all parameters are in the 'normal' range then a normal flight condition is assumed.	IF {Pitch AND Roll AND Pitch Rate AND Captain Roll Command AND ny} ARE {Normal} AND {TAWS AND Stall AND CabinAlt AND TCAS AND BadT/O} ARE {False} THEN {No accident occurring}
If any of the parameters in isolation is considered to be 'excessive' then a trigger is raised.	IF {Pitch OR Roll OR Pitch Rate OR Captain Roll Command OR ny} ARE {Excessive} OR {TAWS OR Stall OR CabinAlt OR TCAS OR BadT/O} ARE {True} THEN {Accident is occurring}
If a number of parameters in combination are considered 'marginal', a trigger is raised.	IF {Pitch AND Roll AND Pitch Rate } ARE {Marginal} OR {ny} IS {Marginal} THEN {Accident is occurring}

A large amount of detail is needed in order to fully describe the system outlined above, including membership functions, logic rules, weightings and fuzzy logical methods. For this reason, the full details have not been included. More importantly, however, than the specific approach adopted is whether the fuzzy approach is able to offer a viable alternative to the binary logic approach.

The results show that of the 68 accidents and incidents, all were detected and on none of the 621 normal flights were false positives generated. The normal flights (N158 and N179) for which nuisance triggers were generated with the binary logic approach no longer generate nuisance triggers with this fuzzy logic system. This is due to the fact that the fuzzy approach does not use the "Overspeed", nor the Vertical Speed parameters. Also, accident A036 that could not be detected by the binary logic approach is now detected correctly. This is thanks to a different nose-down pitch limits (-11° for the fuzzy approach, and -20° for binary one).

A problem exists however around the issue of a trigger occurring during an accident flight due to a condition which was apparently unrelated to the accident. An example of this occurs in flight A001; the fuzzy system raised a trigger nearly 35 minutes (2088 seconds) before the end of the data set. This trigger was raised due to a roll angle above 43 degrees being sustained for 3 seconds. Clearly in this case, the trigger event was unrelated to the accident. However, in other cases the distinction may not be so evident. Determining which events are "part of" the accident would require an analysis of each event individually, which was not warranted for this initial investigation.

In its current form, the fuzzy system does not fulfil its potential to offer a smoothly varying output; the system described is a rudimentary 'proof of concept' which would benefit from further development. A more refined output value will allow the level at which triggering occurs to be adjusted.

With further development, the model could become increasingly sophisticated and it would benefit from being tuned to an even larger normal data collection, such as that gathered through an FDM programme.

However, this fuzzy system was able to trigger on all accident/incident flight datasets whilst triggering on none of the normal flight datasets, proving the fuzzy approach to be potentially useful.

2.2.3 Airbus study

Airbus launched an internal study in order to define emergency criterias, similar to the ones described in paragraph 2.2.1. Equations based on flight parameters detect the following “unsafe events”:

	Unsafe event	Corresponding criteria equations
1	Excessive pitch	PITCH > 30° OR PITCH < -20° OR PITCH > +20° AND PITCHRATE>3°/s OR PITCH < -15° AND PITCHRATE<-3°/s
2	Excessive roll	|ROLL| > 60° OR |ROLL| >45° AND |ROLLRATE|>10°/s AND ROLL*ROLLRATE > 0
3	Stall	Stall Warning = TRUE
4	Overspeed	CAS > Diving speed OR MACH > Diving Mach
5	Excessive acceleration	Nz > 2.6g OR Nz < - 1.1g OR |Ny| > 0.4g
6	Ineffective command	CPT or FO roll (resp pitch) full order recorded for more than 3 sec with no associated roll (resp pitch) rate
7	Undue use of rudder	Rudder pedal max deflection AND no engine failure
8	Excessive vertical speed	|V/S| > 10,000 ft/min
9	Low speed	CAS < 100 kts AND A/C in flight
10	TAWS / GPWS	TAWS / GPWS alert = "PULL UP"
11	TCAS	TCAS RA = TRUE

They have been tested on 9,333 long range flights from one airline and on 11 accidents flights from the BEA’s database.

The recorded data of the 9,333 commercial flights contained 9 “unsafe events” in 8 flights. Among the 9 “unsafe events”:

- 6 were triggered due to spurious recording of flight data (spurious spikes recorded on the vertical acceleration parameter and on the Mach parameter).
- 3 genuine events were detected: 2 “Excessive pitch” and one “Low speed”.

All 11 flights of the accident data set successfully triggered an “unsafe event”.

Analysis of both commercial flights and accidents provided evidence that spurious flight data can be recorded. This can occur in nominal and in abnormal situations for different reasons including: measuring system dysfunction, poor signal shielding against parasites or recording process. Thus, in the process of using these recorded data to trigger an "unsafe event", appropriate data refining and filtering techniques should be first considered.

In addition, tests were run on a relatively low amount of data from one airline, on long range flights only, which probably biased the results. As the commercial flight data come from one unique airline with one central hub, around 50 % of the flights have the same final destination. It is therefore suspected that approach and landing characteristics for this particular airport influenced the statistical results of the study.

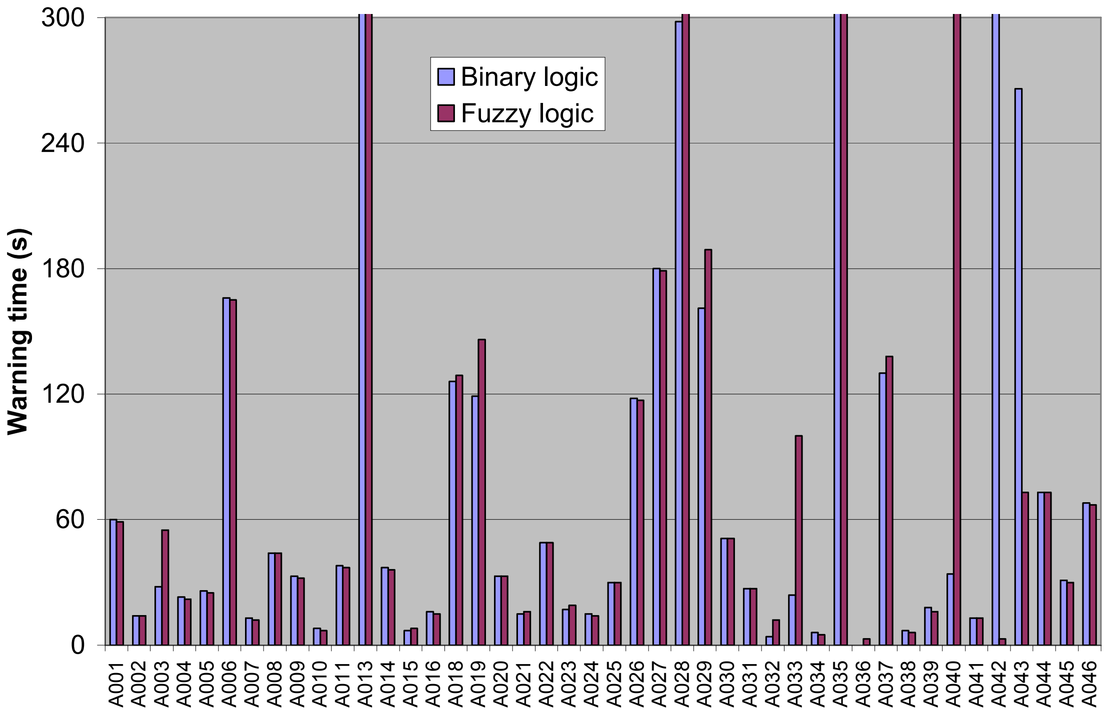
Nevertheless, testing of the proposed criteria was conclusive. It allowed detecting all genuine "unsafe events" on both commercial flights and accident cases. Noise level due to spurious triggering was observed to be relatively low (0.6 spurious triggering every 1,000 flights).

In order to account for the variety of flight operations around the world, further testing is needed with other airlines, other aircraft and from different parts of the world.

2.3 Warning times

The set of criteria defined in paragraph 2.2.1 and 2.2.2 was run against all the flights of the database. Appendix 4 shows the flights for which each criteria of the binary logic approach was true and, for accidents only, the corresponding warning times[9]. Any given accident might have one or several criteria that work (except for A036 that has no detection with the binary logic approach).

The best warning times for each accident are represented on the figure below.



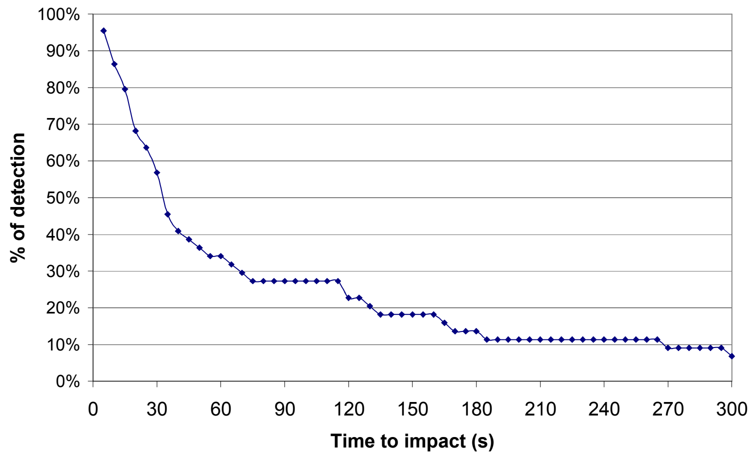
[9] Time between the detection of an emergency and the time of impact

Results are similar for most accidents:

Binary logic approach	Fuzzy logic approach
Out of the 44 accidents, 43 were detected correctly. Warning times range from 4 seconds to 10,019 seconds. The average value is 345 seconds. The median value is 33 seconds.	All accidents are detected. Detection times range from 3 seconds to 10,018 seconds with an average value of 353 seconds and a median value of 34.5 seconds[10].

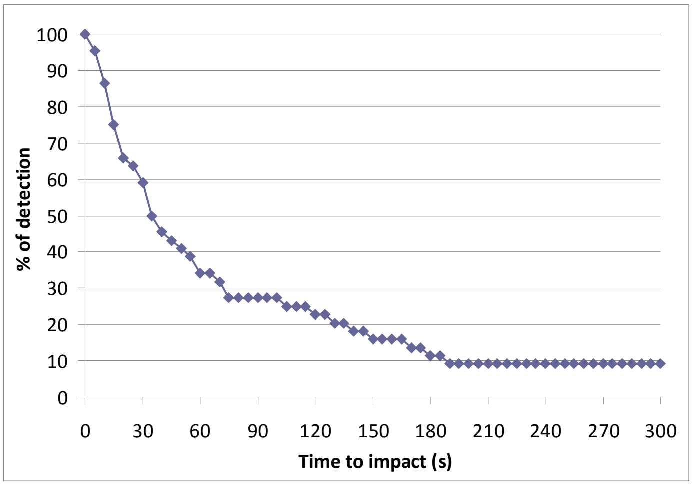
A statistical distribution of the warning times for all accidents in the database is presented on the following figures:

All accidents – Binary logic approach



The results indicate warning times greater than 15 seconds in 80% of the cases, greater than 30 seconds in 57% of the cases, greater than 60 seconds in 34% of the cases and greater than 120 seconds in 23% of the cases.

All accidents – Fuzzy logic approach

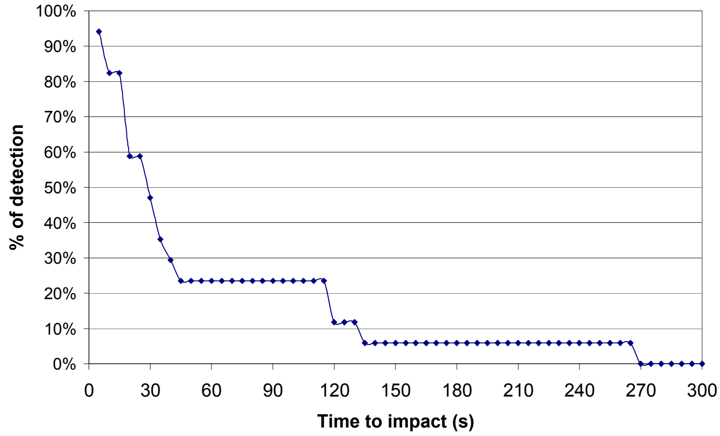


The figure shows that the warning time was greater than 15s for 75% of accidents, greater than 30s for 59% of accidents, greater than 60s for 34% of accidents and greater than 120s for 23% of accidents.

[10] These values do not include situations which triggered the detection system earlier but were apparently unrelated to the accident

The results by flight phase are as follows:

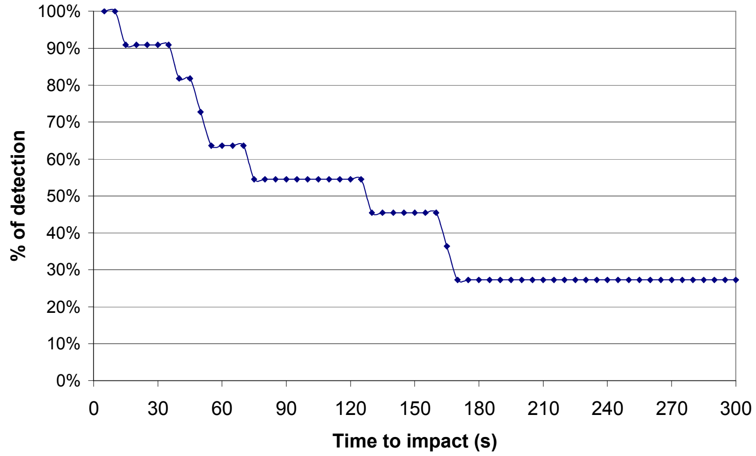
Accidents in climb or takeoff phase – Binary logic approach



Warning times:

- greater than 15 seconds in 82% of the cases,
- greater than 30 seconds in 47% of the cases,
- greater than 60 seconds in 24% of the cases and
- greater than 120 seconds in 12% of the cases.

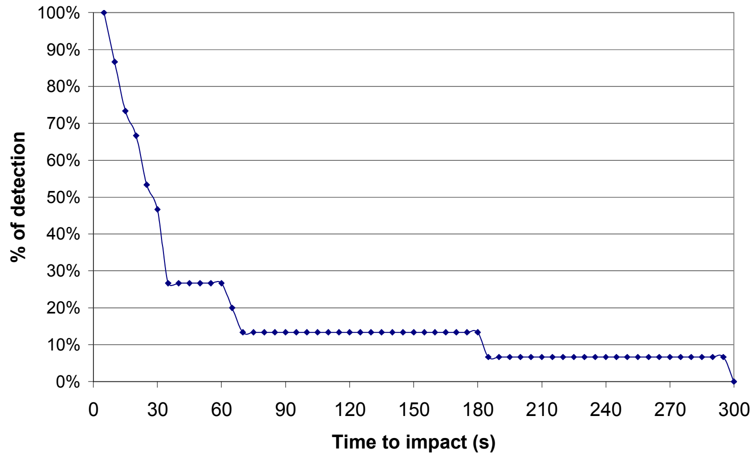
Accidents in cruise - Binary logic approach



Warning times:

- greater than 15 seconds in 91% of the cases,
- greater than 30 seconds in 91% of the cases also,
- greater than 60 seconds in 64% of the cases and
- greater than 120 seconds in 55% of the cases.

Accidents in approach phase - Binary logic approach



Warning times:

- greater than 15 seconds in 73% of the cases,
- greater than 30 seconds in 47% of the cases,
- greater than 60 seconds in 27% of the cases and
- greater than 120 seconds in 13% of the cases.

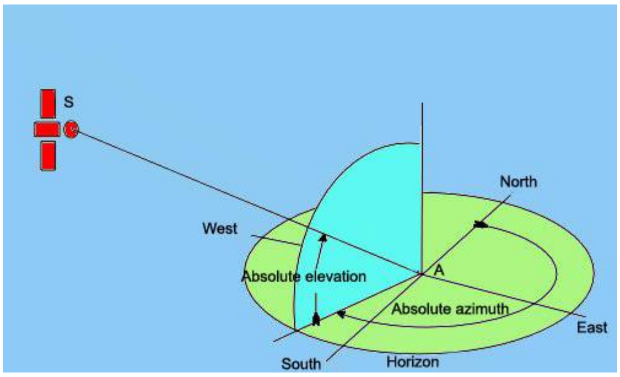
These warnings times are to be compared with the performance of the different satellites communication systems (SatCom) or other systems.

2.4 Sending data using SatCom

For aircraft equipped with SatCom (Inmarsat or Iridium), the call is established at the beginning of the flight and the communication is possible as long as the antenna is visible by the satellite.

The visibility of the antenna depends on the elevation to the satellite.

This figure illustrates the absolute elevation from an antenna at point A to a satellite, i.e. the elevation if the aircraft has level wings.



The relative elevation depends on aircraft's pitch, roll, heading, latitude, and longitude and on satellite positions. When the relative elevation is greater than 0, the antenna is visible by the satellite. Otherwise the antenna is masked.

The absolute elevation from an aircraft with level wings might be positive at a given point on Earth, but the relative elevation at that same point can become negative as the aircraft is banking away from the satellite.

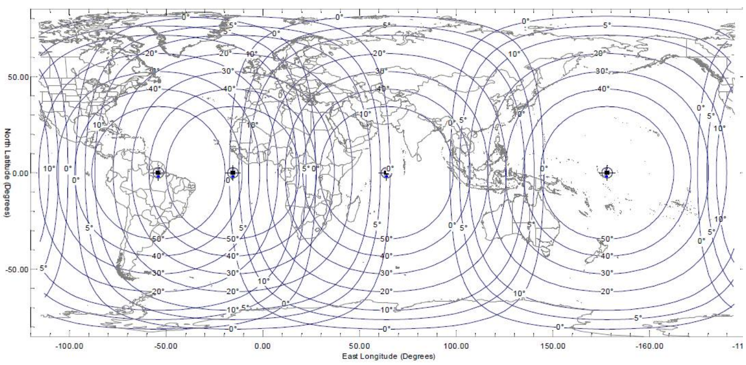
When the antenna is masked, the transceiver goes into 'link outage' mode which means that it will attempt to reacquire the link but will not drop the call. The link outage may last up to approximately 11 seconds. So if within 11 seconds, the link becomes available again, data transmission can restart without delay.

Past the 11 seconds, the call will be dropped. The SatCom system will then need to re-scan the available beams, establish a radio link, perform necessary location update, get a channel allocation and re-establish the radio link. This typically can take up to 40 seconds.

2.4.1 Connectivity with Inmarsat system

The vast majority of Inmarsat antennas on Air Transport widebodies are High Gain Antennas (HGAs) phased arrays, and are mounted on top of aircraft. They are near the front of the aircraft for Airbus A330/A340/A380 (all top-mounted). They are around ⅔ back for Boeing B747/B777 (mainly top mounted but some side-mounted). All Inmarsat SatCom antennas on air transport aircraft are steerable and are controlled by the SatCom avionics. The system computes the azimuth and elevation (relative to airframe) and sends this info to the antenna.

The satellites taken into consideration by the working group are the four "I3" satellites. They are geostationary and their absolute elevation contours are represented on the figure below.



A study launched in cooperation with Inmarsat consisted in assessing the connectivity of the antenna with the satellites for each accident of the database and for different locations on the Earth.

To do so, it was simulated that each accident was taking place in 597 different places on the globe and computed each time when the last possible transmission would occur (taking into account the relative elevations, a link outage time of 11 seconds and a re-connection time of 40 seconds). The longitudes of these 597 points range from 170°W to 170°E with a 10° increment. The latitudes range from 80S to 80N, with a 10° increment also. To these points were added the North and South Poles.

For any given point, the satellite of reference is the satellite whose longitude is the closest to the longitude of the point.

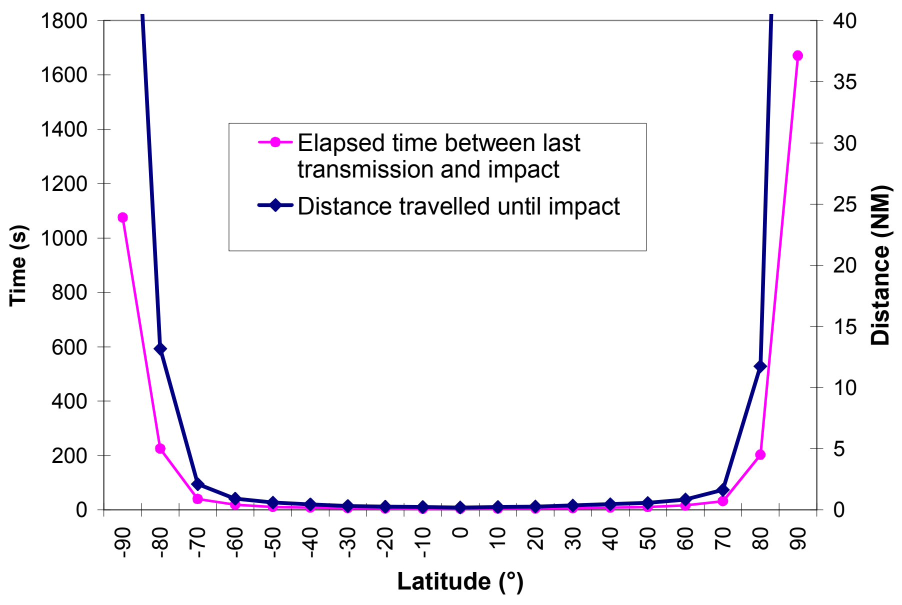
Out of the 44 accidents in the database, 2 do not have pitch, roll or heading parameters (A006 and A016). Therefore, for these 2, the computation of relative elevation could not be performed.

Consequently, the simulation was done for 42 accidents and 597 points, which makes a total number of combinations of 25,074.

For each of those combinations, the 2 following indicators were computed:

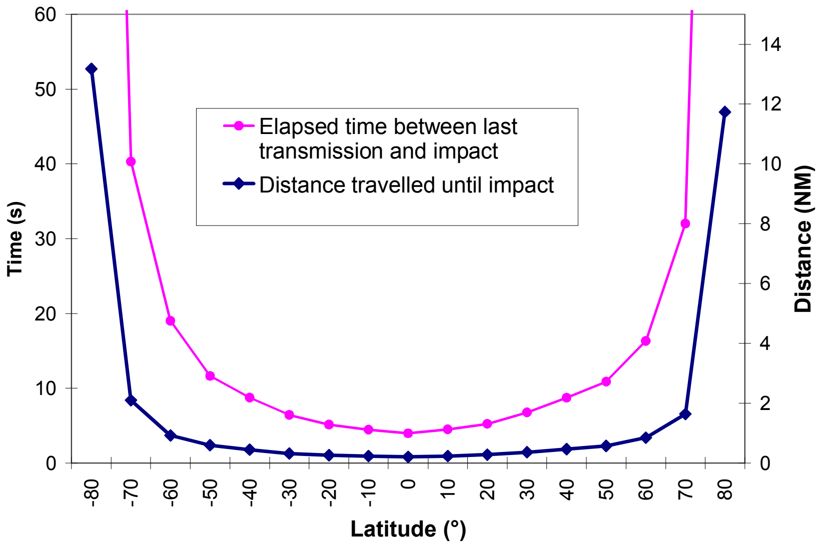
- elapsed time between the last possible transmission and the time of impact,
- maximum distance travelled from that 'last transmission' time until impact. This distance can then be compared to the 4 NM limit proposed in the changes to ICAO's Annex 6 for the determination of the accident position.

Since Inmarsat's satellites are geostationary, the transmission capability depends heavily on latitude. The two indicators were averaged by latitude of all 25,074 combinations.



This figure shows that transmission capability is greatly degraded near the North and South Poles, as the elapsed times between the last transmission and impact as well as the distances travelled until impact increase exponentially as the latitudes approach 90°N or 90°S.

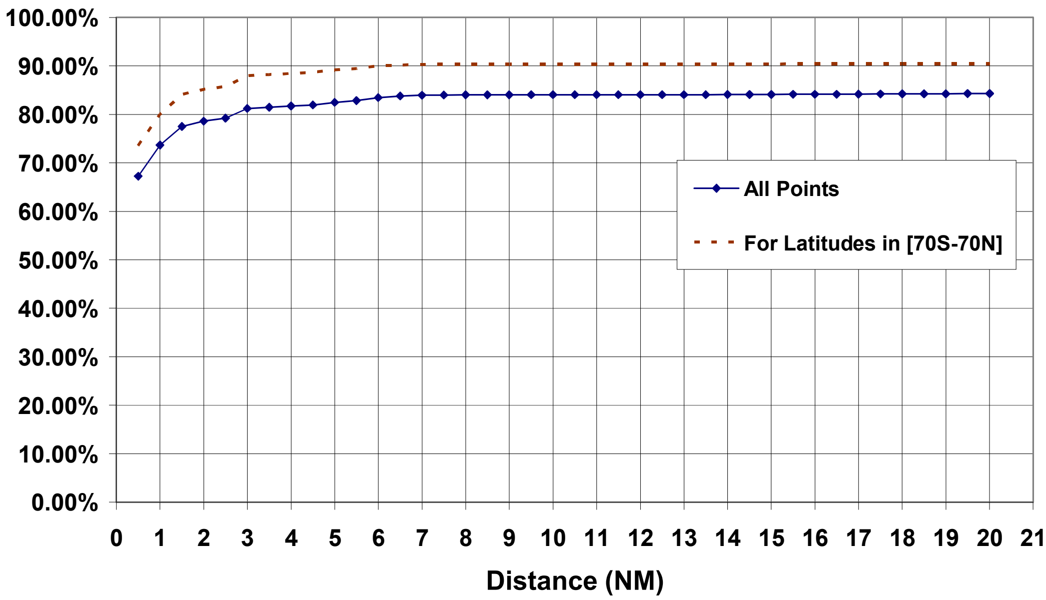
When zooming in on latitudes between 80°S and 80°N, the results are better. The times near the equator are less than 5 seconds, showing that transmission is possible almost to the impact time.
The average distance is under 2 NM for latitudes under 70°, which is under the 4 NM mentioned by the FLIRECP.
Most of the north Atlantic flights remain below the 70°N parallel.



The 'last transmission' times were compared with the times of emergency detection. When the emergency situation was detected after the 'last transmission' time, or when there was no detection at all (accident A036), it was considered that the transmission could not take place. This was the case for 3,874 combinations, which represents about 15% of the combinations.

The graph below represents on the Y-axis the proportion of combinations for which the maximum distance travelled is less than the distance on the X-axis.

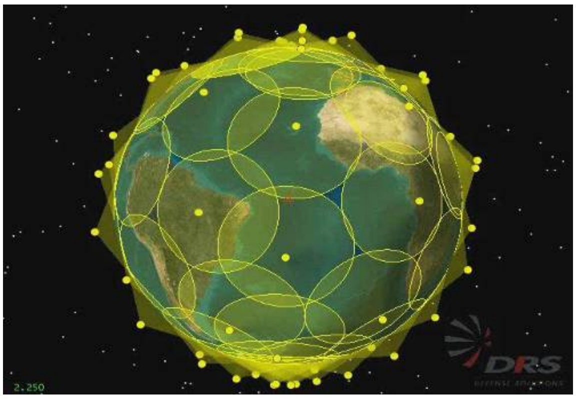
When considering all 597 impact points, it shows that for 82% of the combinations, the distance is less than 4 NM. When looking at only the impact points located between the 70S and 70N parallels, this figure goes to 88%.



It also shows that the curve for all points reaches a maximum of about 85% and does not reach 100%. This corresponds to the 3,874 combinations for which transmission is not possible.

2.4.2 Connectivity with Iridium system

The Iridium constellation is comprised of 66 satellites in Low Earth Orbit (LEO) at a height of approximately 781 km. The satellites orbit from pole to pole over a period of roughly 100 minutes. This constellation design allows for good satellite visibility and service coverage across the globe, particularly at the North and South Poles.



In addition to this pole-to-pole coverage, Iridium advantages include:

- A fully redundant gateway infrastructure
- No reliance on regional infrastructure/ground routing
- Satellite diversity, ensuring a high probability of access
- Security ensured through digital network
- Minimal call set-up time and low latency
- Fully global voice and data communications service

Currently there are more than 20,000 aircraft worldwide that are equipped with Iridium systems. These aircraft range from wide body commercial jets, business jets, and General Aviation aircraft. A growing number of ETOPS aircraft are also being equipped with Iridium systems.

Iridium antennas can be installed almost anywhere on an aircraft due to their small physical size. Multiple Iridium antennas can be installed on a single aircraft to maximize satellite visibility during unusual flight conditions. Even with such antenna configuration flexibility, maintaining reliable connectivity during normal flight conditions can be challenging. During unusual flight conditions, this becomes extremely difficult.

Various tests were performed by two companies (DRS and Astrium/Star Navigation) to assess the performance of the Iridium system. A summary of their work is detailed hereafter.

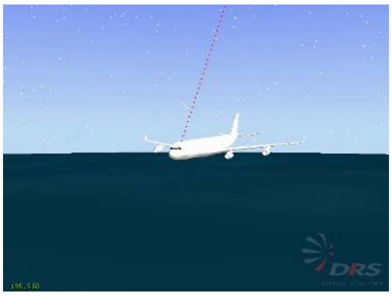
2.4.2.1 DRS Study

In 2003, DRS was asked to address this problem for the United States Air Force. The result was a product named FACE, or Fighter Aircraft Command & Control Enhancement. FACE provided worldwide communication between military command & control facilities and fighter aircraft using the Iridium satellite network. In combat, FACE virtually eliminated out of range aircraft communication problems, significantly improved low altitude communication over urban areas, and reduced close air support response times.

The FACE design utilizes multiple Iridium antennas integrated into the nose cone of a missile shaped pod. These antennas are connected to specialized DRS electronics modules mounted within the pod. FACE pods are mounted on fighter jet wingtips to minimize aircraft masking of the 66 crossed-linked LEO Iridium satellites during flight.

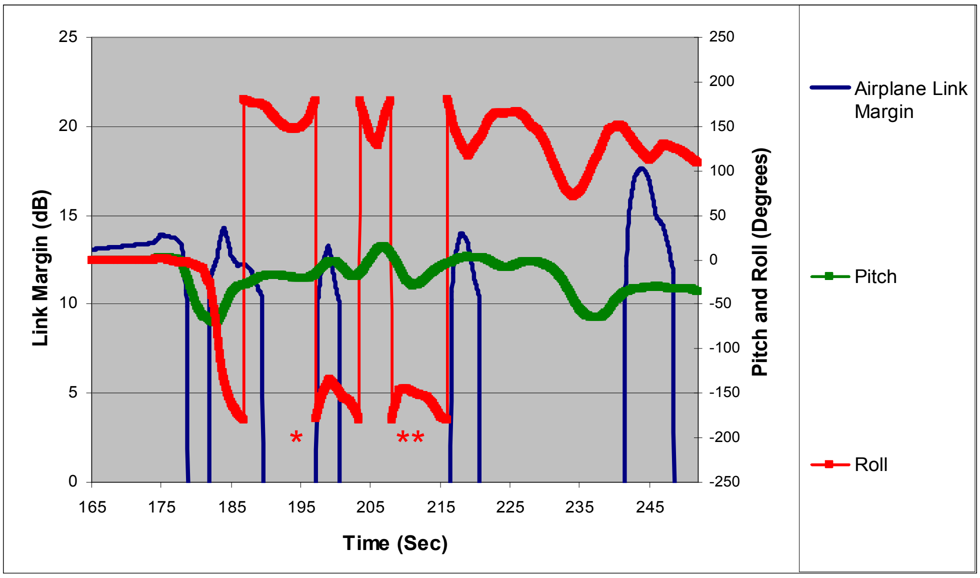
Using FACE technology, incoming Iridium calls to the pod are relayed to the pilot via standard aircraft UHF/VHF radio or intercom. FACE pods provide a robust SatCom link during tactical flight profiles with no aircraft modifications. FACE has been proven, in high dynamic tactical operations, to provide reliable voice communication and aircraft performance data in all aircraft attitudes.

FACE technology has recently been redesigned for use in military, commercial and general aviation aircraft. This new product offering will feature advanced SatCom connectivity. At the request of BEA, DRS performed computations of SatCom antenna connectivity using flight data from commercial aircraft accidents. For this study, DRS generated computer simulated flights from the available flight data, using a commercial jet model and one or more antennas mounted on the aircraft fuselage. The connection to the Iridium constellation is illustrated by a red dotted line from the aircraft antenna to the satellite. When the aircraft is in level flight, the antenna is connected. When the aircraft is upside down, the red line disappears, meaning that the antenna is no longer connected



The graph on the next page shows the results for the last 85 seconds of accident A044 using only one SatCom antenna mounted on top of the aircraft. Accident A044 was chosen because it was considered as having the most extreme attitudes. The satellite connection was evaluated through a parameter called link margin, or the amount of received power that is above the power required for the link to maintain specified performance. According to Iridium, the average expected link margin on the ground with 2 dB of cable loss and free space propagation is 13.1 dB.

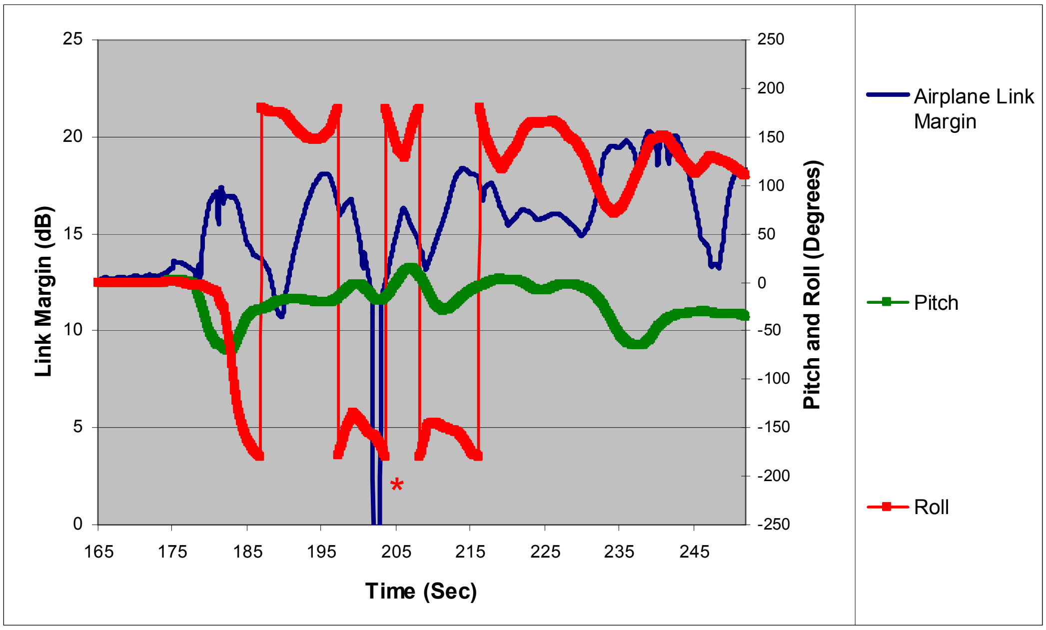
In their study, DRS took into account a link outage time of 10 s and a re-connection time of 30 s.



* High probability of data loss or corruption due to loss of link margin.
* * The call is dropped because the link margin is low for more than 10 seconds. It tries to reconnect but never has the required 30 seconds to reestablish a call.

This graph above shows that the last SatCom transmission occurs 50 seconds prior to impact.

DRS performed a similar simulation using data from accident A044, but with multiple antennas mounted on the aircraft fuselage. The following graph shows the results:



* Loss of Link Margin is due to masking from the tail of the plane. The call will not be dropped because the loss of connection is only one second long. Minimal probability of data loss or corruption due to loss of link margin.

This graph above shows that transmission is possible to the point of impact.

This study showed that SatCom systems which use a single antenna perform poorly in most high dynamic environments. Satcom systems which use two antennas perform well in many airborne environments, but potentially lose data in extreme environments. SatCom systems with more than two antennas have the potential to perform extremely well in all aircraft environments, regardless of aircraft attitude.

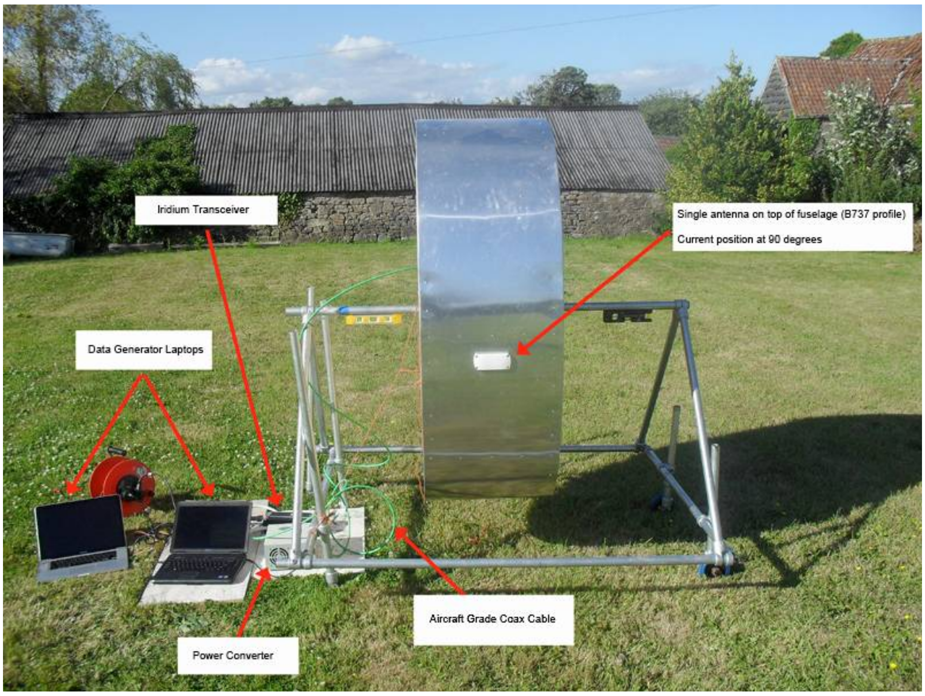
2.4.2.2 Star Navigation/Astrium study

Mid-2010, Star Navigation Systems/Astrium launched a test programme to quantify the connectivity performance of the STAR-ISMS^{TM} system at unusual aircraft attitudes. The initial stage of this test programme was to demonstrate the signal reception, transmission capability and data integrity (e.g. no data loss or corruption) of an Iridium omni-directional antenna on a “Proof of Concept” (PoC) Ground Test Rig.

The PoC Ground Test Rig comprised a simulated fuselage test section and a mounting rig. The test section was designed and built to simulate exterior surface radii of popular narrow-body aircraft and business aircraft. The mounting rig comprised a central spindle that mounted the test section, supported by a tubular steel “A” frame. The test section could be easily rotated through 360 degrees of roll, and elevated and secured up to 90 degrees of pitch.

The Ground Test Rig equipment installation for data transmission assessment used the following components:

1. One Iridium aircraft low profile, omni-directional antenna
2. Commercial aircraft grade co-axial cable
3. One commercial (aircraft qualified) Iridium transceiver
4. Specially configured laptop computer(s) – acting as an ARINC 429 and ARINC 717 data generator, providing simultaneous ARINC429 and ARINC717 data for transmission.



To demonstrate the PoC test objectives it was considered that:

- Iridium network connectivity could be adequately confirmed using the “Register” indicator on the transceiver LED indicator panel.
- Signal strength could be adequately assessed using the transceiver signal strength LED
- Connectivity consistency could be adequately assessed using flight data transmission streaming and was assessed using the “Register” and “Data Call” LED’s, “Signal Strength” LED and confirmation/analysis of the data received on the ground station.
- Post-transmission flight data integrity confirmation was achieved through manual data analysis

After basic system function checks to confirm satisfactory operation, static transmission tests with the antenna position at 0°, 90°, 270° and 180° were performed. These tests were followed by dynamic tests with a roll angle varying from 0 to 360° at an approximate roll rate of 90°/s.

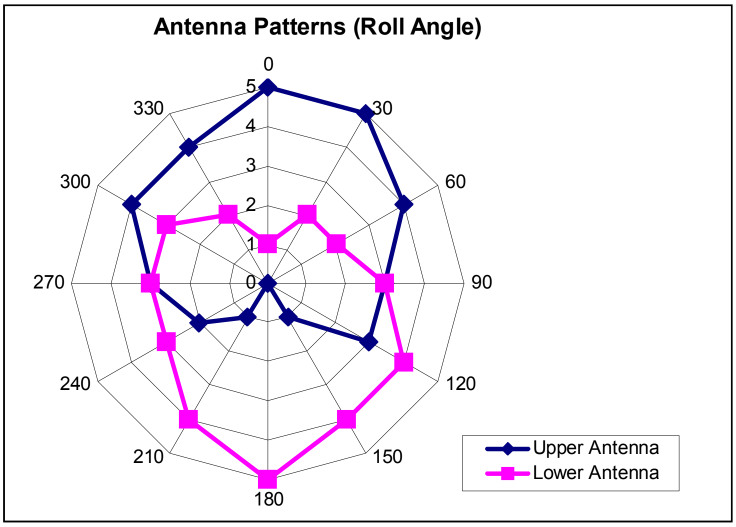
The ability to transmit flight data at all but the most extreme aircraft attitudes with a single antenna was demonstrated. Using a single top-mounted antenna, the Iridium connectivity is considered to be extremely robust while fuselage attitude remains between 270° and 90°. However, Iridium connectivity reliability deteriorates when fuselage attitude is increased beyond 90° up to 270°.

A second test was performed with a dual antenna installation configuration. The second antenna was installed at the opposing fuselage section location, and a further assessment of antenna reception signal strength performed, as indicated by the figure below. A switch box was then introduced into the antenna co-axial cabling and attached to both antennae simultaneously. Signal strength with this configuration was re-assessed, and found to be essentially identical. No loss of signal strength was noted.

For testing of full connectivity through 360 Degrees, voice transmission was used to assess quality and integrity by means of an Iridium handset. Following satisfactory initial system check-out, the test section was then rotated through 360 degrees, switching antennae manually at the 90° point to ensure that the uppermost antenna was transmitting at all times. This was performed at low, medium and high roll rates.

Good quality voice connection was maintained at all times, and no interruption of signal due to switching was noted. It is notable that very high integrity of signal was achieved using a non-optimum installation.

This figure shows the signal strength on a scale from 0 to 5 for the upper and lower antenna as the fuselage was rotated from 0 to 360°.



The influence of pitch on the signal quality is considered to be minimal as the roll attitude was considered to be a more extreme test, and basic assessments noted that the signal reception data did not indicate any significant variation in reception patterns in any axis.

These data transmission tests demonstrated quantatively the sensitivity signal strength and actual data transmission to roll attitude, and showed qualitatively how a simple antenna switching solution will provide complete coverage with consistent connectivity.

Hence the test data from this PoC installation is considered to demonstrate satisfactory connectivity performance for a simple installation to ensure integrity of data transmission through a full 360° rotation of the fuselage section. The concept of antenna switching to ensure signal connectivity at all attitudes (and particularly at high roll rates) is considered to be demonstrated.

2.5 Activation of ELTs prior to impact

ELTs (Emergency Locator Transmitter) are transmitters that can be tracked in order to aid in the detection and localisation of aircraft in distress. They are radio beacons that interface worldwide with the international Cospas-Sarsat satellite system for Search and Rescue (SAR). When activated, such beacons send out a distress signal, which, if detected by satellites, can be located by trilateration in combination with triangulation.

In the case of 406 MHz ELT which transmit a digital signal, the beacon can be uniquely identified almost instantly (via GEOSAR[11]), and furthermore a GPS or GLONASS position can be encoded into the signal, which provides instantaneous identification of the registered user and its location. Frequently, by using the initial position provided via the satellite system, SAR aircraft and ground search parties can home-in on the distress signals from the beacon and locate the concerned aircraft or people. ELTs can be activated automatically by shock typically encountered during aircraft crashes or manually.

In 2005, ICAO mandated that all aeroplanes and helicopters for which Parts I, II, and III of Annex 6 of the Convention on International Civil Aviation applied, be required to carry at least one ELT operating in the 406 MHz band. With a 406 MHz beacon, the position of the event can be relayed to rescue services more quickly, more reliably and with greater accuracy than with the 121.5 Mhz beacons.

The Cospas-Sarsat System has been undoubtedly helpful for Search and Rescue teams in numerous aircraft accidents on a worldwide basis. Despite these successes, the detection of ELT signals after an aircraft crash remains problematic. Several reports have identified malfunctions of the beacon triggering system, disconnection of the beacon from its antenna or destruction of the beacon as a result of accidents where aircraft were destroyed or substantially damaged. Even when the beacon and its antenna are functioning properly, signals may not be adequately transmitted to the Cospas-Sarsat satellites because of physical blockage from aircraft debris obstructing the beacon antenna or when the antenna is under water.

Possible improvements to the performance of 406 MHz ELTs during aircraft accidents have been impaired by some of the limitations of the current Cospas-Sarsat LEOSAR[12] and GEOSAR systems. These combined systems do not provide a complete coverage of the Earth at all time. As a consequence, beacons located outside the areas covered by the LEOSAR and GEOSAR satellites at a given moment cannot be immediately detected, and must continue to transmit until a LEOSAR satellite passes overhead. However, the

[11] Geostationary SAR
[12] Low Earth Orbit SAR

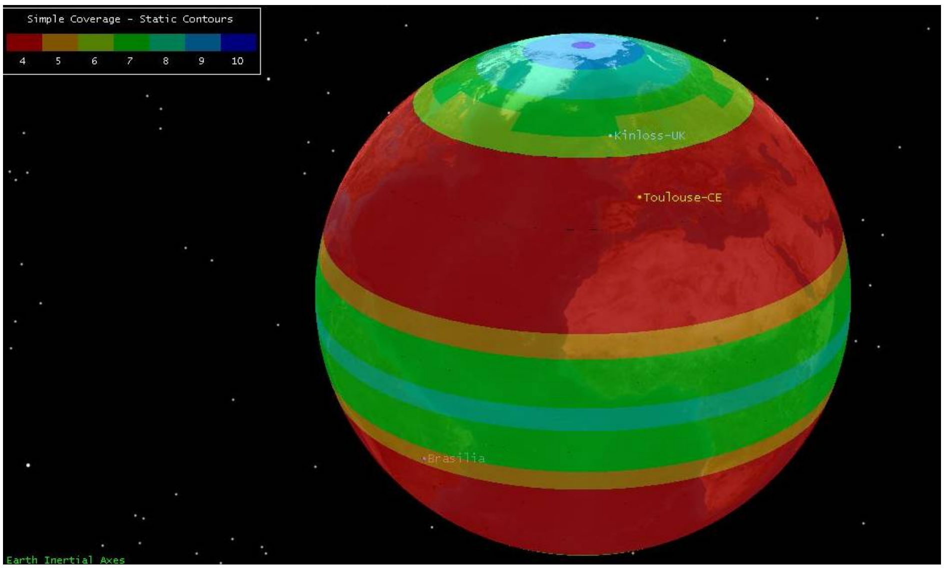
deployment of the MEOSAR[13] system in the coming years will significantly reduce or eliminate these limitations, significantly increasing the probability of an early detection and location determination of ELTs.

Indeed, the MEOSAR system has a large number of satellites, changing orbital positions and with large fields of view. This new system will rely on SAR repeaters embarked onboard future GPS, Galileo and GLOSNASS satellite constellations. MEOSAR satellites will be able to provide near-instantaneous detection, identification, determination of triangulated position of 406 MHz ELT and receipt of encoded position. One of the expected advantages of the future system consists of an enhanced ability to locate a distress beacon in a very short time. MEOSAR satellites travel across the sky much slower than LEOSAR satellites (6 hours compared to 15 minutes). They can therefore be positioned nearly overhead an ELT for about an hour and the chances of a distress signal being relayed to ground stations are significantly increased.

Furthermore, the MEOSAR system will provide several possible transmission paths for relaying data to the ground segment, including the encoded location of the beacon when available. This is what a CNES[14] study shows: considering a Galileo constellation of 27 satellites, a simplified analysis determined that there would always be at least 4 satellites visible from anywhere on Earth. The proportions of the Earth's area where 5, 6, 7, 8, or 9 satellites will be visible at the same time are also indicated in the table below.

Minimum Number of Visible Satellites	4	5	6	7	8	9
% of Earth area	100%	50%	37%	33%	5%	2%

These results are illustrated on the figure below.



In addition, preliminary analysis of the MEOSAR system showed that once a full constellation of MEOSAR satellites is operational, beacons will potentially see between 6 and 10 satellites at all times anywhere on Earth. A beacon burst containing an encoded localisation would

[13] Medium Earth Orbit SAR
[14] Centre National d'Etudes Spatiales (French Space Agency)

have a high probability of being relayed to the ground system via at least one of the many satellite paths available even if the aircraft is in an unusual attitude.

The expected capability of the MEOSAR system to detect and locate a beacon within a very short time anywhere on Earth offers new possibilities for designing ELTs with more reliable performance in aircraft accidents.

The BEA contacted the Cospas-Sarsat Secretariat at the end of July 2010 to investigate whether improvement in future ELTs could be developed to activate ELTs before impact or even have ELTs transmit a limited set of parameters. The Cospas-Sarsat Secretariat indicated that it was the appropriate time to submit the needs of our working group, as the initial high-level requirements for next generation beacons were about to be determined.

As a result, the BEA was invited in the French delegation to attend the Cospas-Sarsat “Experts Working Group On Next Generation Beacon Requirements” meeting that took place in September 2010 near Washington, DC. The purpose of the meeting was to draft the initial operational requirements for the next generation beacons.

Suggestions were made in the past to initiate the transmission of distress signals prior to an airplane crash, when the pilot (or an aircraft computer) would determine that the aircraft is in a distress situation. The benefit of implementing such an operating mode was however impaired by the limitation of the LEOSAR system to reliably provide timely localisation shortly after an ELT activation. With the current LEOSAR system, several minutes are typically required before a location could be determined. This delay, which could stretch to a few hours, is incompatible with the usually short period of time available between the preliminary signs of a distress situation and an aircraft crash, as demonstrated in paragraph 2.3.

This limitation will disappear with the upcoming Cospas-Sarsat MEOSAR system. Preliminary testing has already demonstrated that localisation within 5 kilometres could be achieved with a single burst transmission and that accuracy within 1 km might be envisaged for beacons specifically designed for the MEOSAR system. Additional tests will be performed during the MEOSAR Development & Evaluation phase to assess accuracies achieved for fast moving objects. The minimum performance requirement set in the MEOSAR Implementation Plan requires that an independent localisation (independent of any encoded location) be obtained within 10 minutes after the first beacon message. It is however essential that bursts occur to take advantage of this enhanced capability.

To do so, some of the current beacon requirements were revised, such as:

- ELT activation on indication of emergency: current activation mechanisms are either automatic (based on shock and/or water activation) or manual. Activating ELTs prior to impact would increase the chances of successful transmissions. This requirement would not be part of the minimum requirement list for Cospas-Sarsat certification. However, it would be available and it would be up the national Civil Aviation authorities to mandate it or not for aircraft under their jurisdiction.
- First burst transmission timeliness: the time between the activation of an ELT and the first burst, currently specified at 50 seconds, could also be reduced to ensure that data transmission is initiated before an aircraft crash. A tentative requirement is to set this time at 3 seconds. It is interesting to compare this time with following warning times: 95% of accidents have a warning time greater than 5 s, 86% greater than 10 s, 80% greater than 15 s and 57% greater than 30 s.
- Burst repetition rates: in order to increase the chances of accurate localisation in a short time, a more rapid burst repetition rate could be considered shortly after activation. A tentative requirement is to set this rate at 10 s in the first 30 seconds. After that, the rate return shall to its normal operational repetition rate (50 seconds or higher).

- Antenna characteristics: the current antenna pattern, optimised for the LEOSAR system and elevations ranging from 5° to 60°, could be modified to better locate MEOSAR beacons at higher elevation angles (close to 90°).

A timeline set out at the end of Cospas-Sarsat Experts' Working Group meeting plans to have the operational requirements approved by the Cospas-Sarsat Council at the end of 2011 and the technical evaluation completed by the end of 2014. A MEOSAR Development & Evaluation campaign is scheduled to occur between January 2012 and December 2014 and would include the use of 2nd generation 406 MHz beacon prototypes. Approved beacons compatible with these new requirements could be available on the market by the end of 2015. The MEOSAR Full Operational Capability is expected to be achieved in 2018.

2.6 Regular data transmission

The transmission of position data at a regular rate (every *x* minutes) could be an alternative to the triggered transmission based on detection of an emergency situation. The following are elements to help determine how frequently the regular transmission should occur to fulfill the objective of a 4 NM search area.

2.6.1 Case of AF447 accident

The ACARS system, integrated in the ATSU on Air France's Airbus A330, is used to transmit non-vocal messages between an aircraft and the ground by VHF or satellite communication. AF447 aircraft was programmed to automatically transmit its position approximately every 10 minutes.

On June 1st 2009, the last position report occurred at 2 h 10 min and 24 maintenance messages were received between 2 h 10 min and 2 h 15 min. These messages all transited via the same satellite (Atlantic Ocean West, operated by the Inmarsat Company) and SITA's ACARS network.

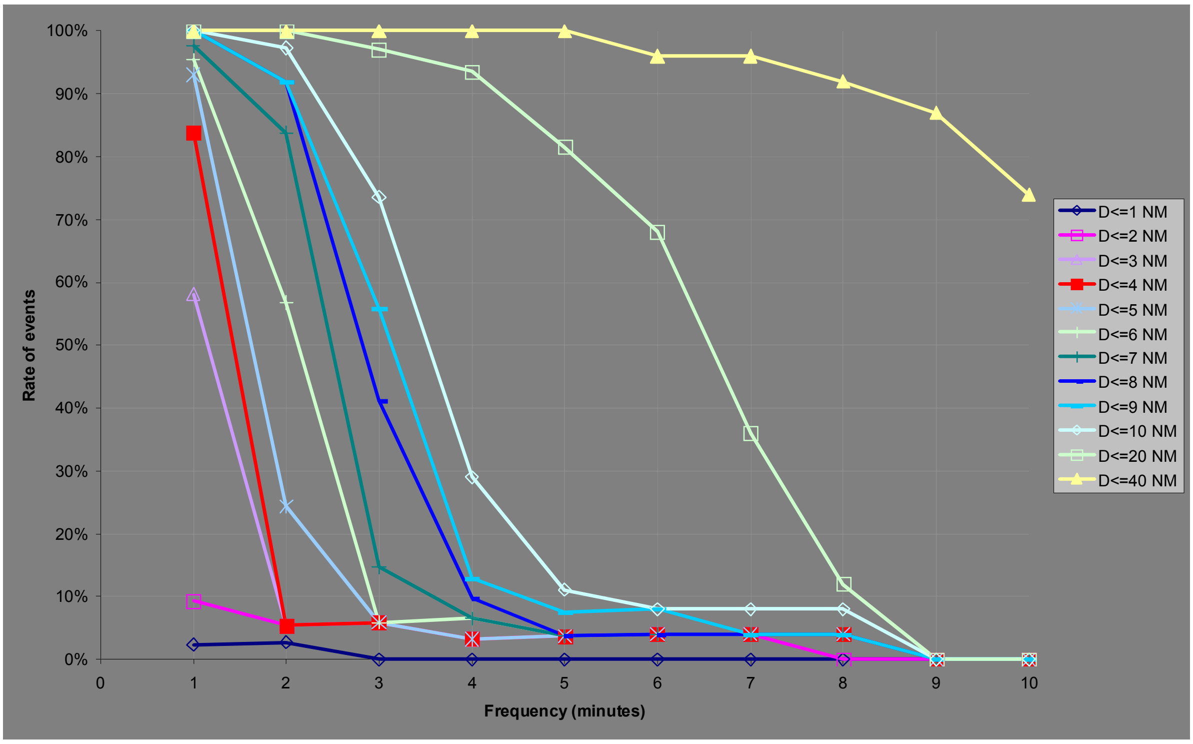
The maximum distance the aircraft could have feasibly travelled was computed from the time of its last reported position to the time when a scheduled response from the ACARS system was not received. The impact time was estimated based on the time of the last ACARS message received and the expectation (unfulfilled) of a subsequent message in the next 60 seconds. This analysis indicates that the end of the flight occurred between 2 h 14 min 26 s and 2 h 15 min 14 s, which makes a flight time since the last reported position of about 5 minutes. Considering a maximum ground speed of 480 kt (or 8 NM/min), this makes a search area in the shape of a disk of radius 40 NM centered of the last known position. This area extends over more than 17,000 km² and is situated more than 500 NM from the coastline.

2.6.2 Study based on the database

The database of accidents collected in the framework of the working group was used to assess the distance between a hypothetical last reported position and the point of impact.

Various rates of transmission (from every minute to every 10 minutes) were considered. The computed distance is based on the time of the estimated last transmission (using Inmarsat system) and the time of impact, using the recorded groundspeed when available, and otherwise the airspeed. This computation is conservative, as it is made as if the aircraft was flying straight and level until the impact, without any heading change or any rate of descent.

The following chart summarizes the results of these computations. It shows the percentage of accidents for which the search area is within a set distance (1 NM to 40 NM) versus the rate of transmission. For example, if the position is sent every 2 minutes 85 % of the aircraft from the accident database impact within a circle of 7 NM (green line) from the last position reported. If the position is sent every 3 minutes 15 % impacted within 7 NM.



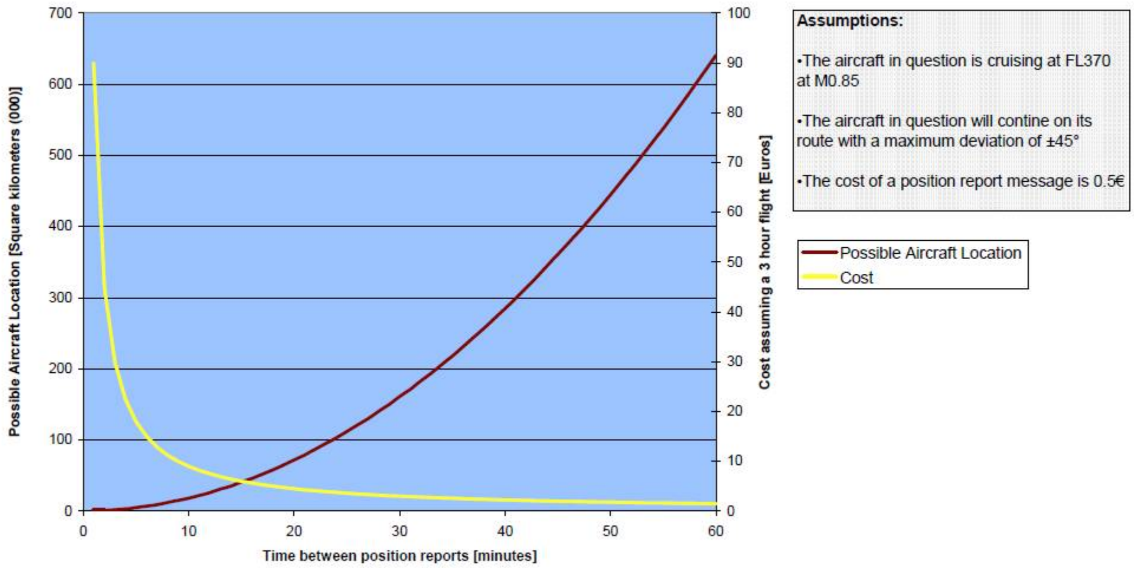
This chart indicates for example that 85 % of the impact positions are within 4 NM from the last reported position if the rate of transmission is every minute (red line) and that 95% are within 6 NM for the same rate of transmission.

2.6.3 OPTIMI project

The SESAR Joint Undertaking (SJU) launched a project, called OPTIMI (Oceanic Position Tracking Improvement and Monitoring Initiative), to improve the monitoring and position tracking of aircraft while in remote or oceanic areas. As well as technical solutions, the challenge included optimizing coordination between services in order to speed up rescue reaction times and accident analysis and diagnosis. The project aimed to deliver recommendations that can be implemented as of 2011. The needs for OPTIMI are in four main areas:

- Locating planes over oceanic and remote areas – Currently, when a flight leaves areas that are well-covered by air traffic control (ATC) radar systems, the plane communicates its location to ATC services only occasionally. In the case of an accident this can increase the time taken for search and rescue services (SAR) to respond.
- Rapid reaction to accidents – Efficient search and rescue services (SAR) are dependent on the location information in order to reach passengers rapidly.
- Accessing flight data and cockpit voice (‘Black Box’) recorders – In case of an accident, investigators depend on the data from the ‘Black Box’ to analyze causes. In oceanic and remote areas, their physical recovery is often difficult and time consuming.
- Avoiding future recurrences – Rapid diagnosis of the cause of an accident can reveal repetitive problems that may cause further occurrences. A quick diagnosis can prevent this.

The study showed that periodic reporting would not provide sufficient knowledge of aircraft position in itself to fulfil the OPTIMI requirement unless a very short period is used (around 1 minute), in which case it is expensive and has a high bandwidth requirement. The following figure shows a comparison of the financial cost and possible aircraft localisation for different position reporting periods.



After the assessment of the current situation and sets of in-flight demonstrations involving commercial flights in three different Atlantic oceanic regions (NAT, EUR and AFI), the Consortium responsible for the project delivered their report to the SESAR Joint Undertaking in January 2011 with recommendations in four main areas:

- ***Technology***: to encourage the equipage and use of Future Air Navigation System products (FANS 1/A) for Oceanic Area Control Centres and aircraft flying oceanic areas; this will cover in particular ADS-C and Controller Pilot Data Link Communications (CPDLC);
- ***Procedures***: to transmit automatically every 15 minutes the aircraft position and to trigger automatic transmission of position when a deviation from the planned route is detected;
- ***Economic***: to optimize the cost of the communications for ATC purposes in the oceanic areas along the service provision chain;
- ***Policy/ regulatory***: rescue and area control centres to jointly develop protocols for notifications and interventions in emergency situations.

The Consortium recommended also to further develop the technologies and procedures for the downloading of aircraft safety critical data to the ground on an event-triggered basis, together with the possibility of creating a Central Repository to manage this information. The SAT-OPTIMI project will be dealing with these topics.

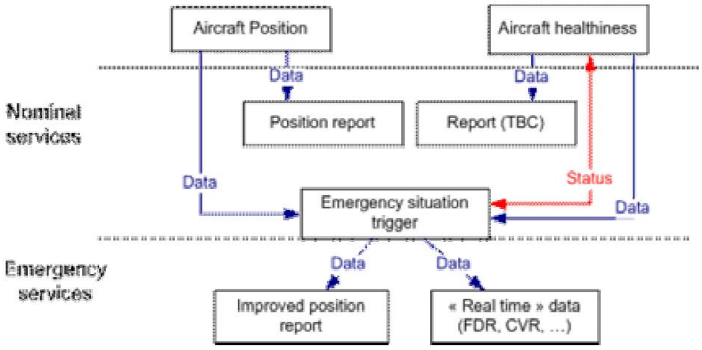
More details are available online at http://www.sesarju.eu

2.6.4 SAT-OPTIMI project

The objective of the SAT-OPTIMI (Satellite Oceanic Position Tracking Improvement and Monitoring Initiative) project is to conduct a study that will present feasibility and options for the best use of satellite infrastructure and technology to ensure full deployment of the oceanic and remote tracking services; i.e. using satellite infrastructure to deploy services as defined by the OPTIMI project conducted in 2010 by the SESAR JU. The SAT-OPTIMI study is a follow-on study complementing the OPTIMI study by investigating alternative technical solutions beyond FANS-1A, applicable to oceanic/remote airspace and non VHF covered area, but also by looking at future, mid-term (beyond 2013) and longer term (by 2020), services deployment able to support such evolved remote tracking services.

A major improvement to be considered in cost/safety trade-offs is to develop an airborne system able to detect emergency conditions to start or accelerate the pace of data transmission, and to decrease such pace if the emergency conditions is no longer detected:

- In emergency conditions, timely delivery of position reports can be performed without using the existing data-link applications (FANS-1/A) and its associated protocols, with reporting rates in the order of a few seconds instead of the current existing FANS-1/A one minute limitation.
- In nominal conditions, current priority, precedence and pre-emption mechanism could be significantly improved with the use of new satellite generation services.



Therefore, the SAT-OPTIMI study is analysing in details two types of innovative satellite based tracking solutions:

1. A standalone, non FANS-1/A, Iridium based solution for reporting aircraft data to airlines operational centres in anticipated emergency conditions,
2. The use of new satellite generation services, compatible with FANS-1/A, such as Inmarsat SwiftBroadband oceanic safety services.

The SAT-OPTIMI study is scheduled to be completed by mid-2011.

2.7 Operational benefits

In addition to helping in accident investigations, triggered or regular data transmission can also help aircraft operators improve their flight operations procedures, increase efficiency and save cost, by:

- Monitoring and analyzing in real time the main on board systems, which can download flight data either periodically (scheduled) or “on demand”, to operations centers on the ground.
- Tracking aircraft continuously, while monitoring their status, health and performance.

The benefits for airlines of such systems are numerous, as they can:

- Maximize fleet’s aircraft utilization by accurately monitoring airframe/components current and past usage profiles,
- Improve fleet management while reducing operating and maintenance costs,
- Pinpoint location of the aircraft almost instantaneously.

Operators of an existing data streaming system report paybacks on investment in 6-18 months.

See appendix 1 for a list of existing systems.

3 – ASPECTS OF INTEREST

The working group identified a number of areas that are of interest for the assessment of triggered transmission.

1. Detection criteria	The emergency criteria described in this report were evaluated on close to 10,000 flights. Evaluating them against an even larger set of recorded flights would confirm the accuracy of nuisance detection rate measurement. The fuzzy logic approach described in paragraph 2.2.2 could be further tested against flight data coming from an airline's FOQA datasets.
2. Elapsed time between detection times and transmission times	The process of triggered transmission can be broken down into several steps. Once trigger conditions are met, a small package of data is formed. This package is forwarded to the communications system, which has to receive it and carry out the necessary processing. The package can then be transmitted from the aircraft. This process, although fast with modern technology, can still take up to a few seconds. One company stated that their system takes a few milliseconds to develop and transmit the message. The transmission times described in paragraph 2.4.1 were computed by assuming that this time is null, as no definite value could be obtained by the BEA.
3. Flight tests	Antenna performance with aircraft in unusual attitudes was assessed by the working group with 3 different methods: one by making simulations based on 42 real accidents at hundreds of locations around the globe. A second simulation with ground test equipment and a final one through computer simulation. Some results from military aircraft operating with 2 or 4 antennas were also presented and are encouraging. Performing additional flight tests with aerobatic aircraft equipped with SatCom capabilities would help quantify and document antenna performance in unusual attitudes.
4. Effect of pitch and roll rates with Inmarsat system	Section 2.4.1 of this report describes how Inmarsat antenna would perform in 42 accident situations around the world. This study focuses only on antenna visibility with the satellite constellation, as aircraft attitudes vary in 3 dimensions. However, no effect of pitch rate or roll rate was considered. Comparing Inmarsat beam steering capabilities to these rates could reveal additional limitations of transmission with the Inmarsat system when aircraft are in unusual attitudes. It is important to note however that AF447 was able to send 24 maintenance messages during the last four minutes of its flight.
5. Impact of false positives for SAR	If next generation ELTs were to be activated automatically in flight, special attention should be paid to not calling out SAR personnel needlessly. ELTs operating on 406 Mhz transmit an encoded operator ID. If the ELT beacon is registered with the SAR national authorities, then a confirmation is first sought by the SAR service before launching a rescue team. However, if nuisance activation is too frequent, it might be a deterrent to SAR. Lowering the nuisance rate of emergency detection criteria to a level acceptable to SAR organizations will make the automatic activation of ELTs a solution with great potential.

6. Switching between antennas	The various Iridium-based systems presented in the report work with several antennas located around the aircraft. These systems rely on switching mechanisms that select the antenna with the best line of sight to the satellite constellation to transmit. It is not always clear to this working group how these systems operate and in particular what is their source of inertial information.
7. Antenna location and masking	The working group did not look at all antenna locations and the corresponding masking effect generated by aircraft sections blocking the line of sight between the antenna and the satellites.
8. Transmission continuity with VHF	The working group looked into transmission continuity of SatCom systems when aircraft are in unusual attitudes. However, there are other means of transmitting information, such as for example VHF Data Link Mode 2 (VDL/2). ADS-B and VHF antennas are being installed all around Greenland and on oil platforms, enabling VHF coverage in the North Atlantic. If more stations are installed around the globe, VDL/2 could also be used for data transmission in other remote and oceanic areas. Studying VHF transmission continuity for aircraft in unusual attitudes would determine whether VDL/2 could be a viable solution for triggered transmission in case of an emergency.

4 – CONCLUSION

The BEA created this working group to assess the technical feasibility of triggering the transmission of data on indication of emergency in order to help locate wreckage after accidents of fixed-wing aircraft over maritime or remote areas.

A study based on real accident/incident cases and real normal flights proved that criteria based on a limited set of recorded flight parameters can detect 100% of these accidents and incidents. The study also showed that these same criteria can be adjusted so that close to no nuisance transmission would be generated (a fuzzy logic approach generated no nuisance triggering, while a simple binary logic approach generated 1 minute of nuisance transmission for every 282 hours of flight).

This study proves that developing reliable emergency detection criteria is achievable. The robustness of detection could be further improved with more elaborate criteria and additional parameters available on modern aircraft data buses, not available for this study.

The warning times, or times between detection and impact, are at least 5 seconds for 95% of the accidents, at least 15 seconds for 80% of them and at least 30 seconds for 57% of them. When considering only accidents that occurred during the cruise phase, the warning times increase significantly: all have a warning time greater than 10 s and 91% of them have a warning time greater than 30 s.

A simulation run for all the accidents in the study and all around the world compared these warning times with the transmission capability using the Inmarsat constellation. The results showed that for 85% of the cases, a transmission of data would be possible before impact with the surface. Furthermore, for 82% of the cases, the corresponding search zone for the wreckage would be contained within a 4 NM radius.

Studies as well as actual tests in flight conducted with the Iridium constellation showed that SatCom systems which use two antennas perform well in many airborne environments, but potentially lose data in extreme environments. SatCom systems with more than two antennas have the potential to perform extremely well in all aircraft environments, regardless of aircraft attitude.

An analysis shows that if position information were sent every minute, 85 % of the accidents in the study would have an impact position within a radius of 4 NM from the last reported position.

Cooperation with Cospas-Sarsat has started and the activation of ELTs before an accident is now a high-level operational requirement for next generation beacons. The new requirements will also improve the ELT's performance in the first 30 seconds to increase the chances of accurate localisation within a short period of time. The fact that beacons will potentially see between 6 and 10 satellites at all times anywhere on Earth makes the likelihood very high of at least one burst being received. The localisation with only one burst should be within 5 km. It could be significantly smaller if the bursts contain messages with the encoded location or if several bursts can be transmitted before impact.

Based on all these results, the working group concludes that it is technically feasible to significantly reduce the search area for wreckage by:

- Triggering transmission of appropriate data via SatCom prior to impact, and/or
- Automatically activating next generation ELTs prior to impact, and/or
- Increasing the frequency of position reports.

The working group also suggests that the location radius of 4 NM is a realistic aim for 2020.

The BEA is planning to issue a safety recommendation on this basis in the framework of the AF447 accident. Consequently, regulators and the industry are invited to conduct further analysis in these 3 areas.

Appendices

Appendix 1: Existing systems

Appendix 2: List of accidents/incidents

Appendix 3: List of parameters in database

Appendix 4: Warning times per criteria

Appendix 1 : Existing systems

The following are examples of systems that can send data automatically from an aircraft to a ground station based on flight parameters for maintenance/monitoring purposes.

System's name	Company	Brief description
CMS (via ACARS) Centralized Maintenance System	Airbus	The Centralized Maintenance System (CMS) facilitates maintenance operations. It acquires and saves certain messages transmitted by the Flight Warning System (FWS) or the test functions integrated in various systems (BITE). It generates maintenance reports, including CFRs (when the aircraft is in flight) and PFRs (once the aircraft has landed). The CFRs are transferred to the ATSU (Air Traffic Service Unit) before being transmitted via ACARS (Aircraft Communications Addressing and Reporting System), integrated in the ATSU. The reports can then be analyzed on the ground using AIRMAN (AIRcraft Maintenance ANalysis). The objective of this tool is to help airline maintenance departments to anticipate unscheduled maintenance events and to make decisions in the frame of troubleshooting. Twenty-four maintenance reports relative to flight AF447 were received on the day of the accident after the last position report.
TAMDAR	AirDat LLC	TAMDAR (Tropospheric Airborne Meteorologic Data Reporting) is a global real-time atmospheric sensing and satellite data communication solution designed for easy integration with any commercial fixed wing aircraft. This system provides reports of the atmosphere (icing, turbulence, winds aloft, relative humidity, pressure, airspeed, pressure and GPS altitude, GPS stamp), and other aircraft system data required by the participating airline (real-time tracking, OOOI event reporting, satellite voice, EFB and text datalink, etc.). TAMDAR provides both regular interval reports (time or pressure based default), as well as triggered event reports (icing, turbulence, as well as operational events like OOOI). TAMDAR is a global solution, and has been fully operational on commercial aircraft since 2004. TAMDAR data is used operationally by NOAA (NWS, NCEP, AWC), and for accident investigation by NTSB.
AHM Airplane Health Management	Boeing	Airplane Health Management uses real-time airplane data to provide enhanced fault forwarding, troubleshooting and historical fix information to reduce schedule interruptions and increase maintenance and operational efficiency. AHM integrates the remote collection, monitoring and analysis of airplane data to determine the status of an airplane's current and future serviceability or performance. It converts the data into information that you can use to make the operational or "fix-or-fly" decisions. AHM automatically monitors, collects, and transmits service levels using ACARS through the installed Aircraft Condition Monitoring System (ACMS). This includes tire pressure, oxygen pressure, hydraulic fluid, APU, and engine oil levels. This system was installed on the B747-400 operated by UPS that crashed in Dubai on September 3, 2010. It successfully sent data while the aircraft was still in flight prior to the crash.
DTS Data Transmission System & Brite Saver	ECT Industries	DTS is an on-board tracking and data transmission equipment that uses the Iridium satellite network. It transmits pre-programmed messages selected by the user or automatic messages triggered by a particular event. This system was installed on an helicopter AS350B3 that crashed in Adélie Land (Antarctica) on 28 October 2010. DTS was operating at the time of the accident and the wreckage was found approximately

		500 meters from the last DTS-transmitted position. Brite Saver is an onboard Iridium based tracking and monitoring system available for helicopters and airplanes. Flight data can be collected either from a Data Acquisition Unit, a Vehicle Engine Monitoring Display or through any available sensors. Data is analyzed in real time and stored in the systems memory which can be hardened. On top of the aircraft's position which is sent periodically, any threshold overrun or alert sensed by the system will immediately trigger a streaming transmission of relevant information to the ground on a dedicated or web-based software. Each aircraft position and messages are displayed on an aeronautical map. After landing, the entire flight data log can be transferred to the ground station which is then used to screen for any unusual trend, warning sign of a possible breakdown. The system is currently operational onboard helicopters and tested for airplanes.
AFIRS UpTime Automated Flight Information Reporting System	FLYHT	AFIRS UpTime is a satellite-based system that allows aircraft operators to manage and monitor aircraft operations anywhere, anytime, in real-time. afirs UpTime gathers, stores, and transmits data, and delivers information via Iridium satellite. The system provides: • OOOI Tracking • Flight Following • Engine Trends • Engine/Airframe Exceedance • Voice/Text Communications FLYHTStream, an emergency data streaming mode, provides the additional level of needed safety for aircraft passengers. It can be automatically triggered (when a parameter goes outside the airplane flight manual) or manually triggered so if the crew is too busy to request help, FLYHTStream can start sending critical data such as position reports, equipment status reports and flight data recorder information to people in operations departments who may be able to help. The system uses an Iridium Network and UpTime data packets to stream this data to the ground anywhere around the globe. Approximately 275 aircraft have been equipped with AFIRS to date representing 33 operators in 6 continents (including an ACJ flying onto the ice runway in Antarctica). The AFIRS system has been certified by Transport Canada, FAA, EASA, and CAAC (China) for a large number of aircraft types.
ISMS™ In-flight Safety Monitoring System	Star Navigation/ Astrium	ISMS™ is an on-board flight monitoring system that provides a 'virtual window into an aircraft'. It is a commercial, air to ground communication system that automatically and securely transmits flight data and incident alerts via satcom. ISMS™ continuously monitors selected avionic systems on the aircraft as it flies, instantly analyzing and transmitting the data and any incident alerts via satellite to a secure ground control center. The ISMS™ system allows ground control the ability to monitor trends, predict possible failures, schedule repairs and assist the flight crew to take preventative action as required. It acts as an early warning system, detecting the earliest signs of potential problems. It performs these functions in "real-time" and provides essential safety monitoring to the benefit of passengers, aircraft personnel and ground crew. ISMS™ works to augment existing systems, not replace them. It is a "stand alone" system, invisible to the flight crew that reduces pilot workload and provides an additional wealth of real-time flight data and information to commercial operators. This system is currently in operations for testing purposes onboard several large transport category aircraft.

Appendix 2: list of accidents/incidents in database

Num	ACType	Flight Phase	Occurence Category ID	Occurence Description
A001	A320	Approach	LOC-I	Loss of Control In Flight
A002	A320	Approach	CFIT	Controlled Flight Into Terrain
A003	B737	Climb	CFIT	Controlled Flight Into Terrain
A004	CRJ100	Approach	CFIT	Controlled Flight Into Terrain
A005	A310	Climb	LOC-I	Loss of Control In Flight
A006	MD-82	Cruise	LOC-I	Loss of Control In Flight
A007	B737	Approach	CFIT	Controlled Flight Into Terrain
A008	F100	Climb	ICE	Icing
A009	Concorde	Climb	F-NI	Fire/Smoke (Non-Impact)
A010	DHC-6	Climb	SCF-NP	System/Component failure or malfunction (non-powerplant)
A011	ATR72	Cruise	ICE	Icing
A013	B737	Cruise	SCF-NP	System/Component failure or malfunction (non-powerplant)
A014	Shorts360	Climb	SCF-PP	System/Component failure or malfunction (powerplant)
A015	B747	Climb	CFIT	Controlled Flight Into Terrain
A016	F27	Approach	LOC-I	Loss of Control In Flight
A018	A310	Cruise	LOC-I	Loss of Control In Flight
A019	B737	Climb	LOC-I	Loss of Control In Flight
A020	A300	Climb	LOC-I	Loss of Control In Flight
A021	Saab340	Climb	LOC-I	Loss of Control In Flight
A022	B737	Cruise	MAC	Airprox/TCAS/Loss of Separation/Mid-Air Collision
A023	B737	Climb	CFIT	Controlled Flight Into Terrain
A024	CRJ200	Takeoff	ICE	Icing
A025	A300	Approach	LOC-I	Loss of Control In Flight
A026	A320	Climb	MAC	Airprox/TCAS/Loss of Separation/Mid-Air Collision
A027	A310	Approach	LOC-I	Loss of Control In Flight
A028	BAe146	Approach	CFIT	Controlled Flight Into Terrain
A029	Tupolev-154M	Cruise	LOC-I	Loss of Control In Flight
A030	Ilyushin-18V	Cruise	LOC-I	Loss of Control In Flight
A031	Tupolev-154M	Approach	LOC-I	Loss of Control In Flight
A032	Ilyushin-76TD	Climb	CFIT	Controlled Flight Into Terrain
A033	B737	Approach	AMAN	Abrupt Maneuvre
A034	Yakovlev-42	Approach	CFIT	Controlled Flight Into Terrain
A035	B737	Cruise	SCF-NP	System/Component failure or malfunction (non-powerplant)
A036	Ilushin-76TD	Approach	CFIT	Controlled Flight Into Terrain
A037	Ilyushin-76MD	Climb	CFIT	Controlled Flight Into Terrain
A038	Tupolev-134	Approach	CFIT	Controlled Flight Into Terrain
A039	A300	Climb	LOC-I	Loss of Control In Flight

Num	ACType	Flight Phase	Occurence Category ID	Occurence Description
A040	ATR72	Approach	LOC-I	Loss of Control In Flight
A041	B737	Cruise	LOC-I	Loss of Control In Flight
A042	B757	Cruise	LOC-I	Loss of Control In Flight
A043	B757	Climb	LOC-I	Loss of Control In Flight
A044	MD-82	Cruise	SCF-NP	System/Component failure or malfunction (non-powerplant)
A045	A330	Approach	LOC-I	Loss of Control In Flight
A046	A321	Approach	CFIT	Controlled Flight Into Terrain
I001	A310	Approach	LOC-I	Loss of Control In Flight
I002	DHC-8	Climb	ICE	Icing
I003	CRJ705	Cruise	LOC-I	Loss of Control In Flight
I004	A319	Cruise	TURB	Turbulence Encounter
I005	Falcon900	Cruise	LOC-I	Loss of Control In Flight
I006	A330	Cruise	LOC-I	Loss of Control In Flight
I007	B737	Approach	LOC-I	Loss of Control In Flight
I008	A330	Climb	SCF-NP	System/Component failure or malfunction (non-powerplant)
I009	Saab340	Approach	ICE	Icing
I010	Embraer120	Approach	FUEL	Fuel related
I011	Saab340	Approach	ICE	Icing
I012	Saab340	Approach	TURB	Turbulence Encounter
I013	B717	Approach	LOC-I	Loss of Control In Flight
I014	B737	Cruise	SCF-NP	System/Component failure or malfunction (non-powerplant)
I015	B777	Climb	SCF-NP	System/Component failure or malfunction (non-powerplant)
I016	B747	Cruise	SCF-NP	System/Component failure or malfunction (non-powerplant)
I017	A320	Approach	LOC-I	Loss of Control In Flight
I018	BAe146	Cruise	ICE	Icing
I019	B737	Approach	LOC-I	Loss of Control In Flight
I020	B777	Approach	UNK	Unknown or undetermined
I021	B777	Approach	UNK	Unknown or undetermined
I022	A330	Approach	MAC	Airprox/TCAS/Loss of Separation/Mid-Air Collision
I023	A330	Climb	MAC	Airprox/TCAS/Loss of Separation/Mid-Air Collision
I024	B717	Cruise	ICE	Icing

Appendix 3: List of parameters for accident and normal flight datasets in the database

The file lengths are 1 hour max for accident flights and whole flights for “normal” ones. All datasets were provided as Microsoft Excel spreadsheets at a sample rate of 1 Hz (1 data point per second).

Note: some parameters are not available in some datasets

	Parameter name	**Units**	**Description/Comments**
1	Altitude	ft	Pressure altitude Combined parameter (Altitude coarse+Altitude fine)
2	Airspeed	kt	Can be Indicated Airspeed, Calibrated Airspeed or Computed Airspeed
3	Ground speed	kt	
4	Pitch angle	°	Positive sign=nose-up
5	Roll angle	°	Positive sign=right wing down
6	Magnetic Heading	°	1 to 360°
7	Engine 1 power level	Various	N1 or EPR or Torque
8	Engine 2 power level	Various	
9	Radio Altitude	ft	Can be coming from radio-altimeter 1 or 2 or both combined into one parameter.
10	Vertical speed	ft/min	Is either recorded or will be derived from Altitude
11	nx	g	Longitudinal acceleration Positive sign=deceleration
12	ny	g	Lateral acceleration Positive sign=right turn
13	nz	g	Normal acceleration Positive sign=up
14	Flap/Slat configuration	Discrete	0=Clean; 1=Take-off configuration;2=Approach configuration
15	TAWS status	Discrete	GPWS or EGPWS Alert or Warning, whatever the mode. (0=No Warning;1=Warning)
16	STALL warning	Discrete	Can be stick shaker activation Can be information coming from CVRs. 0=No Stall; 1=Stall
17	Cabin Altitude Warning	Discrete	0=No Warning; 1=Warning
18	Master Warning/Caution	Discrete	0=No Warning/Caution; 1=Warning/Caution
19	Left AOA	°	Left True Angle of Attack (or AOA1) Positive sign=up
20	Right AOA	°	Right True Angle of Attack (or AOA2) Positive sign=down
21	A/P Engaged	Discrete	0=Auto-Pilot disconnected; 1=Auto-pilot engaged
22	Engine 1 Ice Detection Warning	Discrete	0=No Ice; 1=Ice
23	Engine 2 Ice Detection Warning	Discrete	0=No Ice; 1=Ice
24	Engine 1 N2	%	
25	Engine 2 N2	%	
26	Wing Anti-Ice	Discrete	0=OFF; 1=ON
27	Engine 1 Anti-Ice	Discrete	0=OFF; 1=ON
28	Engine 2 Anti-Ice	Discrete	0=OFF; 1=ON
29	Fuel Quantity	lb	Sum of quantities of all tanks
30	Gross Weight	lb	
31	CG	%	Center of Gravity
32	Engine1 Fuel Flow	lb/h	
33	Engine2 Fuel Flow	lb/h	
34	Engine1 Bleed Air	Discrete	0=OFF; 1=ON
35	Engine2 Bleed Air	Discrete	0=OFF;1=ON
36	Gear Selector Position	Discrete	0=UP; 1=DOWN

	Parameter name	Units	Description/Comments
37	True Airspeed	kt	
38	Captain pitch command position	°	Positive sign=nose up
39	F/O pitch command position	°	Positive sign=nose up
40	Captain roll command position	°	Positive sign=right
41	F/O roll command position	°	Positive sign=right
42	Rudder pedal position	°	Positive sign=right
43	Left Aileron Position	°	Positive sign=up (turn left)
44	Right Aileron Position	°	Positive sign=up (turn right)
45	Rudder position	°	Positive sign=turn right
46	Left Elevator Position	°	Positive sign=Nose down
47	Right Elevator Position	°	Positive sign=Nose down
48	TCAS RA	Discrete	0=No Advisory; 1=Advisory
49	Engine1 Fire	Discrete	0=No Fire;1=Fire
50	Engine2 Fire	Discrete	0=No Fire;1=Fire
51	Overspeed warning	Discrete	VMO/MMO OVERSPEED 0=No Warning; 1=Warning
52	Spoilers position	°	As many parameters as there are spoilers. May vary with aircraft type. 0°=retracted.

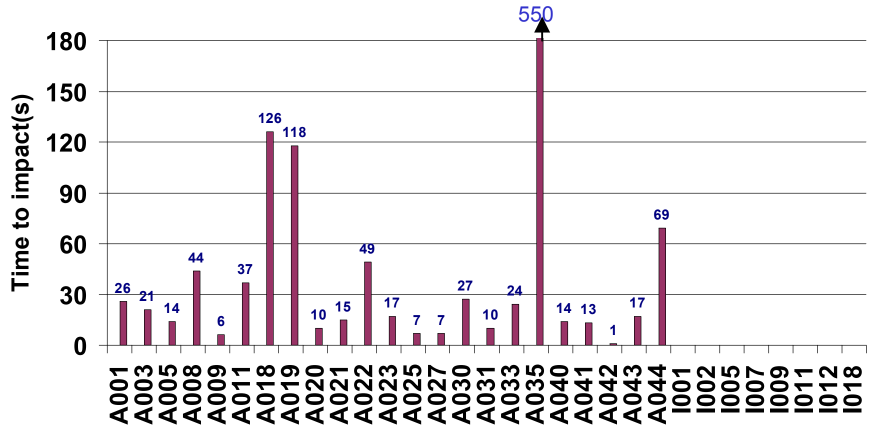
END

Appendix 4: Warning times (time to impact) by criteria using the binary logic approach

Excessive Bank

`{|Roll|>50°}` **OR** `{|Roll|>45°`**AND**`|Roll rate|>10°/s}`

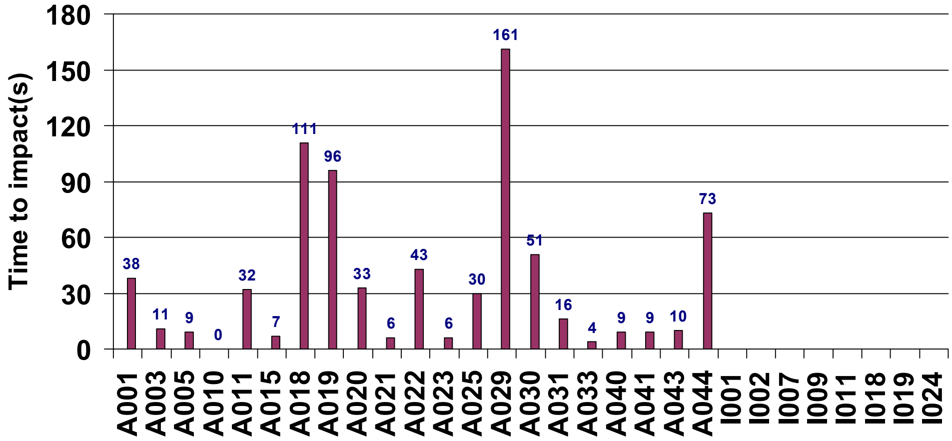
Confirmation time : 2 sec



Excessive Pitch

`{Pitch>30°}` **OR** `{Pitch<-20°}` **OR** `{Pitch>20°` **AND** `Pitch rate>3°/s}` **OR** `{Pitch<-15°` **AND** `Pitch rate<-3°/s}`

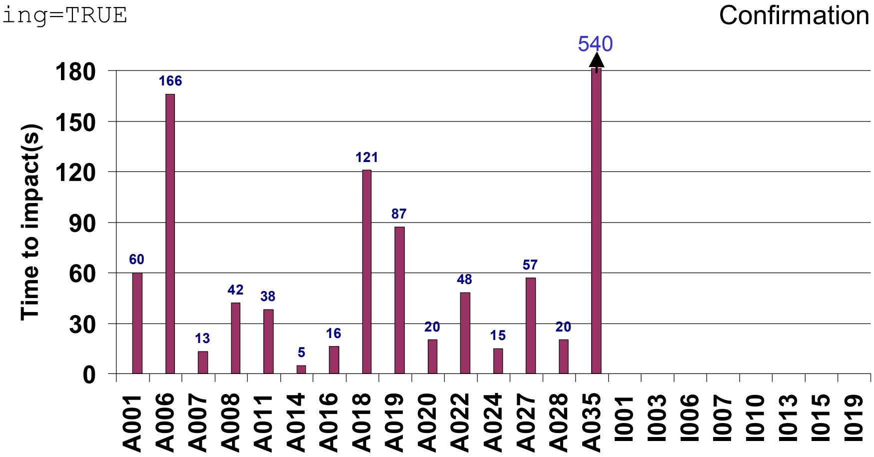
Confirmation time : 2 sec



STALL

`STALL Warning=TRUE`

Confirmation time : 1 sec

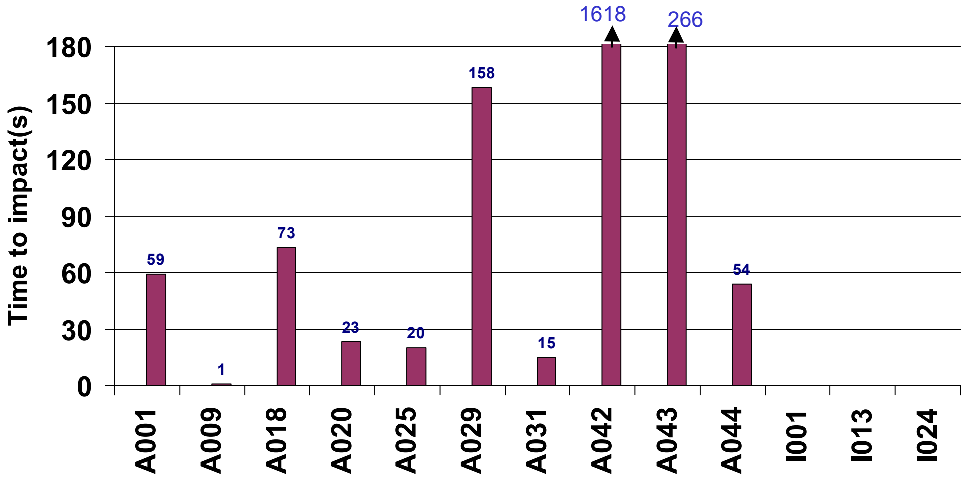


Low CAS

{CAS<100kt(*) **AND** Radio altitude>100 ft}

(*) 60 kt for DHC-6

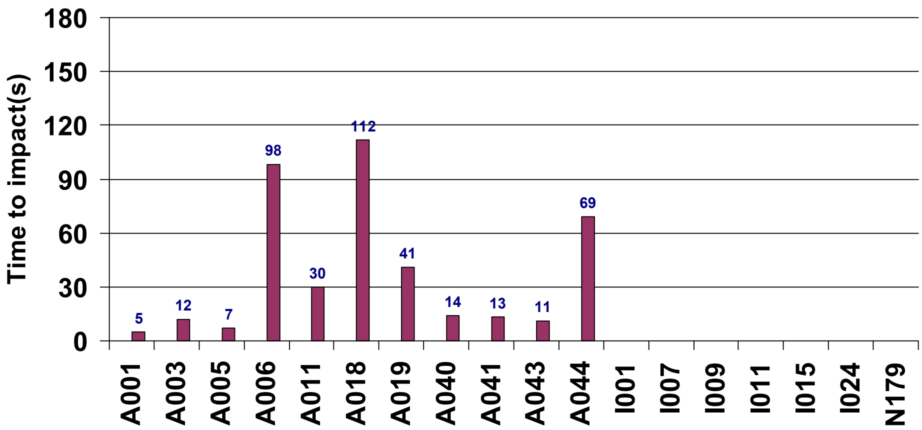
Confirmation time : 2 sec



Excessive Vertical speed (V/S)

{|V/S|>9000 ft/min}

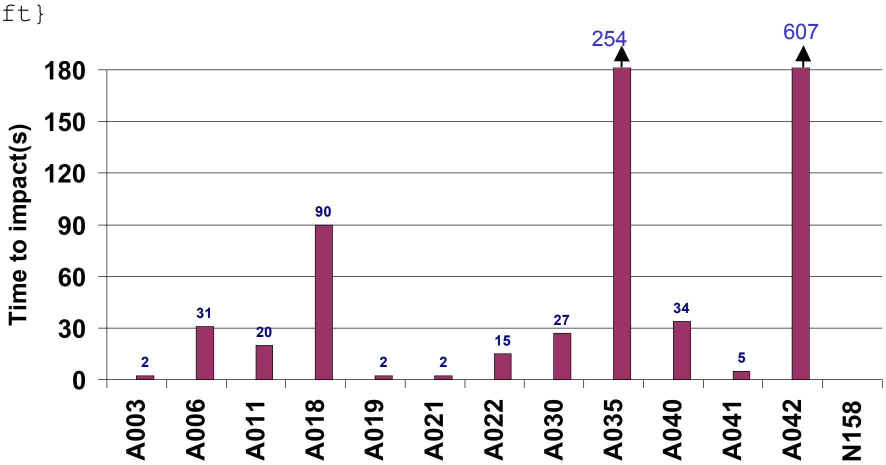
Confirmation time : 2 sec



Overspeed

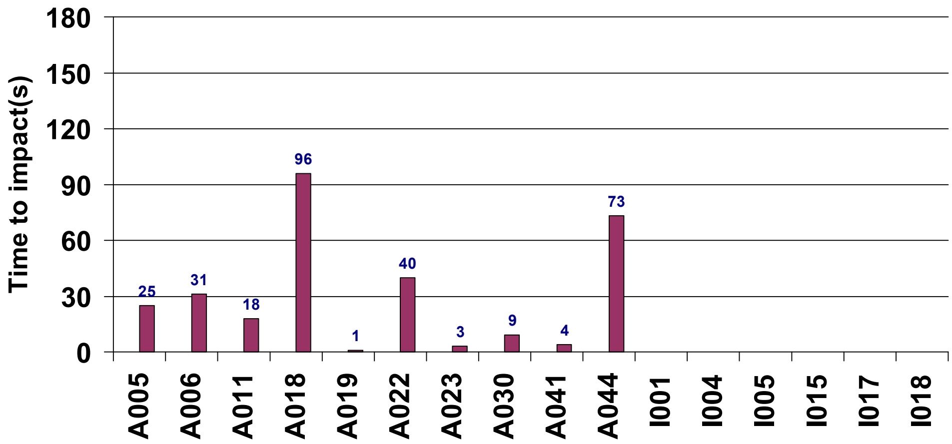
{IAS>400kt} **OR** {OVERSPEED Warning = TRUE **AND** Alt<15000 ft}

Confirmation time : 2 sec



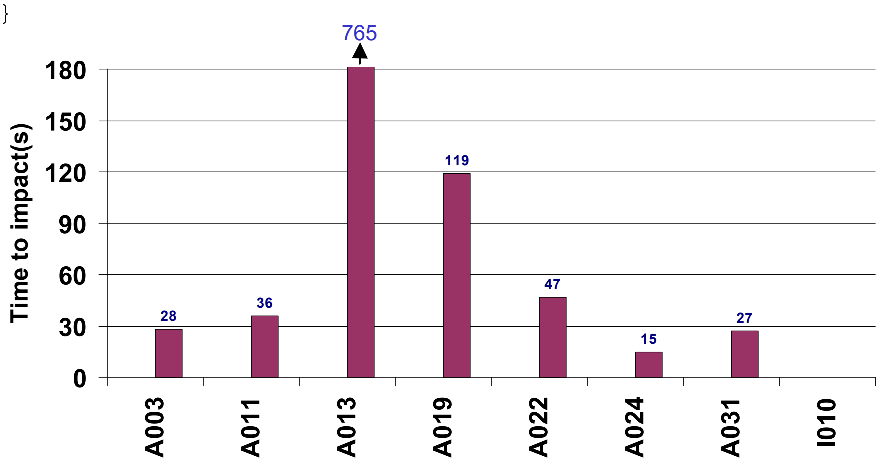
Unusual load factors

`{nz>2.6g OR nz<-1.1g } OR {|ny|>0.25g}` Confirmation time : 2 sec



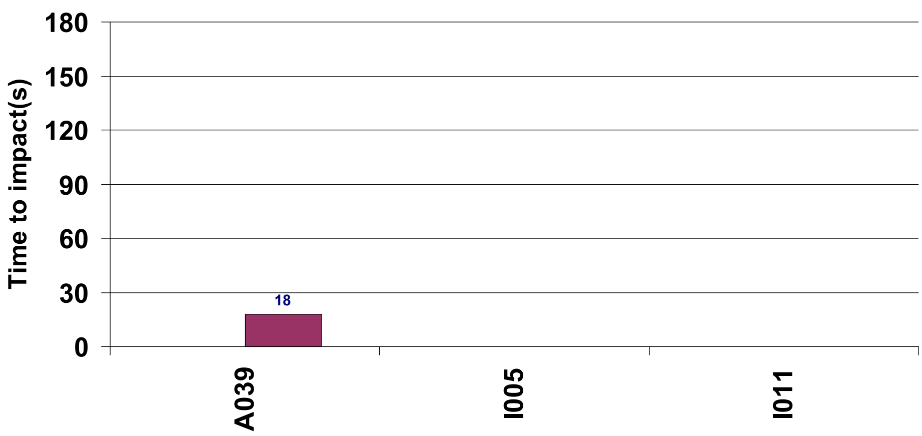
Excessive roll command

`{|Captain Roll cmd|>50 OR |F/O Roll cmd|>50 } AND {IAS>80 kt}` Confirmation time : 2 sec



Excessive use of rudder

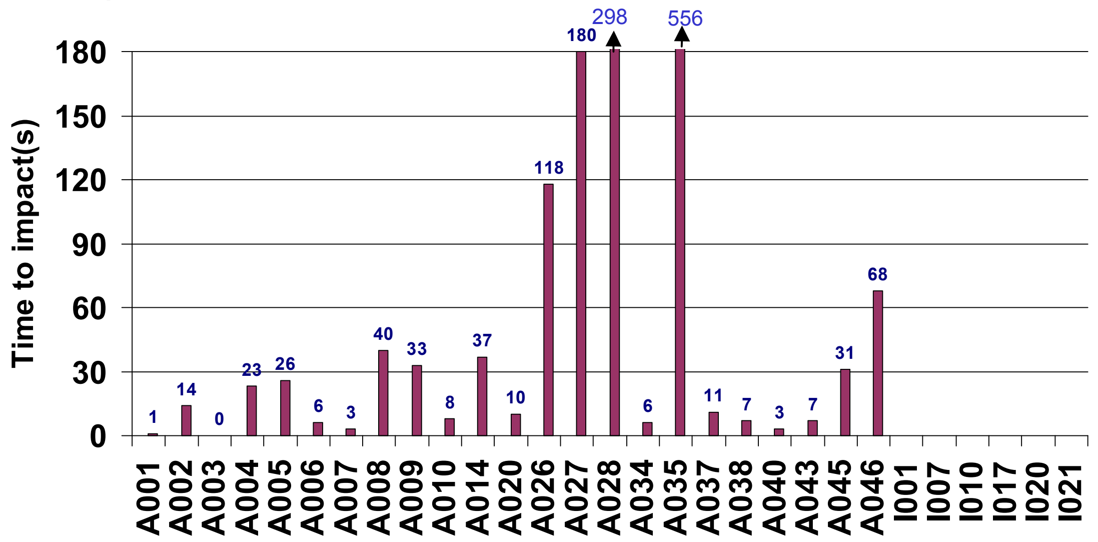
`{|Rudder position|>6° AND IAS>240 kt}` Confirmation time : 2 sec



TAWS warning

`TAWS warning/alert = TRUE`

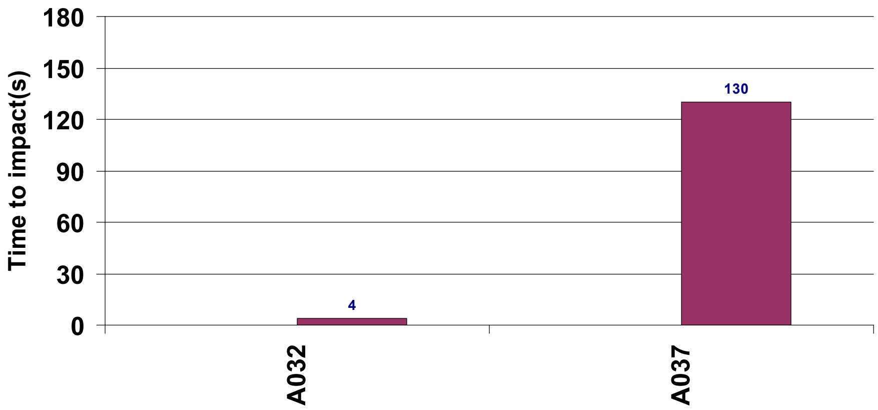
Confirmation time : 1 sec



Too low altitude
(poor altitude gain after takeoff)

`{40<Radio Altitude<100` **AND** `Eng1N1>80%` **AND** `Eng2N1>80% }`

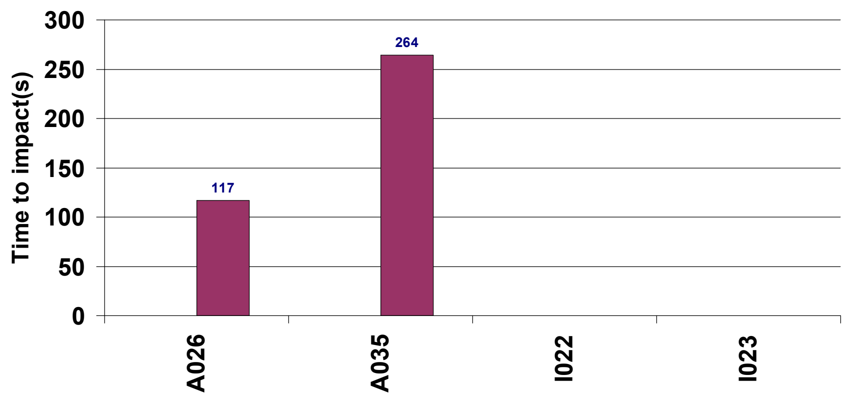
Confirmation time : 10 sec



TCAS

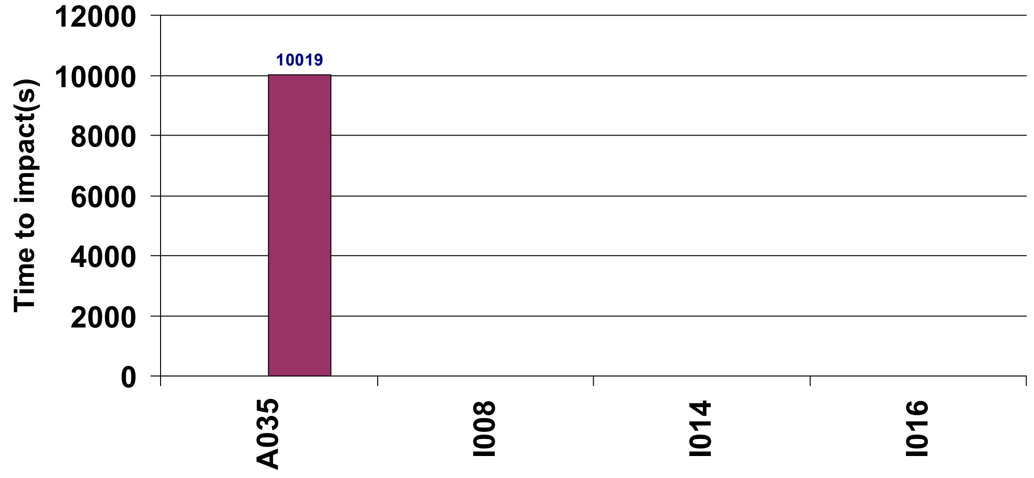
`TCAS RA = TRUE`

Confirmation time : 1 sec



Cabin Altitude Warning

`CABIN ALT WARNING = TRUE` Confirmation time : 10 sec



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