2017 (6th) MIT STAMP Workshop
MIT, Cambridge, USA
30th March 2017.

Applying Causal Analysis based on STAMP (CAST) Accident Analysis

Case Study: Runway Incursion

Tenerife North (Los Rodeos) Airport: March 1977

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Agenda

- Event Description: **Runway Incursion**
- Brief Overview:
  - How I applied the STAMP-based Process: **Causal Analysis based on STAMP (CAST)** *Accident Analysis Process*
- Overview of my results:
  - Hierarchical Control Structure (HCS) Model & Development
  - Signifcant Observations

27th March 1977

40th Anniversary of the Deadliest Accident in Aviation History

Aviation's equivalent: RMS Titanic Disaster, April 1912.

Ironies, coincidences & bad luck

- "The magnitude of the accident speaks for itself, but what makes it particularly unforgettable is the ***startling set of ironies and coincidences*** that preceded it. Indeed, most airplane crashes ***result not from a single error or failure***, but from a ***chain of improbable errors and failures***, together with a stroke or two of ***really bad luck***. Never was this illustrated more calamitously - almost to the point of absurdity - than on that Sunday afternoon 40 years ago."

-PAA Pilot Patrick Smith

http://www.telegraph.co.uk/travel/comment/tenerife-airport-disaster/

Runway Incursion

- Tenerife North Airport (Los Rodeos) Airport, Canary Islands, Spain.
- Sunday 27th March 1977
- 1706 Local Time
- Weather:
  Rapid variability
  Light Rain & Fog Patches (8/8 Cloud Coverage)
  300 m Runway (RWY) visibility (vis).
  500 m, intermittent to 5 km Approach vis.
  i.e. *Very Foggy!*

Aircraft Involved

Take-off

PH-BUF

KLM Boeing 747

Taxiing

N736PA

Pan Am Boeing 747

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For illustration (N736PA not pictured).
Image Source: https://upload.wikimedia.org/wikipedia/commons/2/2e/Boeing_747-121%2C_Pan_American_World_Airways_-_Pan_Am_AN1399875.jpg
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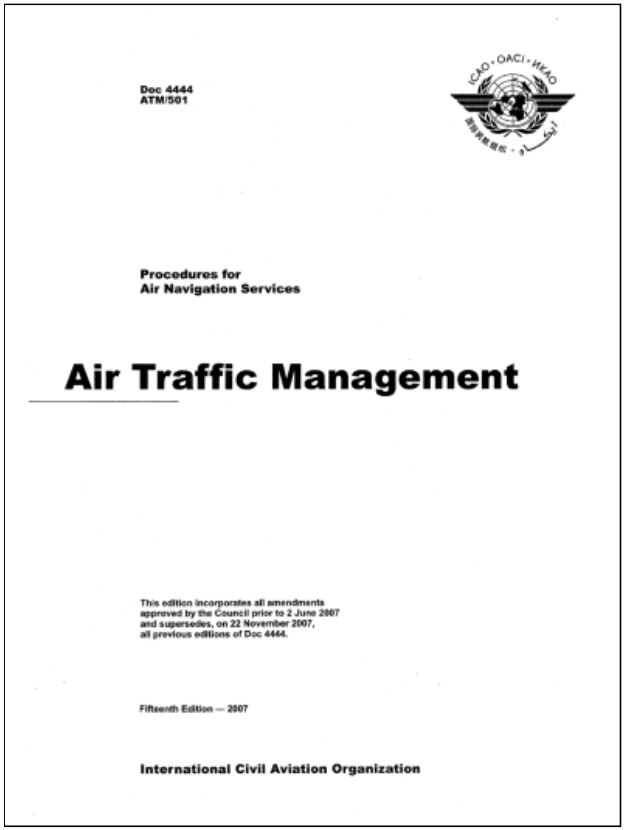
What is a Runway Incursion?

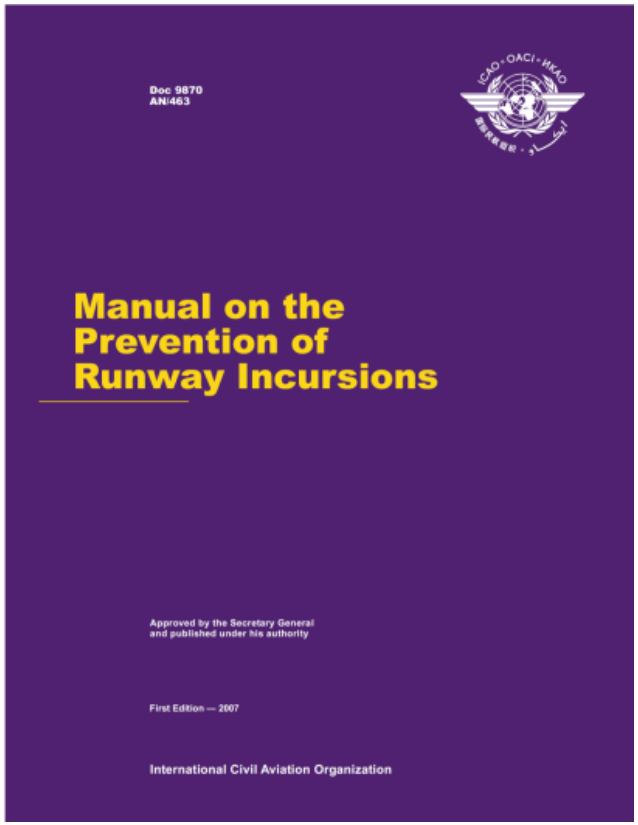
Definition*

The *Procedures for Air Navigation Services — Air Traffic Management* (PANS-ATM, Doc 4444) defines a runway incursion as:

"Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft."



ICAO Doc 4444
ATM/501
Fifteenth Edition - 2007



ICAO Doc 9870
AN/463
First Edition - 2007

CAST Accident Analysis: Why was the Control Structure Inadequate?

Image Source: http://www.crashdehabsheim.net/autre%20crash%20teneriffe.htm

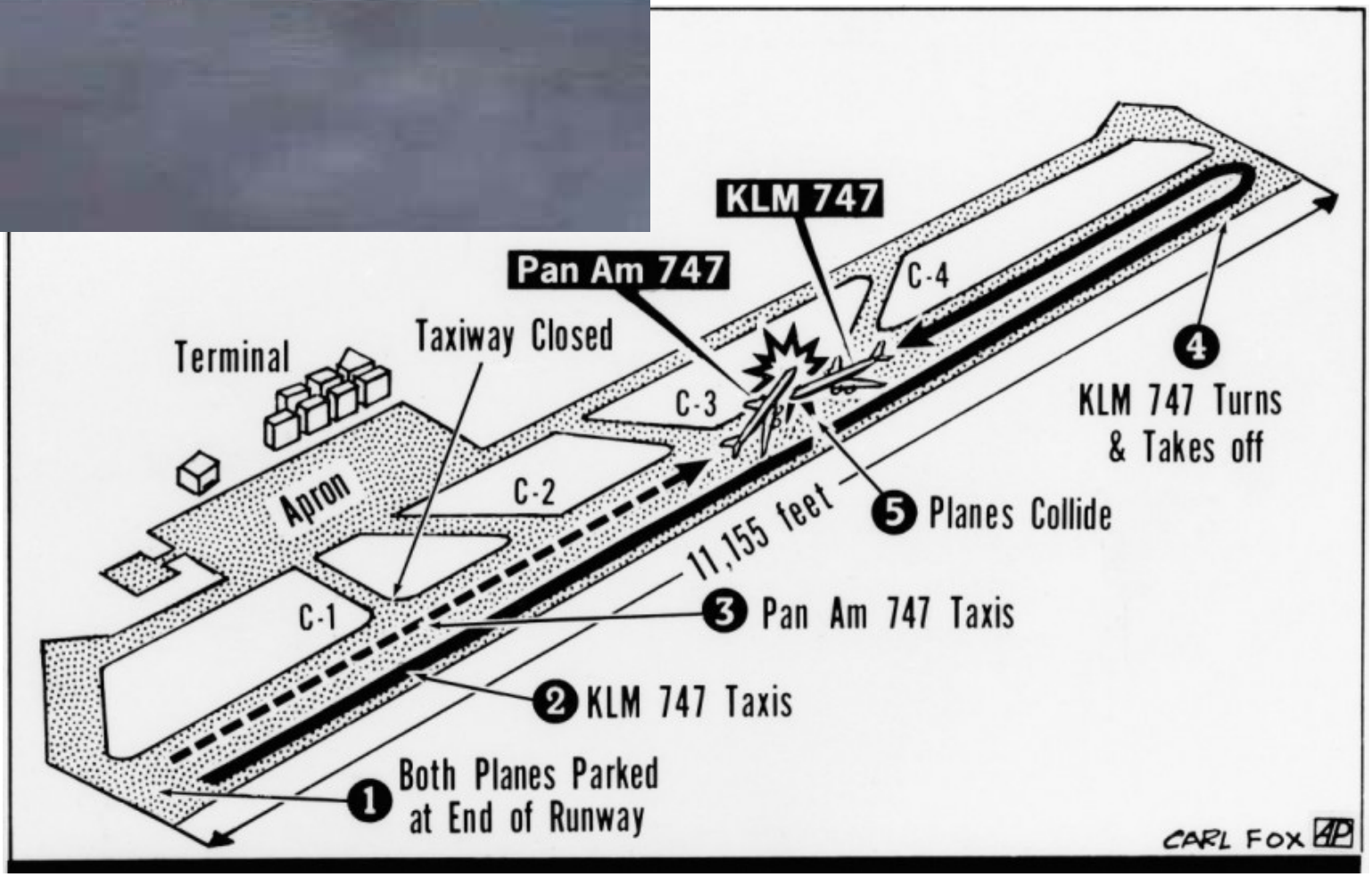


Image Source: http://goflightmedicine.com/tenerife-disaster/

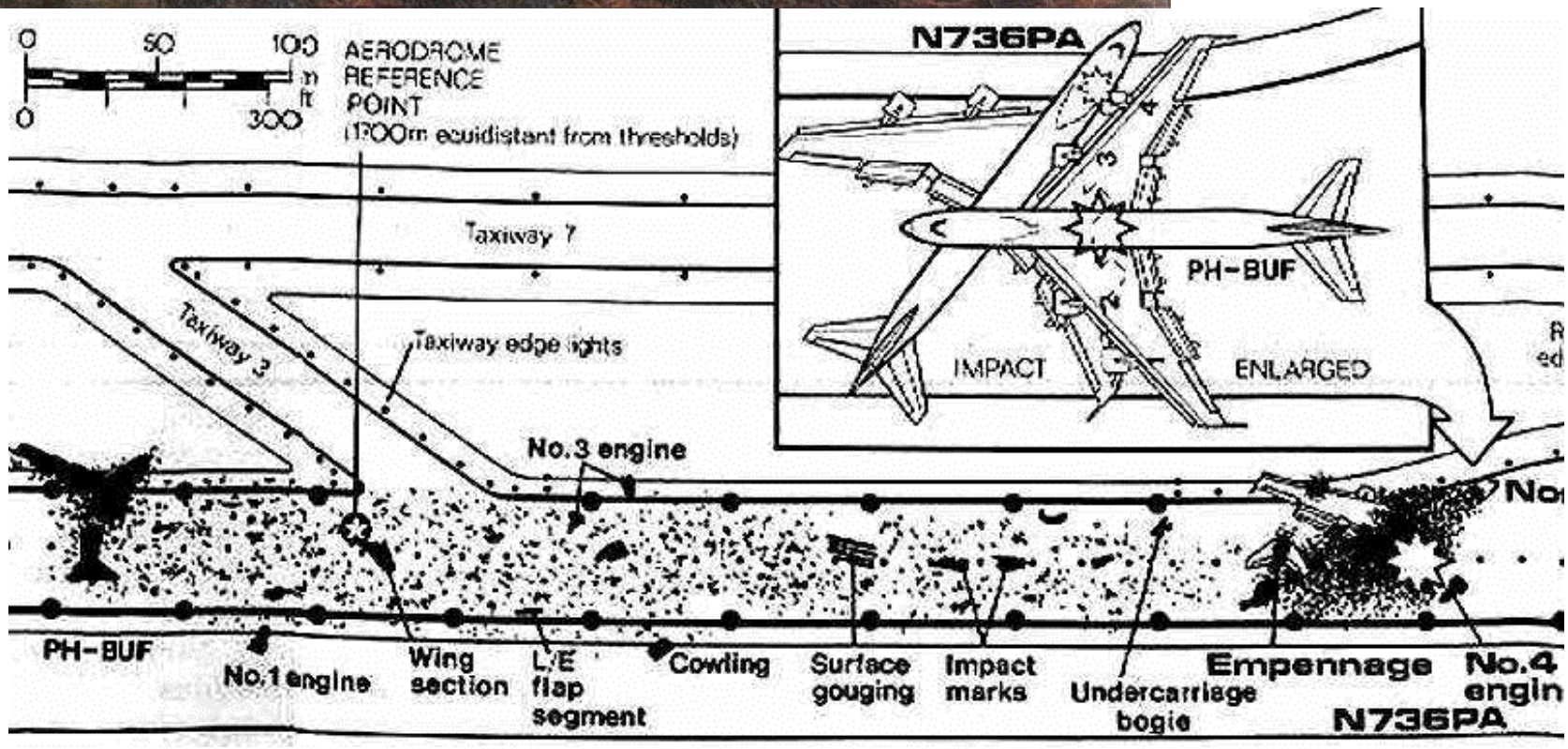


Image Source: http://www.crashdehabsheim.net/autre%20crash%20teneriffe.htm

Event Specific- Outcomes

- Accident Outcome:
  - 2 x Boeing 747 jumbo jets collided on the RWY
  - 583 killed + 61 Injured
    KLM 248 (all onboard) + Pan Am 335
  - Loss of 2 x Boeing 747 jumbo jets
  - Damage to Airport facilities
  - Major disruption to airport operations
  - Insurance & Legal Claim estimate: $2.25 Billion*
    (Time Magazine 1977)
    - *1977 $, in 2017 approx. $9 Billion

3 x Basic Causes

- KLM TO without Clearance
  (believed they had clearance*).
- Misunderstanding between ATC & KLM,
  -use of "usual terminology"
- PAA1736 still present on RWY, missed the exit.

Hazards

- Hazards / Hazardous Behaviour (states / events) associated with this Event:
  - Main Hazard: [H-01] Runway Incursion:
    - Presence of an Aircraft, Vehicle or Person on the protected area of a surface designated for the landing and take-off of Aircraft ***when an Aircraft is landing or taking-off***.
  - [H-02] Conflicting trajectories that lead to a loss of safe separation margin between Aircraft, Vehicles or People.

High-Level Safety Constraints (HLSC)

Hazard	HLSC
[H-01] Runway Incursion: Presence of an Aircraft, Vehicle or Person on the protected area of a surface designated for the landing and take-off of Aircraft when an Aircraft is landing or taking-off.	[HLSC-01] The HCS shall *prevent the presence of* an Aircraft, Vehicle or Person on *the protected area* when an Aircraft is *landing or taking-off*.
	[HLSC-02] The HCS shall *prevent the presence of* an Aircraft, Vehicle or Person on *the protected area* when an Aircraft is **in a position to** *land or take-off*.
[H-02] Conflicting trajectories that lead to a loss of safe separation margin between Aircraft, Vehicles or People.	[HLSC-03] The HCS shall *prevent trajectories that lead to a loss of* safe *separation margin* between Aircraft, Vehicles or People.

Are you familiar with this Accident?

Details of the Radio Communications amongst the various Aircraft and ATCO?

PA Captain N736PA	PA FO N736PA	Air Traffic Controller	KLM FO PH-BUF	KLM Captain PH-BUF	KLM FE PH-BUF	Other Aircraft	Emergency Response Management	External Disturbance
16:56		Request permission to Taxi.						
		Authorised.						
16:58		Backtrack RWY 12 for TO on RWY 30.						
17:02	Request permission to Taxi.							
	Authorised. Leave at 3rd taxiway on the left.							
17:03		Passing taxiway C-4.						
		Acknowledged.						
At end of RWY perform 180, report ready for ATC Clearance.								
17:04	RWY Centreline lights Unserviceable.							
	Leave RWY at 3rd taxiway on the left. Report leaving RWY.							
17:05:36.7		KLM 4805 at the end of the runway, in position for departure.						
17:05:41.5			Wait a minute, we don't have an ATC clearance.					
17:05:44.6			No, I know that, go ahead, ask.					
17:05:50.8		Now ready for TO, waiting for ATC clearance						
17:05:53.4								
17:06:08.1		KLM ATC Clearance.						
1706:09.6		Acknowledged…						
17:06:12.3				We gaan ... check thrust. [We're going ... check thrust].				
1706:17.8		We are now *at take-off* [or "*uh..taking off*"].						
1706:18.2		OK...						
17:06:20.3	And we're still taxiing down the runway,	*2 sec pause*						
1706:21.2	the clipper one seven three six.	...Stand by for take-off, I will call you.						
17:06:25.5		Ah, papa alpha one seven three six report the runway clear.						
17:06:29.6	OK, will report when we're clear.							
17:06:31.7		Thank you.						
17:06:32.4				Is hij er niet af dan? [Is he not clear then?]				
17:06:34.1				Wat zeg je? [What do you say?]				
17:06:34.7				Is hij er niet af, die Pan American? [Is he not clear, that Pan American?]				
17:06:35.7				Jawel. [Oh yes. - emphatic]				
17:06:40.5	PA Capt sees KLM landing lights at approx. 700 m							
17:06:43.5			V-1.					
17:06:44.0			PH-BUF (KLM 4805) starts rotation.					
17:06:45.9	Get off! Get off! Get off!							
17:06:50		**COLLISION**						
+ ? secs		Fire / Explosion Report						
+ ? secs							**CRASH, CRASH, CRASH**	

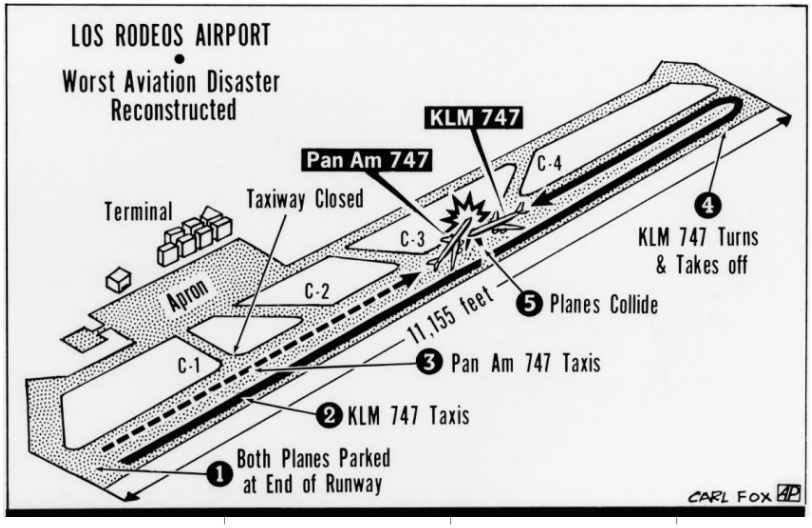
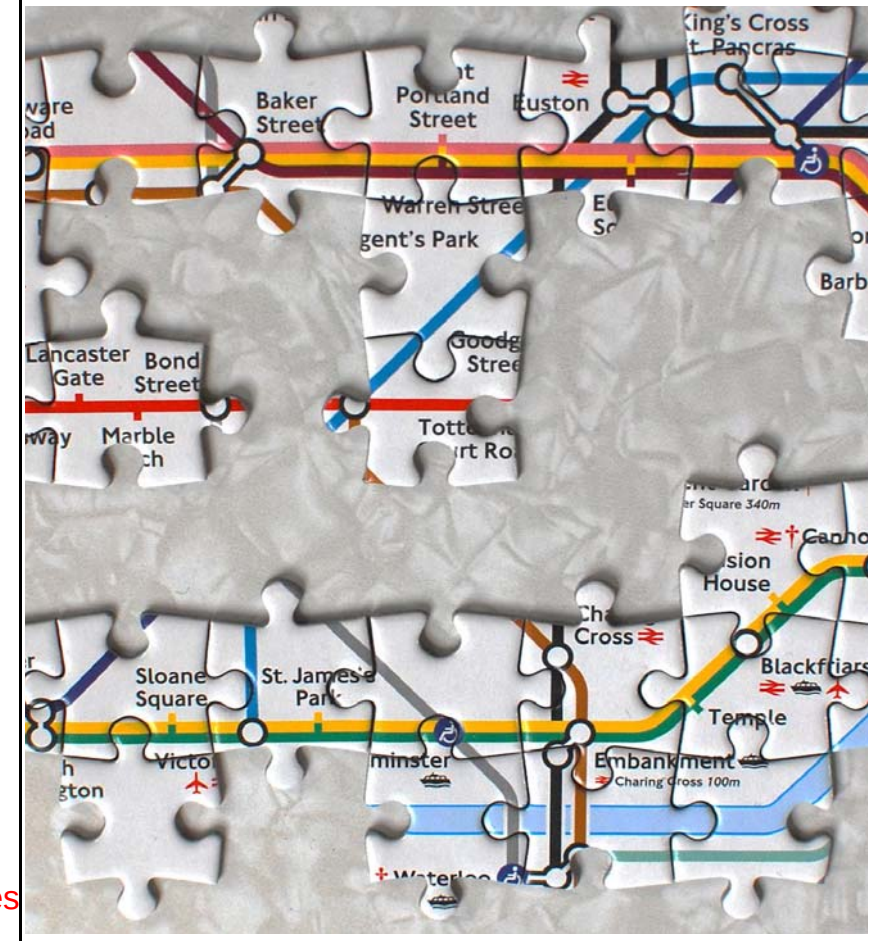


Image Source: http://goflightmedicine.com/tenerife-disaster/

A *superficial analysis* of **What** happened and a *partial indication* as to *some of the reasons* **Why** the event happened.

Controllers / Controlled Processes / Actuators / Sensors (System Components)		
Subsecretaria de Aviacion Civil, Spain	Aircraft (Boeing 747) N736PA (PA1736)	NL.gov
Accident Investigation	**PA1736 Aircrew**	Crew Duty Time Regulations
Accident Investigation Report	Aircraft PA1736 Trajectory / Path	**KLM Airline**
Aircraft (Boeing 747) PH-BUF (KLM4805)	Runway Centre Lights	US.gov
KLM4805 Captain	Procedures for Restricted Visibility	NTSB
KLM4805 First Officer (FO)	Radio Recorder	**Pan American Airways**
KLM4805 Flight Engineer (FE)	Cockpit Voice Recorder (CVR)	Boeing
Aircraft KLM4805 Trajectory / Path	Flight Data Record (FDR)	Emergency Response Management
Airport / ATC Management	Voice Recording Transcript	Rescue Workers
Radio Equipment	Airfield Weather Service	Hospital
Air Traffic Control Officer (ATCO)	ES.gov	Guardia Civil
Approach Controller	International Civil Aviation Organisation (ICAO)	Local Commercial Radio Station
Ground Controller	Doc 4444 Procedures for Air Navigation Services- Air Traffic Management Standard Phraseology	Members of the Public
Runway Controller		Fuerzas Armadas Guanches (Terrorist Org.)
Airfield Layout		Bomb
Airlfield Layout Map		



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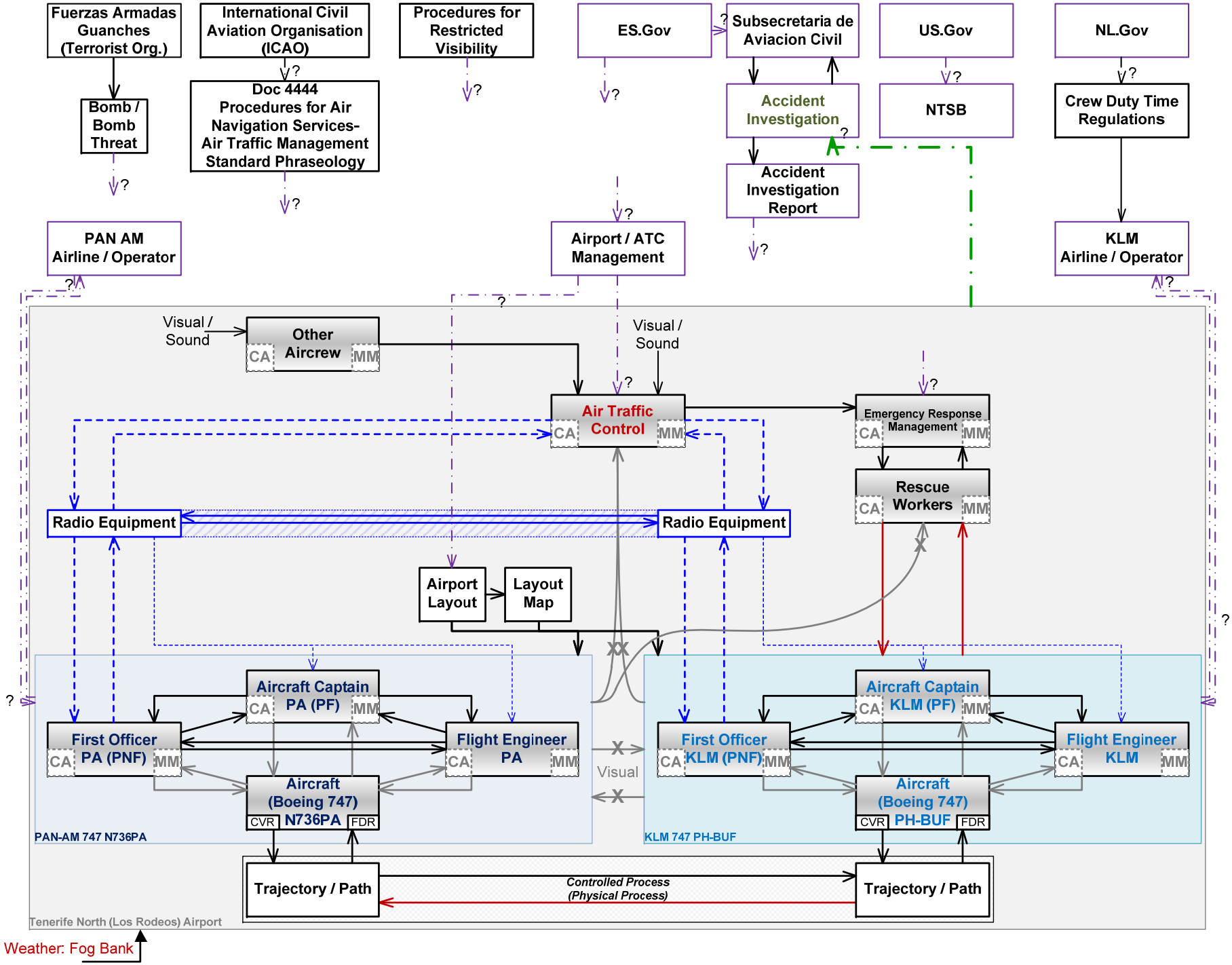
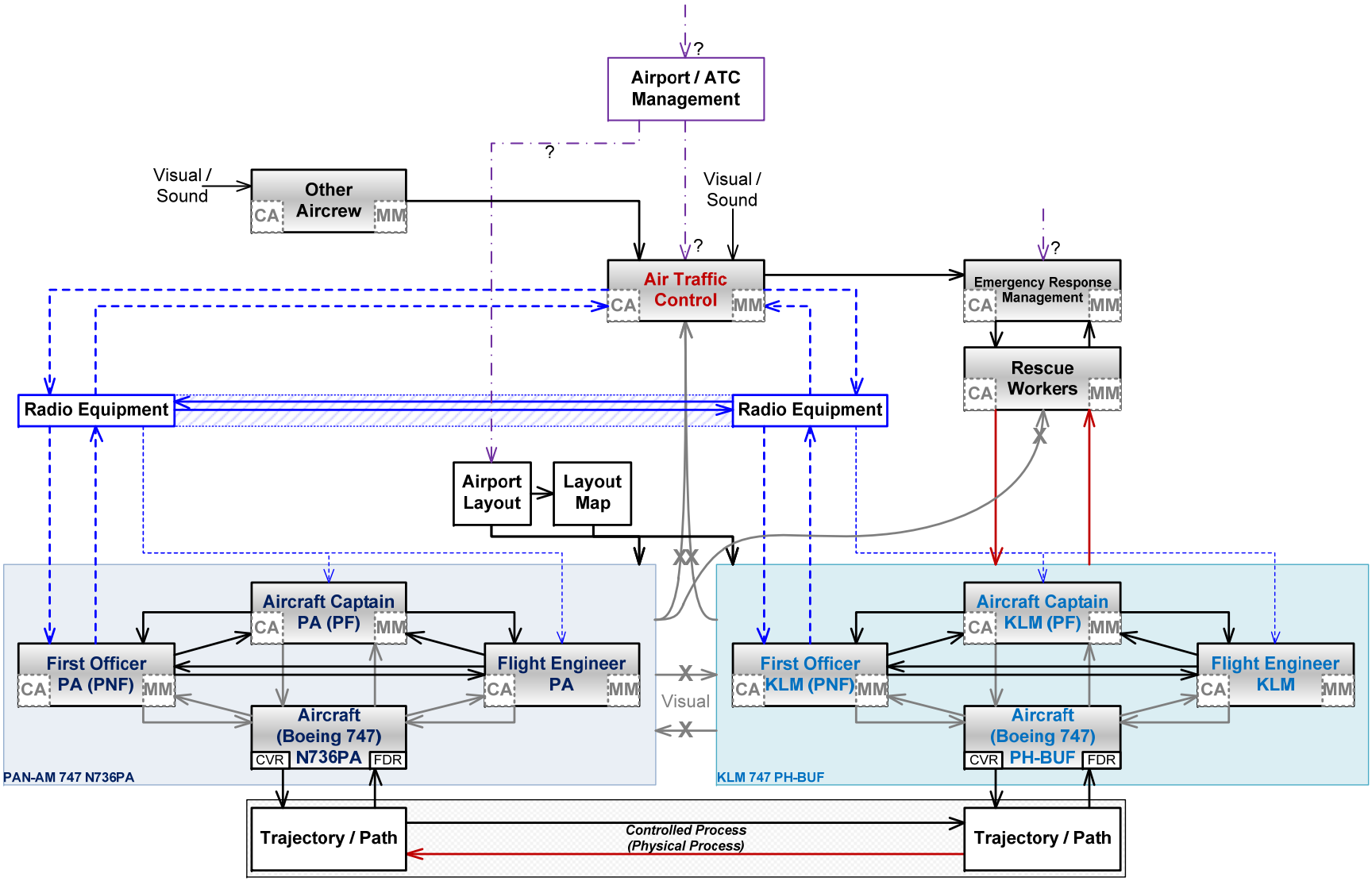
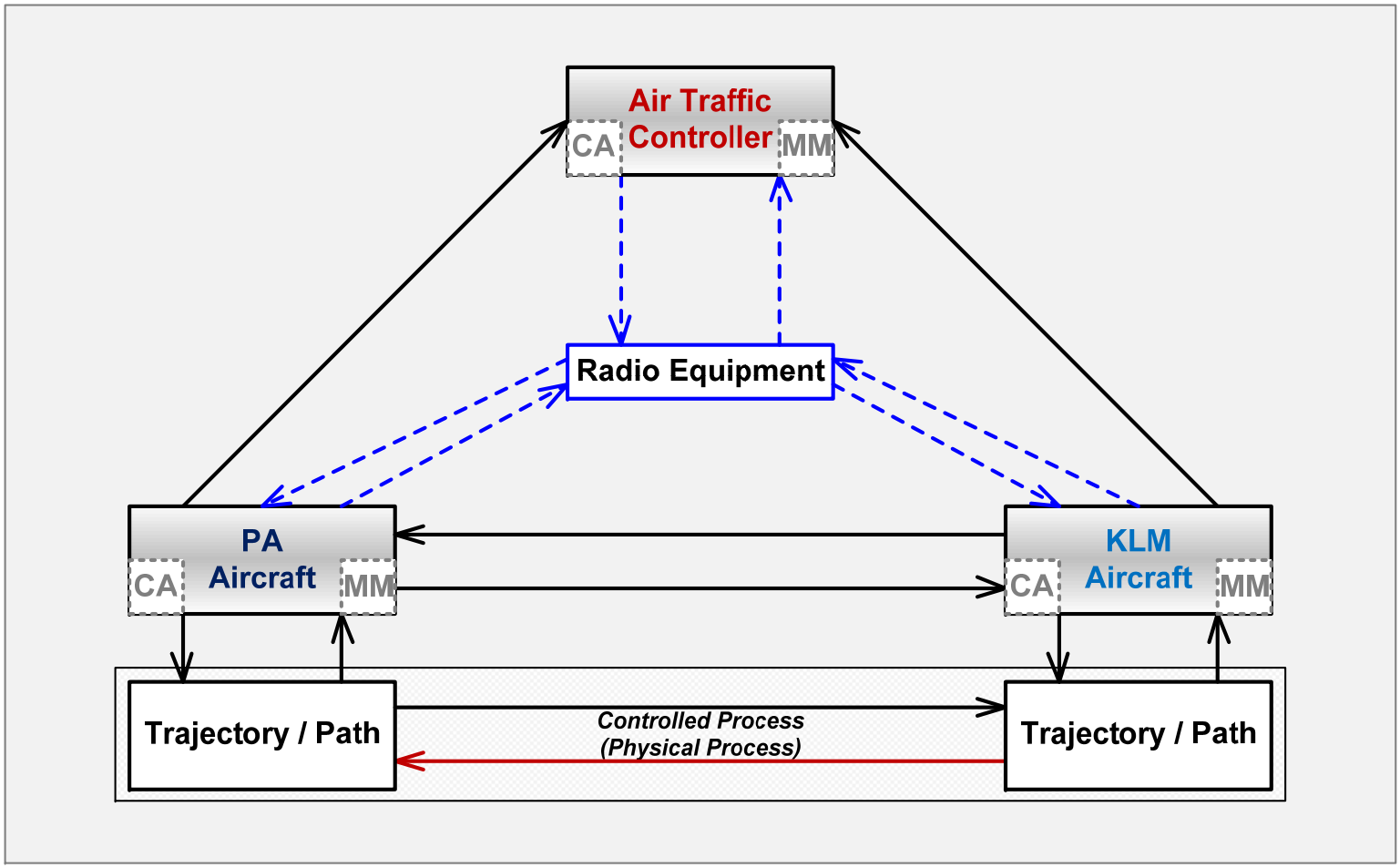
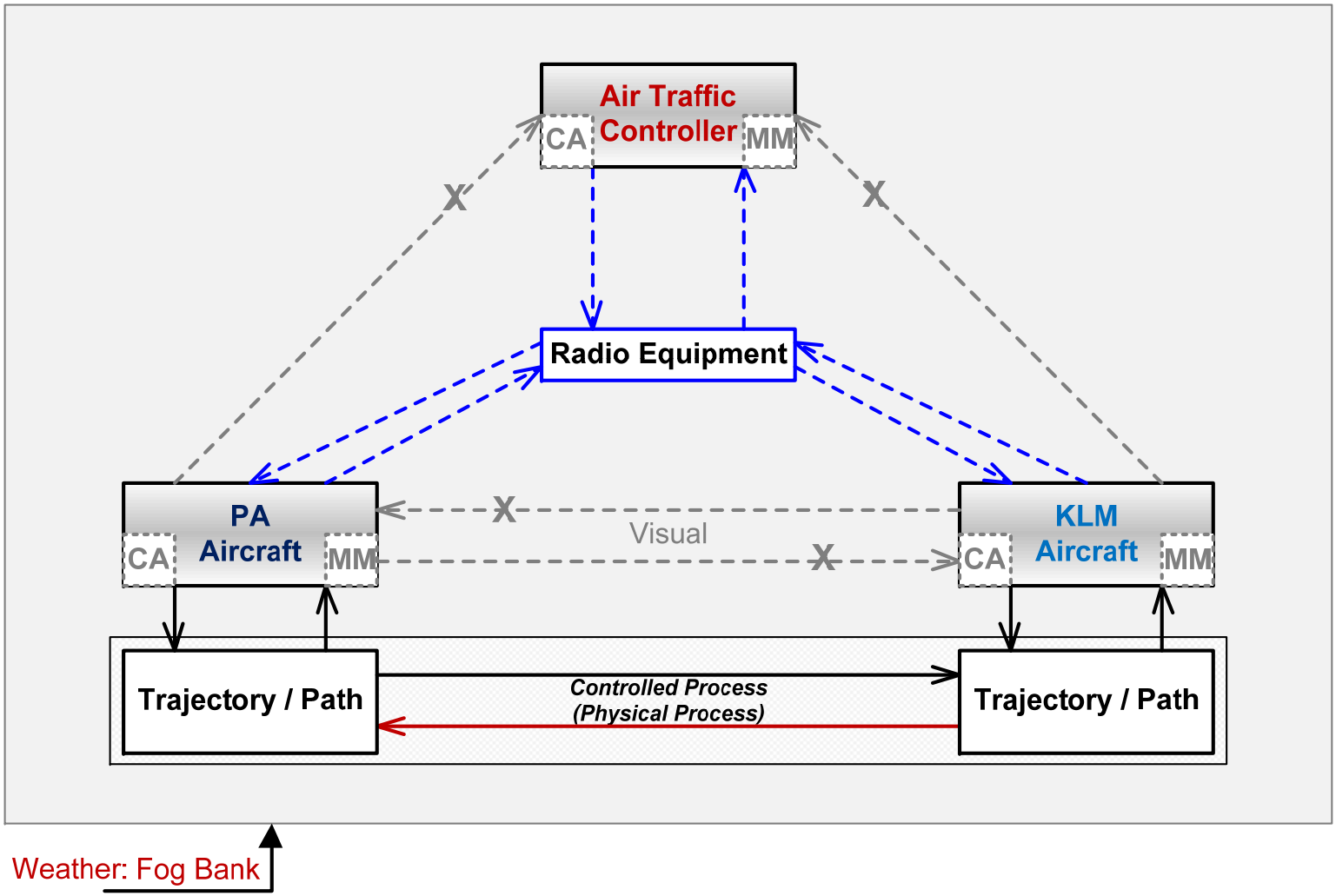
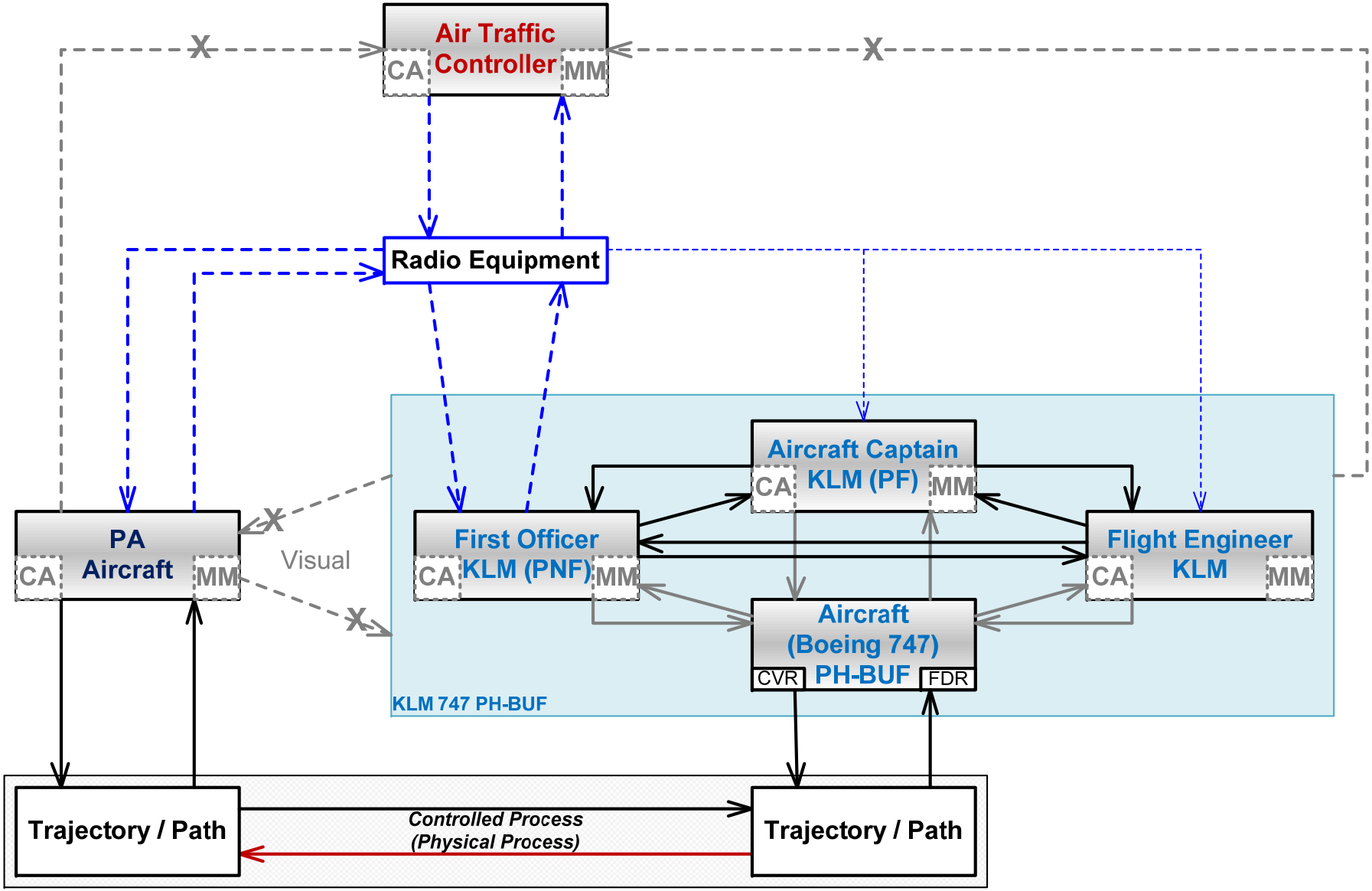








HCS: Casual Analysis



KLM Captain:

CAST Accident Analysis

Safety Constraints, Requirements & Safety-related Roles / Responsibilities

- [HLSC-01.01] Aircrew shall prevent the presence of an Aircraft, Vehicle or Person on the protected area when an Aircraft is landing or taking-off.
- [HLSC-02.01] Aircrew shall prevent the presence of an Aircraft, Vehicle or Person on the protected area when an Aircraft is in a position to land or take-off.
- (**Unenforced**) [HLSC-03.01] Aircrew shall prevent trajectories that lead to a loss of safe separation margin between Aircraft, Vehicles or People.
- Captain shall safely operate, command & manoeuvre the aircraft in accordance with:
  - Mission Objectives (Flight Plan)
  - Operating Rules (including Aircraft Operational Envelope, e.g. Ground manoeuvring limits)
  - Regulations (e.g. Crew Duty Time Regulations)
  - FO & FE input
  - ATC Instructions

Control & Feedback Ability: Actuators & Sensors

- Human Mk1
- No evidence was presented that the Controller's ABILITY to enact Control Actions or receive Feedback Information was compromised, failed in some form or was inadequate.
- Native Dutch speaker, English a second language. Accented communication.
- "Filter effect" (ALPA Report). KLM Captain & FO apparently did not hear the PAA1736 Trx on top of the ATCO Trx, which generated a Squeal, but was somewhat readable, and then the subsequent clear Trx between the ATCO & PAA1736, whilst KLM4805 was conducting the TO.
- Workload and arousal level high. [**REC**: assess each Controller in the Control Structure for their Workload & Arousal Level to indicate how susceptible they are to perform inadequately.]

Control Actions

- Captain was performing checklists, whilst FO was communicating with the ATCO.
- Manoeuvred KLM4805 through a 180 degree turn, in fog, on a 45m runway (The 747 is a large aircraft!).
- Commanded FO to request ATC & Take-off Clearance. [REC: Consider the appropriateness of requesting effectively two clearances simultaneously.]
- (**UCA**) Initiated TO before FO had completed read-back of the ATC (Route) clearance to ATCO. [REC. TO shall not commence until the instruction read back and acceptance by the ATCO has occurred.]
- (**UCA**) Initiated TO without TO Clearance. [**OFFICIAL REC**: Exact compliance with instructions.]
- (**UCA**) Captain dismissed FE question regarding whether PA1736 was clear of the RWY.
- Attempted to pull-up and flyover PA1736.

Process / Mental Model

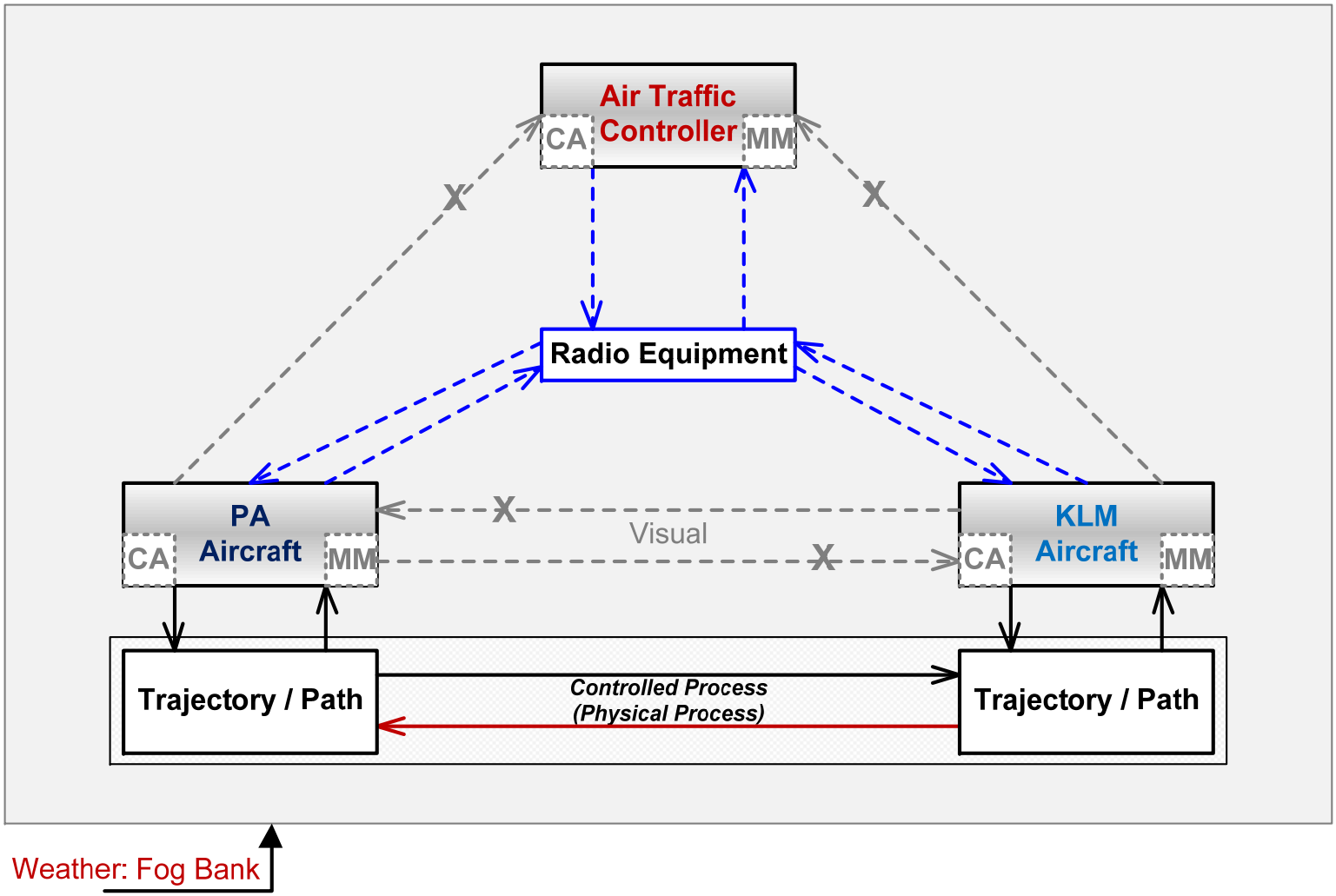
- ATC instructions are usually safe.
- KLM4805 cleared to taxi to the holding position of RWY12 and change frequency from surface 118.7 to approach 119.7. Note: frequency changes change the Control Structure & interactions amongst Controllers. No details are included in the investigation report.
- RWY is clear, PA1736 had vacated the RWY.
- Weather / visibility was rapidly changing & Close to TO visibility minimums.
- ATCO issued an ATC (Route) & TO Clearance together.
- ATCO acknowledged that KLM4805 was taking-off with "OK".
- KLM FE interrupted a critical phase of flight with an apparently nonsensical question about the RWY being clear.
- Captain may not have heard the ATCO or PAA Trx due to the Squeal / interference, and / or due to focus on a critical phase of flight. Not expected to respond to messages not containing their callsign.

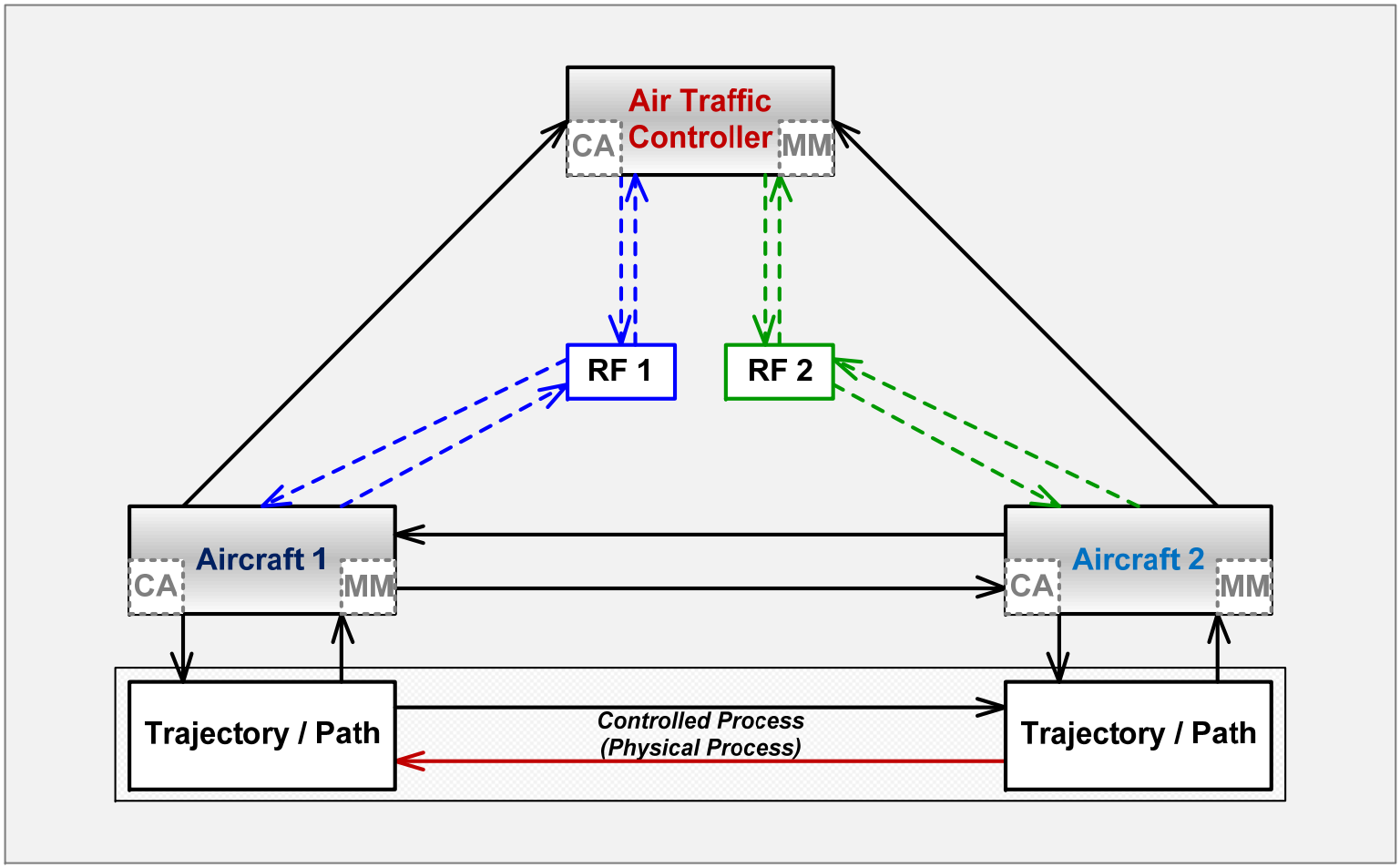
Interactions

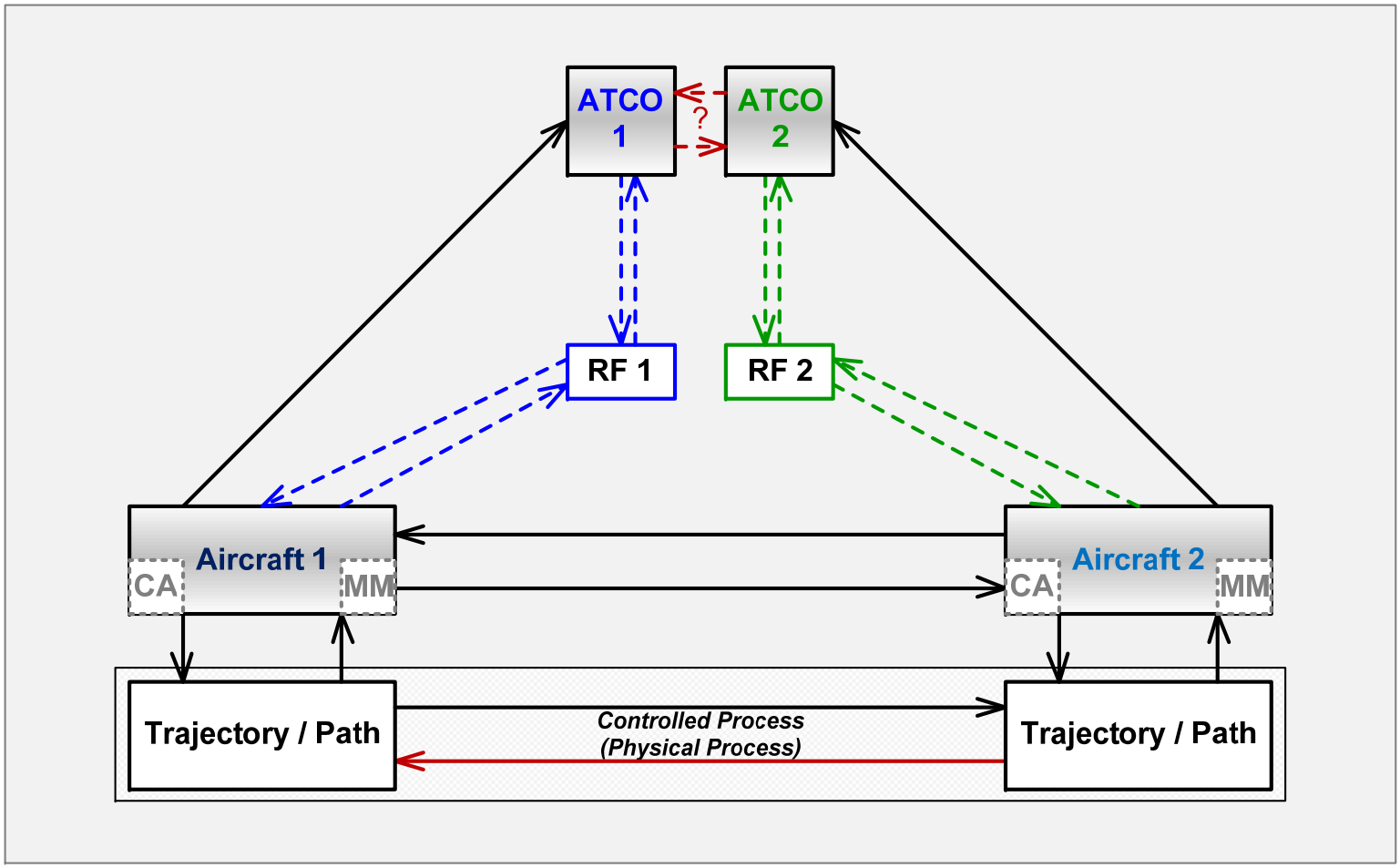
- ATCO issued permission to taxi / backtrack along the RWY and perform 180.
- Crew struggled to understand Taxi instructions, particularly from Ground Controller.
- RWY Centreline lighting unserviceability.
- FO reminder that KML4805 had yet to receive an ATC (Route) Clearance or TO Clearance.
- ATCO & PAA1736 Simultaneous Trx causes Radio Squeal / Interference / Heterodyne-effect. Unclear Trx on KLM4805 Flightdeck (though not unintelligible) [REC: safety critical and time critical commands amongst controllers shall not corrupted / blocked or otherwise prevented.]
- FE question regarding whether PA1736 was clear of the RWY.
- FO called V1.

Contextual Factors

- Aircrew must trust that ATC instructions are safe, but are also expected to remain vigilant.
- Challenges with communication due to multi-language / culture / accents.
- Tenerife Airport not designed or equipped for so many aircraft, especially jumbo jets (& their PAX).
- Low cloud / fog / rapidly changing / deteriorating visibility conditions presented a significant challenge to each controller's ability to see the RWY and each other.
- NL.gov Crew Duty Time Regulation removed Captains discretion to extend Crew Duty Time and imposed absolute rigidity. [REC]
- KLM Captain was a senior pilot at the airline & an instructor >10years. Potential susceptibility to behaving as though he was on a Training / Simulator sortie, where he would typically behave as a pseudo-ATCO for the purposes of training.
- KLM FO was inexperienced.
- Most of the contextual factors are considered **normal pressures**, i.e. a normal part of being a Pilot and operating under those conditions.







ATCO:

CAST Accident Analysis

Safety Constraints, Requirements & Safety-related Roles / Responsibilities

- (**Unenforced**) [HLSC-01.2] ATC shall prevent the presence of an Aircraft, Vehicle or Person on the protected area when an Aircraft is landing or taking-off.
- (**Unenforced**) [HLSC-02.2] ATC shall prevent the presence of an Aircraft, Vehicle or Person on the protected area when an Aircraft is in a position to land or take-off.
- (**Unenforced**) [HLSC-03.2] ATC shall prevent trajectories that lead to a loss of safe separation margin between Aircraft, Vehicles or People.
- The ATCO is responsible for controlling traffic in the manoeuvring area and the runways available for take-off and landing.
- (**Unenforced**) ATC shall use unambiguous instructions.
- ATCO's shall coordinate amongst themselves.

Control & Feedback Ability: Actuators & Sensors

- Human Mk1
- No evidence was presented that the Controller's ability to enact Control Actions or receive Feedback Information was compromised, failed in some form or was inadequate.
- Native Spanish speaker, English a second language. Accented communication.
- Workload and arousal level high.

Control Actions

- (**UCA**) Instructed KLM4805 to perform 180 turn at end of RWY + report ready for ATC (Route) Clearance.
- Informed both KLM4805 and PAA1736 that RWY centreline lights were unserviceable.
- Instructed PAA1736 to leave the RWY at the 3rd exit & report clear of RWY.
- (UCA) KLM4805 ATC (Route) Clearance was provided with a delay and included the words Take Off. [OFFICIAL REC: Avoid use of Take-Off in the ATC Clearance.] [OFFICIAL REC: Enforce time separation between the ATC Clearance and the Take-Off Clearance.]
- Acknowledged KLM4805 Trx with "OK" 2 second pause, then followed up with "Standby for take-off, I will call you". (The 2nd part of the message suffered interference from the simultaneous Trx from PAA1736).
- Acknowledged PAA1736 Trx that they were still taxiing down the RWY, and requested PAA1736 Report when clear of the RWY.
- Attended to flights IB185 & BX387, whilst awaiting PAA1736 to clear the RWY.
- Initiates Fire Alarm and informs Fire Rescue Service to prepare for urgent departure.

Process / Mental Model

- PAA1736 will leave the RWY at 3rd exit and will report when clear of RWY.
- KLM4705 reported ready at RWY holding point for ATC (Route) clearance.
- ATCO had no indication that KLM4805 was not stationary (missing feedback).
- ATCO not expecting KLM4805 to take off, perhaps interpreted the KLM FO comment that they were "at take off / were taking off" as that KLM4805 was at takeoff position*. *Some inconsistencies between [source information] and witness testimonies when contrasted with facts.
- ATCO could not know that a squeal made his message unreadable.
- Fog prevented the TWR from becoming aware of the exact location of the Fire and whether 1 or 2 aircraft were involved.
- Note: No information was presented regarding:
  - ATCO's knowledge of the 747 geometry and ground movement capabilities, and how fog might make manoeuvring more difficult.

Interactions

- ATCO did not use formally prescribed radio phraseology, which was normal practice at the time.
- The use of "OK" which coincidentally had a confirmatory context, that was unintended.
- TWR heard an explosion quickly followed by a second.
- Aircraft parked on the hard standing, and in the air above the airfield report seeing fire to the TWR.
- ATCO & PAA1736 Simultaneous Trx cause whistling in the TWR and unclear Trx on KLM4805 Flightdeck (though not unintelligible).
- Airport Layout Plan did not designate Taxiway exit numbers.
- Note: No detailed information was presented regarding:
  - Whether there was miscommunication / miss-coordination amongst the GRND Controller and the RWY Controller.

Contextual Factors

- ATCO must trust that Aircrew will carry out instructions and report back if not possible, or unsure, but ATCO are also expected to remain vigilant.
- No GRND RADAR facilities. Even with GRND RADAR this would not necessarily have prevented this specific accident.
- Airfield and Airfield Map had no markings / signs as to what the various taxiway designations.
- ATCO distraction / ATCO environment disturbances. [REC: the operational environment inside the TWR should be recorded.] Note: Football Match controversy, not investigated by the Spanish Investigation.
- ATCO had been on duty all day and were dealing with significant traffic far beyond normal conditions and aircraft they had not dealt with before (747).
- ATCO may not have been familiar with the aircraft operational capabilities / limitations, e.g. 747 taxiing limitations / geometry.
- Standard Procedures & Terminology in ICAO Doc 4444 PANS-RAG & ICAO Annex 10, however, Not for requesting / providing ATC & TO Clearances. [REC: investigate ICAO Doc 4444 and ensure that Standard Procedures & Terminology are included requesting / providing ATC & TO Clearances.]

PA Aircrew:

CAST Accident Analysis

Safety Constraints, Requirements & Safety-related Roles / Responsibilities

- **Unenforced** [HLSC-01.01] Aircrew shall prevent the presence of an Aircraft, Vehicle or Person on the protected area when an Aircraft is landing or taking-off.
- **Unenforced** [HLSC-02.01] Aircrew shall prevent the presence of an Aircraft, Vehicle or Person on the protected area when an Aircraft is in a position to land or take-off.
- [HLSC-03.01] Aircrew shall prevent trajectories that lead to a loss of safe separation margin between Aircraft, Vehicles or People.
- Crew shall safely operate, command & manoeuvre the aircraft in accordance with:
  - Mission Objectives (Flight Plan)
  - Operating Rules (including Aircraft Operational Envelope, e.g. Ground manoeuvring limits)
  - Regulations (e.g. Crew Duty Time Regulations)
  - FO & FE input
  - ATC Instructions
- Crew shall manage radio communications with the Air Traffic Controllers, including changing radio frequencies.

Control & Feedback Ability: Actuators & Sensors

- Human Mk1
- No evidence was presented that the Controller's ability to enact Control Actions or receive Feedback Information was compromised, failed in some form or was inadequate.

Control Actions

- (**UCA**) Requested ATCO permission to taxi
- Requested ATCO clarification of taxi clearance 3 x times. [REC: clarify apparent confusion in communications, was it the language of the Investigation Report, or actual confusion)
- (**UCA**) PA1736 taxied past the 3rd exit off the RWY. [OFFICIAL REC: Exact compliance with instructions].
- (**UCA**) PAA1736 did not contact the ATCO when they suspected they had passed / missed the turning for 3rd exit.
- (**UCA**) PAA1736 did not contact ATCO and state they were heading for the 4th exit.
- (**UCA?**) Urgent Trx "we're still taxiing down the RWY, the clipper 1736". (This Trx interfered with the ATCO broadcast "Standby for take-off, I will call you".
- PA1736 attempted to avoid the path of KLM4805 by turning and accelerating off the runway.

Process / Mental Model

- Uncertainty regarding how many RWY exits they had passed.
- Uncertainty regarding the clearance provided by the ATCO, given that the 3rd exit would have forced PAA1736 to make some very difficult manoeuvres (Z-shape).
- PAA1736 suspected that the ATCO meant the 4th exit, as this was an easier manoeuvre for the aircraft to make.
- PAA1736 considered that that the ATCO must know the geometry and ground performance of the 747, and that logically the ATCO must mean the 4th exit.
- KLM4805 had not yet received their TO clearance and so would not be expected to TO.
- KLM4805 ambiguous statement that KLM4805 was at take-off (we're taking off) prompted concern enough to Trx that PAA1736 was still on the RWY.
- It was not possible for PAA1736 crew to know that their Trx had potentially not been received by the ATCO or KLM4805.

Interactions

- Crew struggled to understand Taxi instructions, particularly from Ground Controller.
- Neither the Airport Layout Plan, or the actual Airfield itself, designated Taxiway exit numbers.
- ATCO & PAA1736 Simultaneous Trx cause whistling in the TWR and unclear Trx on KLM4805 Flightdeck (though not unintelligible).

Contextual Factors

- Aircrew must trust that ATC instructions are safe, but are also expected to remain vigilant.
- PAA1736 crew highly irritated by the delay induced by KLM4805 refuelling.
- PAA1736 crew workload levels would be relatively high as they taxied, completing checklists, listening to the radio chatter, etc.
- PAA1736 Captain would have preferred to have stayed clear of the RWY until KLM4805 had departed but did not express this preference to the PAA1736 FO, or to the ATCO.
- Visibility conditions presumably prevented PAA1736 crew from seeing the Taxiway exits, especially since they are positioned high up above the surface in the Cockpit of the 747.
- RWY lighting was unserviceable.
- PAA1736 crew may have also missed the 3rd exit due to their passing it at approx. the same time as KLM4805 was receiving its ATC (Route) Clearance, which the PAA crew would be keen to hear, as this would have been the same or similar for ATC (Route) Clearance that they would be required to take.

No information:

- The Official Spanish investigation Report does not include any detail or investigation of the ATCO, or of the PAA1736 crew.
- Number of unanswered questions:
  - why did the ATCO permit two aircraft on the RWY coincidentally, and why did the PAA1736 crew not leave the RWY at the 3rd exit.
  - How many ATCO were present in the TWR and which were performing what service and on what Radio Frequencies, i.e. GRND Control, RWY Control, or APRCH Control, or a combination.
  - The ALPA Report mentioned that there were 2 x ATCOs and 3 x radio frequencies in use.
  - Post accident crew report that Aircraft were taking off ahead of them apparently without clearance, or at least not from the RWY controller on the RWY control frequency. It transpires there were 3 x ATCO working on 3 x Frequencies giving both Taxi, Takeoff and ATC Clearances not on the "correct" frequencies.
  - Was the ATCO distracted?

Final Thoughts

- Radio Comms & Mental Models
- This event occurred on a what was a relatively normal day in Tenerife, foggy weather, but mixed up with a with a few abnormal conditions.
- Strictly, No Failures occurred.

Final Thoughts

- Ask the Q: Is todays HCS really adequate for normal AND abnormal conditions?
  - What specific changes to the HCS are necessary to enforce the High Level Safety Constraints under all conditions?
  - Is use of Radio Comms. for Real Time Safety Critical Commands really acceptable?

Final Thoughts: Near Misses

- Any near miss / Incident reveals that the HCS is inadequate!
- **--->MASSIVE Learning Opportunity**.
- *Cheap* learning opportunity!

Applying CAST to Runway Incursion: Webinar Replay:
https://youtu.be/p74YEpl_720

YouTube Channel:
www.SystemSafetyRevolution.com

Thank you for your time.

Future STAMP Webinars? Register your interest:
http://www.SystemSafetyWebinar.com/

Links

- Subsecretaria de Aviacion Civil, Spain. Accident Investigation Report (English Translation), 12/7/1978, approx. 60 pages.
  - http://www.fomento.es/MFOM/LANG_CASTELLANO/ORGANOS_COLEGIADOS/CIAIAC/PUBLICACIONES/HISTORICOS/A-102-103-1977/
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