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RESEARCH PROJECT EASA.2020.C43

QUICK RECOVERY OF FLIGHT RECORDER DATA (wireless transmission)

Report D4

Assess challenges and limitations of the two selected solutions

An Agency of the European Union

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REPORT D4

Assess challenges and limitations of the two solutions

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1 INTRODUCTION

1.1 QR-FRD Study Presentation

"*The overarching objective of the* Quick Recovery of Flight Recorder Data (QR-FRD) *study is to identify and assess technical solutions for the automatic wireless data transmission to quickly recover flight recorder data after an accident in a remote land area or an oceanic area for the purpose of faster understanding of the causal and contributory factors of an accident*" (EASA QR-FRD CFT,[Ref 17]).

The overall objectives of the project are to identify and to assess a series of candidate solutions for the wireless transmission of flight recorder data from commercial air transport aircraft in case of an accident (or a serious incident) in a remote land area or an oceanic area while considering thoroughly the challenges, constraints and limitations of each technical solution and the challenging conditions of an accident (or a serious incident). The evaluation of the candidate solutions will address the technical feasibility and maturity, the performance, the related constraints as well as the cost indicators in comparison to current flight data recorder installations.

The aircraft considered for the study are modern commercial air transport aircraft with a maximum take-off mass of over 27 tons, equipped with redundant combined flight data recorder (FDR) -cockpit voice recorder (CVR) capable of recording flight data, flight crew and flight deck audio, data link messages as well as, depending on the type certificate, flight crew – machine interface recordings (ICAO Annex 6 Part I, Section 6.3, [Ref 18]), and mandated to have a Flight Recorder Data Recovery (FRDR) means on-board.

A further investigation of the performance levels achievable will be carried out by developing several simulation exercises for two of the candidate solutions, applying representative operational conditions for aircraft accidents (and serious incidents) and aiming at analyzing the options for recovering the most useful data. In addition, the legal implications associated to the wireless transmission of flight recorder data, considering the existing data protection frameworks and the related ICAO Annex 13 provisions will be investigated.

The results of the feasibility project, together with the practical recommendations for the implementation of the candidate solutions, will be presented to a group of stakeholders involved in accident investigations and consolidated with the feedback received.

The activities undertaken within the QR-FRD study, and their respective documented outcomes are the following:

1. **Task 1 - Accident conditions relevant for wireless flight recorder data transmission:**
    - **Objective**: Identify and describe the technical and environmental factors which might affect the aircraft, its engines and its systems during the accident flight, and which need to be taken into account for maximizing the chances of successful wireless transmission of flight recorder data.
    - **Outcome**: A report (D1) of accident conditions which might affect the successful wireless transmission of flight recorder data (e.g. loss of power or equipment, excessive roll or pitch angles, in-flight fire, ditching …), and explaining the impact of such factors.
2. **Task 2 - Overview of technical solutions for automatic wireless transmission of flight recorder data:**
    - **Objective**: perform a screening of possible technical solutions for automatic wireless transmission of flight recorder data (flight data, audio and flight-crew interface recordings, data link messages…) in case of an accident (or serious incident) in a remote land area or an oceanic area.

- **Outcome**: A solution overview report (D2) identifying the necessary technologies and capabilities of the communication infrastructure, as well as aspects not yet mature, and discussing the potential effects of factors listed in D1 on the presented solutions. In addition, D2 will recommend the 2 most relevant technical solutions for further investigation to be performed under Task 3.

3. **Task 3 - Technical investigation of two technical solutions for automatic wireless transmission of flight recorder data:**
    - **Objective**: perform a technical investigation of the two most relevant technical solutions as identified in Task 2 and assess their performances for the automatic and wireless transmission of the data required to be recorded and retained by crash-protected flight recorders.
    - **Outcome**: A study report (D3) presenting technical solutions and detailing the two selected technical solutions (concept of operation, data transmission trigger logic (e.g. continuous or triggered), airborne functions and equipment, performance, communication infrastructure…).
4. **Task 4 – Assess challenges and limitations of two technical solutions:**
    - **Objective**: Assess the challenges and limitations of both technical solutions presented in Task 3 and comparison of their expected performance.
    - **Outcome**: An evaluation report (D4) of challenges and limitations addressing main technological enablers and their respective levels of maturity, reliability of main functions, impacts on flight crew procedures, ground handling and maintenance, as well as airline operations…
5. **Task 5 – First consultation of the stakeholder's group:**
    - **Objective**: Obtain the feedback of a group of stakeholders (accident investigation authorities, aviation regulators, operators of large commercial aircraft, associations of commercial pilots) on works performed under Tasks 1 to 4, with a view to incorporate this feedback into the analyses and assessments and to update the corresponding reports.
    - **Outcome**: A stakeholder feedback report (D5) containing the composition of the group of stakeholders, comments and questions raised by the stakeholders and replies as well as changes made to the different reports (D1 to D4).
6. **Task 6 – Simulation of technical solutions:**
    - **Objective**: Prepare an experimental set-up for the performance assessment of the two solutions investigated in Task 3, in particular for the comparison of the respective transmitted dataset (volume, accuracy, completeness, consistency) including reliability and robustness to factors identified in Task 1.
    - **Outcome**: A simulation report (D6) containing the detailed description of the performed simulations, as well as graphics showing the variation in performance when parameters (pitch and roll angles/rates, altitude, location of the aircraft…) are varied.
7. **Task 7 - Scenario-based study of legal aspects:**
    - **Objective**: Assess the legal aspects of data transmission over assets located on the territories of several countries or in space, in order to identify possible inconsistencies with ICAO Annex 13, legal uncertainties and risks for the protection of flight recorder data.
    - **Outcome**: A legal study report (D7) describing the legal framework applicable to the various assets of the communication infrastructure by which data will be transmitted or processed or recorded, scenarios of accidents in various places and with various setups, the potential issues for the protection and the transmission of data to the competent safety investigation authority, as well as proposals to ensure that the transmission service provider and the recipient of the flight recorder data are legally responsible for the preservation and the protection of transmitted flight recorder data.
8. **Task 8 – Second consultation of the stakeholder's group and additional simulation work:**

- **Objective**: Obtain the assessment of a group of stakeholders on the report resulting from Tasks 6 and 7, with a view to incorporate this feedback, to run where necessary complementary simulations and to update the simulation report.
- **Outcome**: A stakeholder feedback report (D8) containing the composition of the group of stakeholders, comments and questions raised by the stakeholders and replies as well as changes made to the different reports (D6 and D7), and possibly simulations and code.

9. **Task 9 – Conclusions and way forward:**
    - **Objective**: Conclude on the concept of automatic wireless transmission of flight recorder data in case of an accident and propose a way forward.
    - **Outcome**: A final report (D9) containing a general reflection on the works performed during the project, the feedback and recommendations received during the stakeholder meetings, the aspects of the concept of automatic wireless transmission of flight recorder data remaining to be explored or showing very challenging issues, a proposed approach for the development of compliance means and material in order to facilitate the performance demonstration to competent authorities, as well as practical recommendations to progress the maturity of this concept and prepare their implementation.

Figure 1 depicts the overall approach taken for the QR-FRD study and the relationship between the different deliverables.

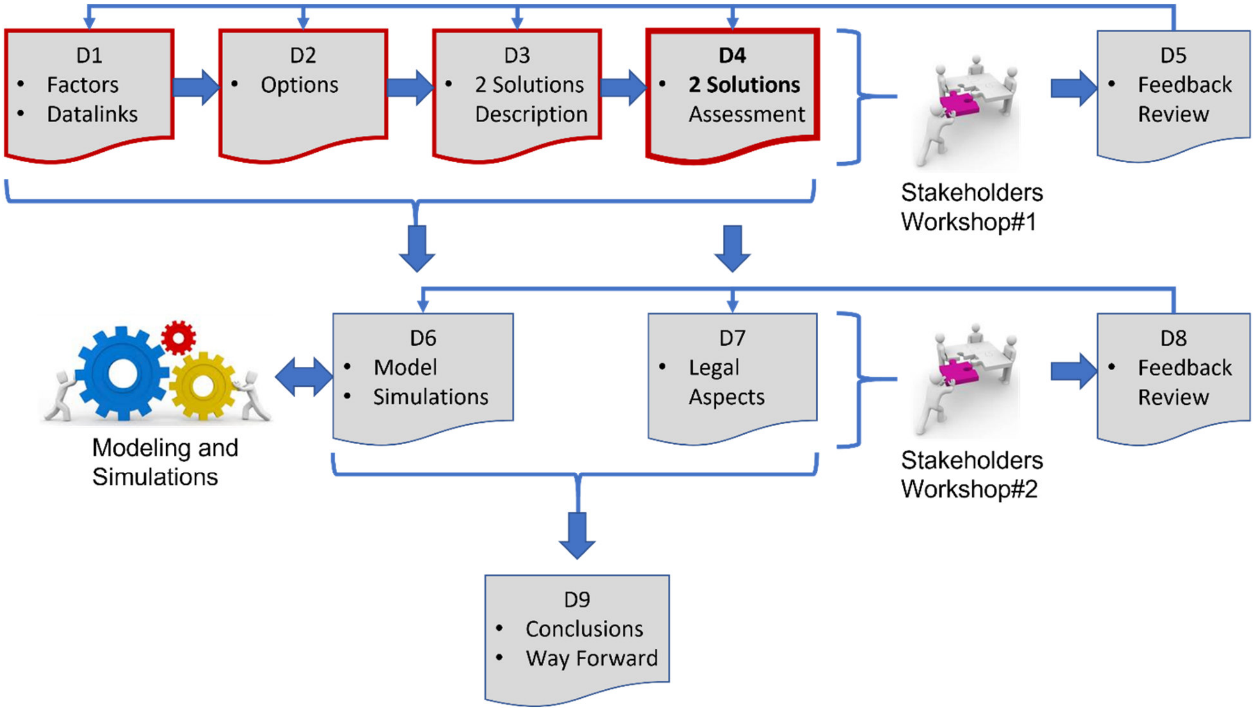


Figure 1: QR-FRD Study Approach and Deliverables Relationship

1.1 Scope of This Report

The present document corresponds to D4 as depicted Figure 1. It summarizes analysis and findings from Task 4 “Assess challenges and limitations of the 2 solutions” of the QR-FRD study.

It aims at:

- identifying the benefits, constraints, and technical feasibility issues of the two solutions for the wireless transmission of flight recorder and
- comparing their expected performance based on findings and conclusions from task 3 “Technical investigation of the 2 solutions” [Ref 3].

1.2 Organization of the Document

This document is part of Task 4 “Assess challenges and limitations of the two solutions” of the QR-FRD study, and is organized as follows:

Chapter 1, “INTRODUCTION”, (the present chapter), primarily provides background information on the initiation of QR-FRD studies and defines the scope of the present document.

Chapter 2, “REFERENCE DOCUMENTS”, provides the list of reference documents used for the drafting of the present document.

Chapter 3, “DEFINITIONS AND ACRONYMS”, provides definitions of terms and acronyms used in the present document.

Chapter 4, “SOLUTIONS COMPARISON”, compares means considered for the different functions identified in D3 [Ref 3] for the two solutions, and assesses their current maturity levels. It also provides insight on their respective reliability figures, foreseen impacts on operational procedures, and resilience to factors identified in D1 [Ref 1].

Chapter 5, “BENEFITS, CONSTRAINTS AND TECHNICAL FEASIBILITY ISSUES” identifies benefits, constraints, and technical feasibility issues for the two solutions.

Chapter 6, “ADDITIONAL CONSIDERATIONS”, addresses other global aspects of QR-FRD solutions such as data security and legal aspects, and identifies further research topics necessary to mature the solutions.

Chapter 7, “QUANTITATIVE TESTS IN SIMULATION ENVIRONNEMENT”, describes the modeling and simulation framework for activities undertaken within Task 6 of the study.

“ANNEX A: SELECTED SOLUTIONS OVERVIEW”, is a reminder on the overall airborne system architecture for the two solutions, extracted from D3 [Ref 3].

2 REFERENCE DOCUMENTS

[Ref 1] QR-FRD Study D1: “Accident conditions relevant for wireless flight recorder data transmission”, Aug 2021

[Ref 2] QR-FRD Study D2: “Overview of Technical Solutions for Automatic Wireless Transmission”, Ed 00, Nov 2021

[Ref 3] QR-FRD Study D3: “Technical investigation of the two solutions”, Ed 00, Dec 2021

[Ref 4] EASA Acceptable Means of Compliance (AMC) and Guidance Material (GM) Annex IV – Part CAT, Feb. 2016

[Ref 5] EASA ETSO-C159d, “Next Generation Satellite Systems (NGSS) Equipment”, July 2020.

[Ref 6] EUROCAE ED-79A/SAE ARP-4754A “Guidelines for Development of Civil Aircraft and Systems”, Jan. 2011

[Ref 7] EUROCAE ED-112A, “MOPS for Crash Protected Airborne Recorder Systems”, Sept. 2013.

[Ref 8] EUROCAE ED-203A / RTCA DO-356A, “Airworthiness Security Methods and Considerations”, June 2018

[Ref 9] EUROCAE ED-243A, “MOPS for Avionics Supporting Next Generation Satellite Systems (NGSS)”, Apr. 2019

[Ref 10] ED Decision 2020/006/R, “[…] CS-25 - Amendment 25, and […] AMC and GM to Part 21 - Issue 2, Amendment 10, Aircraft cybersecurity”, 24-June-2020.

[Ref 11] ARINC-664 P7, “Aircraft Data Network” Prt 7, Avionics Full-Duplex Switched Ethernet Network, Sept. 2009

[Ref 12] ARINC-811, “Commercial Aircraft Information Security Concepts of Operation and Process Framework”, Dec. 2005

[Ref 13] ICAO Annex 13 “Aircraft Accident and Incident Investigation”, 12th Edition, July 2020

[Ref 14] Regulation (EU) No 996/2010 of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation and repealing Directive 94/56/EC

[Ref 15] ICAO - Doc 9756 “Manual of Aircraft Accident and Incident Investigation”

[Ref 16] Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation)

[Ref 17] [R00] EN-EASA.2020.HPV.06, Quick Recovery of Flight Recorder Data Call for Tender

[Ref 18] ICAO Annex 6 – Operation of Aircraft – Part I – International Commercial Air Transport – Aeroplanes, Ed. 11, July 2018

3 DEFINITIONS AND ACRONYMS

Term	Definition
Abnormal Situation	A situation "in which it is no longer possible to continue the flight using normal procedures but the safety of the aircraft or persons on board or on the ground is not in danger." (https://www.easa.europa.eu/sites/default/files/dfu/EASA_EHEST_HE_11.pdf) Could be assimilated to "Alert phase: a situation wherein apprehension exists as to the safety of an aircraft and its occupants." as defined by ICAO Annex 12. However, this definition, along with the definition of "Distress phase" are from an air traffic controller perspective and are meant to manage search and rescue operations. The QR-FRD perspective, though maybe concurrent, is however different and aircraft oriented.
Distress Situation	"*A situation wherein there is a reasonable certainty that an aircraft and its occupants are threatened by grave and imminent danger and require immediate assistance*." (ICAO Annex 11, "Distress Phase") This situation usually triggers Search and Rescue operations.
Flight recorder data	Any type of data recorded by the flight recorders that would be used for the purpose of complementing accident/incident investigation. Flight recorder data may include: • Mandatory and optional flight parameters recorded by flight data recorders • Audio recordings between the flight crew members and any other station • Audio recordings of the acoustic environment of the cockpit • Messages and information exchanged over data link • Imagery from displays inside the cockpit and interactions of flight crew members with instruments and displays
Historical flight recorder data	Flight recorder data that has been stored prior to the trigger condition for possible transmission.
Real-time flight recorder data	Flight recorder data meant to be transmitted nearly instantaneously as they are collected, either by streaming (all along the flight) or after trigger (abnormal or distress situation is detected).
Technology Readiness Level (TRL)	A method used to measure and assess the maturity of a particular technology, or of components of a system. Levels of maturity are defined as follows: TRL1: basic principles observed TRL2: technology concept formulated TRL3: experimental proof of concept TRL4: technology validated in lab

Term	Definition
	TRL5: technology validated in relevant environment TRL6: technology demonstrated in relevant environment TRL7: system prototype demonstrated in operational environment TRL8: system complete and qualified TRL9: actual system proven in operational environment

Table 1: Definitions

Acronym	Definition
ABAC	Attribute-based Access Control
ACD	Aircraft Control Domain
ACMS	Aircraft Condition Monitoring System
ADFR	Automatic Deployable Flight Recorder
AES	Advanced Encryption Standard
AIA	Accident Investigation Authorities
AISD	Airline Information Service Domain
aka	also known as
APU	Auxiliary Power Unit
CMU	Communication Management Unit
COTS	Commercial Off the Shelf
CVR	Cockpit Voice Recorder
DAR	Direct Access Recorders
EASA	European Union Aviation Safety Agency
ECSS	European Cooperation for Space Standardization
ESA	European Space Agency
EUROCAE	European Organization of Civil Aviation Equipment
FB	Functional Block
FCIFAU	Flight Crew Interface Acquisition Unit
FDAU	Flight Data Acquisition Unit
FDAL	Functional Design Assurance Level
FDIU	Flight Data Interface Unit
FDR	Flight Data Recorder
GDPR	General Data Protection Regulation
ICAO	International Civil Aviation Organization
ISO	International Organization for Standardization
IUEI	Intentional Unauthorized Electronic Interaction
LZMA	Lempel-Ziv Markov chain Algorithm
FDM	Flight Data Monitoring
PIESD	Passenger Information and Entertainment Service Domain
PKI	Public Key Infrastructure

Acronym	Definition
QAR	Quick Access Recorders
QR-FRD	Quick Recovery of Flight Recorder Data
RBAC	Role-based Access Control
RSA	Rivest-Shamir-Adleman
SATCOM	Satellite Communications
SFTP	Secure File Transfer Protocol
SHA	Secure Hash Algorithm
SMS	Safety Management System
SWaP-C	Size, Weight, and Power - Cost
TPM	Technological Protection Measures
TRL	Technology Readiness Level
VPN	Virtual Private Network

Table 2: Acronyms

4 SOLUTIONS COMPARISON

This section provides a couple of 2-column tables used to compare the two solutions in terms of general features, technological enablers along with their respective level of maturity, reliability, and robustness incl. data security, impacts on operational procedures for the main stakeholders, as well as resilience to factors impacting transmissions and resolution of factors improving the transmission of flight recorder data. These factors were identified in D1 [Ref 1].

Aspects common to both solutions such as expected performance, data protection, economic indicators and weight and power considerations are also discussed later in the section.

This comparison is based on the solutions presented in D2 [Ref 2] and detailed in D3 [Ref 3], and recalled hereafter.

Figure 2 presents the two solutions and the functional allocations on the different hardware and assets.

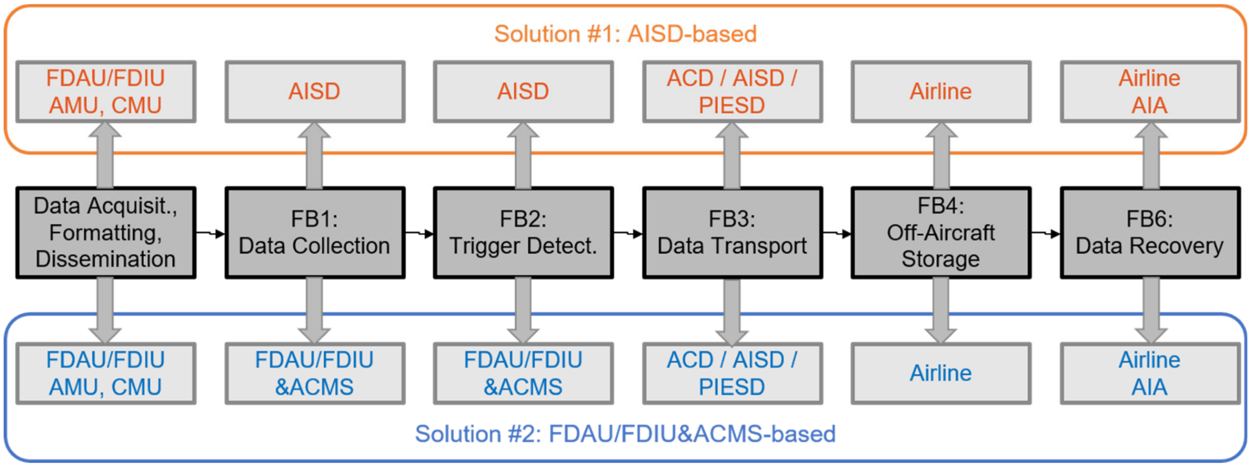


Figure 2: Presentation of the two solutions: “AISD-based” (top) and “FDAU/FDIU&ACMS-based” (bottom)

The proposed distribution of the selected options (features) across two “software” solutions is summarized in the following table:

Option / Feature	Software Solution#1	Software Solution#2	Comment
Transmission mode	Continuous (streaming)	Triggered	
Merging	Yes	No	See Note 1
Chunking	Fixed	Fixed	See Note 2
Compression	Yes	Yes	
Signature	Yes	Yes	
Encryption	Audio only	Global	

Option / Feature	Software Solution#1	Software Solution#2	Comment
Storage	Limited	20 minutes minimum[1]	
P2P Secure Connection	SFTP	SFTP	
Datalink Media Mgt	PIESD (Cell + Satcom)	PIESD (Satcom)	

Table 3 : Options for Software Solutions #1 and #2

Note 1: Merging distribution used to be TBD and Yes respectively. It is now Yes and No due to confusion between merging and mixing.

Note 2: Chunking distribution used to be Fixed and Adaptive (TBD) respectively. It is now Fixed for both solutions, additional research on adaptive chunking being needed (cf. §6.3).

Note: For the sake of simplicity, the set of Software Solution#1 features was allocated to Hardware Solution#1 (“AISD-based”), and the set of Software Solution#2 features was allocated to Hardware Solution#2 (“FDAU/FDIU&ACMS-based”). Nevertheless, whichever the hardware solution, any software solution would apply. The allocation is arbitrary (cf. D3 [Ref 3]).

[1] As mentioned in D2 **Error! Reference source not found.**, there is no technical limitation to the size of the buffer. CVR and DLR have a minimum recording duration of 2 hours. The two cases (20 minutes and 2 hours) will be considered during the simulation activities undertaken within Task 6 of the QR-FRD study.

4.1 Solutions Enablers

The following table lists the different enablers for the two selected solutions and assesses their respective maturity levels. It is based on the functional decomposition defined in D3 [Ref 3] and system architectures recalled in ANNEX A: SELECTED SOLUTIONS OVERVIEW.

<table>
<tr><th>Solution #1 “AISD-based”</th><th>Solution #2 “FDAU/FDIU&ACMS-based”</th></tr>
<tr><td colspan="2"><b><i>FB1: Data Collection / Overall Processing Sequence</i></b></td></tr>
<tr><td>The overall processing sequence for data collection in Solution #1 is the following:
1. Collect flight recorder data and digitize analog audio inputs
2. Gather TBD (e.g. 4-second) chunks
3. Timestamp the chunks
4. Compress (using same or different compression algorithms) each chunk of flight recorder data
5. Encrypt the audio chunks
6. Merge the chunks in a single archive
7. Sign the archive
8. Store the archive ready for transmission
<b>TRL 2</b></td><td>The overall processing sequence for data collection in Solution #2 is the following:
1. Collect flight recorder data and digitize analog audio inputs
2. Gather TBD (e.g. 4-second) chunks into files, one per flight recorder data type
3. Timestamp each file
4. Compress (using same or different compression algorithms) each file
5. Sign each file
6. Encrypt each file
7. Store the files for future transmission (buffer historical data before a trigger is detected, temporarily for real-time transmission after a trigger is detected depending on priority scheme).
<b>TRL 2</b></td></tr>
<tr><td colspan="2"><b><i>FB1: Data Collection / Digitization</i></b></td></tr>
<tr><td colspan="2">The AISD router (Solution#1) and the FDAU/FDIU&ACMS unit (Solution#2) collect the flight recorder data from different sources (i.e. FDAU or FDIU, AMU, CMU (ACD router) and “FCIFAU”).
The major impact on existing units will be the addition of an audio channels acquisition and digitization capability, assuming the flight crew and flight deck audio sources are analog. However, the firmware (vocoders) enabling this capability exists already in digital radios and in CVR. As such, the audio acquisition and digitization would be TRL8-9.
The units will likely necessitate hardware modifications to route the new signals from the connectors.
<b>TRL 8</b></td></tr>
<tr><td colspan="2"><b><i>FB1: Data Collection / Chunking</i></b></td></tr>
<tr><td colspan="2">Flight recorder data are recorded during a defined timeslot (duration chunk to be defined by task 6) prior to their processing.
A fixed 4-second time slot is proposed as a starting point. This value may evolve after the simulations undertaken during Task 6 are performed. Also, it may be envisioned to have this value evolving over time depending on transmission conditions (adaptive chunking), i.e. larger chunks when transmission is optimal, smaller chunks as transmission performance degrades.
<b>Fixed duration chunking: TRL 9</b></td></tr>
</table>

Solution #1 “AISD-based”	Solution #2 “FDAU/FDIU&ACMS-based”
FB1: Data Collection / Timestamping	
The different records are time stamped at the time flight recorder data collection begins. **TRL 9**	
FB1: Data Collection / Compression	
The different records are compressed using the same lossless compression technique or using dedicated compression techniques depending on their data type to increase compression efficiency. Compression is based on commonly used LZMA lossless compression algorithms as a baseline[2]. Other specific techniques will be considered for audio and imagery if simulations confirm the need.	
TRL 9	**TRL 8**
FB1: Data Collection / Encryption	
Only audio recordings (flight crew and flight deck audio) are encrypted prior to their transmission. Encryption is based on commonly used AES 256 algorithms **TRL 9**	All data files are encrypted prior to storage into the buffer. Encryption is based on well-known AES 256 algorithms. **TRL 5**
FB1: Data Collection / Merging	
Flight recorder data corresponding to a time slot (chunk) are merged into a single archive to be transmitted as a whole, regardless of their type. This is a common AISD router feature. **TRL 9**	No merging is performed to allow processing and transmission of files dedicated to a single flight recorder data type. **NA**
FB1: Data Collection / Signature	
The archive is signed prior to its transmission. Signature is based on commonly used SHA-256/RSA algorithms **TRL 9**	All data files are signed prior to their storage into the buffer. Signature is based on well-known SHA-256/RSA algorithms **TRL 5**

[2] The LZMA (or its second version, LZMA2) is an efficient lossless algorithm commonly used nowadays in avionics and is proposed as a baseline for the study. Other algorithms (cf. D3 [Ref 3]) are considered in standards for future communication systems. These algorithms will be evaluated in next activities of the study (namely Task 6 “Modeling and Simulations”), especially for audio and imagery compression.

Solution #1 "AISD-based"	Solution #2 "FDAU/FDIU&ACMS-based"
FB1: Data Collection / Storage	
As the solution considers continuous transmission of flight recorder data (no pre-trigger buffering of historical data), storage should be minimal and primarily due to transmission issues. **TRL 9**	As the solution considers triggered transmission of flight recorder data, a minimum of 20 minutes[3] of historical data are stored prior to trigger detection using a cyclic buffer where the oldest data are replaced by the most recent ones. **TRL 9**
FB2: Trigger Detection	
➔ transmission starts automatically at the beginning of the flight As the solution considers continuous transmission of flight recorder data, transmission is expected to start as soon as the QR-FRD airborne suite is operating and linked to ground servers, the aircraft still at the gate. As such the "trigger" detection by the AISD router will be limited to: • Power-on / system initiation checks • Connectivity checks • Cryptographic key checks Transmission will stop when the system is turned off at the gate.	➔ transmission starts as soon as a singular event is detected As the solution considers triggered transmission of flight recorder data, transmission is expected to start as soon as the ACMS unit detects a trigger condition and warns the AISD router to "unstack" the pre-stored flight recorder data (real-time and historical). The trigger condition will be evaluated as discussed in D3 [Ref 3] (distress or abnormal flight situations), or be manually initiated (test, maintenance, quality inspection…). Transmission will automatically stop when no trigger condition exists after a confirmation period, and the stack of pre-stored historical flight recorder data is empty. **<u>Note</u>**: Triggered transmission of real-time flight recorder data may last until the aircraft is at the gate depending on the trigger condition (cf. abnormal situation). Trigger logics already exist in ACMS but need to be tuned for the QR-FRD purposes. The implementation in the ACMS function is divided into 2 distinct parts: • A fixed and qualified software engine • A reprogrammable configuration database that defines the conditions that must be triggered
TRL 9	**Trigger engine: TRL 9** **Trigger configuration: TRL 3**

[3] Up to 2 hours as an option to be confirmed by the simulations.

Solution #1 “AISD-based”	Solution #2 “FDAU/FDIU&ACMS-based”
FB3: Data Transport / Point-to-Point Secure Connection	
Both solutions rely on a secure point-to-point connection set between the AISD router and servers on the ground. It is anticipated that this connection will be set-up long before triggered transmission needs it, as the set-up may take time especially when transmission performance is not optimal. The commonly used secure file transfer protocol (SFTP) is proposed as a baseline. SFTP indeed brings protection mechanisms (typically authentication and encryption) on the data being transferred over the air and on ground networks. An IP Security (IPSec) virtual private network (VPN) with Public Key Infrastructure (PKI) certificates may be an option. **TRL 9**	
FB3: Data Transport / File Transfer Management	
File transfer management mainly consists in “unstacking” the newly released real-time flight recorder data archive and routing it to the selected transmission media. The AISD router is responsible for the function. In case of transmission performance degradation, a few retries may be managed, and hence a couple of archives temporarily buffered. The stack depth will depend on the archive (hence chunk) size as well as the nominal transmission performance. **TRL 9**	File transfer management mainly consists in “unstacking” either the newly released real-time flight recorder data archive or buffered historical flight recorder data files according to a predefined priority scheme (cf. D3 [Ref 3]) and routing it to the selected transmission media. Both, the ACMS unit and the AISD router are responsible for the function. In case of transmission performance degradation, a few retries may be managed, and hence non-transmitted real-time data will be added to the historical data buffer. **TRL 2**
FB3: Data Transport / Data Link Media Management	
As continuous transmissions are envisioned to start on the ground, continue in the air over oceanic and remote regions, and end on the ground, both cellular telephony and satellite communication media will be managed by the AIDS router and possibly the PIESD router.	Triggered transmissions are envisioned to occur when the aircraft is in the air, only satellite communication media will be managed by the AIDS router and possibly the PIESD router.
Managing quality of service as well as preemption of PIESD transmissions still needs refinement. **No PIESD router modification: TRL 9** **PIESD router modification[4]: TRL 2**	

[4] Managing quality of service as well as preemption of PIESD transmissions may require software (inter router exchanges) or hardware (discrete signal) modifications.

<table>
<tr><th>Solution #1 “AISD-based”</th><th>Solution #2 “FDAU/FDIU&ACMS-based”</th></tr>
<tr><td colspan="2">The satellite constellation considered to meet the QR-FRD requirements is undetermined yet. The availability of the service may depend on the deployment level of the constellation, hence a “TRL” associated to the availability of the satellite communication media.
‘Mega-constellations’ of communications satellites in Low Earth Orbit (LEO) in course of deployment are very good candidates but are not yet flight proven. However, supplying aircraft with these systems seems to be part of the strategy of the new players.
TRL 6</td></tr>
<tr><td colspan="2"><b><i>FB4: Off-Aircraft Storage / Secure Storage</i></b></td></tr>
<tr><td colspan="2">Flight recorder data received on the ground, either continuously or after a trigger condition is detected, are securely stored on ground servers owned by the airline or by a contracted organization. This may depend on the size of the airline and/or the way it manages Safety Management System (SMS) and Flight Data Monitoring (FDM) programs.
Datalink service providers and cloud-based storage providers offer these types of services.
TRL 9</td></tr>
<tr><td colspan="2"><b><i>FB4: Off-Aircraft Storage / Retention Policy</i></b></td></tr>
<tr><td>Flight recorder data is stored on the ground for the entire duration of the flight and for all the flights the airline operates, regardless of whether an incident, a serious incident or an accident occurred or not.
In the case of nominal flights or when an incident is reported, the airline may use the flight recorder data, incl. audio recordings, following recommendations provided in AMC/GM Annex IV Part CAT [Ref 4] for its SMS and FDM programs, maintenance, or quality inspection (cf. D3 [Ref 3]). Also, flight crews should be able to prevent the airline from accessing audio recordings as they currently do with the bulk erase features of CVR (cf. D3 [Ref 3]).
In the case of a serious incident or an accident, the airline and the flight crew should still[5] have access to the flight recorder data for that specific flight, provided they cannot disseminate related data without the approval of the investigation authorities[6].</td><td>Flight recorder data is stored on the ground for part of the flight and after a trigger is detected reflecting a situation that could lead to a serious incident or an accident (cf. D3 [Ref 3]).
The designated accident investigation authorities should be able to access the flight recorder data, as well as the airline provided it cannot disseminate related data without the approval of the investigation authorities.</td></tr>
</table>

[5] In the case of crash-protected recorders, which are part of physical evidence, the airline should not try to read the data out because this might alter the recorded data. For the wireless transmitted data, the airline may still access the data that it owns, data protection mechanisms or copies ensuring data used by the investigators were not altered.

[6] In case of Annex 13 investigations, all involved stakeholders are bound by the confidentiality of the investigation works.

<table>
<tr><th>Solution #1 “AISD-based”</th><th>Solution #2 “FDAU/FDIU&ACMS-based”</th></tr>
<tr><td colspan="2">Existing standards, regulations, policies, and procedures may need to be adapted to cope with the handling and retention of flight recorder data stored on the ground in a cloud-based environment.
There obviously are issues to solve should the airline be able to access and use real-time flight recorder data in real-time, i.e. during the flight. Signature may not be perceived as a sufficient means to guarantee data protection (i.e. authentication and integrity).
NA</td></tr>
</table>

<table>
<tr><th>Solution #1 “AISD-based”</th><th>Solution #2 “FDAU/FDIU&ACMS-based”</th></tr>
<tr><td colspan="2"><b><i>FB6: Data Recovery / Access Management</i></b></td></tr>
<tr><td colspan="2">Several access management (aka access control) techniques exist to guarantee authentication of the users and authorization for appropriate access to protected data.
Many organizations and people are involved in flight recorder data recovery, with privileges that may vary over time. As such, multiple technologies may need to work in concert to achieve the required level of access control, among which Role-based Access Control (RBAC) and Attribute-based Access Control (ABAC). However, the establishment of the access control models to flight recorder data will be challenging.
<b>Access control techniques: TRL 9</b></td></tr>
<tr><td colspan="2"><b><i>FB6: Data Recovery / Authenticity Checking</i></b></td></tr>
<tr><td colspan="2">Authenticity, and integrity, checking based on signature is primarily meant for accident investigators authorities. It is a means proposed for them to verify no one / nothing tampered the flight recorder data between the time it was collected and the time the investigators had access to it.
The designated accident investigation authority will be provided with the necessary cryptographic key through the Public Key Infrastructure (PKI) set in place for the purpose (cf. D3 [Ref 3]). The PKI should be refined in future activities following task 7 of the study that will address regulatory, legal, and societal aspects of QR-FRD.
<b>Signature is based on commonly used algorithms (cf. above): TRL 9</b>
<b>PKI principles and techniques: TRL 9</b></td></tr>
<tr><td colspan="2"><b><i>FB6: Data Recovery / Decryption</i></b></td></tr>
<tr><td>Decryption mainly concerns the flight crew and flight deck audio recordings. These were encrypted to address privacy purposes.</td><td>Decryption concerns all flight recorder data. These were encrypted to address data protection purposes.</td></tr>
<tr><td colspan="2">Accident investigation authorities, but also the airline, will want to decrypt the recordings at some point but for different purposes (cf. D3 [Ref 3]).
The designated accident investigation authority, as well as the airline, will be provided with the necessary cryptographic key through the Public Key Infrastructure (PKI) set in place for the purpose (cf. D3 [Ref 3]). The PKI should be refined in future activities following Task 7 of the study that will address regulatory, legal, and societal aspects of QR-FRD.
<b>Encryption is based on commonly used algorithms (cf. above): TRL 9</b>
<b>PKI principles and techniques: TRL 9</b></td></tr>
<tr><td colspan="2"><b><i>FB6: Data Recovery / Decompression</i></b></td></tr>
<tr><td colspan="2">Accident investigation authorities, but also the airline, will want to decompress the recordings at some point but for different purposes (cf. D3 [Ref 3]).
<b>Compression is based on commonly used lossless compression algorithms (cf. above): TRL 9</b></td></tr>
</table>

<table>
<tr><th>Solution #1 “AISD-based”</th><th>Solution #2 “FDAU/FDIU&ACMS-based”</th></tr>
<tr><td colspan="2"><b><i>FB6: Data Recovery / File Assembly</i></b></td></tr>
<tr><td colspan="2">Accident investigation authorities, but also the airline, will want to reassemble the chunked files at some point but for different purposes (cf. D3 [Ref 3]).
This operation will basically consist in concatenating the different files based on their timestamp, into larger files covering large portions of the flight if not its entirety. A dedicated tool may need to be developed to process the full set of files for a specific flight.
<b>TRL 9</b></td></tr>
<tr><td colspan="2"><b><i>FB6: Data Recovery / File Splitting</i></b></td></tr>
<tr><td>Accident investigation authorities, but also the airline, will want to split the chunks into separate files (per data type) at some point but for different purposes (cf. D3 [Ref 3]).
This operation will basically consist in “de-archiving” the different files based on their data type. A dedicated tool may need to be developed to process the full set of files for a specific flight.
<b>TRL 9</b></td><td>NA.
Individual files are regenerated per data type.
<b>NA</b></td></tr>
</table>

Two figures, respectively Average Maturity and Global Maturity, have tentatively been defined to compare the two solutions and provide an indication on how far the proposed solutions are from industrialization and deployment.

<table>
<tr><th colspan="2"><i>Average Maturity (scoring = sum of TRL / (number of applicable TRL * 9))</i></th></tr>
<tr><td><b>95%</b></td><td><b>83%</b></td></tr>
<tr><td colspan="2"><b>The main differences in the scoring of the two solutions are in TRL for data protection (lower for Solution #2) and for trigger evaluation (low and only for Solution #2). Other minor differences concern the TRL of functions (e.g. Compression) that are also implemented differently in the two suites.</b></td></tr>
<tr><td colspan="2"><b><i>Global Maturity (scoring = product of TRL / (9^(number of applicable TRL)))</i></b>[7]</td></tr>
<tr><td><b>13%</b></td><td><b>0.2%</b></td></tr>
</table>

Table 4: Solutions enablers and levels of maturity

[7] This formula, based on the product of TRL for functional blocks acting in sequence, may be more relevant than the one based on the summation of applicable TRL.

4.2 Global Reliability

4.2.1 Functional Design Assurance Aspects

The following table tentatively assesses the global reliability of the two solutions, based on functional design assurance levels defined in ED-79A/ARP-4754A [Ref 6]:

- FDAL E (no effect): failure has no effect
- FDAL D (minor): failure may cause inconvenience
- FDAL C (major): failure may cause stress
- FDAL B/A (hazardous/catastrophic): failure may cause injuries/death

Note: ED-79A/ARP-4754A typically applies to the airborne segment of the QR-FRD suite. The other segments, especially the ground-segment, use different methodologies and classifications if any, when not in house development guidelines. As such, FDAL per se would not be defined for systems in these segments. Comparison of the FDAL of the full QR-FRD suite with the one for current crash-protected recorders (FDAL D) will hence be difficult.

Solution #1 "AISD-based"	Solution #2 "FDAU/FDIU&ACMS-based"
FB1: Data Collection / Acquisition and Digitization	
By AISD router: FDAL D/E **Note**: In accordance with current practice, the "flight parameters" collected by the AISD router are dedicated to maintenance or flight quality inspection (FDM programs). The definition of these records is done by the FDM program responsible, or the maintenance responsible. These definitions, performed via a user modifiable software (UMS), are not qualified, and are only validated by practice. However, since the AISD router collects data from the FDAU (cf. system description in annex), it will be able to collect both, qualified flight parameters designated for the flight data recorder, and non-qualified flight parameters designated to direct or quick access recorders (DAR or QAR).	By FDAU/FDIU: FDAL C **Note**: The "flight parameters" issued by the FDAU/FDIU are the ones designated for the flight data recorder. These data, defined in a certified and not modifiable software, have been validated and qualified
FB1: Data Collection	
By AISD router: FDAL D/E	By ACMS unit: FDAL D/E
FB2: Trigger Detection	
NA	By ACMS unit: FDAL D/E

<table>
<tr><th>Solution #1 “AISD-based”</th><th>Solution #2 “FDAU/FDIU&ACMS-based”</th></tr>
<tr><td colspan="2"><b><i>FB3: Data Transport</i></b></td></tr>
<tr><td colspan="2">By AISD router: FDAL D/E
CS-ETSO / ETSO-C159d [Ref 5] specifies reliability figures for the next generation satellite systems as minor failure condition for the loss or malfunction of the system intended function, and major failure condition for the loss or malfunction of security partitioning. This would lead to FDAL D/C
ED-243A [Ref 6] contains the minimum operational performance standards (MOPS) for avionics that provide Aeronautical Mobile Satellite (R) Services (AMS(R)S) by means of satellite communications technologies scheduled to become operational in context of the global and regional ATM and CNS modernization (i.e. next generation satellite systems).
By SATCOM Transceiver (airborne): FDAL D/E
The European Space Agency (ESA) and European Cooperation for Space Standardization (ECSS) has issued a series of standards and handbooks to be used for satellite space and ground systems development (https://ecss.nl/standards/). These standards will need to be further explored.
ISO/TC 20/SC 14 (Space Systems and Operations) has issued a similar series of standards, some of which addressing safety requirements, typically ISO 14620-1:2018 “Safety requirements – Part 1: System safety”, and ISO 14620-3:2021 “Safety requirements – Part 3: Flight safety systems” (https://www.iso.org/committee/46614.html). These standards will need to be further explored.</td></tr>
<tr><td colspan="2">No standard was identified concerning the development methodology of terrestrial networks/infrastructure development. Telecommunication companies seem to use their own guidance material, their main concern being security.
ISO SC 27 “Information security, cybersecurity and privacy protection” has issued more than a dozen standards in the ISO/IEC 27000 family to enable organizations of any kind to manage the security of assets such as information entrusted by third parties. The most well-known are ISO/IEC 27001 “Security techniques – Information security management systems – Requirements” and ISO/IC 27003 “Security techniques – Information security management systems – Guidance”. Other address the governance of information security (ISO/IEC 27014), cloud services (ISO/IEC 27017), network security incl. use of security gateways and VPN (ISO/IEC 27033 series).
However, most are based on the analysis of acceptable risks, and there is no gradation or level equivalence to FDAL.</td></tr>
</table>

<table>
<tr><th>Solution #1 “AISD-based”</th><th>Solution #2 “FDAU/FDIU&ACMS-based”</th></tr>
<tr><td colspan="2"><b><i>FB4: Off-Aircraft Storage</i></b></td></tr>
<tr><td colspan="2">No standard was identified concerning the development methodology of data storage infrastructure development. Again, security is the main concern.
See discussion above on ISO/IEC 27000 series reference material. ISO/IEC 27040 is dedicated to storage security.</td></tr>
<tr><td colspan="2"><b><i>FB6: Data Recovery</i></b></td></tr>
<tr><td><b><u>Note</u></b>: The counter part of the note for “FB1: Data Acquisition” above, is that the accident investigation authorities need to be provided with the definition of the flight data records by the <b><i>airline</i></b>.</td><td><b><u>Note</u></b>: The counter part of the note for “FB1: Data Acquisition” above, is that the accident investigation authorities need to be provided with the definition of the flight data records by the <b><i>airframer</i></b>.</td></tr>
<tr><td colspan="2">There are a couple of organizations working on the standardization of web technologies. These organizations include, among others, the international World Wide Web Consortium (W3C) addressing development methods and usages, the WHATWG focusing on HTML specifications, WICG focusing on browsers, and ECMA TC39 focusing on JavaScript. The standards provide guidelines, best practices, and techniques for developing web-based applications.</td></tr>
<tr><td colspan="2"><b><i>Miscellaneous</i></b></td></tr>
<tr><td colspan="2">ISO/IEC 27001 would typically apply, providing guidelines for cybersecurity developments, including the use of COTS as well as vulnerabilities checks (cf. discussion above)</td></tr>
<tr><td>Data linked certificates: FDAL D/E</td><td>Hardcoded private key(s): FDAL D</td></tr>
</table>

Table 5: Global reliability

4.2.2 MTBF Aspects

Reliability figures in terms of “mean time between failure (MTBF)” for the QR-FRD solution is dictated by the figure of the weakest component in the QR-FRD suite, starting with the FDAU and the AISD router, continuing with the PIESD router, SATCOM systems, and ending with the access control portal.

This figure should be compared with that of crash-protected flight recorders, basically > 100,000 hours (*source: miscellaneous flight recorder data sheets*).

Note: At the time this version of the document was drafted, no MTBF figure for the different airborne equipment were publicly available.

The overall daisy chain of the QR-FRD solution will likely result in a worse reliability figure, yet to be calculated. Installing a redundant QR-FRD suite on the airborne side will have major effects on the suite development (redundancy management software typically), and its installation (double weight, wiring and power consumption basically). Without speaking of certification and provision costs.

For this “hardware related” reliability aspects, both solutions are quite similar and would provide figures with same order of magnitude. However, from an operational standpoint, Solution #1 may present a slight advantage over Solution #2, for which the FDAU/FDIU & ACMS unit is central for collecting data. In case of failure of that unit, no flight recorder data would be transmitted, whereas only flight data would not be transmitted should the FDAU fail in Solution #1. Nevertheless, investigations would be compromised and solely rely on audio, datalink, and flight crew-machine interface recordings.

4.2.3 Cyber Resilience Aspects

The cyber resiliency of connected aircraft systems remains an essential topic of discussion across multiple segments of the aviation industry. Modern airplanes are indeed equipped with networks and systems that share data with the flight crew, passengers, other aircraft, air traffic controllers, and the airline operation center in ways that were not previously feasible. As a result, avionics systems should be properly protected to not be at risk of a variety of potential cyberattacks.

EASA has considered state-of-the-art means of protection against these threats when certifying new products or new parts and amended accordingly CS-25 typically to reflect those means of protecting aircraft systems against these security threats (cf. ED Decision 2020/006/R, [Ref 10]).

EUROCAE jointly with RTCA have developed ED-203A / DO-356A [Ref 6] to provide methods and considerations for showing compliance for airworthiness security during the aircraft life cycle. It was developed as a companion document to ED-202A / DO-326A "Airworthiness Security Process Specification" which addresses security aspects of aircraft certification and to ED-204 / DO-355, "Information Security Guidance for Continuing Airworthiness" which addresses airworthiness security for continued airworthiness.

ARINC-811 [Ref 12] provides a common understanding of information security concepts as they relate to airborne networks, and a framework for evaluating the security of airborne networked systems. It is meant to bridge airline organizations and the terrestrial network security industry. Other Series 800 standards address top-level networking definition describing aircraft domains, file servers and other infrastructure (821), end-to-end datalink encryption (823), guidance for usage of digital certificates on airplane avionics and cabin equipment (842).

ISO 20214:2015, “Space data and information transfer systems – Security architecture for space data systems”, is a high-level systems engineering reference enabling engineers to better understand security concepts required to secure space systems.

ISO/IEC 27000 series would apply at global (end-to-end) level as well as individual link level of the QR-FRD chain.

4.2.4 Loss of Electrical Power Considerations

ED-112A [Ref 7] defines requirements for recording interruption recovery after a power interruption. Section 2-5.3.10, for the CVR description, mentions: "*The intent of the RIPS [recorder independent power supply] is to allow for continued operation for 10 minutes (+/-1 minute) applied in all cases when power to the recorder is removed.*"

Conformance to this requirement for power interruptions will have major impacts on the system should the same constraints apply to QR-FRD solutions.

In the present architecture, the crash protected recorder systems are powered by an essential electrical power network[8] to answer these continuous recording conditions.

As of today, only the FDAU/FDIU&ACMS unit is powered with the same essential electrical power network and may be compliant with the constraints for both proposed solutions. The communication systems are not compliant with such constraints, being neither connected to the essential electrical power network, nor supply their own internal power sources (battery or equivalent).

The possible solutions to answer to these requirements should have major impacts. The main one is about the weight of the onboard energy storage (battery). The addition of extra computers on the non-interruptible network should require increasing the battery storage capacity, hence, their volume and weight.

An evolution of the airplane to answer to this point will require a significant modification.

Note: Similar considerations would also apply to several factors identified in D1 [Ref 1], like:

- Factor 1: "Loss of power on all engines while the aircraft is still in flight",
- Factor 2: "Loss of equipment that is a non-essential load for electric systems
- Factor 5: "In-flight fire [or in-flight loss of aircraft physical integrity], which does not completely destroy the aircraft"
- Factor 6: "Collision with land or water, which does not completely destroy the aircraft"
- Factor 7: "Post-impact fire, when the crash does not completely destroy the aircraft"

It does not seem reasonable to consider a crash-protected QR-FRD suite, and the issues will have the same effect on both solutions.

[8] The essential electrical power network must be able to power the systems at least 10 minutes after all other power sources (engines, auxiliary power unit (APU), …) are down.

4.3 Expected Performance

The expected performances are divided into two categories, the performance of the system and performance from an operational perspective.

Both are common to the two solutions as there is no predefined performance values but value ranges.

The system performance depends on several factors such as the service providers in the first place (if it satisfies the range provided bellow) but also the antenna installed on the aircraft for example. For the latter, generally, there are different types of antennas the airline may choose from without considering the QR-FRD related required performance.

Not all configurations will be evaluated. The simulation undertaken within Task 6 will be able to test several possible combinations of parameter within the range and their impact on the overall performance.

Data Parameter	Min	Max
Encryption expansion ratio	0.15%	
Signature size (RSA)	1024 bits	
Lossless data compression ratio	2:1 (binary data)	5:1 (text data)
JPEG compression ratio	10:1	
Transmission Parameter	**Min**	**Max**
Antenna directionality (azimuth / hemisphere)	360°	360°
Typical handover duration (ms)	0	500
Worst case handover duration (seconds)	150	300
Best reception cone (from zenith)	0-45°	0-60°
Degraded reception cone (from zenith)	45° - 70°	60° - 75°
No reception cone (from zenith)	above 70°	above 75°
Reconnection duration (seconds)	4	30
Upstream throughput (Mbps)	10	50
Latency (ms)	50	1000

Table 6: Expected system performance

Note: Compression time and encryption time are negligeable in comparison with the transmission characteristics cf. D3.

Regarding the **operational performance**, the end user expectations are:

- a minimum of 20 minutes of historical flight recorder data available
- an efficient access control to the data (roles and attributes)
- a total confidence in the stored data

4.4 Detailed Data Protection

Data protection is common to the two solutions. The choice of an encryption algorithm will not affect the data protection requirements but can have impact on performance (asymmetric keys for example) and maintenance (key management).

Here is a graphical recall of data protection mechanism explained in report D3.

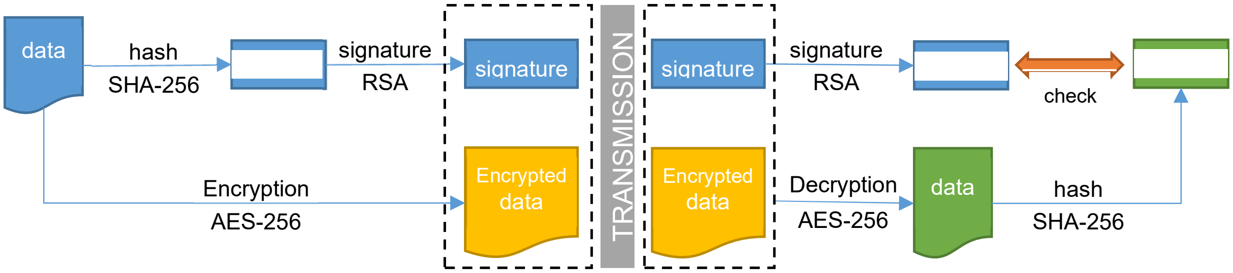


Figure 3: Data protection mecanism principle

4.5 Operational Procedures Impacts

The following table tentatively assesses the operational procedures impacts for the two solutions.

Solution #1 “AISD-based”	Solution #2 “FDAU/FDIU&ACMS-based”
Flight Crew Procedures	
The processing of flight recorder data and their transmission is automated. Nevertheless, it is expected the flight crew checks the QR-FRD suite built-in-test status during pre-flight checks. Pre-flight checking procedures for proper operation of the crash-protected recorders may need to be adapted accordingly.	
Ground Handling Procedures	
The equipment part of the QR-FRD suite do not need to be removed once installed for other purposes than maintenance[9]. No specific impact identified.	
Maintenance Procedures	
Cryptographic certificates are data linked.	Cryptographic private keys are “hardcoded” or “data loaded”. *To reduce the maintenance costs, it is not planned to update periodically the unit private key and associated certificate. Nevertheless, if required by an exceptional event, the unit keys and certificate can be updated in unit factory or maintenance lab. In accordance with the data loading security infrastructure deployed by the Airline, update of the unit key and certificate should be possible by a data loading operation onboard (this solution is under investigation).*
The validation workload would be “doubled” with two complete sets of data (originating from crash-protected recorders and QR-FRD) to validate.	

[9] The proposed solutions are based on already installed avionics, but wiring additions are expected for inputs other than flight data. Also, it may be necessary to add a failure status to the flight warning computer and/or dedicated message in the cockpit. There is no decision at the time of the drafting of the present document on whether or not the QR-FRD solution is part of the aircraft minimum equipment list.

Solution #1 “AISD-based”	Solution #2 “FDAU/FDIU&ACMS-based”
	Manual triggering for maintenance / inspection purposes is necessary. The proper reception of flight recorders data must be checked periodically. Especially the audio records may be subject to quality evaluation and fix up of the system if needed. For this purpose[10], a manual input may be used to trig transmission (on ground, the duration of the transmitted flight recorder data is verified, as well as their quality, especially for the audio recordings, and an inspection report is issued). In accordance with current practice, a test every year is a first evaluation of this need. **Note**: A message uplinked, may request the crew to manually trigger the transfer of FRD data, for tests purpose.
Policies and procedures should be set in place to recover and use the flight recorder data for test / quality inspection purposes.	

[10] Flight recorder recordings may be used by the operator in normal operations, in the framework defined by Annex 6 Part I 3.3, and, for EU-based operators, Part-CAT CAT.GEN.MPA.195 point (f).

Solution #1 "AISD-based"	Solution #2 "FDAU/FDIU&ACMS-based"
Airline and Accident Investigation Authorities Procedures	
Policies and procedures should be set in place to recover, use and preserve the flight recorder data for after a nominal flight, and after occurrences that require reporting according to Regulation (EU) 376/2014 (cf. D3 [Ref 3]) (airline), a serious incident and an accident (accident investigation authorities and airline).	Policies and procedures should be set in place to recover, use and preserve the flight recorder data for after a serious incident, and an accident (accident investigation authorities and airline). Following the reception of the flight recorder data: • In case of serious incident or accident, the AIA may request the records. Using the files signature, the AIA can authenticate the data and to link these data to the aircraft and to the time of occurrence. As the file are encrypted, only the AIA can read them out, and decode and concatenate the files to recover the full recordings. • In case of detection of a temporary event, with no flight incident or accident end, the flight recorder data are not requested and transmitted to the AIA. The airline is free to use the data for its FDM program.
Note: It is important that the original flight recorder data, received following an accident, a serious incident or an occurrence identified by the investigating authority, be preserved by the airline (or a contracted organization) for a period of 60 days or until otherwise directed by the investigating authority (EASA AMC&GM Part CAT [Ref 4], CAT.MPA.195(a))	
A procedure should be set in place to check flight recorder data reception during pre-flight checks (i.e. as soon as the QR-FRD solution is expected to start its continuous transmission).	
QR-FRD Solution Manufacturer	
Largely due to the use of commercial off the shelf (COTS) products in the equipment, the manufacturer will have to conduct periodic cybersecurity vulnerability surveys, if not already, and extend the assessment to the QR-FRD component it oversees. The manufacturer may also have to periodically perform (or contract an ethical hacker service to perform) penetration tests to ensure the equipment is resilient to cyberattacks.	

Table 7: Operational procedures impacts

4.6 Resilience to, and Resolution of, Factors Impacting Transmission

The following table tentatively assesses the resilience to the first 10 factors identified in D1 [Ref 1], as well as resolution of the last 4, for the two solutions.

<table>
<tr><th>Solution #1 “AISD-based”</th><th>Solution #2 “FDAU/FDIU&ACMS-based”</th></tr>
<tr><td colspan="2"><b><i>Factor 1: “Loss of power on all engines while the aircraft is still in flight”</i></b></td></tr>
<tr><td colspan="2">As mentioned in §4, loss of power will affect the whole QR-FRD airborne suite, incl. routers the data link systems. To mitigate the effects, the installation should consider connecting the whole suite to the backup power source.</td></tr>
<tr><td colspan="2"><b><i>Factor 2: “Loss of equipment that is a non-essential load for electric systems”</i></b></td></tr>
<tr><td colspan="2">Depends on the system, outside of the QR-FRD suite, experiencing failure (sensor, avionics, acquisition/management system…).</td></tr>
<tr><td colspan="2"><b><i>Factor 3: “Significant [or unusual] pitch and roll attitudes”</i></b></td></tr>
<tr><td colspan="2">Extreme values of pitch and/or roll attitude will mainly affect the pointing performance of mechanical SATCOM antennas (depending on provider and/or installation), hence transmission performance in flight.</td></tr>
<tr><td colspan="2"><b><i>Factor 4: “Unusual [or excessive] pitch and roll [and yaw] rates”</i></b></td></tr>
<tr><td colspan="2">Extreme values of pitch and/or roll and/or yaw rates will mainly affect the pointing performance of mechanical SATCOM antennas, hence transmission performance in flight.</td></tr>
<tr><td colspan="2"><b><i>Factor 5: “In-flight fire [or in-flight loss of aircraft physical integrity], which does not completely destroy the aircraft”</i></b></td></tr>
<tr><td colspan="2">None of the components in the QR-FRD suite is fire resistant compared to crash-protected flight recorders. Impacts will depend on damages caused by fire while in flight.</td></tr>
<tr><td colspan="2"><b><i>Factor 6: “Collision with land or water, which does not completely destroy the aircraft”</i></b></td></tr>
<tr><td colspan="2">None of the components in the QR-FRD suite is crash resistant compared to crash-protected flight recorders. Impacts will depend on damages caused by the crash.</td></tr>
<tr><td>Performance depends, basically, on the time left to transmit temporarily buffered real-time data.</td><td>Performance depends, basically, on the time left to transmit still buffered historical data.</td></tr>
<tr><td colspan="2"><b>Factor 7: “Post-impact fire, when the crash does not completely destroy the aircraft”</b></td></tr>
<tr><td colspan="2">None of the components in the QR-FRD suite is fire resistant compared to crash-protected flight recorders. Impacts will depend on damages caused by fire after the crash.</td></tr>
<tr><td>Performance depends, basically, on the time left to transmit temporarily buffered real-time data.</td><td>Performance depends, basically, on the time left to transmit still buffered historical data.</td></tr>
<tr><td colspan="2"><b>Factor 8: “Aircraft sinking into water, after ditching, which does not completely destroy the aircraft”</b></td></tr>
<tr><td colspan="2">None of the components in the QR-FRD suite is fire resistant compared to crash-protected flight recorders. Impacts will depend on damages caused by water after ditching.</td></tr>
<tr><td>Performance depends, basically, on the time left to transmit temporarily buffered real-time data.</td><td>Performance depends, basically, on the time left to transmit still buffered historical data.</td></tr>
</table>

Solution #1 “AISD-based”	Solution #2 “FDAU/FDIU&ACMS-based”
Factor 9: “Aircraft out of range of ATC surveillance systems within the 60 minutes preceding the accident and until the accident”	
Transmission performance relies on the performance (coverage and available throughput) of the SATCOM data link solution selected for QR-FRD purposes.	
Factor 10: “Inappropriate architecture or link solution impacting the bandwidth of the global system in an emergency situation”	
Less impacted than Solution #2, as the connectivity is established with ground servers since the beginning of the flight and no historical data need to be transmitted in the continuous transmission case.	Early triggers should allow connections should they not be present, while the aircraft is still not experiencing extreme flight conditions.
High speed SATCOM should provide sufficient bandwidth unless the aircraft experiences extreme flight conditions. This should be confirmed by the simulations undertaken within Task 6 of the study.	
Factor 11: “Duration of emergency situations”	
NA (continuous transmissions)	Depends on the trigger condition and its detection. **Note**: The objective of the trigger definitions is to get an “emergency situation” with a duration of 3 of 4 minutes. This objective can be reached, in particular when the aircraft is in cruise phase over the ocean. Based on such duration, the transmission of the last 20 minutes of flight recorder data[11] should be assumed (refer to document D3, section 4.2.2.12 [Ref 3].
Factor 12: “Location of the aircraft in emergency situations”	
Transmission performance relies on the performance (coverage and available throughput) of the SATCOM data link solution selected for QR-FRD purposes.	
Factor 13: “Integrity of transmitted data”	
Data protection mechanisms, typically signature, guarantee the authentication and the integrity of the flight recorder data transmitted by the aircraft and stored on the ground.	
Factor 14: “Transfer Protocol”	
IP-based protocols are used to transmit the flight recorder data securely over high-speed data links.	

Table 8: Resilience to factors identified in D1

[11] These evaluations, done in D3, exclude the flight crew-machine interface recordings.

4.7 Economic Indicators

The costs are split into non-recurring costs (NRC) and recurring costs RC).

The **NRC** are comparable for both solutions. The equipment purchases costs depend on the equipment manufacturer business model. Equipment installation and certification costs depends on final architecture choice such as robustness to the loss of power, redundancy and cannot be evaluated in the frame of this study.

The **RC** mainly depend on the amount of data transmitted (equipment operation costs) and the service provider offer which is independent from the choice of one solution. The equipment maintenance costs that include the cryptographic key management can neither be evaluated as PKI management is not yet defined.

4.7.1 Transmission Costs Estimations

Transmission costs will basically be proportional[12] to the amount of flight recorder data transmitted over the air. As such, the transmission costs of Solution #2 (triggered) would be dwarfed by those of Solution #1 (continuous). The following table (based on computations from D2 [Ref 2]) tentatively illustrates the ratio between the two options.

<table>
<tr><th>Solution #1 “AISD-based”</th><th>Solution #2 “FDAU/FDIU&ACMS-based”</th></tr>
<tr><td><i>Based on an average of 2 hours flight</i></td><td><i>Based on an average of 20 min of flight recorder data transmitted (278 Mbyte)</i></td></tr>
<tr><td colspan="2">$6.10^{6} : 1$</td></tr>
<tr><td><i>1,666 Mbyte per flight</i></td><td><i>Event[13] occurs 1 per 1 million: 278 byte per flight</i></td></tr>
</table>

These costs should be balanced against potential economic benefits from wireless recovery of flight recorder data (flight data in particular[14]) for the airline, such as:

- SMS and FDM programs
- Real-time maintenance and troubleshooting
- …

4.8 Weight and Power Consumption

No change, as of today, equipment already installed.

Minor gains will be achieved through the replacement of one of the crash-protected combined flight recorders with the QR-FDR solution.

[12] Figures publicly available on the Internet are of a couple of Euros per Mbyte for aeronautical high-speed SATCOM services.

[13] Based on accident occurrences and triggers as defined by BEA for “distress situations” (cf. D3 [Ref 3]). When considering “abnormal situations”, there would be several thousand of occurrences that would likely last till the end of the flight. The ratio between the two options would hence not be that large, but nevertheless be significant. The figures based on occurrences statistics will be refined in the next version of the present document.

[14] Flight data are already used for FDM programs (and must be according to Part-ORO, ORO AOC.130). The use of audio and imagery recordings for SMS is permitted (Part-CAT CAT.GEN.MPA.195 point (f)) but the data protection conditions are more stringent as they may have a privacy contents.

5 BENEFITS, CONSTRAINTS AND TECHNICAL FEASIBILITY ISSUES

The following table tentatively assesses the benefits, constraints, and technical feasibility issues for the two solutions.

Solution #1 "AISD-based"	Solution #2 "FDAU/FDIU&ACMS-based"
BENEFITS	
Centralization of the acquisition of all data, processing, and transmission management by the AISD router	Centralization of the acquisition of all data by the FDAU/FDIU & ACMS unit
No reliance on a trigger condition evaluation logic (continuous transmission)	SATCOM transmission costs for the purpose of incidents and accidents investigations will be proportional to the number of occurrences and the duration of their respective situation. The transmission costs, compared to those of continuous transmissions for every flight, still needs refinement (cf. §4.7.1) but is expected to be significantly less expensive.
Flight recorder data may be used by the airline (assuming policies in place) for its SMS and/or FDM programs, as well as for test/inspection purposes.	
The wiring to the two crash-protected combined flight recorders could be reduced when replacing one of the units, ultimately, by the QR-FRD solution[15]. This would translate into a slight reduction of wiring complexity and weight.	
CONSTRAINTS	
	Point-to-point secure connection may need to be ready upfront to optimize data transmission, especially historical data, should transmission conditions degrade rapidly after the trigger condition is detected.
Policies and procedures to may need to be set in place to "lock" access to the flight recorder data for the airline in case of a serious incident or an accident.	Manual trigger required to transmit data for test/inspection purposes.
Flight recorder data transmitted whatever the issue of the flight, for all equipped aircraft.	There is no guaranty that the full contents of historical data are transmitted, especially when the duration of the "emergency phase" is less than 3 or 4 minutes. This fact occurs when the major incident or accident happens, the aircraft not being in cruise phase. When the aircraft is close to the ground (take-off, approach, or landing phase) the emergency phase duration will be limited, and only a part of the record can be transmitted.
Need for a mechanism to protect audio recordings from "free" airline access.	
TECHNICAL FEASIBILITY ISSUES	

[15] Depending on the maturity and reliability of the QR-FRD solution, configurations may range from 2 crash-protected combined recorders and a QR-FRD solution to an automatic deployable combined recorder and a QR-FRD solution.

Solution #1 “AISD-based”	Solution #2 “FDAU/FDIU&ACMS-based”
None identified so far.	

6 ADDITIONAL CONSIDERATIONS

6.1 Data Security

The security analysis covers two key areas:

- A first key area (aka airworthiness security) that assesses the security impact of the introduction of the QR-FRD solution in the aircraft architecture with respect to safety
- A second key area that deals with cybersecurity for legal aspects.

Regarding the security impact, a security assessment shall be conducted against any potential intentional unauthorized electronic interaction (IUEI) the QR-FRD solution could bring with security threats and vulnerabilities that would lead to unacceptable safety impacts.

This assessment will result in the identification of the possible new sources of attacks such as, additional communication interfaces from/to aircraft safety critical domains (i.e. the Aircraft Control Domain), or additional applications and data exchanges supporting the QR-FDR functions. Assets targeted by these attack paths will be identified and safety impacts quantified.

The combination of the attack difficulty (“event likelihood”) and the impact severity will aid in deciding whether the risk is acceptable, or if the architecture needs mitigation means to ensure an acceptable risk level, or if the design needs modification.

This security assessment usually follows the methodology described in ED-203A / DO-356A [Ref 6].

Regarding the legal aspects, there is a need to identify security risks and tackle security challenges regarding the legal aspects covering data transmission and storage. To achieve that goal, a security vulnerability analysis of the QR-FRD solution shall be conducted to define the security objectives and security measures addressing the needs for confidentiality, integrity, and availability.

6.2 Main Legal Aspects

Until now, flight recorder data were stored within the recorders fixed aboard an aircraft. Therefore, access to the flight recorder data was associated with access to the aircraft wreckage and guaranteed to the investigators of the State of occurrence.

The QR-FRD process completely changes this situation.

In May 2021, the ICAO Accident Investigation Panel (AIPG) Working Group published a working paper (AIPG/6-WP/6 05/05/2021) pointing out:

- that the introduction of a QR-FDR technology creates *“the potential for scenarios in which the flight recorder or flight recorder data may be held by one or more States not participating in the accident or incident investigation”* (AIPG/6-WP/6 §2.3)
- the involvement of satellites or / ant multiple ground stations and *“as a result, there may be multiple full or partial electronic copies of the flight recorder data available in different States, including States not participating in the accident investigation”* (AIPG/6-WP/6 §2.5)
- that the Articles 5.14 and 5.16 of the Annex 13 already state that any State shall provide the State conducting the investigation with all the relevant information available to it (flight recorder records included if the aircraft lands in a State other than the State of Occurrence). However, this obligation to provide data is *“upon request to the State conducting the investigation”* and *“this implies that the State conducting the investigation knows all of the possible locations where the data may be stored and how to make such a request. Given the large possible number of storage locations and third-party providers, this may not be practical in all cases”* (AIPG/6-WP/6 § 2.9)

As a result, the ICAO Accident Investigation Panel (AIPG) Working Group concluded:

- that the definition of flight recorders should be revised "*to explicitly include systems that transmit data for storage off the aircraft for the purpose of complementing accident/incident investigations"*
- and a new standard be adopted which *"must ensure that any full or partial electronic copies of transmitted flight recorder data are provided to the State conducting the investigation without requiring a request"*

Moreover, coexisting sources of data (physical data recorders and transmitted data) in different locations should not lead to allow for more than one investigation (Annex 13 identifies one single State responsible for the investigation).

How far flight recorder data transmitted and stored through the QR-FRD process can still be considered as "recorded data" in the sense of ICAO Annex 13 will be addressed in D7 later in the study.

These legal aspects are considered in this chapter which will be developed further in the scenario-based study (Task 7). Its purpose is to assess the main legal challenges and limitations of the introduction of the additional QR-FRD process.

We can identify the main issues within the changes brought by the new process using the different functional blocs (FBs) as follows:

PHYSICAL DATA RECODERS	**TRANSMITTED DATA PROCESS**
Existing legal framework (ICAO, others…)	**Is existing framework relevant? sufficient? compatible? New regulations needed ?**
• Data continuously acquired and stored on dedicated recorders located on board	• Data acquisition, formatting, dissemination and FB1 (data collection)
• Accident: INCERFA, ALERFA, DETRESFA procedures and/or evidence of an accident	• Trigger detection in solution #2 FB2
• Data recorder retrieved and physically transported by AIAs (possibly under supervision of Judicial Authorities)	• Data transport (air and space segment) FB3
• Data stored in AIAs laboratories (possibly under supervision of Judicial Authorities)	• Off aircraft storage (ground) FB4
• Data recovered from physical recorders in AIAs laboratories (possibly under supervision of Judicial Authorities)	• Data recovery FB6
• Investigation	**• Investigation**

The following table lists the different main legal issues raised by the new process.

FB1: Data Collection / Acquisition and Digitization
Legal issues for both solutions • Data ownership: ▪ possible distinction between unprocessed data and organized data bases ▪ possible need to provide a right of access for AIAs as the data might be considered airlines property (unlike the present situation where data are physically under AIA’s control) • Data encryption: need to find a balance between data security, the prevention of possible conflict of interest at the transport and storage phases, and the need to be compatible with system test and maintenance procedure
FB2: Trigger Detection
Solution #2 • Possible need to harmonize triggers by setting standards through regulation
FB3: Data Transport
Legal issues for both solutions • Data transport service providers’ contracts likely to be legally reviewed and regulated • Legal framework: GDPR regulation for personal data • Use of Passenger Information and Entertainment Services Domain (PIESD) for QR-FRD purposes: is it consistent with the commercial agreements signed by the companies for the implementation of the network?
FB4: Off-Aircraft Storage
Legal issues for both solutions • Data storage: ▪ need to regulate activities and contracts of service providers: data center robustness, mandatory fail-safe system, protection against cybercriminality; ▪ need to manage airlines’ conflict of interest by making any tampering of the data impossible ▪ need to regulate the storage in secured servers / cloud-based storage, incl. duration of the storage, conservation of data after safety investigations, access to storage… • Dissemination of data in different countries: a global regulation is needed to avoid conflicting legal situations. Need to define a retention policy / storage life to guaranty timely data recovery by AIAs.

FB6: Data Recovery

- Need to amend ICAO Annex 13 and EU Regulation 996/2010 as appropriate
  - To prevent airlines’ conflicts of interest and protect the credibility of the investigation (management of data access key)
  - To prevent data withholding by the State of data storage (see amendment suggested for the Annex 13 §5.14.1/2 by AIGP Working Paper of May 2021 AIGP/6-WP/16)
  - To warrant free access of AIAs to recorder data
  - To regulate judicial authorities’ access
    - Cooperation agreements between AIAs and judicial authorities (as provided by Annex 13 § 5.4.4) will need to be reviewed
    - Potential conflicting requests from judicial authorities of different countries need to be anticipated
  - To regulate third parties’ access

In order to review the different combinations of accident locations, states of registry and states of operator, a scenario-based study will be conducted. The legal consequences related to each of these combinations will be examined in regard to the relevant regulations. Investigations of past accidents such as the total fuel exhaustion over the Atlantic and landing in Lajes in 2001 (Air Transat - A330) or the disappearance of the MH370 in 2014 are some examples of scenarios that will be used to “test” the new system from a legal perspective.

6.3 Additional Research Needed

The following additional research or investigation topics needed to mature the QR-FRD solution have been identified so far during the study:

- ***Audio compression***: ED-112A [Ref 7]requests a specific acquisition and compression characteristics for both the flight crew and flight deck audio channels. These algorithms, described in the 80's-90's, are not up to date. Especially for the flight crew audio channels, the ratio size of the record versus quality of the recovered audio should be challenged. Perhaps, the use of a well-known lossy audio compression algorithm (JPEG, or other) can provide a better efficiency.
- ***Adaptative chunk***: Vary the chunk size depending on the QoS and throughput of the IP connectivity (decrease of the chunk size when the transmission degrades to limit the loss of data as a chunk is entirely transmitted or lost) rely on information provided by the communication stack of the various possible communication means. This is not implemented today and the benefits for such solution required tests in representative environment.
- ***Trigger logic***: several possible trigger conditions have been identified in D3 [Ref 3], and detection algorithms proposed. However, a couple of trigger conditions are low TRL and would need further research, among which:
    - ***Deviation from the planned flight path***: uncleared deviations from the planned flight path should be monitored and ultimately trigger an alert and initiate the transmission of flight recorder data. These deviations could result from severe weather circumnavigation, but also flight crew incapacitation after health problems or hijacking. Flight path monitoring and detection of deviation are being studied as safety nets on the ground side. Nevertheless, since triggering QR-FRD transmission from the ground is not retained as an option, it could be worth considering implementing conformance monitoring tools on board as well.
    - ***Flight crew incapacitation***: At the time the present document was written, the automated detection of "flight crew incapacitation" is only at the research & technology (R&T) level (i.e. TRL 3-4). The feasibility of this detection system is not yet ensured. Additional studies are necessary to have these systems used in the trigger logic.
- ***Quality of Service and PIESD router***: Should PIESD bandwidth be preempted to give precedence of QR-FRD transmissions over passenger applications transmission, mechanisms such as quality of service / prioritization by the PIESD data link solution (DSP level) should be analyzed thoroughly. Use of a discrete signal between the AISD router and the PIESD router notifying the latter of top priority transmissions is also an option to be further investigated.
- ***Impact on the ARINC-664P7 [Ref 11] (aka AFDX®) network***: Transmission of flight recorder data including flight crew-machine interface recordings (FCMIR) across the airborne QR-FRD suite will increase the traffic over the Avionic Full Duplex (AFDX) switched ethernet network. Once FCMIR are standardized, impact of the QR-FRD traffic on the switched ethernet network should be further investigated.
- ***Flight Recorder Data Recovery Suite***: Once the access management principles are defined allowing both the accident investigation authorities and the airline to recover the flight recorder data, the infrastructure as well as tools necessary for access management, data recovery and processing, etc… should be developed. Further investigations and prototyping of these tools are foreseen, likely based on the ownership of the tools, interactions between the involved parties and their respective skills.
- ***Tests in a Representative Environment***: Though the two solutions show high TRL (cf. §4.1), further steps such as prototyping and tests in a representative environment will be necessary to mature the solutions and pave the way towards industrialization and deployment.

7 QUANTITATIVE TESTS IN SIMULATION ENVIRONNEMENT

A model will be developed in order to characterize the solutions.

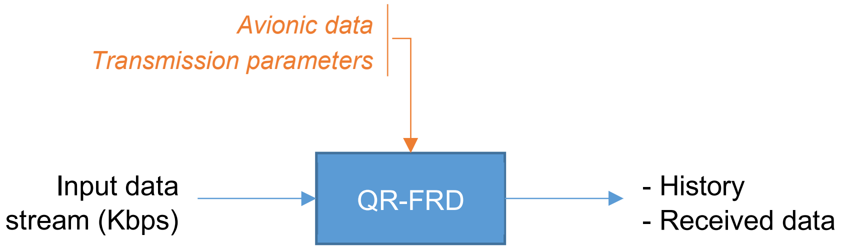


Figure 4: QR-FRD black box

Simulation will be performed based on a model using manual scenario and flight database (accident, incident, nominal) for a set of trigger configuration and for a set of parameter configuration (cf. grey box of Figure 5: Model overview).

The main outcomes will be:

- Data quantity and throughput versus input data variation (pitch, roll…)
- The influence of the chunk size on the transmission performance (including overhead, protocol negotiation, error rate)
- The amount of data received on ground before the accident according to the triggers (several set of triggers will be evaluated)

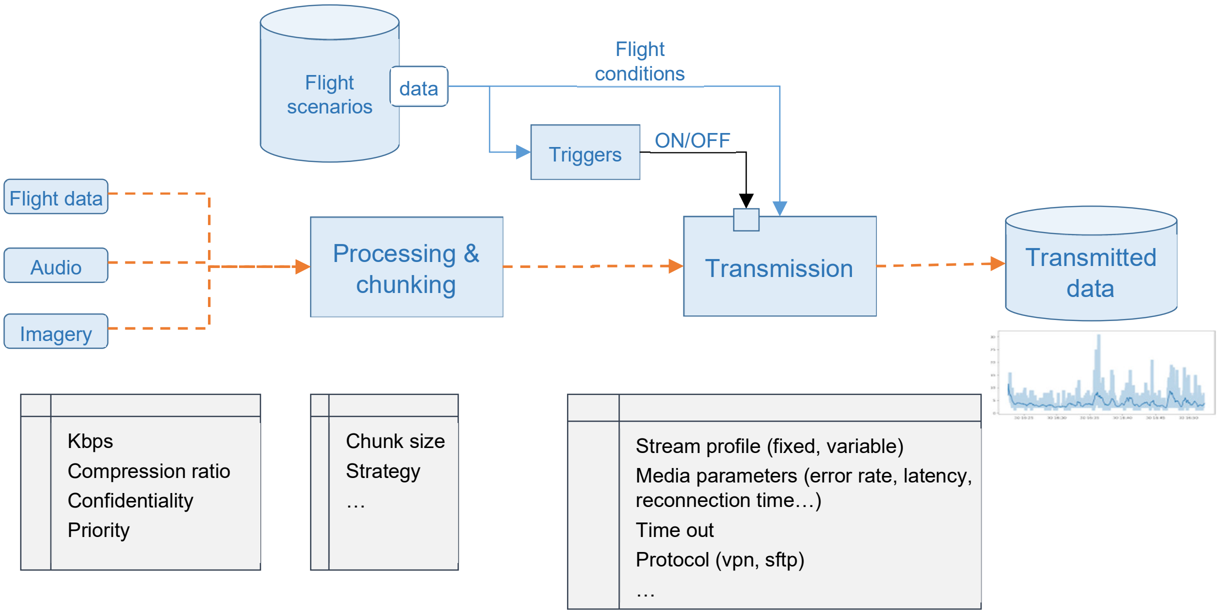
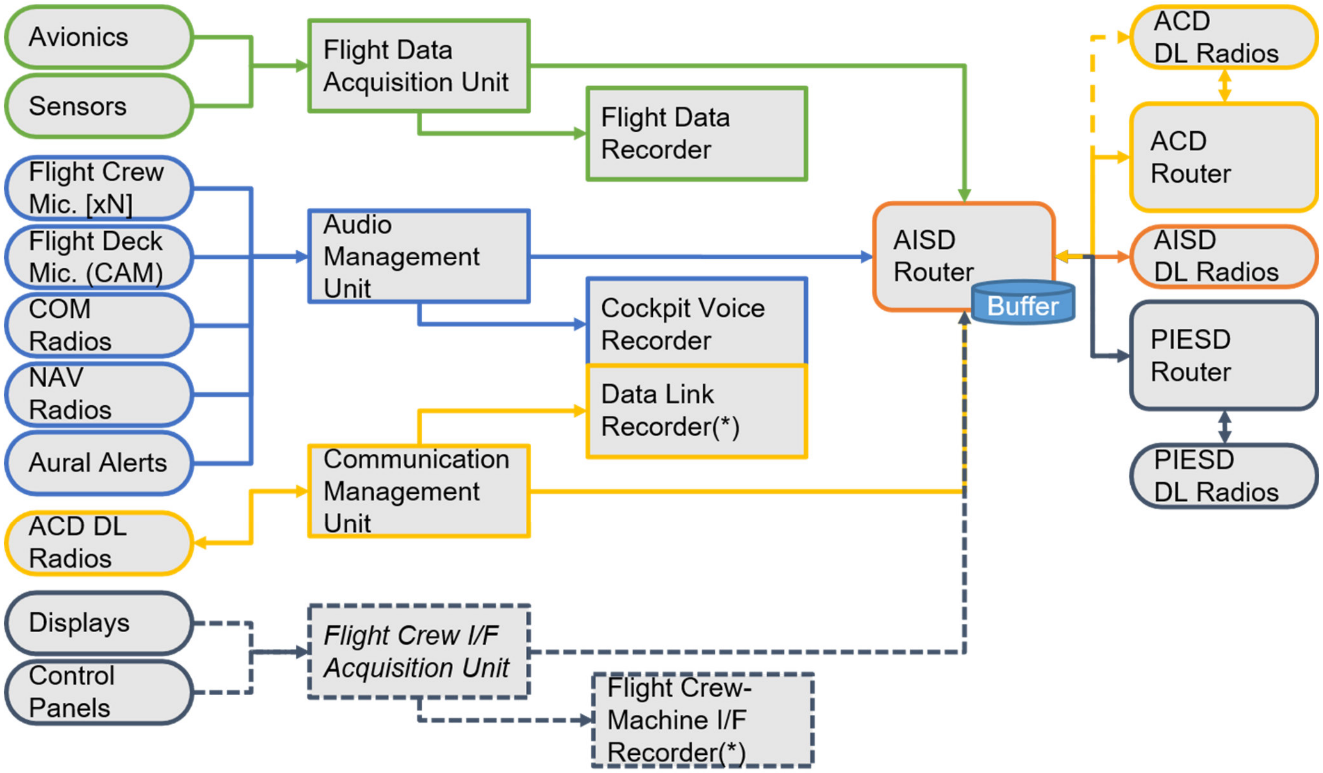


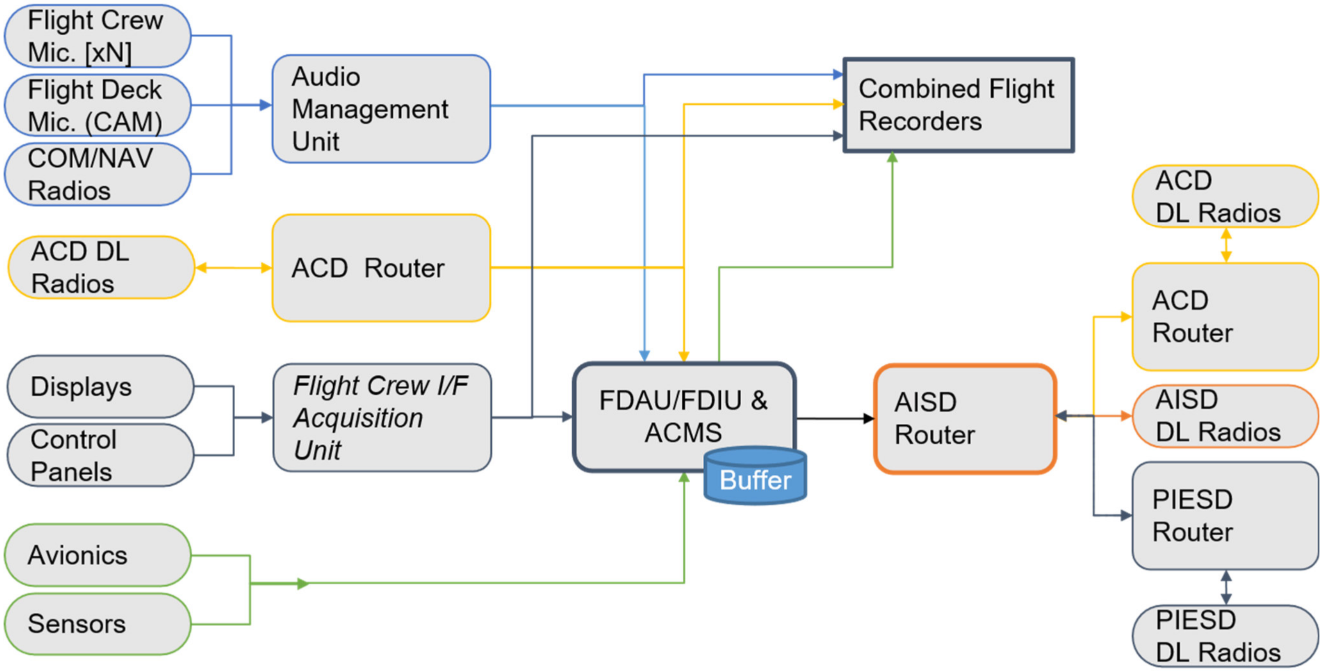
Figure 5: Model overview

ANNEX A: SELECTED SOLUTIONS OVERVIEW

The following figure, extracted from D3 [Ref 3], provides an overview of the system architecture for Solution #1 “AISD-based”, articulated around the AISD router.



The following figure, extracted from D3 [Ref 3], provides an overview of the system architecture for Solution #2 “FDAU/FDIU&ACMS-based”, articulated around the FDAU/FDIU&ACMS unit and the AISD router.



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