EASA
European Aviation Safety Agency

Final Report EASA_REP_RESEA_2007_2

Research Project:

Investigation of the technical feasibility and safety benefit of a light aeroplane operational Flight Data Monitoring (FDM) system

An agency of the European Union

Research Project EASA.2007/2

Investigation of the technical feasibility and safety benefit of a light aeroplane Flight Data Monitoring (FDM) system

Final Report

16.12.2008

Technische Universität Braunschweig
Institut für Flugführung
Dipl.-Ing. Rudolf Hankers
Dipl.-Ing. Falk Pätzold
Hermann-Blenk-Str. 27
D-38108 Braunschweig

messWERK GmbH
für Mess- und Anzeigetechnik
Dr.-Ing. Matthias Cremer
Dipl.-Ing. Jan Troelsen
Hermann-Blenk-Str. 27
D-38108 Braunschweig

i) Table of Content

ii) List of illustrations

iii) List of tables

1 Acknowledgements

The study “Investigation of the technical feasibility and safety benefit of a light aeroplane Flight Data Monitoring (FDM) system” was funded by the European Aviation Safety Authority (EASA).

The study was executed by the Institute of Flight Guidance at the Technical University Braunschweig (Germany) in cooperation with messWERK GmbH für Mess- und Anzeigetechnik in Braunschweig.

2 Executive Summary

Flight Data Monitoring (FDM) is mandatory for large aeroplane operations in Europe since 2005. Experience gained over many years has shown that FDM can make a continuing improvement in the standard of everyday aeroplane operations.

The overall aim of this study is to demonstrate the capability of a low-cost Flight Data Monitoring (FDM) system for single engine light aeroplanes. The predetermined budget of less than 5.000€ per installed system and 2€ per flight hour direct operating costs for post flight data analysis services shall not be exceeded.

Five possible application scenarios to use on-board data for safety improvement and assumptions about the possible safety benefit were described. As FDM system consist not only of technical parts the assessment of the safety benefit will examine if the technical solution is restricting possible applications.

To investigate the technical feasibility it must be known which states of the aeroplane must be observed. Several criteria for the design were discussed in detail, ranked and conflated. For every possible state a technical solution and its costs were estimated. Flight trials were used to investigate some low cost sensors in comparison to high accurate reference system. Based on these results three prototype designs were derived for three different technical conditions of light aeroplane.

To keep the cost limit of 5.000€ it is necessary to restrict the application for maintenance if the aeroplane does not provide digital data sources. For more modern aeroplane it is feasible to serve all defined application scenario with a system within the financial limit.

Flight Data monitoring (FDM) most suitable as part of Safety Management Systems (SMS) can improve safety of light aeroplane aviation. The demands on non-commercial light aeroplane must be considered carefully. In all cases potentially misuse must be precluded because FDM is no “policing” system. User acceptance must be understood as essential necessity for a purposeful FDM.

3 Background

The flight operation of light aeroplane is very heterogeneous: They are used for sports and leisure purposes as well as for several commercial applications. It is necessary to increase the safety permanently to keep the acceptance of aviation in the population and to assure the economic potential. Any road traffic fatality causes an economical damage of 1.2Mio€, in aviation it will be nearly the same. The overall goal of all efforts of increasing flight safety is the decrease of the number of incidents and accidents, injuries and deaths.

The safety of an aeroplane depends on how it is operated within prescribed limitations. Operational flight recording on large civil aeroplanes has been developed over the last couple of decades and enables a routine access to flight data. This access to flight data has been used to support incident analysis, accident prevention, flight efficiency, maintenance and training. The systematic, pro-active and non-punitive use of digital flight data from routine operations to improve aviation safety is called “Flight Data Monitoring (FDM)”, see e.g. [29].

Flight Data Monitoring (FDM) is mandatory for large aeroplane operations in Europe (OPS-1) since 2005. Experience gained over many years has shown that FDM can make a continuing improvement in the standard of everyday aeroplane operations. Safety Management Systems (SMS) are considered a best practice standard and are becoming mandatory globally. FDM can complement an effective implementation of SMS.

Once reserved for large aeroplanes, now sophisticated avionic systems are becoming common place in single engine light aeroplanes. Today technology has advanced to a point where it has become possible to transfer and process large quantities of data at high speed and low-cost. An inexpensive Personal Computer (PC) can communicate and process data and present advice or diagnose problems. Contemporary advances in electronic technology should make it possible to provide the functionality of FDM systems in an integrated on-board system at a fraction of weight and cost of conventional systems fitted to Part 25 large aeroplanes.

Most General Aviation single-engine light aeroplanes have no systems that make data digitally available for a monitoring system. Thus a light aeroplane FDM system must be capable of reliably distilling useful information from limited data. That's why the selection of recordable states is the most crucial part. As the users are very cost sensitive, the costs of a light aeroplane FDM system must be in a justifiable ratio to the safety benefit. Therefore it shall be analysed whether the knowledge of certain, easy to record states, could help to avoid an accident or incident in the future and to improve pilot training and maintenance.

In all types of operation careful safeguards need to be established to ensure that data collected by FDM systems is used for the purpose of improving safety.

For practical reasons it would be necessary to show that a system for single engine light aeroplanes could be realised at low-cost. Typically such systems need to be available at less than 5.000€ per installed system. Also, estimated FDM data analysis services should not exceed 2€ per flight hour direct operating costs. These cost numbers are initial values and must be set into relation to the possible safety and financial benefit.

This study shall consider experiences made with FDM on large aeroplane operations. Especially the minimum operation performance specification (MOPS) for large aeroplane flight data recorder (ED-112) and the preliminary results of EUROCAE WG-77 (General Aviation Flight Data Recorders) that is developing a FDM performance standard, shall be used.

In the ONBASS study [4] concepts for active onboard systems were developed. The contrary option is a passive on-board system. The safety gain of a passive system is given due to post flight analysis and assessment.
ONBASS is a Specific Targeted Research Project (STREP), partly funded by the European Commission under the Aeronautic and Space thematic priority of the 6th Framework Programme.

4 Aims and Objectives

The overall aim of this study is to demonstrate the capability of a low-cost Flight Data Monitoring (FDM) system for single engine light aeroplanes to improve aviation safety. The predetermined budget of less than 5.000€ per installed system and 2€ per flight hour direct operating costs for post flight data analysis services shall not be exceeded. In accordance with the Tender Specifications several targeted applications of the aspired system are to be regarded.

In the following the terms “states of an aeroplane”, “states to observe” and “states to record” will be used. The ”states to observe” are naturally a subset of the possible states, accordant the “states to record” are a subset of the “states to observe”. See glossary for a detailed explanation.

4.1 Original Aims and Objectives

The original aims are represented in a serial approach to the topic. Within five work packages the following subordinate aims shall be pursued:

In work package 1 (WP.1) the states to be observed by the FDM shall be denominated. The basic assumption of our proposal was that these states can be logically derived from impartial, statistical analysable criteria. Assumed statistical analysable criteria are: analysis of accident/incident scenarios, parameterised regulations and interviews of experts and users. The frequency of entry of any state is the primary ranking criterion. Accordant the needed accuracy (data rate, time synchronisation and value exactness) can be named. The list of states and their needed accuracy can be used to identify the required extent of sensors.
The proposed investigation of real time warnings was not further pursued, because the focus of this study is on passive systems.

Based on a definite list of states to observe, the second work package (WP.2) will work out possible sensor configurations.

It is perceptible that several of the states at an aeroplane can not be measured easily by using a sensor. Instead of a direct measurement the system state observer techniques can be used to determine the needed information. This can be a simple calculation in some cases, but for the estimation of some states a complex *Kalman* filter is needed. For saving costs some states might be observed by using system state observer techniques instead of using a dedicated sensor. With an optimised sensor configuration the sensor hardware that fits the minimum requirements, can be chosen.

In work package three (WP.3) the flight trials were performed by using the sensor hardware determined in WP.2 and a high precision reference system. The use of a fully equipped aeroplane with high precision sensors, allowed extensive comparisons and additional a numerical top-down approach. As a compromise – due to the limited budget of this study – the data acquisition hardware was not a minimised system in view of costs, weight, space and power consumption.

The work package WP.4 merged the cognitions from WP.3 and other criterions to a prototype design under strict observance of the costs.

In the final work package WP. 5 the safety benefit, based on the ranking criteria of states, shall be assessed. In reflexion to the assumptions and the trials a refined answer to the problem definition shall be given by naming the potential safety benefit in relation to the effort. The technical feasibility can be derived from this contemplation presumably as a matter of costs.

4.2 Widening of Objectives

While executing WP.1 several non-technical and statistically difficult ascertainable aspects have exposed as not negligible. The heuristic based criterions gave no hard facts to exclude or include states.

Furthermore an application of a FDM system for accident investigation matters may cause some conflicting needs to the utilisation for maintenance and training purposes. The chosen serial approach – from statistical analysis via a technical solution to the assessment of the safety benefit – disregards the needs and potential of safety benefit assessment.

The purpose of the Flight Data Monitoring (FDM) is not clearly defined for light aeroplane. In several publications the potential benefit is stated, but without a founded implementation. In particular in the USA several commercial providers are using the term *GA-FDM* for products that may partial fulfil the aims of this study. That's why this study has to be widened at first, to possible purposes and applications of FDM for light aeroplane. The practical usage will be described as base for an assessment of the safety benefit and for the selection of states to be observed.

The purpose of mostly non-commercial flying and maintenance of light aeroplane must be considered. Possible adverse effects of FDM shall be considered as well.

4.3 Summary of Aims and Objectives

The justification for certain sets of states should initially be worked out with statistical analysable (heuristically) criterions derived from its application area to get impartiality. These criterions must be amended by discussing the purpose of FDM for light aeroplane and by non-impartial aspects.

The sets of states needed to comply with the purposes of FDM for light aeroplane will be discussed regarding its realisation and its costs.

The safety benefit will be assessed regarding the described purpose and applications of FDM for light aeroplane.

5 Literature and Market review

5.1 Literature review: Flight Data Recording in Commercial Aviation

The history of FDR started in 1958 when the first systems had to be installed onboard “de Havilland Comet” aeroplane after several in-flight break ups. The recording of a few selected states took place on a steel tape; the values were engraved in the tape.

The next step was the recording on a magnetic tape (FIFO); the main, hard to fulfil requirements were fire resistance and mechanical problems. Today only solid state FDR are in use with modern aeroplane; there are no movable parts anymore so there is a great resistance against vibrations or shocks. These recorders use either large capacity computer memory chips or semi-conductor memories to store the data.

The FDR must withstand accelerations up to 3.400 g and temperatures up to 1.100°C; it must be protected against salt-water for 30 days at a water depth of 6100 m. They can store the states of at least 25 hours of flight time by using the FIFO-principle. All data will be recorded in digital format (mainly ARINC 429, 573, 717).

JAR-OPS 1.715 [14] requires the usage of a FDR for multi-engine turbine aeroplane with 10 seats or more during commercial operation.

„(a) An operator shall not operate any aeroplane first issued with an individual Certificate of Airworthiness on or after 1 April 1998 which:

(1) Is multi-engine turbine powered and has a maximum approved passenger seating configuration of more than 9; or

(2) Has a maximum certificated take-off mass over 5 700 kg, unless it is equipped with a flight data recorder that uses a digital method of recording and storing data and a method of readily retrieving that data from the storage medium is available.“

How many and which states must be recorded depends on the aeroplane size; for the A380 1024 states will be stored.

The flight data recorder will be supported by the cockpit voice recorder (CVR); there are the same requirements for crash protection, but the maximum recording time was only 30 minutes up to the year 1995, thereafter 2 hours.

There are some aircraft where saving weight is a priority (e.g. helicopters). For this reason helicopters are permitted to carry a single CVFDR (combined Voice and Flight Data Recorder) instead of the usual two units.

One possible future advance in flight recorder technology, is a recorder that records visual data from the cockpit (storage of video signal on solid-state memory).

Both the flight data recorder and the cockpit voice recorder have proven to be valuable tools in the accident investigation process (e.g. the reason for the crash of an Airbus due to oscillating ruder inputs, after a wake-vortex-encounter and the following break-up of the vertical stabilizer, could only be found with the help of the FDR). They can provide information that may be difficult or even impossible to obtain by other means. When used in conjunction with other information gained in the investigation the recorders are playing an ever increasing role in determining the probable cause of an aeroplane accident.

5.2 Literature review: Flight Data Monitoring in Commercial Aviation

The following quoted subsections of Amendment 26 to ICAO Annex 6 – Operation of Aircraft – are the legal basis for today's Flight Data Monitoring in Commercial Aviation:

- 3.6.3: From 1 January 2005, an operator of an aeroplane of maximum certificated take-off weight in excess of 27,000kg shall establish and maintain a flight data analysis programme as part of its accident prevention and flight safety programme.
- 3.6.4: A flight data analysis programme shall be non-punitive and contain adequate safeguards to protect the source(s) of the data.

The common used definition of Flight Data Monitoring is:
"*Flight Data Monitoring (FDM) is the systematic, pro-active and non-punitive use of digital flight data from routine operations to improve aviation safety.*", see e.g. [29].

The objectives of FDM are described in several publications and shall not be quoted in detail. A brief and accurate overview is taken from [29]:

"A FDM system allows an operator to compare their Standard Operating Procedures (SOPs) with those actually achieved in everyday line flights. A feedback loop, preferably part of a Safety Management System (SMS), will allow timely corrective action to be taken where safety may be compromised by significant deviation from SOPs. The FDM system should be constructed so as to:

1. Identify areas of operational risk and quantify current safety margins.

2. Identify and quantify changing operational risks by highlighting when non-standard, unusual or unsafe circumstances occur.

3. To use the FDM information on the frequency of occurrence, combined with an estimation of the level of severity, to assess the risks and to determine which may become unacceptable if the discovered trend continues.

4. To put in place appropriate risk mitigation techniques to provide remedial action once an unacceptable risk, either actually present or predicted by trending, has been identified.

5. Confirm the effectiveness of any remedial action by continued monitoring."

The given requirements are formulated in a way that allows establishing well fitted solutions for any operator, following the principle: "One size doesn't fit all".

Flight Data Monitoring (FDM) is also referred to as Flight Operations Monitoring (FOM) or Flight Operations Quality Assurance (FOQA).

Especially commercial providers of FDM services highlight a potential cost decrease, e.g. because of maintenance on demand, as a by-product.

The nature of a FDM is characterised by the operational part (A/C), a ground based analysis and assessment part and a reacting feedback part to A/C operation.

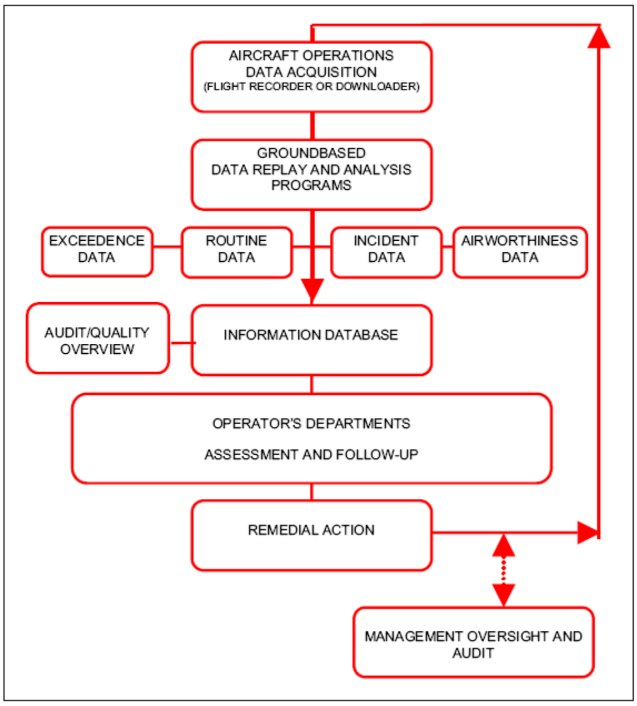


Figure 1: FDM information flow acc. [29]

FDM integrated within the Safety Management System (SMS)

"An FDM programme held remote from all other safety systems of an Operation will produce lower benefits when compared with one that is linked with other safety monitoring systems. This other information gives context to the FDR data which will, in return, provide quantitative information to support investigations that otherwise would be based on less reliable subjective reports. Air safety reporting, avionic and systems maintenance, engine monitoring, ATC and scheduling are just a few of the areas that could benefit." [29]

This recommendation will be implemented by any operator that has to establish a SMS according JAR-OPS1:

"Based on the ICAO Annex 6 Pt 1 recommended practice, JAR–OPS 1.037 states that "an operator shall establish an accident prevention and flight safety programme, which may be integrated with the Quality System, including programmes to achieve and maintain risk awareness by all persons involved in operations. ICAO Doc 9422 (Accident Prevention Manual) gives appropriate guidance material and describes a risk management process that forms the basis of an operator's SMS." [29]

The common used definition of Safety Management System is:
"*A safety management system (SMS) is an organized approach to managing safety, including the necessary organizational structures, accountabilities, policies and procedures.",* see e.g. [37].

Conclusions

- FDM is most effective as an integrated part of a Safety Management System, but is also beneficial without an embedment into a SMS
- FDM is mandatory for aeroplanes exceeding 27to MCTOW
- The basic principles of SMS and FDM can be adopted for typical light aeroplane operation (without considering costs)
- FDM is proposed to decrease operational costs

5.3 Market review: Flight Data Recording systems for light aeroplane

There is a bunch of small systems for data recording in light aeroplane – but up to now there is no complete system which may be used in every certified aeroplane.

There are some recording systems which are capable to sample single data e.g. recording g-meter (like the TL-3424 [49]) or the Flydat for Rotax-engines where some engine states are stored.

An example for an engine monitoring system is the "JPI EDM 700" [43]. The Engine Data Management 700 system is an advanced and accurate piston engine-monitoring instrument. Using the latest microprocessor technology, the EDM will monitor up to twenty-four critical states in your engine, four times a second; it records and stores data up to 30 flight hours. Post flight data retrieval is accomplished with the help of special data retrieval software to a Palm computer. Beside the data storage this system is FAA approved as a primary source for the basic engine states. The price is approx. 3.000 US-$ without installation.

From Capacq/USA comes the GA-FDM [41] for Cirrus aeroplane; this system provides Cirrus pilots with a “plug and play” flight data monitoring, recording and analysis system. Capacq states the following advantages for the use of their FDM:

- risk and resource management for airframes
- early identification of adverse safety trends
- adherence to aeroplane operating manual limitations
- flight reconstruction and visualization for accident/incident investigations
- enhanced maintenance records with g-loading, flap over speed, redline warnings
- fuel management reports
- possibility of increasing TBO (time between overhaul) intervals

There is even the possibility that status reports are e-mailed automatically to the maintenance facility. Based on 40 flight hours/month there are total costs of about 9 US-$ per hour; this includes the installation and leasing of the system and monthly QA reports (operations, exceedances, maintenance)

Another example is Lange Aviation who uses an online UMTS-link to check the condition of the engine and the batteries of their Antares electrical powered gliders.

A data monitoring system which is already used in (non-certified) ultralight aeroplane is produced by the German company KAPI [40]; the price (without installation) is approx. 2.000 €, but it may not be used in certified aeroplane.

While all of these systems may work properly the demands for a complete data recording and monitoring system in certified aeroplane are much higher. This can be seen by comparison to a certified system for bigger aeroplane. An FDR for large transportation aeroplane has a target price of approx. 25.000$ (plus installation), but because all data are already usually available on board of these aeroplane (in almost all aeroplane as digital data in ARINC format) no additional sensors are required. If additional sensors are required the price will increase dramatically.

The situation for light aeroplane is quite different because there are only very seldom instruments with electrical output which can be used for data recording. For the time being the price for a FDR system that fits GA aeroplane will be composed of the two main topics: sensor package plus data recording.

5.4 Literature review on topic “safety benefit”

The ONBASS study report D1.1 ([5], Appendix1) represents a detailed essay about „analysis of safety systems“ in several transportation and industrial domains. We agree with this approach to analyse this topic widespread. We tried to find generalised methodical approaches to quantify the safety benefit ourselves.

The analysed sources are listed in Ch. 11.3.9. The fundamental difference between considered industrial domains and the light aeroplane operation is, that the listed safety improvement methods mostly try to exclude humans from the safety relevant positions, while *human-in-the-loop* is an essential part of the nature of operating light aeroplane. Especially the common measure of so-called „safety locks“ – automated interferences into the controls of the system – must be discussed critically in view of non-commercial flying.
The analysed literature about safety assessment in the automotive domain is using case-related but no generalized approaches. The application of this method would extend this study.

<u>Conclusion</u>
No helpful literary sources could be found. Many specific investigations and analysis can be found but no generalised methods for safety benefit appraisal.

5.5 Interviews on topic safety benefit in automotive domain

The ONBASS study report D1.1 ([5], Ch13.2) states “many similarities” between the automotive domain and light aeroplane. We agree at the point that light aeroplane and cars are comparable pertaining to the ownership structure and operational constrains. The commercial use of light aeroplane is comparable to taxi companies use of cars.

This comparison reaches fast its borders: The technological difference between today’s automobiles and light aeroplane to be considered is huge. The periods of time for renewal of the light aeroplane fleet are much longer than in the automotive domain, see Ch. 7.3.3.3. To improve safety within several years not only improvements to new aeroplane are necessary but measures for existing aeroplane too.

However this approach was used to get information about the managing of safety systems technology adoption in the automotive domain, especially the appraisal of the resulting safety benefit. The quotations are from persons involved in research and development, in the surroundings of an important automotive manufacturer. They are not individual-related quotable but give a pragmatic impression:

„ ... gut instinct management decisions ... “
„ ... pushed by selling ... “
„ ... 90% for *Auto, Motor und Sport*[1]... “ (=marketing impact)

What can be learned from the automotive domain is the principle to adopt new technologies from luxury class to compact class. Furthermore onboard data storing systems for accident investigation were a topic years ago. The failure of this initiative, mostly due to acceptance problems and regress problems, must be mentioned.

[1] *Auto, Motor und Sport* – Influential German automotive journal

6 Methodology and Implementation

The self-conception of our work is not to repeat the work of other groups but to set own accents and focuses on the topic from our point of view. The results of other groups and studies shall be embedded, as well as all the lessons that were learned in the past. Technical solutions shall be investigated in principle.

6.1 Not successful approaches

Two different approaches were considered but both did not lead to the expected results. The cognitions of these approaches were used to develop an advanced approach, see 6.2. That's why they are represented at first.

6.1.1 Direct approach

A FDM system is a technical system that is based on recording aeroplane state data. All possible states of an aeroplane are included in the state vector that is discussed in Chapter 7.4.2. The feasibility of the system strongly depends on the number of states that have to be known (observed), and consequently the *states that have to be recorded* (costs of sensors).

The direct approach (or statistical/technical/heuristic) is based on the assumption, that the *states to observe* can be logically derived from impartial statistical analysable criterions. Assumed statistical analysable criterions are analysis of accident/incident scenarios, parameterised regulations and interviews of experts and users. Five different sources were chosen:

i)	Accident Data	Analysis of ECCAIRS data
ii)	Certification Specifications (CS)	CS-23, CS-VLA
iii)	Aeroplane Flight Manuals (AFM)	Subset of ii), F-172, A-210
iv)	Training	Training guidelines
v)	Maintenance	Survey at maintenance company

Table 1: Sources for state ranking

For any entry in one of the mentioned sources - any accident in the accident data base, any subsection in the CS or any information in the AFM - can be translated into states. Or in other words: What states are needed to describe any entry in the source?

The result is a relative frequency of any state in the theoretical state vector. It was assumed ahead of the study that the importance of any state can be derived from its relative frequency (a kind of ranking). The set of states should have been a selection of the best ranked until the budget would have been bailed. If the finally selected set of states would match the state translation of an entry in the sources, this entry could be discarded as evidence for safety benefit.

The content statement of the sources is not considered in this approach.

6.1.1.1 Results of direct approach

Complete state lists were compiled for iii) and v), partially for ii). During this work the disbelief in the assumption of giving equal weight to each entry arose. The content statement of the sources is lost in this approach.

The provided accident data base was not feasible for this purpose as stated in Chapter 7.3.1.2. The assortments of suitable training guidelines lead to the question if not adapted training guidelines are meaningful for the design of a FDM system. Or must the training concept follow the technical options?

Furthermore this approach ignores:

- Unspecific and non parameterised needs
- Personnel experience enclosed in quotes
- Appraisal of safety benefit doubtful (mechanism of safety benefit)

The direct approach fails due to ambiguous criterions and the need to expand the scope of considerations.

6.1.2 Reverse approach

The idea of the reverse approach was to look at the topic from the point of safety benefit assessment. As this task was originally scheduled at the end of the study, but is now the initial point, it is named “reverse” approach. It’s based upon the argument that the justification of a FDM is finally the verification of a safety benefit.

To pursue this approach a generalised methodical theory to quantify the safety benefit is essential. As stated in Chapter 5.4 and 5.5 no such theory could be found in literary sources. As the found safety benefit valuations are typically case-related the development of a comprehensive set of case scenarios would mismatch the extent of this study. The safety benefit will have to be assessed more generally.

6.2 Multi criteria approach (abstract)

The multi criteria approach is used because the direct and the reverse approach (see. Ch. 6.1.1 and Ch. 6.1.2) did not succeed. The partial results compiled there will be included completely in this approach. The name of this approach is derived from the finding that all relevant criteria of any nature must be gathered in the beginning. These criteria are to be brought into a justified connection.

The following steps were carried out:

(1) Description of possible applications of FDM for light aeroplane
(2) Formulation of criteria for assessment of the safety benefit regarding (1)
(3) Collection and detailed description of all relevant criteria for the design of a FDM system
(4) Rating of the accumulated criteria in regard to significance
(5) Concept for combination of the criteria
(6) Listing of principle technical solutions
(7) Derivation of appropriate solutions for any application regarding (1)
(8) Derivation of a system with maximised conformance to (1)
(9) Derivation of a system for flight trials
(10) Execution and assessment of flight trials
(11) Assessment of the overall concept (technical feasibility)
(12) Conclusions on safety benefit

This approach is taking the full range of the development of a technical system from the general conception to realisation into account. The problems with later entry points into this topic are defused. This approach is open to criteria and aspects of all kind.

6.3 Multi criteria approach (detailed description)

The multi criteria approach is used because the two ahead applied approaches failed. While the direct approach (see 6.1.1) was based on the assumption, that the topic can be handled with heuristic means, failed due to ambiguous criterions or rather the need to expand the scope of considerations. The reverse approach (see 6.1.2) was not successful because of absence of a generalised methodical theory to quantify the safety benefit. The partial results compiled, while working on the two failed approaches, are basis for this advanced approach.

The name of this approach is derived from the finding that all relevant criteria of any nature must be gathered in the beginning. The criteria found are not equivalent. They must be discussed and brought into a justified connection.

The following work steps had to be carried out. The principle is to develop the solutions from the general to the detail. As this is not the first approach within this study these steps were carried out not exactly in this order.

(1) <u>Description of possible applications of FDM for light aeroplane</u>
Without knowing the application goals the design of a tailored system is hardly possible. In addition it must be clarified whether more than one application scenario can be fulfilled meaningful at the same time.
See Ch. 7.1.

(2) <u>Formulation of criteria for assessment of safety benefit regarding (1)</u>
With the designated applications of FDM it can be derived which measures shall increase safety of light aeroplane operation. Appropriate criteria can be formulated, with which reaching this goal can be checked.
See Ch. 7.2.

(3) Collection and detailed description of all relevant criteria for the design of a FDM system

Apart from first obvious technical criteria a multiplicity of lines of argumentation results. The necessity of each criterion has to be stated and arranged separately in detail in the next work procedure. Thus a basis for the further treatment of the criteria collection results. The criteria can be requirements/regulations, accident data, financial specifications, individual and common experiences, etc.

See Ch. 7.3.

(4) Rating of the accumulated criteria in regard to significance

In (3) found criteria are not under any circumstances equivalent as source of information. Thus there are criteria to evaluate as exclusion criteria (e.g. user acceptance), while other criteria may not pay any contribution to decisions after detailed discussion.

This criterion collection is to be arranged according to the force of expression which can be classified. Some criteria are only useful for the compilation of the aeroplane state vector.

See Ch. 7.4.1

(5) Concept for combination of the criteria

The evaluated criteria are to be brought together to an evaluation tool for FDM system solutions. For this it needs a suitable model, in order to meet the different kinds of criteria. In this step the state vector is also provided as by-product.

See Ch. 7.4.2 and 7.4.3.

(6) Listing of principle technical solutions

To each entry or to each group of entries in the state vector, possible solutions are to be presented with advantages and disadvantages concerning the application scenarios.

See Ch. 7.5.

(7) Derivation of appropriate solutions for any application regarding (1)

With the help of the single solutions a technical system for each application scenario stated in (1) has to be compiled considering the application goals.

See Ch. 7.6.1 to 7.6.6.

(8) Derivation of a system with maximised conformance to (1)

An overall system shall be designed with the help of a single solution for applications targeted in (1) to achieve a maximum of the depicted safety benefit.

See Ch. 7.6.7.

(9) Derivation of a system for flight trials

The investigations in (7) and (8) release a configuration, which is examined in the flight trial.

See Ch. 7.7.1.

(10) Execution and assessment of flight trials

In the flight trials the quality of the low-cost solution will be demonstrated and thus their suitability will be examined with the help of the high precision reference system.

See Ch. 7.7.2 and 7.7.3.

(11) Assessment of the overall concept (technical feasibility)

With the results from (10) it can be assessed whether the stated FDM applications specified in (1) can be served within the given cost frame.

See Ch. 8.

(12) Conclusions on safety benefit

Due to the estimation of the technical feasibility, with the given cost frame, the potential safety gain can be determined.

See Ch. 8.

7 Outputs and Results

Within this study all civil single-engine aeroplane ([1], Ch. 2.1) below 2250kg (acc.[13], Id319 – mass group) will be considered, without constrictions of age or numbers produced of accordant type. The certification specifications CS-23 [15] and CS-VLA [16] are to apply.

The increasing commercial utilisation of aeroplane of this scope shall not be considered explicitly. In [2] the term *Business Travel Aviation* is used to include this fact. The use of the later suggested system for commercial used aeroplane is well possible but depends on future regulations.

7.1 Application scenarios of FDM for light aeroplane

Since 2005 the legislation according to JAR-OPS1.037(a)(4), see [14], requires the implementation of the *Flight Data Monitoring* (FDM) for commercially operated aeroplanes with a maximum certified take-off weight of 27'000 kg and more. For smaller aeroplane it is not mandatory.

Several commercial providers offer FDM services for light aeroplane, e.g. [41]. This proves that the whole cycle of in-flight data recording, post flight analysis and reacting can be established for light aeroplane. Even the regulatory approval of an application is demonstrated (Engine trend monitoring system – ETMS, see [41]).

As FDM is embedded beneficially in a SMS, the following state is valid for FDM too:
“All management systems must define policies, procedures, and organizational structures to accomplish their goals.” [33].

The feasibility of the FDM principle is demonstrated for light aeroplane. While the potential *cost benefit* of FDM will be used due to market economy principles, the *safety benefit* is not in that fortunate position. The costs due to the safety benefit must be in an acceptable ratio to the costs of a light aeroplane. The more different kinds of analysis are done the better that ratio, because one hardware investment is used more often. The *kinds of analysis* are named *application scenarios* in the following.

The detailed development of a complete FDM system for small aeroplane is neither part of this study nor would be possible in the extent of this study. However no optimised system can be designed, for which the application purpose is not known. For the assessment of the safety benefit the knowledge of application scenarios is essential.

Following five possible applications for a FDM system for light aeroplane are described. The required data can be classified in *time domain data* and *statistical data*, the relative frequency of use and the relevancy of the direct operating costs (DOC) are ranked.

7.1.1 Quality improvement of flight operation and training

This application corresponds directly to the FDM idea:
All in-flight data is analysed and assessed – automated or manually – by a third party. Findings and results are sent to the pilot and the operator and handled according the established operator’s FDM regulations. This direct flight data evaluation is detecting deficiencies of pilot’s performance.
It is based on the knowledge of standard operation procedures (SOP). The light aeroplane fleet is very heterogeneous compared to large aeroplane and it will be extensive to define SOP’s for all types.

The FDM system can be used for the development of SOP’s too. Although this exceeds the limits of FDM to a SMS it is mentioned here, because FDM will probably be embedded in a SMS in light aeroplane operation as well as it is in large aeroplane operation today. Generally spoken the in-flight data will be analysed to identify potential ineffective or hazardous procedures in training or other operation.

The potential gain of safety benefit is comparable to the direct flight data evaluation mentioned in Ch. 7.1.3. The following picture demonstrates how a pilot assessment and a SOP assessment can work together within a SMS.

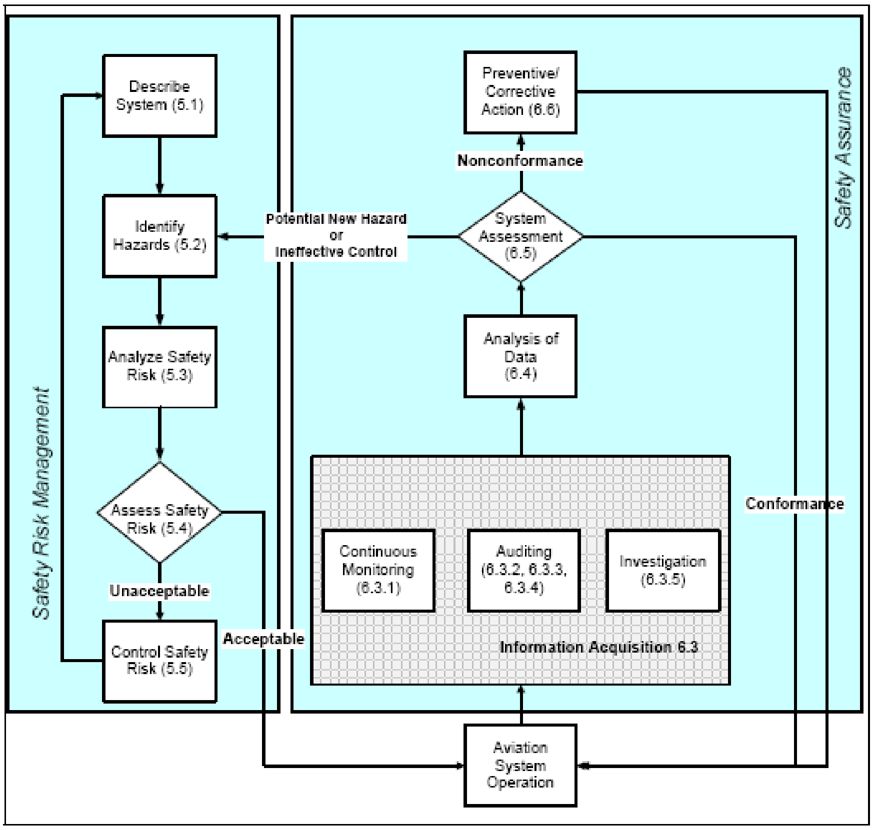


Figure 2: Risk management and safety assurance processes, see [33]

Relative frequency of use: High / selective

Data type: Time domain data and statistical data

DOC relevancy: High

7.1.2 Maintenance

The attention of maintenance personnel is focused on technical conditions of the aeroplane engine, the airframe and other aeroplane systems. The knowledge of the prehistory of components since the last regular maintenance can help to identify urgent technical problems. The FAA approved *engine trend monitoring system* (ETMS, [41]) is an example for an established system.

Detecting any defects which has the potential to lead to an accident or incident and which can be early identified (prior to the next scheduled maintenance) and be repaired in an unscheduled maintenance action would remove the risk of an accident or incident and as such consequently contribute to improve safety.

The usage of a FDM system for technical monitoring requires a simple to operate, robust, economic and fail-safe system. The fail-safe requirement is based on the fact that any alerting or warning due to a sensor failure will result in general loss of confidence of the system and/or lead to unbeneficial costs.

Relative frequency of use: High

Data type: Statistical data

DOC relevancy: High

7.1.3 Direct application in training and other operation

The direct application describes the primary use of recorded data for self-study. Automated limit exceedance checks or automated checks for derivation from standard operation procedures (SOP) may be included. The pilot is responsible for the usage of the data. No warnings or messages are generated to third parties. This usage can be done at any PC with appropriate software.

The pilot can reflect its actions and the use of this method can be a part of the whole training process. This self-awareness concept is highly safety beneficial. The voluntariness increases the user acceptance in non-commercial flying, but of course is a disadvantage as not all pilots will participate.

The usage of a FDM system for training and other operation requires a simple to operate, robust and economic system. The data preparation and presentation must be manageable under the very different conditions of light aeroplane training organisations and light aeroplane operators. It must be mentioned that an advantageous application in training needs didactical concepts and trained flight instructors.

Relative frequency of use: Medium

Data type: Time domain data

DOC relevancy: High

7.1.4 Accident/Incident investigation

The accident/incident investigation of light aeroplane is not a FDM application in the above described meaning, because it is reactive and not proactive. But it’s a case related data analysis and interpretation and in this way similar to FDM. The regular provision of a basic set of aeroplane state data for accident/incident investigation will clearly improve the quality and the outcomes. Although the accident/incident investigation seems to be the preferential application for a flight data recorder, the sustainability compared to other possible applications must be discussed carefully.

The set of recorded states shall represent the direct accident investigation needs. The costs for data analysis are to be classified as less important, because other costs are dominating. Furthermore a FDM system is unsuitable for cost reduction in accident investigation, because the advantage of having data leads to the need to interpret this data properly.

Relative frequency of use:	Occasionally
Data type:	Time domain data
DOC relevancy:	Low

7.1.5 Administrative needs

In statement KOM(2007)869 [2] the Commission of the European Union ascertained that coherent data about *General Aviation* and *Business Travel Aviation* are not available (subsection 17) but are indispensable for purposeful legislative work (subsection 19). The object of this study can be used to handle these needs. The basic FDM principle of “non-policing” can be retained with an accurate data privacy concept.

Although this is not a real FDM application it may increase the overall benefit of the aspired system. It is comparable to fleet statistics offered by commercial light aeroplane FDM provider.

Relative frequency of use:	High
Data type:	Statistical data
DOC relevancy:	High

7.1.6 Summary of application scenarios

Application scenario		Relative frequency of use	Type of data needed	Relevancy of DOCs
A	Quality improvement of flight operation and training	High / selective	Time domain and statistical	High
B	Maintenance	High	Statistical	High
C	Direct application in training and other operation	Medium	Time domain	High
D	Accident/Incident investigation	Occasionally	Time domain	Low
E	Administrative needs	High	Statistical	High

Table 2: Comparison of application scenarios

While A, B and C are within FDM objectives, the applications D and E are using the same (on-board) infrastructure.

7.1.7 Findings of other groups

i) Mitchell et. al. [34] describes three areas of potential safety benefit for a light aeroplane FDM system:

1. Flight training
2. Maintenance scheduling
3. Accident investigation

ii) The company CAPACG is promoting it's FDM service using the following picture:

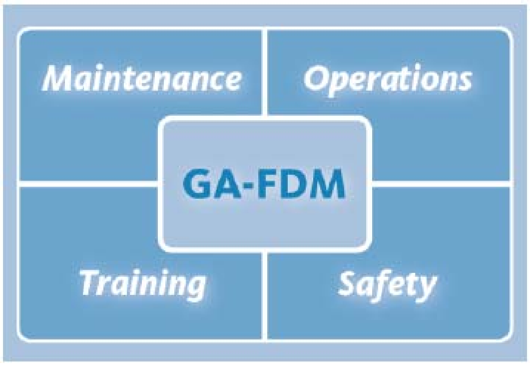


Figure 3: FDM content acc. [41]

iii) The EUROCAE WG-77 discusses to concentrate on a Flight Data Recorder for accident/incident investigations because of the difficulty to balance the requirements of all possible applications [9].

It can be concluded that the contemplated application scenarios are nearly the same in the quoted sources and in this study. Differences in details are less important for the assessment of the technical feasibility. The most critical question is the balance of the applications in the design of the system.

7.2 Safety benefit discussion

One objective of this study is the assessment of the safety benefit of a light aeroplane FDM system. Or more stringent formulated: The aspired technical system shall offer the best safety benefit for given costs. (The optimisation of the cost saving aspect of FDM is a predestined task for the market.) For this optimisation the assessment assumptions must be known.

An assessment according to the assumptions of the direct approach is not possible because the direct approach was not successful. At an earlier stage of this study a model for *safety benefit cycles* was used to demonstrate the role of the technical part within a FDM system:

- The *Flight Data Recording* device records selected states that characterise the pilot's actions, the most beneficial technical conditions of the aeroplane and the interaction of pilot and aeroplane.
- Within the *Analysis* the recorded data are pre-processed for the assessment, e.g. the angle of attack is calculated.
- The *Assessment* checks the occurrence of limit exceedances, deviations from defined procedures and the trend of engine data.
- Any safety related finding of the *Assessment* must have a *Feedback* on the pilot and/or the aeroplane. This can be an extra training for the pilot or an unscheduled maintenance of the aeroplane.

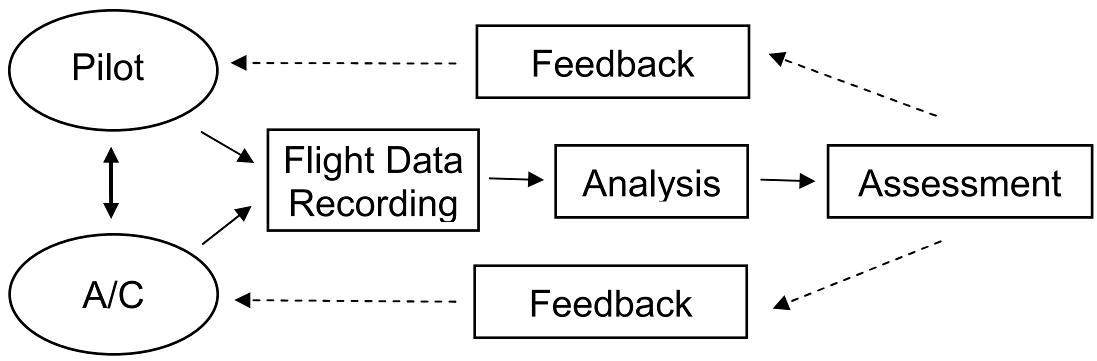


Figure 4: Safety benefit cycle, principle

It is obvious that a safety benefit is only possible, if this cycle is closed.

But this the core problem of an assessment of the safety benefit within this study: The focus of this study is on the technical feasibility and not the development of a whole FDM system. Without a detailed development of the feedback-part it will not be possible to assess a real safety benefit. Also the literature research did not provide generalised, but only case-related methods for the assessment of safety benefit. A detailed case-related safety benefit assessment is not possible within this study.

In order to obtain statements about the safety benefit, the following assumptions were made:

The safety benefit of a FDM that is embedded in a SMS is higher than the safety benefit of a stand-alone FDM system. A substantive quantification of that decrease is only possible by analysing detailed planned or established FDM systems. In the context of this study it is assumed that, the safety benefit of the technical part of the FDM is not decreased by non-technical factors (e.g. human errors in handling the FDM).

An ideal SMS would theoretically prevent all accidents and would decrease the number of incidents to a minimum. As commonly known no real existing system is perfect. The rate of deviation from the ideal state cannot be designated within this study. In the context of this study it is assumed that, the safety benefit of the technical part of the FDM is not decreased by non-technical factors (e.g. incomplete SMS procedures).

In the absence of a detailed assessment of the non-technical surrounding of the aspired system a *potential safety benefit* shall be appointed. This is the quantitatively seen safety benefit of a certain application scenario without a decreasing due to technical or non-technical factors.

Later it was assessed whether or not the suggested technical system will adequately fulfil the following assumptions or will decrease the safety benefit of an application scenario.

7.2.1 Assumptions for *potential safety benefit* assessment …

7.2.1.1 … of application scenario A – Quality improvement of flight operation and training

As accident rates for GA in Europe are rare a statistic for the development in the USA is taken:

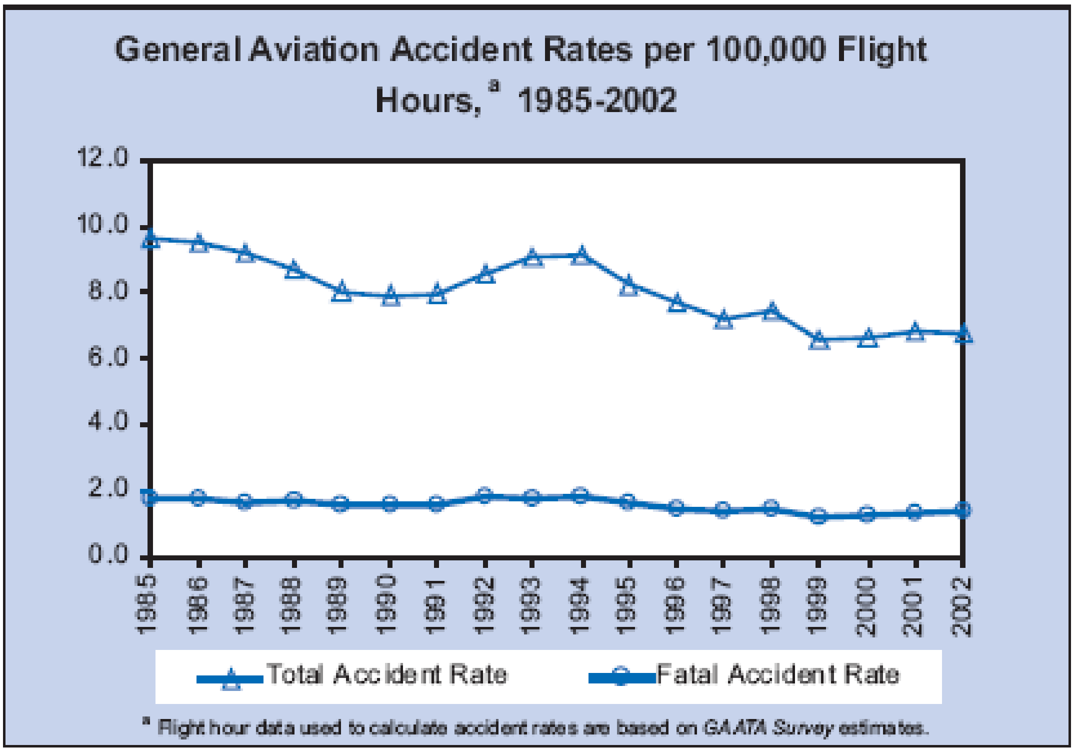


Figure 5: Annual accident rate in GA in the USA [23]

It can be seen that the gradient of the fatal accident rate is negative but small. While the accident rates in the General Aviation are nearly stagnating (see 7.2.1.4) the fatal accident rates in Commercial Aviation are decreasing, see Figure 6. We have no documents that prove that FDM and SMS endeavours are source of the positive progression.

The implementation of FDM for light aeroplane, expected to be embedded in a SMS, is not a singular measure, but raises the permanent adjustment from criteria and procedures to the principle. This offers an enduring safety benefit. It is assumed that FDM can improve light aeroplane operation safety lasting.

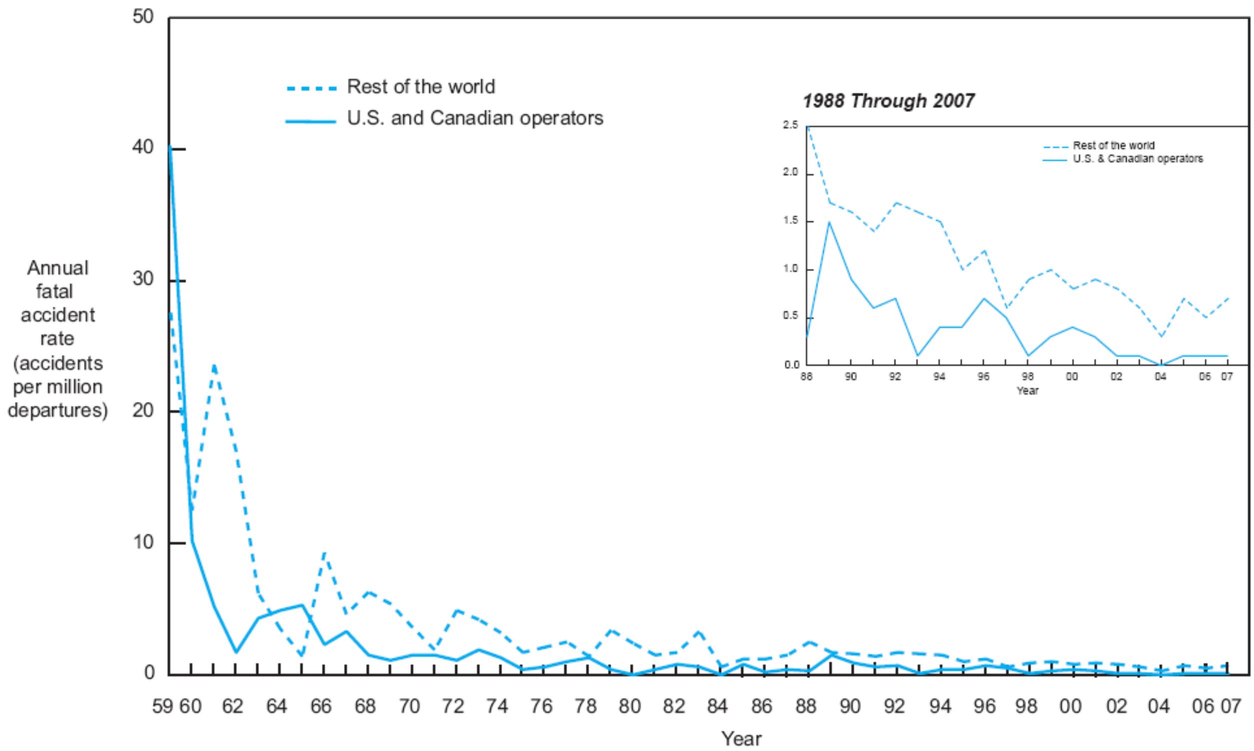


Figure 6: Annual fatal accident rate in Commercial Aviation [20]

7.2.1.2 … of application scenario B – Maintenance

An ideal efficient FDM system embedded in an ideal efficient SMS would prevent all accidents caused by technical reasons. Excepting the residual risk it depends on the efforts, which the community is willing to bring up, how many percent of the ideal aim can be reached. The measures needed to reach a certain (to be defined) *technical level-of-safety* are advantageous to constitute within a SMS. The SMS considerations will show whether it is e.g. more useful to regularly replace a certain component as a preventive measure or to monitor it.

The possible safety benefit of this application is characterised as potentially high, in preventing technical caused accidents/incidents. The over-all safety can be increased by the rate of technical caused accidents/incidents. A safety increase will appear within the first decade after implementation.

7.2.1.3 … of application scenario C – Direct application in training and flight operation

Didactical concepts are essential for applying FDM successfully in training. To account the whole potential of FDM in training, the training concepts are to be adapted. The safety benefit results from a sustainable training, that includes self-

awareness and the principles of a modern safety culture, as regular part of the training. All flight instructors must get trained in using FDM in training.
The safety increasing effect will display over decades, as the number of pilots trained in a FDM adapted training grows. The potential safety benefit is high.

The voluntary self-study usage of flight data, will affect only a certain part of all pilots. The possibility to analyse the own actions, will assist the self-awareness. The safety benefit impact will not be as high as using FDM in training, but it may be a beneficial part in the whole system and increase the user acceptance.

7.2.1.4 … of application scenario D – Accident/Incident investigation

"Whether or not the aircraft hits the ground, should ideally not change the philosophy to determine what, why and how to prevent an accident.", see [5](p.42)

This high ambition is not practicable for light aeroplane, because

- most incidents which do not end up in a subsequent accident are not easy to be determined without the presence of a Flight Data Recording device.
- the financial means are not available to examine all accidents/incidents of light aeroplane in an appropriate intensity. In practice the potential payback of any investigation must be estimated to focus the efforts. See e.g. [21].

Extensive investigations of light aeroplane accidents/incidents take place, if there are fatals or injuries or a public interest is given.

The accident/incident investigation naturally provides cognitions only on investigated accident/incident scenarios. Trends in aeroplane operation that may lead to accident/incidents in the future are hardly to detect.

Figure 7 show absolute numbers of light aeroplane accidents in Germany from 1998 -2007 and Figure 8 ~~the~~ a similar selection for France, Germany and the UK. A small downward trend can be seen, but these figures show only absolute numbers without a relation to time flown or departures (no rates). Compared with the decrease of number of fatals in automotive domain and technological changes, these gradients of absolute numbers are small. This stagnation of accident numbers obviously indicates saturation in knowledge and feedback methods

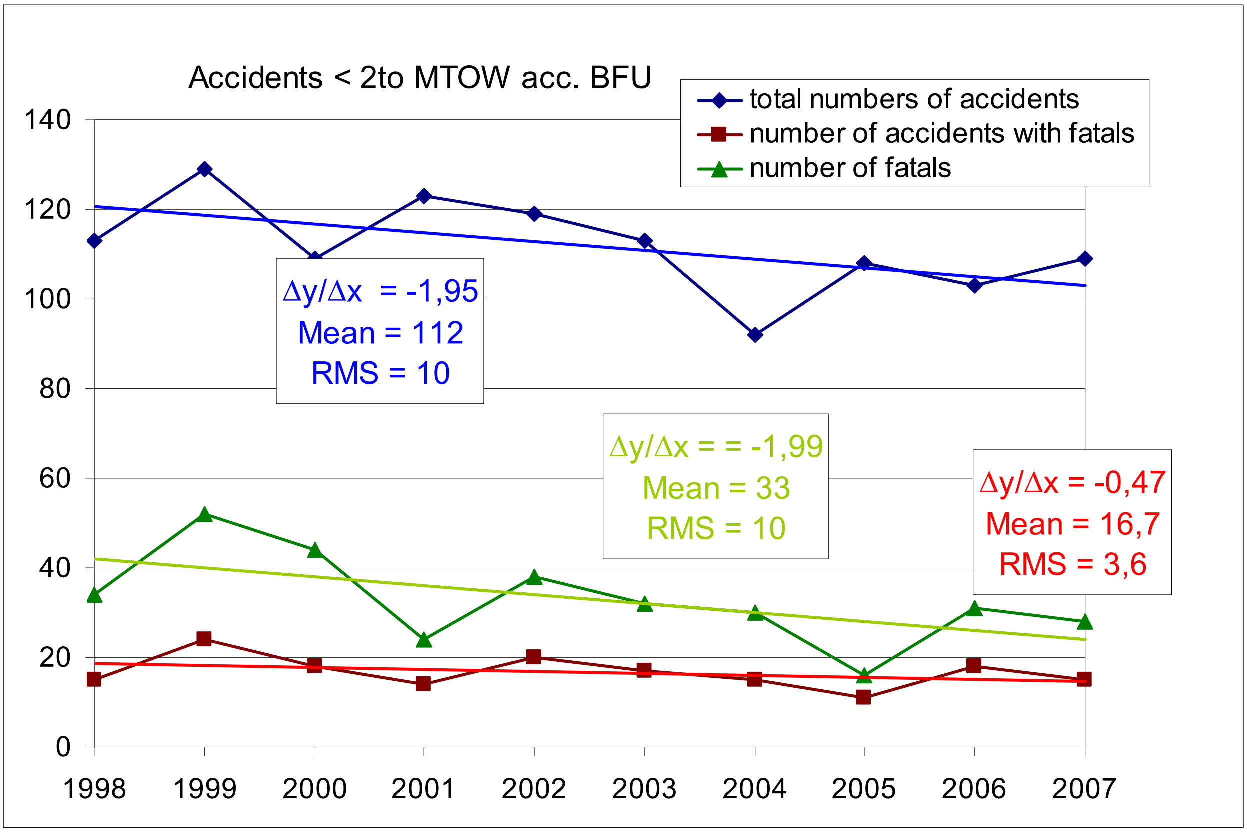


Figure 7: Light aeroplane accidents in Germany 1998-2007, see [17]

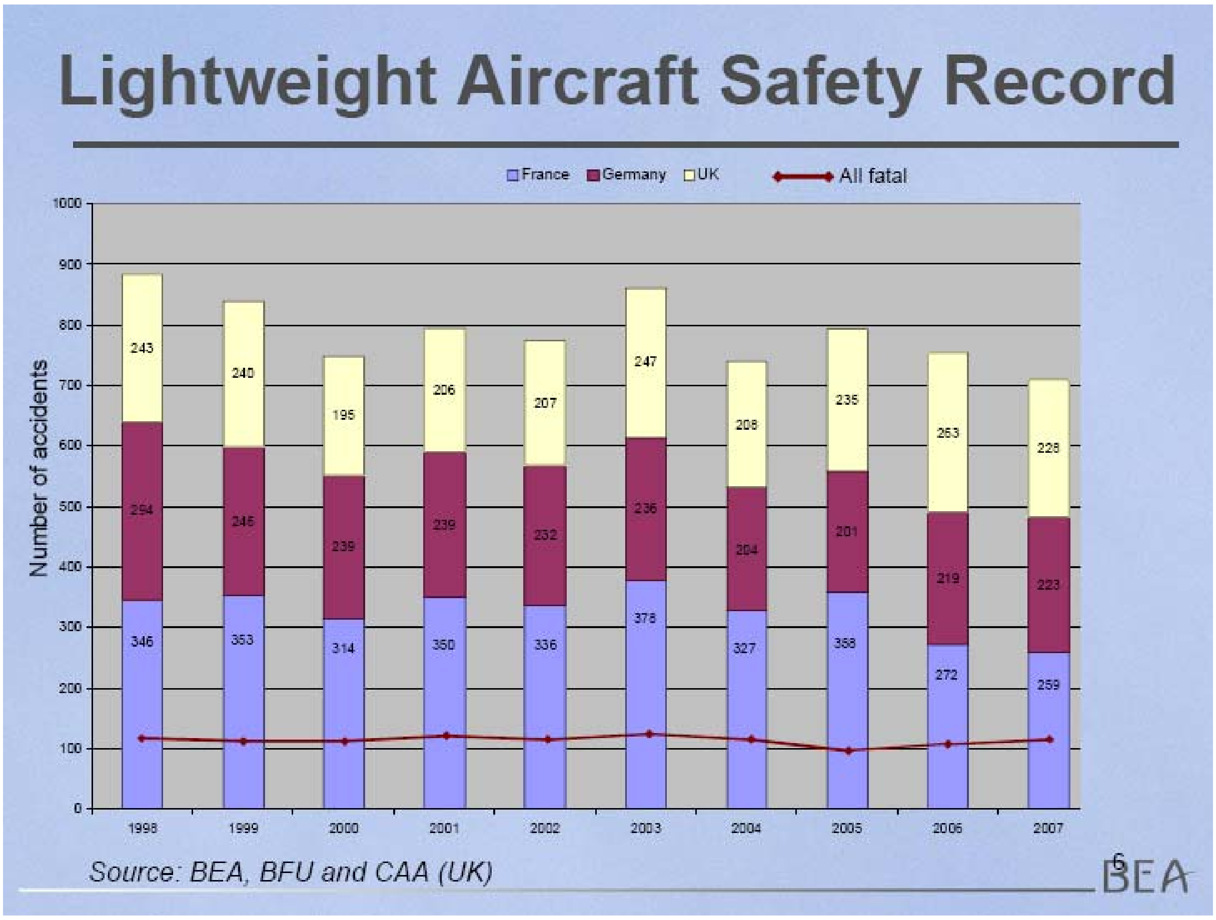


Figure 8: Lightweight aeroplane safety record, see [8]

The usage of the Flight Data Recording device (of the FDM system) for accident/incident investigation will not necessarily increase aviation safety. It will quicken the assessment of individual accidents and will lead to more accurate detailed information. The more accurate knowledge of sequence of accident events must not be mistaken as safety benefit.

The use of on-board data recording for conventional accident/incident investigation of light aeroplanes, will generate only a small safety benefit. If the potential of on-board data recording shall be used, the methods of investigating light aeroplane accidents/incidents must be broadened. Finally this is describing a kind of risk management (see Figure 2) from a re-active position. The full capability of the FDM infrastructure, in the context of accident/incident investigation, can be used if it's part of a SMS.

A safety increase can be expected within the first decade after implementation.

7.2.1.5 … of application scenario E – Administrative needs

The primary effect of a FDM system used for this application is characterised by a rising statistic concreteness of light aeroplane operation. These results would be helpful especially for all bodies dealing with aviation safety, because safety benefit impact assessment can be proven with a reliable statistic basis.

The possible safety benefit of this application is characterised by the potential sustainability, however it is not proven quantifiable within this study. Useful results will be available within the first decade after implementation.

The possible contents of the statistical investigations are expected to be a by-product of the aspired system. These might be cumulative flight times, number of departures, composition of purpose of air activity, regional commonness of certain air activity, etc..

7.2.2 Effects adverse to safety benefit

The user acceptance must be given in general. Each nugatory user’s attitude can reduce the safety benefit. For this the benefit for each pilot must be pointed out, costs must be kept within acceptable limits. The feeling of being observed by the FDM may cause uncertainness by the pilot, or reverse may give an unfounded feeling of safety. The felt complexity must not overstrain an user with average abilities.

7.2.3 Conclusions on safety benefit assumptions

This study deals with the technical concerns of a FDM system. For the assessment of the safety benefit of the technical system it is assumed that non-technical factors do not decrease the safety benefit. The safety benefit assessment of the designed system evaluates whether the system limits the possible safety benefit due to technical reasons.

Application scenario		Expected scale of safety benefit	Time horizon of effects (after adoption)
A	Quality improvement of flight operation and training	Potentially high	1 decade
B	Maintenance	High potential to minimize number of technical accidents/incidents	1 decade
C	Direct application in training and flight operation	Potentially high / Potentially medium	1..3 decades
D	Accident/Incident investigation	Low / Potentially high	1 decade
E	Administrative needs	Potential sustainability	1 decade

Table 3: Comparison of potential safety benefit

7.3 Discussion of design criteria and aspects

The basis of FDM is in-flight recording of aeroplane states. If this data is available onboard – with minimum accuracy, minimum range and minimum rate – then FDR is reduced to data storage in a robust data format (if required on a crash proof storage device). If these demanded states are not available, then additional sensors must be installed and their information output must be transmitted to the flight data recording device.

If the installation of a flight data recording device is required for a certain type of aeroplane (for purposes of accident investigation, FDM or both) this fact will be considered during the construction of this aeroplane. As the life time of light aeroplane and their comparably extensive operation does not force a permanent renewal as in civil large aeroplane operation, the retrofitting capability of a flight data recording device for light aeroplane must be given. Otherwise an increase of safety due to FDM would be not noticeable until some decades later.

The limited financial means do not permit to attain a data extent as in large aeroplane. Rather it must be clarified, considering several aspects and criteria, which set of the possible states offer the best safety benefit. This definitely difficult discussion and balancing, see chapter 6, was not described in any of the sorted sources. The topic of this study concerns a multi state optimisation problem in which the very different nature of the optimisation constrains complicate the solution.

In the following all conceivable criteria, in view of the specified application scenarios and considering the safety benefit assessment assumption, shall be discussed. A sufficient completeness is desired. Once the criteria and aspects are pointed out and discussed individually in chapter 7.3 they will be rated and set it into relationship in chapter 7.4

As stated in chapter 5.2 and 7.1 a FDM system is an extensive system containing an onboard and a ground segment. The question of the technical feasibility of the ground segment can be answered very quickly because once the in-flight recorded data are in a public network several commercial FDM service providers are available.

The critical question is technical feasibility of the on-board segment because the technical implementation will diverge from large aeroplane solutions.

Taxonomy can hardly be found in the criteria and aspects as several are not independent from others. In fact it's a collection of perceptions of the topic.

The found criteria and aspects can be divided into three groups in which the first two groups represent the criteria used for the not successful direct approach, see 6.1.1:

Con't No	**Statistical criteria based on direct approach**
1	Analysis of Certification Specification (CS) and of Aeroplane Flight Manuals (AFM)
2	Accident/Incident data review (ECCAIRS data)
3	Accident/Incident data review (generalised view)
	Interviews / surveys
4	Interview of aeroplane accident investigation experts
5	FDM for flight training
6	Interview of maintenance experts
7	Charter demands
	Other criteria
8	Existing specification (ED-112)
9	Other working groups/studies
10	Technical perspective of light aeroplane (retrofit / new)
11	Cost considerations
12	Solutions for measuring or determination of states
13	Considerations on data qualities
14	Data storing
15	Data transmission
16	Data presentation and analysis

Table 4: Overview design criteria and aspects

In appendix 12.1 all criteria and aspects are discussed in detail. Following summaries of the detail discussions in 12.1 shall give a brief overview.

7.3.1 Statistical criteria – summaries

7.3.1.1 Analysis of Certification Specification (CS) and of Aeroplane Flight Manuals (AFM) – summary

The statistical assessment of sources considers solely a frequency of entry of states. The insufficient assumption that the relative frequency of a state is equal to its importance is the reason for failure of this approach, see 6.1.1.

Because the statistical approach failed a content related analysis of CS-23 [15], CS-VLA [16] and two AFM [25][26]was done. To detect possible exceedances of limitations in CS and AFM at least the following states must be recorded:

- engine states (RPM, OP, OT)
- airspeed
- load factor

7.3.1.2 Accident/Incident data review (ECCAIRS data) – summary

ECCAIRS is a system that EASA uses to store and analyse accident and incident data. It seemed well suitable for statistical investigation of frequencies of correlations between aeroplane states and accident scenarios to determine the preferable states to be recorded in a FDM. As this system is in build-up and is not filled with sufficiently detailed data for this purpose, no cognitions were obtained.

7.3.1.3 Accident/Incident data review (generalised view) – summary

Cumulatively most accidents are caused by human factors while the dominating source of technical problems is the engine. A generalized consideration of accidents leads to a common result: Trajectory and attitude information are a bit more frequent relevant than engine data to describe accidents.

7.3.2 Interviews / surveys – summaries

7.3.2.1 Interview of aeroplane accident investigation experts – summary

The expectations of flight accident investigators from a FDR are faster and more accurate knowledge of accident circumstances. Short: „Any information that helps to understand the situation around an accident/incident is useful.“

The following states are suggested in the order mentioned:

1. Position
2. Altitude
3. Airspeed
4. Accelerations (load factor)
5. Attitude

While this order is logically from general to more detailed information about the aeroplane (seen as a rigid body), a decision whether the suggested engine data or the rigid body state should be preferred was not answered definitely. The cost of a crash protected data storage device is probably not necessary.

Conclusions

- Rigid body state and air data preferred
- Engine data are desired too
- No criteria for an advanced state selection
- Crash protection not essential

7.3.2.2 FDM for flight training – summary

A FDM system can be beneficial if it is used together with adapted didactical concepts. While airborne most student pilots are more or less mentally affected a FDM based debriefing on the ground will be beneficial.

A survey amongst flight instructors has shown a wide acceptance of a FDM within training. The preferences of states are presented in the next table:

most essential:	aeroplane position, aeroplane speed, aeroplane altitude
second important:	engine states, heading, load factor
third important:	aerodynamic states like angle of attack or angle of sideslip

Table 5: Flight instructor's state preferences

The cost limit of 5.000€ might be acceptable if the system fulfills some more purposes than supporting flight training.

7.3.2.3 Interview of maintenance experts – summary

Maintenance experts estimate the flight data recording for maintenance purposes as very worthwhile. Engine and airframe can be maintained more specific. Engine data are the preferred states while load factor and airspeed are seen as being important also.

7.3.2.4 Charter demands – summary

The demands from aeroplane charter businesses are a subset of maintenance demands and administrative needs.

7.3.3 Other criteria – summaries

Various criteria and aspects which will not fit into the two groups mentioned above are discussed in the following.

7.3.3.1 Existing specification (ED-112) – summary

The ED-112 represents the knowledge of half a century of flight data recording and shall be applied as far as useful. Adoptions must be made concerning the number of states to be recorded and its accuracies. The crash protection of data storage devices must be questioned. Two simplifications are suggested. All adoptions are necessary due to cost.

7.3.3.2 Other working groups/studies – summary

The ONBASS study (ONBoard Active Safety System)(see[4]-[7]) is dealing with the potential and the realisation of an active safety system for light aeroplane. It could also be called a real-time risk management as well. This exceeds the FDM principle by far. The much higher requirements of an active system will lead to much more costs than a passive system that is investigated in this study.

What can be learned from this study is the technical implementation of sensors and data treatment.

The working group 77 (WG-77) of the European Organisation for Civil Aviation Equipment (EUROCAE) is dealing with the definition of *minimum operational* *performance specification for lightweight flight recorder* [10]. It's an associated topic to FDM because FDM is based on Flight Data Recording. Several considerations are similar between WG-77 and this study, even the preliminary chosen set of states to be recorded. The detailed technical considerations of the WG-77 are worthwhile for the formulation of the specification and the implementation of a system suitable for daily use. The problem of balancing different interests and needs is reported. It's a core problem also in this study.

We see our work complementary to this working group as we are considering several application scenarios in order to identify balanced principle solutions.

7.3.3.3 Technical perspective of light aeroplane (retrofit / new) – summary

The retrofit of existing airplanes with a FDR is to be regarded explicitly. An exemplary statistic [18] shows a large part of very old aeroplane (single and small multi engine aeroplane), which are still in use; approximate ranges of age are:

up to 10 years	~ 10%
10 to 20 years	~ 10%
20 to 30 years	~ 35%
30 years and older	~ 45%

Table 6: Age of light aeroplane fleet acc. [18]

Since the technology has changed dramatically over this long period of time, there are a variety of different aeroplane types, especially if one considers the equipment with digital electronic systems like modern avionics.
Thus it must be differentiated between state of the art of engines, avionics and other sensors. Two different situations can be found for engine and avionics. As normally no other sensors are installed a modern, adapted systems can be applied if necessary.

Four obvious combinations of technical situations can be fixed. These four combinations will be used as *type of aeroplane* in the context of this study.

type of aeroplane	engine sensors	avionic sensors
I.	analogue, no interface	pneumatic/mechanical/analogue no interface
IIa.	analogue, no interface	digital interface
IIb.	digital interface	pneumatic/mechanical/analogue no interface
III.	digital interface	digital interface

Table 7: Listing of basic technical conditions on A/C

The cost impact depends strongly on the efforts for retrofitting. A modular system or two to four adopted systems are needed.

7.3.3.4 Cost considerations – summary

The tender specification [1] states that the costs shall not exceed 5.000€ per installed system and shall be less than 2€ direct operating costs per flight hour. Detailed economic investigations cannot be carried out in the context of this study. Rather cost factors in principle are to be determined. The scale of costs is to be determined nevertheless, see 7.5 too.

<u>Costs per installed system:</u>
This consideration includes the onboard segment of the FDM. We assumed five different cost factors, from the development till installation, that represent the main costs. As the costs are allocated to a specific number of items, this number is an important difference in the cost factors:

	Cost factor	Number of items to allocate costs	Relative costs per installed system
1.	Development of the system	All light aeroplanes	Low
2.	Certification of the system	All light aeroplanes	Low
3.	Manufacturing	Per system	Direct
4.	Certification of installation (STC)	Number of aeroplanes per type	Dependent on number of aeroplanes per type
5.	Installation	Per system	Direct

Table 8: Expense factors from system development till installation

Following essential findings can be derived for the design of the aspired system:

- o The costs of development (1) and certification (2) can be decreased with a higher number of items. The costs of installation (5) cannot be decreased by a higher number of items.
- o For the selection of states to be recorded the installation (5) and certification (4) efforts must be mentioned, better minimised. The system must be designed minimally invasive.

Operational costs:

Four major points will influence the DOC:

1. Data transmission to a public network
2. Data assessment
3. Feedback
4. Maintenance of the onboard system

With the following assumption of 100 flight hours and one reportable occurrence per year the average operational costs will be 2€/flight hour:

1. Data transmission	0 €	-	
2. Data assessment	1€/flight hour	100 flight hours per year	1€/flight hour
3. Feedback	50€/occurence	1 occurrence per year	0.50€/flight hour
4. Maintenance	50€/examination	1 occurrence per year	0.50€/flight hour
sum		200€/year	2€/flight hour

Table 9: Direct operating costs of FDM

The comparison with a commercial offer [42] brought up costs of about 3US$ per flight hour. DOC within the one-digit Euro per flight hour range seems to be feasible for a basic FDM system.

More detailed cost estimation needs detailed formulated requirements for the FDM system. Any convenience increasing option, e.g. wireless data transmission, will increase the costs.

7.3.3.5 Solutions for measuring or determination of states – summary

For almost every state low-cost sensors are available on the market. Generally higher accuracy increases the price of the sensors. For some states no low-cost sensors are available or the installation costs are extensive. In these cases the state might be observed by means of other measured quantities combined with a dynamical model. In some cases neglecting stochastically and non-linear effects, states can be observed using simple analytical equations.

7.3.3.6 Considerations on data qualities – summary

A state to be recorded can be classified by four values: Accuracy, recording rate, recording range and recording solution.

The recording range can be retained as stated in ED-112 [12]. Data rates presented in ED-155 draft 4 [10] shall be taken as a minimum. Given ratios in ED-112 [12] of sensor accuracy to recording accuracy shall be kept.

The accuracies stated in ED-112 can be attained with large aeroplane navigation systems but not with low cost sensors, as the accuracy of a sensor stands usually in a proportional relation to its price. Considering the statement in 7.3.2.1 that „any information that helps to understand the situation around an accident/incident is useful“, then reductions of accuracies are recommended in favour of a payable system.

It must be mentioned that accuracies depend usually on the operation scenario. Recommendations for the applicable accuracies of the states to observe are made after finalising flight trials. The accuracies demanded in ED-112 are to be seen as aimed target values.

7.3.3.7 Data type and storage – summary

Off the shelf Industrial grade HDD and flash memory storages (as SSD) can be used for storing the measurement data in the aeroplane for FDM although they do not fulfill the requirements of ED-112 [12] or ED-155 version 4 [10]. The price of memory storages is falling exponentially with a factor of about 10 in three years.

To improve the system reliability a journaling file system should be used. Storage of measurement values are easier to handle in auto- and semi-automatic processing and presentation of the data. Video and audio acquisition and storage enables a cost efficient way of storing a great amount of data satisfactory for application scenario D (accident/incident investigation).

The ED-112 [12] defines recording format, range, interval, accuracy and resolution to be implemented by a large aeroplane flight data recorder which should be adapted for light aeroplane purposes. Currently there is no common standardization of data formats for aeroplane. Work in progress is preparation of specification ARINC 657 which should be considered to be used for FDM to be compatible to future FDR software tools.

7.3.3.8 Data transmission – summary

The data transmission for all of the application scenarios can be solved using readout of onboard storage or mobile storage medium at low costs. Today a wide variety of different data storage cards such as USB, SD and CF-cards exist and most likely every pilot and maintenance facility have access to this technology including a PC for visualization and analysis of the data. Furthermore the technology for a wire less data transmission exists today - world-wide coverage (continuously communication) using aviation wireless technology as well as cheaper mobile phone technology at the cost of lower coverage (non-continuously communication).

7.3.3.9 Data presentation and analysis – summary

The different scenarios have different demands on the presentation of the flight data. No demand for special presentation tools can be found in the accident investigation as these bureaus have their own already existing tools. For maintenance and statistical purposes, demonstration in form of charts, tables and diagrams with a technical focus is needed. For flight training a graphical visualization of virtual instruments and VFR charts is needed. For both tasks commercial versions already exist which can be adapted. To reduce the amount of measurement data to be handled without significant loss of information, a pre-processing can be performed in the FDM system.

7.4 Combination of compiled criteria and aspects

The discussed criteria and aspects are to be combined to usable findings about the aspired system. For this the significance of every criterion or aspect has to be estimated, see 7.4.1. The state vector for a common light aeroplane is then provided, which represents the amount of possible states at a light aeroplane, see 7.4.2.

In the following the relevant criteria or aspects, the application scenarios and technical solutions are combined to a principle solution of the task.

7.4.1 Evaluation of criteria and aspects

In this chapter the criteria which were pointed out separately in 7.3 are set into the relationship for the selection of states of interest by classifying in:

(1) Primary criteria / exclusion criteria and aspects
- o Criteria and aspects which are decisive for the solution.

(2) Secondary criteria and aspects
- o Criteria and aspects containing constrains for the solution.

(3) Criteria and aspects useful for compilation of state vector
- o Criteria and aspects that are not relevant for obtaining the solution.

The primary criteria and aspects are highlighted in bold letters in the next table.

7.4.2 Compilation of state vector

The general state vector represents all possible state at a light aeroplane. The definite completeness is not inevitably necessary, a saturation of quantity is sufficient. Therefore all sources mentioned in the previous chapter are merged. Additionally the *Luftfahrtnorm 9300* [3] was included. The result of this consideration is shown in appendix 12.2.

<table>
<tr><th></th><th>Chapter</th><th colspan="2">Criteria and aspects</th><th>Evaluation</th><th>Reason</th></tr>
<tr><td>1</td><td>7.3.1.1</td><td colspan="2">Analysis of Certification Specification (CS) and of Aeroplane Flight Manuals (AFM)</td><td>(3)</td><td>No conclusion about relevant states</td></tr>
<tr><td>2</td><td>7.3.1.2</td><td colspan="2">Accident/Incident data review (ECCAIRS data)</td><td>(3)</td><td>No conclusion about relevant states</td></tr>
<tr><td>3</td><td>7.3.1.3</td><td colspan="2">Accident/Incident data review (generalised view)</td><td>(1)</td><td>Ranking accident scenarios</td></tr>
<tr><td>4</td><td>7.3.2.1</td><td colspan="2">Interview of aeroplane accident investigation experts</td><td>(1)</td><td>Indispensable experience</td></tr>
<tr><td>5</td><td>7.3.2.2</td><td colspan="2">FDM for flight training</td><td>(1)</td><td>Training contents</td></tr>
<tr><td>6</td><td>7.3.2.3</td><td colspan="2">Interview of maintenance experts</td><td>(1)</td><td>Indispensable experience</td></tr>
<tr><td>7</td><td>7.3.2.4</td><td colspan="2">Charter demands</td><td>(3)</td><td>No additional information</td></tr>
<tr><td rowspan="2">8</td><td rowspan="2">7.3.3.1</td><td colspan="2" rowspan="2">Existing specifications (ED-112)</td><td>(2)</td><td>Experience and knowledge</td></tr>
<tr><td>(3)</td><td>No conclusion about relevant states for light aeroplane</td></tr>
<tr><td rowspan="4">9</td><td rowspan="4">7.3.3.2</td><td rowspan="4">Other working groups/studies</td><td rowspan="2">ONBASS study</td><td>(2)</td><td>Solution-related technical realisations</td></tr>
<tr><td>(3)</td><td>No conclusion about relevant states</td></tr>
<tr><td rowspan="2">EUROCAE WG-77</td><td>(2)</td><td>Detailed technical considerations</td></tr>
<tr><td>(2)</td><td>Focus on accident investigation</td></tr>
<tr><td>10</td><td>7.3.3.3</td><td colspan="2">Technical perspective of light aeroplane (retrofit/ new)</td><td>(1)</td><td>Strongly cost-related solutions</td></tr>
<tr><td>11</td><td>7.3.3.4</td><td colspan="2">Cost considerations</td><td>(1)</td><td>Strongly cost-related</td></tr>
<tr><td>12</td><td>7.3.3.5</td><td colspan="2">Solutions for measuring or determination of state</td><td>(1)</td><td>Strongly cost-related</td></tr>
<tr><td>13</td><td>7.3.3.6</td><td colspan="2">Considerations on data rate and accuracy</td><td>(1)</td><td>Strongly cost-related</td></tr>
<tr><td>14</td><td>7.3.3.7</td><td colspan="2">Data type and storage</td><td>(1)</td><td>Different use of principle solutions</td></tr>
<tr><td>15</td><td>7.3.3.8</td><td colspan="2">Data transmission</td><td>(2)</td><td>Solutions available</td></tr>
<tr><td>16</td><td>7.3.3.9</td><td colspan="2">Data presentation and analysis</td><td>(2)</td><td>Solutions available</td></tr>
</table>

Table 10: Evaluation of criteria and aspects

The compiled states are divided into 16 subclasses. Technical solutions and the costs of these 16 subclasses are discussed in chapter 7.5.

Although weather states are crucial factors for a large number of accidents it will not be taken into consideration as there are no low cost sensors known. Biometric data are also not considered.

7.4.3 Conflation of criteria

This chapter gives the most generalised view on the topic within this study. Table 11 combines the application scenarios and state vector subclasses to compare their importance for each application scenario. Some general findings are formulated. The designed systems can be assessed with this table whether or not they are beneficial for every application scenario.

- o The criteria 3 to 6 of and the assumed application scenarios are combined in Table 11.
- o Criteria 10 and 12 of
- o Table 10 will be considered in 7.5 (Detailed solutions and cost analysis)
- o Criteria 11, 13 and 14 of
- o Table 10 have to be considered while deriving sensor configurations in 7.6.
- o The state vector subclass “4. Trajectory and attitude” (see 7.4.2) is divided into trajectory and attitude for the next step because there are essential financial and technical differences in implementation, see 7.5.3 and 7.5.4.

<u>Findings based on Table 11:</u>

- o Preferences of application scenarios D (Accident investigation) and C (Direct application in training and other operation) are very similar
- o Administrative needs (E) are a subset of preferences of C (Direct application in training and other operation) and D (Accident investigation)
- o Preferences of maintenance applications (B) is contrary to C (Direct application in training and other operation) and D (Accident investigation)
- o Application A (Quality improvement of flight operation and training) does not clarify the situation. If FDM is interpreted as an assessment of the AFM limit compliance of flight operation, then air data and engine data are preferred. As FDM is normally dealing with standard operating procedures (SOP) that is why trajectory and attitude data are important too.

state vector subclass / application scen.	Trajectory (4)	Attitude (4)		Air data (5)	Engine (13)	others	rationale
			Inertial data (3)				
A – Quality improvement of flight operation and training	2.	2.	1.c	1.a	1.b	3.	7.1.1
B – Maintenance	-	-	2.	3.	1.	-	7.3.2.3
C - Direct application in training and other operation	1.	2.	2.	1. / 3.	2.	-	7.3.2.2 Table 5
D - Accident/Incident investigation	1.	2.b	2.a	3.	3.	4.	7.3.1.3 and 7.3.2.1
E – Administrative needs	1.	-	-	-	-	-	7.1.5 and 7.3.2.4

Table 11: Conflation of criteria, aspects and application scenarios

<u>Conclusion</u>

A system that shall be applicable for all five application scenarios must consider subclasses 4, 5 and 13.

7.5 Detailed solutions and costs analysis

In this chapter technical and algorithmic solutions and financial aspects are discussed for each subclass of the state vector.

The following subclasses are stated for state vector, see 7.4.2 and 12.2:

1	General
2	Air data
3	Inertial data
4	Trajectory and attitude
5	Wind data
6	Weight and Balance
7	Aerodynamic controls
8	Pilot inputs
9	Pilot inputs (discrete)
10	Cockpit displays
11	Cockpit operation
12	Cockpit warnings
13	Engine data
14	Electrical system
15	Landing gear
16	Cabin

Table 12: State vector subclasses

As far as possible costs options for observing any state will be specified. It must be mentioned that only qualitative conclusions can be obtained. The costs for a mass production will differ. An absolute evaluation of the costs can be obtained by comparing the performance and costs of commercial offers with the performance of the later suggested system, see chapter 8.5.

Assumptions for cost estimation:

According Table 9 the costs of a sensor and its installation are investigated in the following.

The sensor costs contain the procurement of a certified sensor unit. As the certification costs can hardly be determined, the market price for a single sensor is assumed as the price of a certified sensor sold in large quantities.

The installation cost contains manpower, material and paperwork. As these costs are strongly related to the technical situation in every type of aeroplane a cost rate is assumed. For the wiring of one sensor (digital data cable or a power supply) and the mechanical installation an amount of 150€, for the first element of any subclass of the state vector, is used in the later calculations. For every further element a price of 50€ is assumed except engine cabling. For a collection of digital data one cable from the source unit to the data acquisition unit is assumed to be necessary. It must be mentioned that some installations are only necessary once.

In the following the term *state number* (abbreviated *SN*) stands for the number of an element of the state vector according to a consecutively numbering, see 7.4.2 and 12.2.

The subchapters of chapter 0 are named as the subclasses of the state vector. At summary of 0 is given in 7.5.17.

7.5.1 General

As source for the time and the date information (SN1+2) a GNSS receiver is preferred. The conversion into other time systems is unproblematic.

Sensor:	GPS receiver ublox 5 [64]	150€
Installation:	Receiver + antenna	150€ + 50€

The states velocity V and height H (SN2+3) are general states and not exactly specified and that’s why they are not handled.

A radio altimeter (SN5) is seldom installed in light aeroplane. If a digital interface exists its information might be easily recorded. The cost for cabling is in a bad relation to only one state that can be obtained. Alternatively an indicator in the instrument panel can be captured on video.

Sensor:	Onboard	-
Alternative sensor:	Video camera	400€
Installation:		150€

7.5.2 Air data

The dynamic pressure (SN7) is an important flight guidance state. It is the first choice if additional sensors shall be installed within primary aeroplane systems. Alternatively the speed indicator can be captured on video. According the simplification in 12.1.3.1b the financial aspect shall be more important than the requirement in ED-112 [12] that cockpit reading shall be recorded.
This is valid in the following also for the static pressure.

The static pressure (SN6) at the position of the aeroplane can be reconstructed in principle with the knowledge of the QNH and the GNSS height. Its acquisition should only be cancelled if no financially compliant solution is found. As the cabin inside pressure is strongly affected by airspeed, angle of incidence and engine setting it is recommended to us the regular static pressure port to as source.

A solution can be a combined sensor for static and dynamic pressure. Manufacturing costs are increasing moderate but installation costs are practically the same as for a single dynamic pressure sensor. A great number of different sensors at low cost are available on the market with analog and digital outputs. From the sensor raw data the altitude and airspeed can be computed easily using equation for the standard atmosphere.

Alternatively the altimeter can be captured on video.

Sensor:	Combined dynamic + static pressure sensor unit	70€
Installation:		150€

The angles of attack and side slip (SN8+9) can be measured directly by using a wind vane or a 5-hole-probe. As a special nose or wing boom would be necessary to carry this probe a high installation and certification effort is the consequence. Furthermore delicate instruments are at an exposed position on the outside of the aeroplane that is why this is not an option for a low cost FDM. Alternatively the quantities can be computed from other measurements and models.

The angle of attack α can be computed using following equation:

$$\alpha = \frac{n_z \cdot m \cdot g}{q \cdot S \cdot C_{L\alpha}} + \alpha_0 \qquad \{1\}$$

This equation contains the aeroplane specific constants:

S: wing area

C_{La}: lift increase coefficient

α_0: angle of attack at zero lift

The aeroplane mass m is not constant but has to be assumed so, because it is not feasible to find an easy way to get a fairly accurate value.
With actual sensor readings for the dynamic pressure q and the vertical component of the acceleration (load factor n_z times acceleration of gravity g) it is possible to compute the angle of attack. The accuracy of this method is discussed in 7.7.3.

The angle of side slip β can be computed quite similar:

$$\beta = \frac{a_y \cdot m}{q \cdot S \cdot C_{Y\beta}} + \beta_0 \qquad \{2\}$$

This equation contains the aeroplane specific constants:

S: wing area

$C_{Y\beta}$: aerodynamic force coefficient

β_0: offset correction for angle of side slip

To compute the angle of side slip actual readings are required for the dynamic pressure q and the lateral acceleration a_y. The aeroplane mass has to be considered as constant as mentioned before.

Reliable OAT sensors (SN10) are expensive. The value of these sensors is primary the housing not the sensing element. Additionally costs for installation must be considered. The recording of that state is not justifiable within the given cost frame. In cases of high interest external sources must be used, e.g. weather service.

The measurement of humidity (or dew point, SN11) can be done with semiconductor based sensors e.g. HMP50 provided by the company *Vaisala* [63]. The air temperature is measured also. The sensor unit costs about 260€, but that does not include a suitable housing and not the installation.

Sensor:	*Vaisala* HMP50 [63]	260€
Housing:	*Rosemount* F101 or F102 Cheaper realisation possible?	~10k€ ~500€
Installation:		150€

Density, speed of sound, mach number (SN12-14) are computable from SN6-11

7.5.3 Inertial data

The load factor (SN18) can be measured with a single accelerometer. As the installation costs for a single sensor are practically the same as the installation costs of a sensor unit, all six inertial degrees of freedom (SN45-53) should be measured. The higher costs of an inertial measurement unit (IMU) compared with a single axis sensor are justified because of a several states that can be determined on basis of this measurement.

One-axis MEMS sensor:	Several provider	100€
MEMS IMU	e.g. *O-navi* gyrocube + interface [66]	~1000€
Installation:		150€

7.5.4 Trajectory and attitude

The entries of this subclass can be divided into trajectory data (SN25-35, except 27, 30) and attitude data (SN22-24):

Trajectory

A GNSS receiver is without a doubt in spectrum of use of light aeroplane superior to all other detection methods. The set of data does not only contain the position but furthermore the altitude, the horizontal and vertical speed as well. The receivers normally use a standard data output format that is why a decoding and recording is no problem.

Sensor:	GPS receiver ublox 5 [64] incl. antenna	150€
Installation:	Receiver + antenna	150€ + 50€

Attitude (SN22-24)

There are two methods to determine the attitude:

1. GNSS attitude system

   With 3 or more antennas arranged on the aeroplane the three attitude states can be calculated, but the installation costs are high as a precise calibration of the antenna array has to be performed. Currently commercial off-the-shelf systems exceed the predetermined cost of the total FDM system significantly.

2. IMU based system

   All low-cost IMU found on the market do not perform a determination of the attitude and heading. As the drift of these systems (even if temperature compensated) is too high additional sensors with complementary characteristics are required. These could be GNSS-receiver, magnetic sensors or earth perpendicular coupling.

The combination of an IMU and a GNSS receiver with a coupling filter (state observer techniques) is the most sophisticated but also complex method. It includes a sensor error estimation which enables an error correction for system output. In addition the quality of all kinematic states (position, velocity, attitude and acceleration) is improved. As all kinematic states except attitude are available from GNSS and IMU measurements with adequate quality an easier and less complex method can be used. The attitude information can be computed from the IMU data with earth perpendicular coupling where the earth gravity is used as major reference. The poor accuracy of low cost sensors prevents the proper observation of the heading (SN22) using both methods.

As compromise the following method can be used: The heading is calculated using a coupling of ground track (azimuth SN25) and yaw rate. This way the ground track is used as reference for the heading determination. This method enables the detection of dynamic side slip maneuvers. However the mean value for the wind correction angle is filtered to zero.

More precise heading determination (SN22)

Adding a magnetic sensor could improve the determination of the heading. But as the magnetic sensor is normally affected by aeroplane structure and systems the accuracy strongly depends on the calibration. This is proposed to be done while annual compass calibration.

Alternatively a two antenna system could be applied. Contrary to a 3 or more antenna system it is easier to arrange the antenna on the aeroplane. It is assumed that algorithmic solutions will be available determine the heading. The accuracy depends also on the calibration of the antenna arrangement.

The hardware costs and calibration efforts are nearly the same for both solutions. Finally it depends on the aeroplane type which method is to prefer.

Sensor:	e.g. SP-2 magnetometer [72]	150€
Installation:		150€
Alternative:	2nd GPS receiver ublox 5 [64] incl. antenna	150€
Installation:		150€

The vertical air vector angle (SN27) can be computed if the trajectory and the wind vector are known.

The True Airspeed (SN30) is computable from the dynamic pressure (SN7) and the air density (SN12).

7.5.5 Wind data

The wind vector (SN36-38) is the summation of the ground vector and the airspeed vector. If these vectors are not complete some simplifications may be applied to get estimated results. The wind data is calculated with air data (2), inertial data (3) and trajectory and attitude (4).

$$\vec{V}_w = \vec{V}_k - \vec{V} \qquad = \begin{bmatrix} u_k \\ v_k \\ w_k \end{bmatrix} - \underline{\underline{M}}_{gf} \; \underline{\underline{M}}_{fa} \begin{bmatrix} V \\ 0 \\ 0 \end{bmatrix} + \underline{\underline{M}}_{gf} \begin{bmatrix} \dot{\Phi} \\ \dot{\Theta} \\ \dot{\Psi} \end{bmatrix}_f \times \vec{R}_f$$

Probe lever arms

Ground vector

Angular rates

Transformation
f (Θ,Φ und Ψ)

Airspeed vector

Transformation
f (α,β)

Figure 9: Formula for wind determination

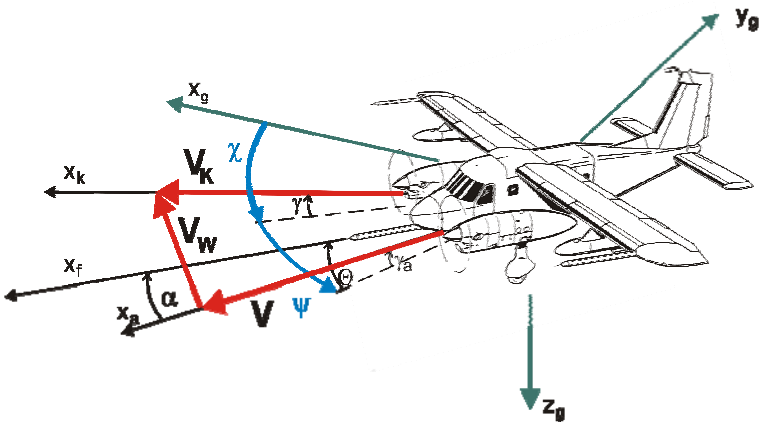


Figure 10: Principle of airborne wind measurement

7.5.6 Weight and Balance

Fitting sensors into the landing gear to determine current weight and C/G position (SN39-45) seems to be technically possible at all, but expensive. No light aeroplane having this feature is known~~ to us.~~

The fuel usage can be measured with a separate sensor (200…500€). But this will allow calculating the fuel mass (SN41) only if the absolute fuel mass before the flight is known.

7.5.7 Aerodynamic controls

Following the suggested simplification of ED-112 [12] according to 12.1.3.1α the deflection of control surfaces, trim tabs, flaps and speed breaks (SN45-53) are not considered separately. Nevertheless it might be appropriate to fit the sensor at the regarding aerodynamic control.

Remark on 7.5.8 – 7.5.16

The following subclasses 8-16 are very similar regarding the possible technical implementations. If indicators in the instrument panel exist they can be recorded by capturing a video. A frame rate for video capturing is suggested in [10].

If no indicators are available, additional sensors for the according states must be installed and connected to the data acquisition unit. Because of the expectation of higher costs for the second option it is justified for particular conditions only. Any control element to be observed must have an electrical output. As normally no control elements are equipped with interfaces, the retrofit costs will be high.

7.5.8 Pilot inputs

The measuring of input forces (SN54) is technically possible. But the installation and calibration will be to expensive compared to the outcome.

The primary flight controls pilot input (SN55) are important states to determine pilots actions. For observation a sensor for every primary control must be installed and calibrated. Alternatively a video capturing of the hand controls is possible but is more complicated for rudder inputs.

Sensor:	Wire rope potentiometer [65]	3x 150€
Installation & calibration:		1x 150€ + 2x 50€

SN56-62 can be recorded with video or via serial installed sensors with digital interface. Single sensors for every control are possible but too expensive.

Brake pressure and brake pedal position (SN63+64) can be recorded if sensors are available; a retrofitting is too expensive.

7.5.9 Pilot inputs (discrete)

As mentioned in the remark above the discrete pilot inputs (SN65-74) can be captured on video or detected with single sensors.
While the engine controls can be observed by the digital engine control unit, all other inputs can be an integrate part of future avionic systems.

7.5.10 Cockpit displays

If the states SN75-79 are not provided by an avionic system interface a video capturing can observe all states.
Some states do not exist in aeroplanes without digital avionic (SN78+79). To provide the other states with retrofitted sensors cannot be justified financially.

7.5.11 Cockpit operation

The findings in the previous chapter are also valid for SN80-82.

7.5.12 Cockpit warnings

To handle the cockpit warnings (SN83-91) it must be known if they are optically, acoustically or both and if the recording of them is worthwhile. The activity of warning devices can be supervised via interface but the warning device should be equipped with a self test routine to ensure the coherence of outputs.
Optical warnings can be ob served with video capturing and acoustical warning with a sound recorder.

7.5.13 Engine data

If the engine is equipped with a digital control unit all states (SN92-106) can be recorded easily. Alternatively all cockpit indicators can be captured on video.
It is possible in principle to connect all sensors of an engine without digital control with a data acquisition unit. Such wiring of an engine was estimated by a maintenance company with about 2.000€. An appropriate signal conditioning is also needed.
The thrust (SN92) can be computed if the rotations speed (SN93) and the manifold pressure (SN94) are known.

Instead of a direct sensor or a video capturing the rotation speed (SN93) can be calculated with a Fourier transformation of the cockpit sound information. Sound capturing is not worthwhile for the observation of any other state (SN94-106) in this subclass but for the observation of any acoustical warning, see7.5.12.

7.5.14 Electrical system

The measuring of the electrical states (SN107-109) is easily possible. Cockpit indicators can be captured on video. A sensor for both values integrated in the electricity network is not expensive but would require a data cable.

Sensor:	Several provider	20€
Installation:		150€

If the power supply of the investigated on-board system is directly connected to the electrical onboard system a cheap voltage (SN107) measurement can be integrated in the data acquisition unit.

7.5.15 Landing gear

Retrofitting of gear position sensors (SN110) is out of scope. A gear indication (if available) in the instrument panel can be captured with a cockpit video camera.

7.5.16 Cabin

Semi-conductor based carbon monoxide detectors (SN112) are available for several industrial applications and might be easily integrated in a FDR inside the cabin. An investigation about the representation of the place of installation must be done (air circulation in cabin). A realistic price for a single sensor could not be obtained.
Alternatively a video capturing of a usual CO detector for light aeroplane can detect this information.

The states of the cabin doors (or hatches, tank cap, ...)(SN112) can be detected with simple switches, see automotive domain. Because of certification and installation costs it will be not payable for retrofitting.

7.5.17 Conclusion on “Detailed solutions and costs analysis”

The preliminary findings of chapter 0 are presented in appendix 12.3. The findings are assigned to the three groups *Avionic*, *Engine* and *Other* (according 7.3.3.3). The groups avionic and engine are divided into the subgroups *conventional (=old-fashioned, analogue)* and *modern (=digital)*.

It can be concluded that 45% (50) of the states belong to *avionic*, 16% (18) to *engine* and 39% (44) to *other*. About two-thirds of the states may be available in the cockpit as instrument indication or because the action takes place in the cockpit (switch selection, etc.).

<u>At this time it can be concluded, see appendix 12.3:</u>

a) for a type I aeroplane (acc. Table 7):
   - 21 states are not realisable or not to be realised (most belong to group *Other*)
   - 21 states (about half of the *Avionic* related states) can be covered with a GNSS-IMU-coupled system
   - 11 of the states can be computed from other states (nearly all belong to the group *Avionic*)
   - 56 states are related to video capturing and 10 to cockpit voice recording

b) for a type III aeroplane (acc. Table 7):
   All states of the subgroups *Avionic* and *Engine* are provided by the aeroplane instrumentation. The boundaries between the groups of states used within this study are not definite. There are already existing devices, which indicate flap setting and canopy state, e.g. *Electronics International MVP-50* [67].
   The task of flight data recording reduces to the purposeful storage of data. To keep the technical conversion of such data logger as simple and inexpensive as possible, it would be helpful to define a minimum operational performance specification for light aeroplane on-board data systems.

c) Type II aeroplane (acc. Table 7) are a selection of Type I and III.

The costs of a FDM system for future aeroplane with a standardised data bus will be much lower than for a comparable retrofit system. The costs will be shifted from the retrofit system to the aeroplane equipment.

It must be considered that the future light aeroplane generations may be more heterogeneously than today. Two main directions of light aeroplane evolution are predicted:

1. Future aeroplanes are equipped with a large amount of sensors for several states, a data network and perhaps an on-board active safety system, e.g. [4] . This will be the preferred choice for commercial operations of light aeroplane.

2. Low-tech aeroplane with only an essential amount of instrumentation and without an on-board data network (similar to nowadays technology) might be the counter part to 1.

As the costs for additional equipment is most relevant in the context of this study they are listed appendix 12.4. If one device is used for observing several states it's marked with the same colour and the same name. The costs for the device are inscribed at the first entry. The data acquisition unit is assumed to be 500€ worth. A crash proof data storage is not included, see 7.3.3.2, 7.3.3.7 and 10.

The chosen sensors are exemplary. As the sum of the costs is about 5.500€ this selection gives an impression of what can be expected for 5.000€.

7.6 Derivation of system configurations

Based on the results of chapter 7.5 sensor configurations that are adapted for every assumed application scenario can be derived. A suggested sensor configuration for a system with a maximal efficiency for all applications will be given at the end of this chapter.

Chapter 7.5.17 depicts the open secret that one size doesn't fit all. As the recording of digital data is not the most cost relevant question at this point, we concentrate on the retrofit consideration.

7.6.1 System configuration for application scenario A

As stated in chapter 7.4.3 the application scenario A (Quality improvement of flight operation and training) does not clarify which states should be observed. If FDM is interpreted as an assessment of AFM limit compliance of flight operation, then air data and engine data are to prefer. But FDM is also dealing with standard operating procedures (SOP) so trajectory and attitude data is also important.

To detect any limit violation according to AFM any state mentioned in Table 23 - Table 25 has to be observed. The devices needed and their costs as assumed in chapter 7.5 are listed below.

	Device	Costs	Number of observed states per device[2]	Costs per observed state[2]
1	GNSS, incl. data acquisition	850€	12	71€
2	IMU + Heading sensor	1.450€	16	91€
3	Static and dynamic pressure	220€	2	110€
4	Temperature (incl. humidity)	910€	5	182€
5	Flap setting	300€	1	300€
6	7 engine state	1.120€	8	140€
7	Onboard voltage	5€	1	5€
	Total	**4.855€**	**45**	**108€**

Table 13: System configuration and costs for application scenario A

[2] Some states are calculated with the measuring of more than one device but mentioned only one time

7.6.2 System configuration for application scenario B

All common states of a piston engine will be measured. Additional sates are the load factor and the dynamic pressure. The GNSS receiver might be merely necessary for time information. But its low costs justify an implementation so the flight phase can be detected and stored (flight mode detection).

	Device	Costs	Number of observed states per device[3]	Costs per observed state[3]
1	GNSS, incl. data acquisition	850€	12	71€
2	Accelerometer	250€	2	125€
3	Static and dynamic pressure	220€	2	110€
4	11 engine state	1.760€	12	147€
5	Onboard voltage and accumulator charging current	205€	2	103€
6	Lightning strike detector	200€	1	200€
	Total	**3.485€**	**31**	**112€**

Table 14: System configuration and costs for application scenario B

7.6.3 System configuration for application scenario C

Application in the training requires the determination of the pilot actions. Due to costs we propose to concentrate on the most important: Primary control inputs and flap selection. The most relevant state of the engine, which should be observed for pilot training, is the flight-mechanically effective thrust. It can be calculated if the rotation speed and the manifold pressure are measured.

[3] Some states are calculated with the measuring of more than one device but mentioned only one time

	Device	Costs	Number of observed states per device[4]	Costs per observed state[4]
1	GNSS, incl. data acquisition	850€	12	71€
2	IMU + Heading sensor	1.450€	16	91€
3	Static and dynamic pressure	220€	2	110€
4	Control inputs (3x), flap setting	1.000€	2 (4)	500€ (250€)
5	2 engine states	320€	3	107€
	Total	**3.840€**	**35**	**110€**

Table 15: System configuration and costs for application scenario C

7.6.4 System configuration for application scenario D

For the accident investigation the data can be stored as video and audio information. In order to examine the plausibility of the data we suggest recording certain data with additional sensors although these information are contained in principle in the video or sound capturing, e.g. dynamic pressure.

	Device	Costs	Number of observed states per device[4]	Costs per observed state[4]
1	GNSS, incl. data acquisition	850€	12	67€
2	IMU + Heading sensor	1.450€	16	91€
3	Static and dynamic pressure	220€	2	110€
4	Video + CVR	900€	54	17€
5	CO sensor	20€	1	20€
	Total	**3.440€**	**85**	**40€**

Table 16: System configuration and costs for application scenario D

[4] Some states are calculated with the measuring of more than one device but mentioned only one time

7.6.5 System configuration for application scenario E

The fundamental content of this application scenario is the statistical evaluation of aeroplane movements. Therefore trajectory information is needed. Of course other data may be usefully evaluated (e.g. engine states for a certain group of the light aeroplane fleet) but this is seen as an additional benefit if the needed sensors are installed due to another application scenario.

Finally the administrative needs can be served with probably every system that fulfils the requirements of one of the other four application scenarios.

	Device	Costs	Number of observed states per device[5]	Costs per observed state[5]
1	GNSS, incl. data acquisition	850€	12	71€
	Total	**850€**	**12**	**71€**

Table 17: System configuration and costs for application scenario E

7.6.6 Assessment of individual solutions for every application

From chapter 7.6.1 - 7.6.5 the conclusion can be drawn that the requirements of the individual application scenarios can be fulfilled within the given budget of 5.000€, considering the accuracy of cost assumptions.

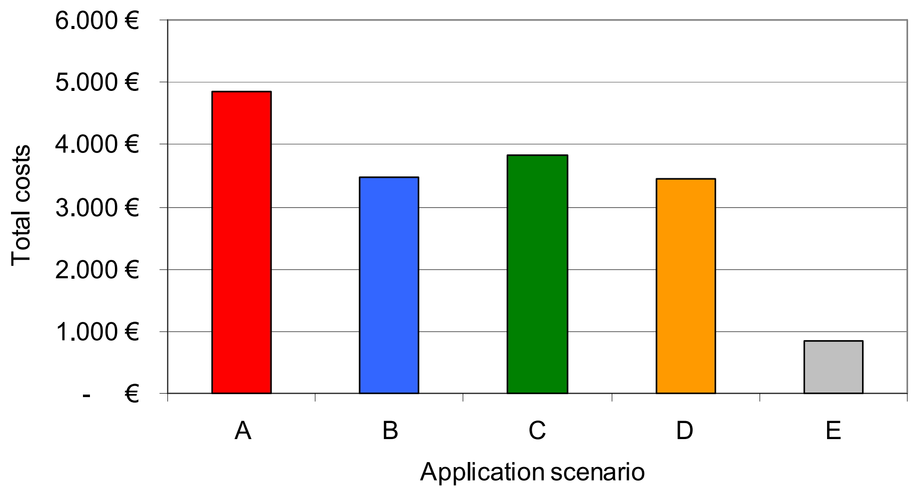


Figure 11: Costs of derived sensor configurations for application scenario A-E

The number of observed states is comparable within the application scenarios except application D (accident/incident investigation):

[5] Some states are calculated with the measuring of more than one device but mentioned only one time

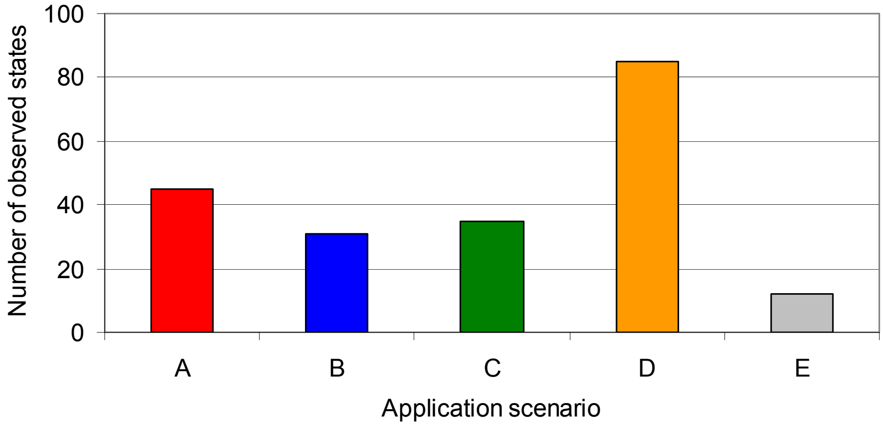


Figure 12: Number of observed states for application scenario A-E

This circumstance is caused by a more expensive data rework for video and audio data. However it affects the *costs per installed system* positively. The technological difference can also be seen in *costs per observed states*:

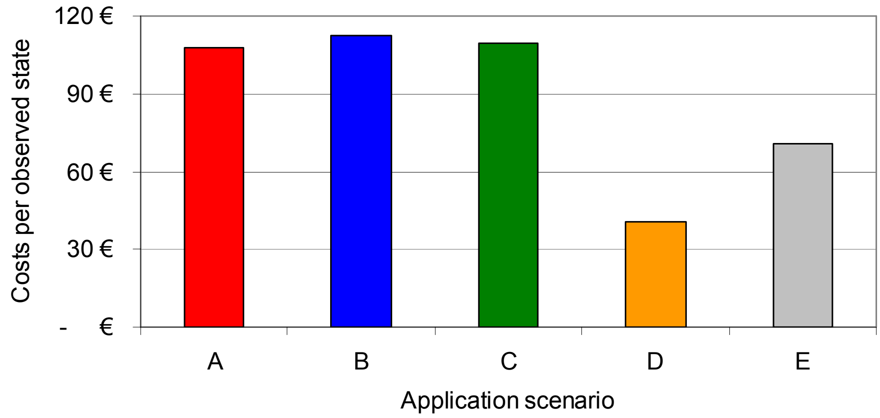


Figure 13: Cost per observed states for application scenario A-E

The *cost per observed state*, excluding video and audio sensors, is about 110€, with variations from 5€ to 300€.

Conclusion

Based on the assumed application scenarios (Ch.7.1) and the discussed design criteria and aspects (Ch. 7.3), the chosen sensor configurations fulfil the cost goal for every application scenario. Attention must be paid to possible inaccuracies of cost estimation. Subject to the correctness of the assumptions the technical feasibility of a FDM for light aeroplane is given within 5.000€ limit per installed system.

An overview of the chosen sensor configurations for every application is given in appendix 12.5.

7.6.7 System configuration with maximum impact regarding all application scenarios

In order to maximise the benefit of the aspired system, and thus also the user acceptance, the system shall cover as many application purposes as possible. At first it is assumed that all five mentioned application scenarios shall be served completely.

Therefore all chosen sensors of the single application scenarios are combined. The result is pictured in appendix 12.5 in the column “Combined”. Several states are measured multiple times. The overall costs are about 7.300€.

The financial uncertainties are high for the depicted systems, because the installation costs may vary intensely depending on the A/C type, see Ch.7.3.3.4., except the proposed sensor configuration for application D. The following exclusions are proposed for deriving a less expensive system that considers all five application scenarios and reduces the installation cost uncertainties:

Device to exclude	Reason	Cost reduction
Temperature + humidity sensor (SN10+11)	Low benefit, alternative source possible for special purposes	910€
Several engine states (SN95-106)	The possible financial benefit of an *engine trend monitoring system* may encourage aeroplane owner to invest from self-interest. *“Safety does not sell.”,* but a potentially money saving measure will sell much better. For accident/incident investigation all states are captured on video. Installation effort is reduced.	1.440€
Lightning strike detector (SN109)	Rare event	200€
CVR	Although there are nearly no simple substitutions for recoding audio data; they seem to be more dispensable compared to other states. That may be caused by a stronger felt privacy reduction by audio than by video surveillance. Although audio information may be worthwhile concessions must be made.	350€
	Total	**2.900€**

Table 18: Exclusions of devices for cost reduction

The modified sensor configuration is presented in appendix 12.5 in column “Reduced” and compared with with the “Combined” configuration in the next table.

	“Combined“	“Reduced“
Measured or calculated states	53	37
States only captured on video	38	48
Total number of observed states	91	85
costs	~7.300€	~4.400€

Table 19: Comparison of "Combined" and "Reduced" sensor configuration (costs per installed system)

This *reduced* sensor configuration strongly constrains the application scenario B (maintenance). Alternatively the following possibilities exists to exclude other devices by debiting other applications, or to reduce the system at all:

- o 550€ could be saved without negating the application scenario accident/incident investigation by excluding the video capturing. However the yield of potentially 48 states is unbeatable for the costs (11.50€ per state).
- o The four pilot inputs (SN55+56) are essential for application C and beneficial for the other application if measured, but are expensive too (4x 250€).
- o Reductions of sensor accuracies may be done
- o Any digital source will save costs, exclusions according Table 18 are obsolete

In principle other combinations and conclusions are possible according to the readers perception.

<u>Conclusion</u>

A beneficial system for all assumed application scenarios (with restrictions to maintenance applications) seems to be realisable within the given cost frame of 5.000€ per installed system even if no digital sources are available.

7.7 Flight trials

7.7.1 Flight trial strategy

The aim of the flight trial was the demonstration of the possible use of low cost sensors for a flight data monitoring system.

Therefore a sensor system as described in the chapter 7.6.7 was installed on board the Cessna 172 of the IFF. The number of sensors represented the “reduced” sensor configuration plus a number of engine instruments. Additionally high precision sensors were installed as reference. The data of both the low cost and high accurate sensors were recorded on a standard data acquisition computer of messWERK.

During the flight trial the following sensors were compared to high accurate sensors:

- GPS receiver
- analogue pressure sensors for air data
- digital IMU with three accelerometers and three gyros

Additional high accurate sensors were installed for the angle of attack and the side slip angle as well as a temperature sensor on a wing boom.

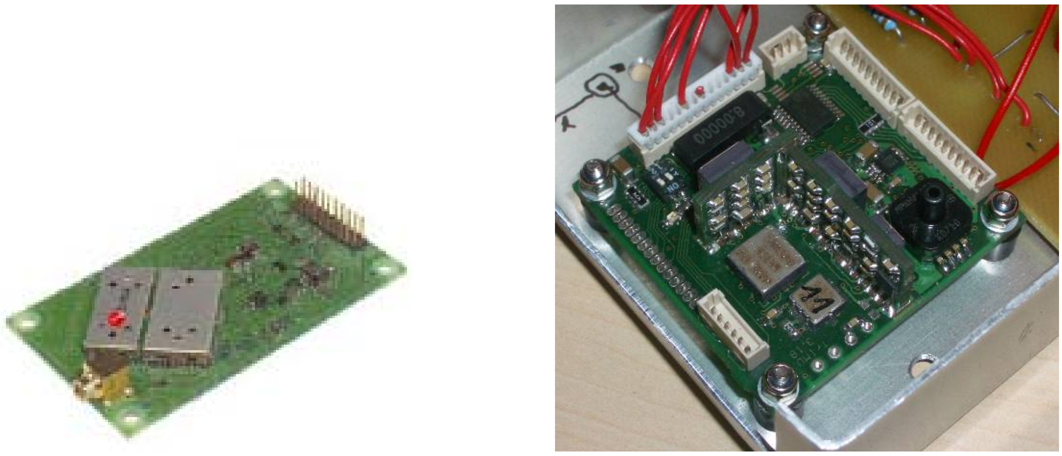


Figure 14: Low cost GPS receiver (left) and low cost IMU

Quantity	sensor low cost	price	sensor high accurate	price
static pressure	SDX15A4	~35 €	Setra B270	1.200 €
dynamic pressure	Motorola MPX 2010	~35 €	Setra D239	1.100 €
GPS receiver	uBlox Antares4	100 €	Novatel OEM V	8.000 €
IMU	Mavionics	1.200 €	iMAR iTrace	72.000 €
Sum		1.370 €		82.300 €

Table 20: Cost comparison low cost and reference system

7.7.2 Execution of flight trials

All sensors were installed on a plate in the baggage compartment of the Cessna 172 "D-EMWF" of the IFF. As pitot-static-source the probe on the wing boom of the research aeroplane was used. The wing boom also contained wind vanes for the direct measurement of the angle of attack and side slip. Additionally the pilot inputs were measured by angle sensors on the control surfaces. The research aeroplane is equipped with additional sensors for most engine states. The sensors are digitized on a separate computer and transferred via a serial data link to the central data acquisition computer.

All sensors were connected to the data acquisition system of messWERK which is designed for flight trialing of small aeroplane.

A low cost video camera (web-cam) was installed on the ceiling of the cabin between the head of the pilot and co-pilot. For the image recording an additional computer was used.

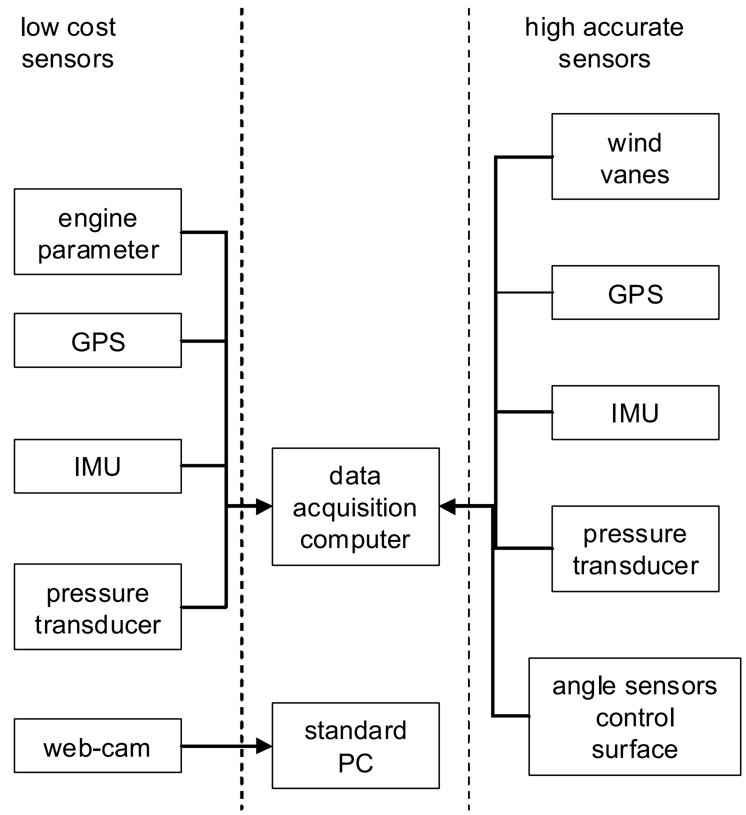


Figure 15: Block diagram of sensor system for initial flight trials

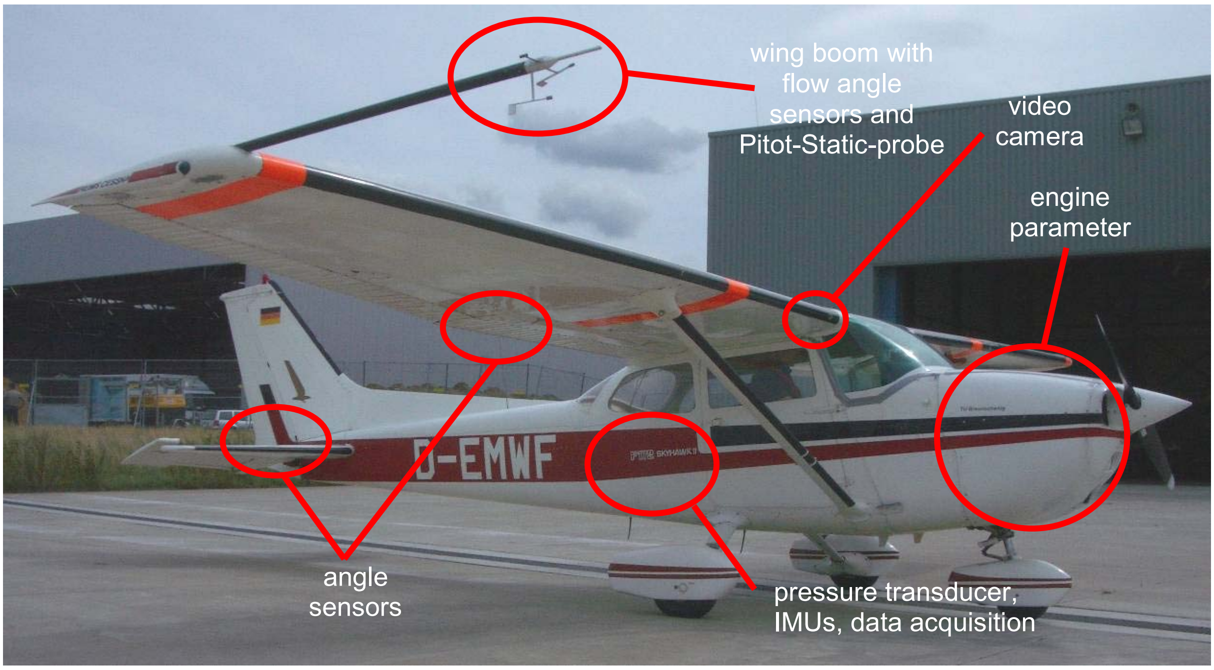


Figure 16: Sensor installation on the research aeroplane

With these instrumentations several traffic patterns were performed.

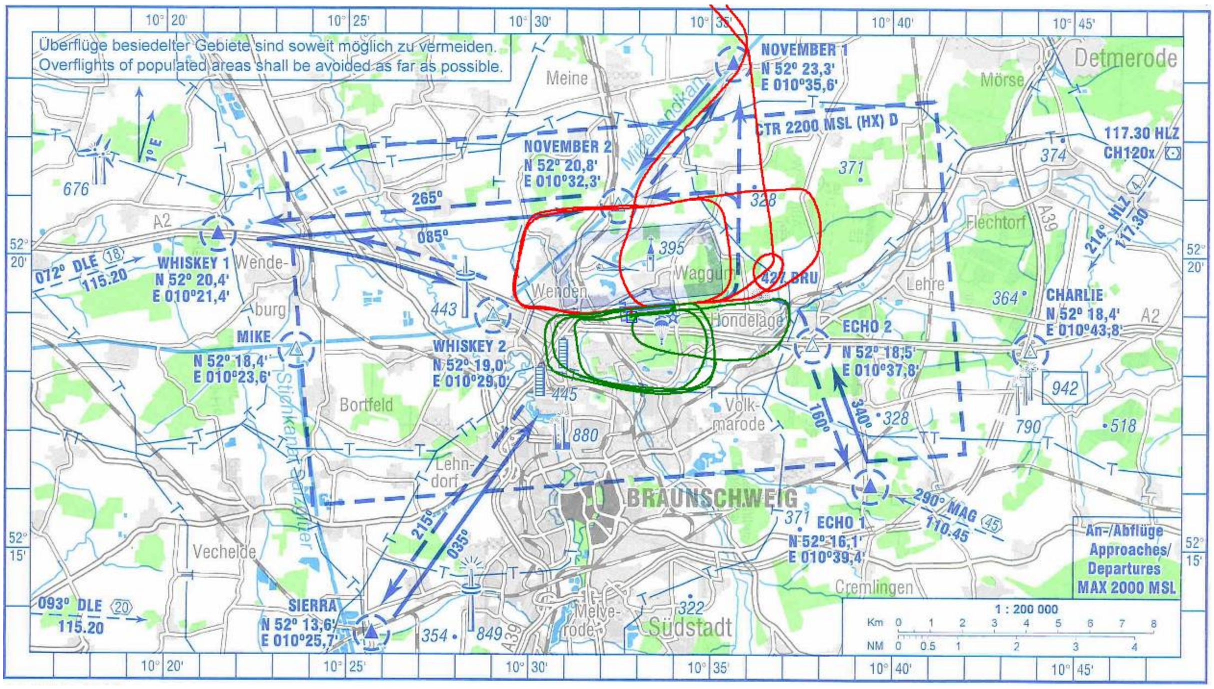


Figure 17: Track of two flights on the visual approach chart of the airport Braunschweig

7.7.3 Results of flight trials

To show the difference between the high accurate and low cost sensors several comparative plots were made.

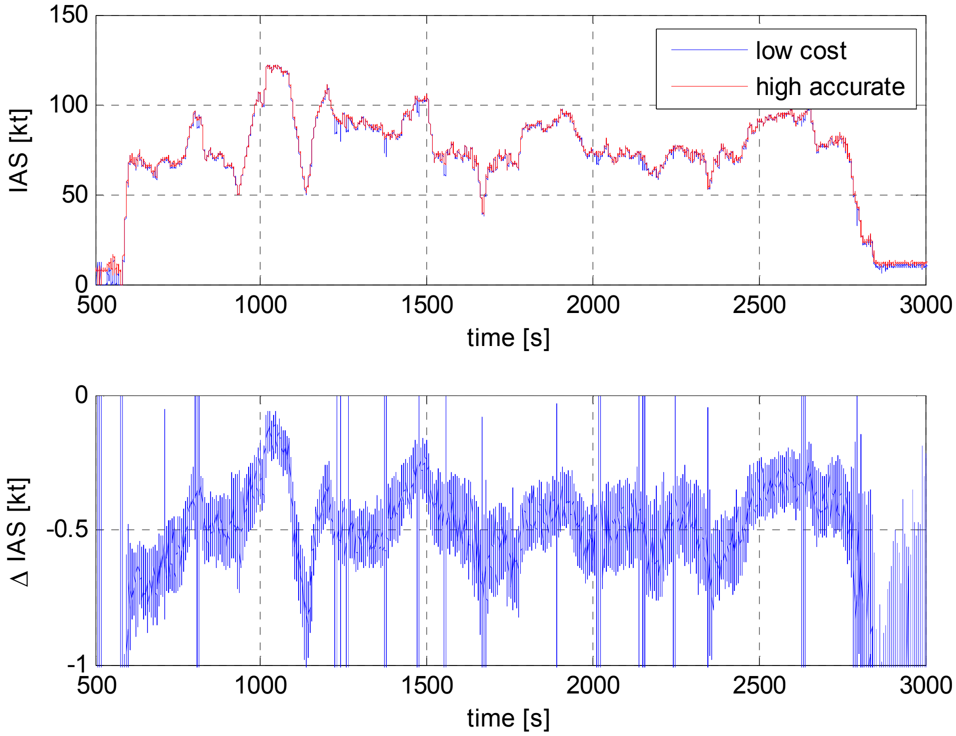


Figure 18: Comparison of airspeed with both sensors

For the airspeed a mean difference of 0.5 knots arises between the high accurate and the low cost sensor. Only in the first minutes the low cost sensor shows a significant warm-up drift in the order of 0.2 hPa. This shows that low cost sensors are usable with sufficient accuracy for this application.

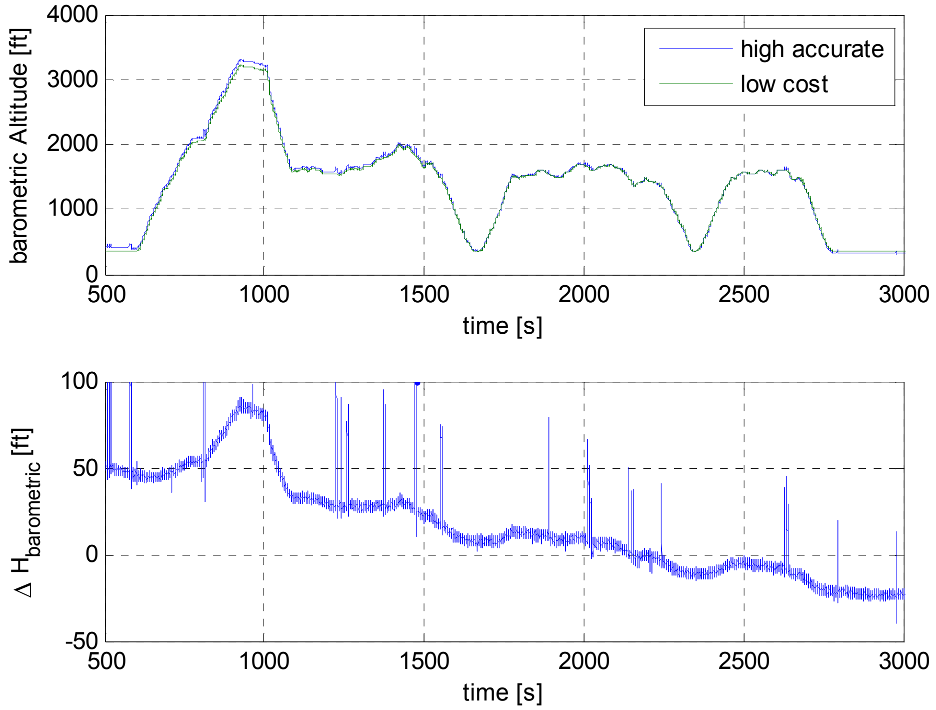


Figure 19: Comparison of altitude sensors

The behaviour of the absolute pressure transducer is quite similar. Over a time period of almost 1 hour the low cost sensors drifts about 80 ft compared to the precision sensor. This would be acceptable for the use in the FDM.

A more difficult situation is found for the attitude determination. Figure 20 shows two different curves for the pitch angle. The red line indicates the result of the precision inertial navigation system. The green line is the result for the low cost IMU obtained with an earth perpendicular coupled mode. After an offset correction (to compensate the misalignment) an error of about 2° to 3° occurs compared to the high precision system. Only for stronger manoeuvres the errors increases up to 5° (at time ≈ 1100 s in Figure 20 below). However the result looks reasonable and manoeuvres can be identified easily.

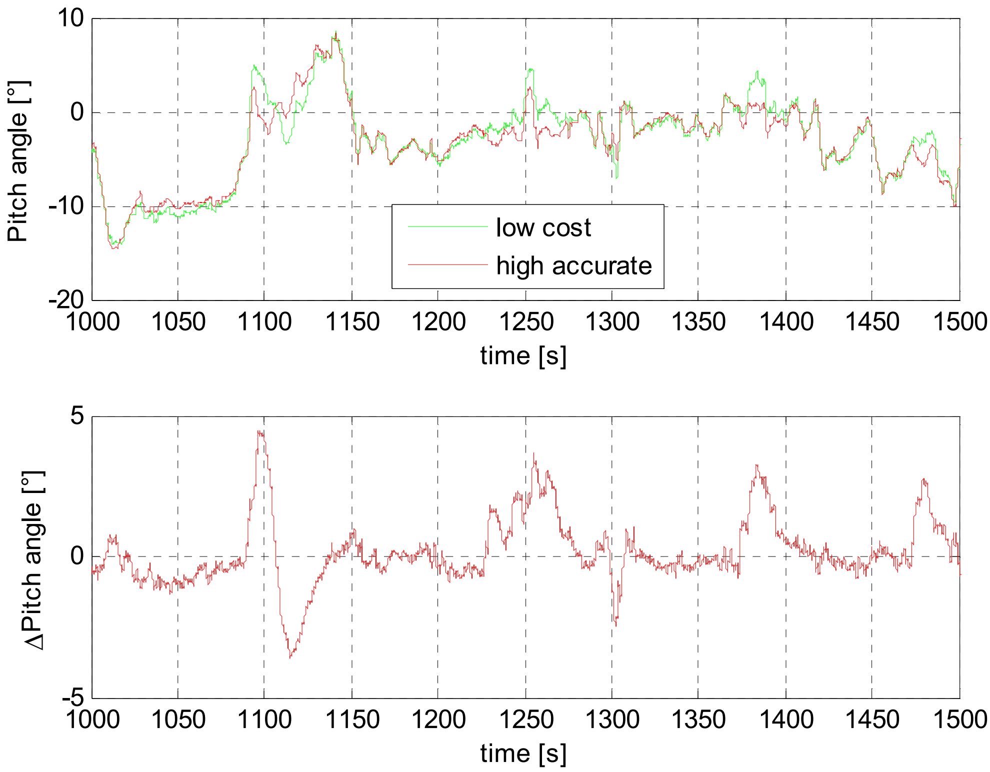


Figure 20: Comparison of pitch angle for high accurate INS and low cost sensor with earth coupled mode

The results for the roll angle look similar.

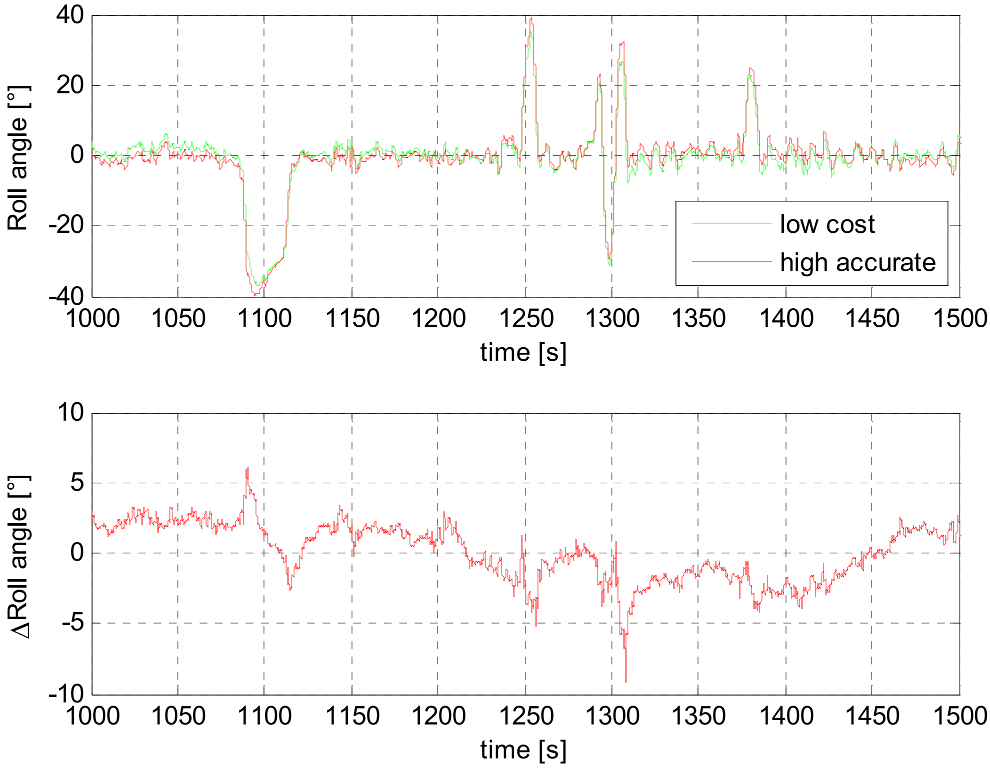


Figure 21: Comparison of roll angle for high accurate INS and low cost sensor with earth coupled mode

The maximum deviation reaches a value of about 5° for manoeuvres and about 3° for level flight. For the clear identification of manoeuvres this is considered to be sufficient.

The heading can not be measured with the low-cost IMU with acceptable accuracy. An estimation of the heading based on the GPS ground track gives results which help to understand the aeroplane movement. The lowpass filtered value of the GPS ground track can be used to sustain the IMU calculation. Unfortunately a steady wind correction angle is almost eliminated by this method. This can be demonstrated with a full turn, depicted in Figure 22. The mean wind was from 200° with 15 knots during this time period. With a mean airspeed of 70 knots the maximum wind correction angle is:

$$WCA = a\tan\left(\frac{Wind}{TAS}\right) = a\tan\left(\frac{15}{70}\right) = 12° \qquad \{3\}$$

The top of Figure 22 shows the time plot of heading obtained from the low cost system, the heading of the precision sensor and the ground track. On the bottom the wind correction angle, which is heading minus azimuth, is depicted for both the low cost and the precision sensor over the heading. At a heading of 20° respectively 200° (when heading is in line with the wind direction) the wind correction angle is zero for the precision sensor. At a heading of 110° and 290° the wind correction angle reaches its maximum value of about 12° as estimated in the equation above. According to the low pass filtering of the GPS track and the high pass filtering of the yaw rate the low cost system shows an extremely damped wind correction angle during the turn.

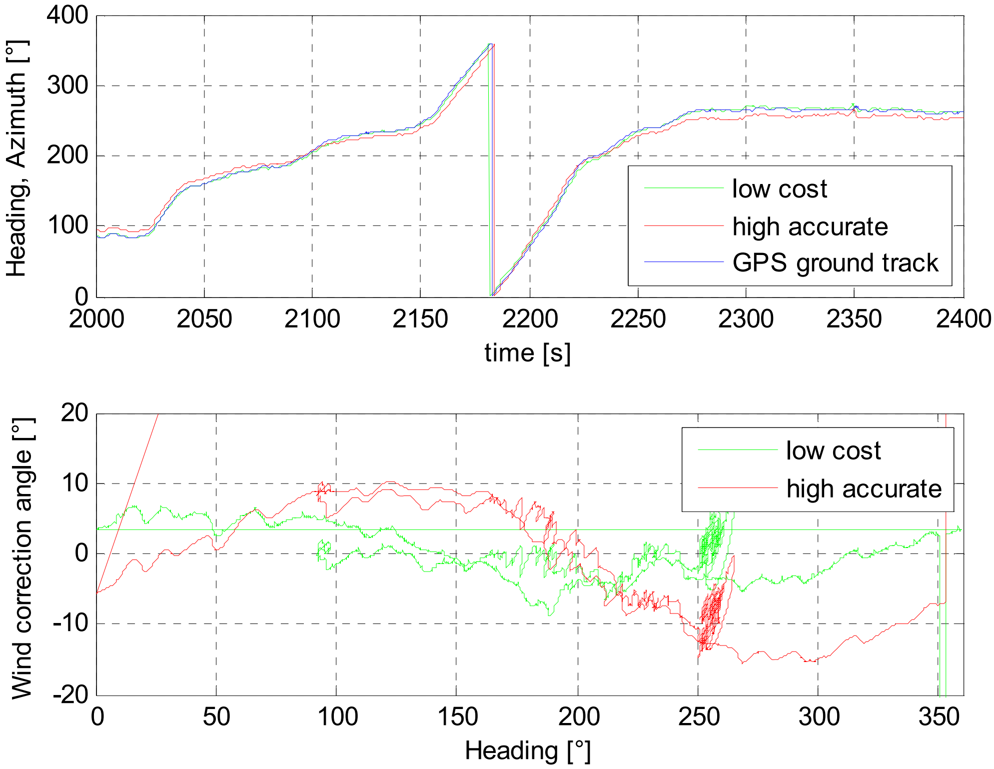


Figure 22: Comparison of heading for high accurate INS and low cost sensor

Summarized, the low cost system with GPS, IMU and earth perpendicular coupling is able to give reasonable results for the pitch and roll angle but not for the aeroplane heading. Another sensor for the heading computation is required. This could be a two antenna GPS system which is not yet available on the market as commercial low cost system, or a magnetic sensor which provides heading information but has to be calibrated precisely with high effort.

Regarding the position measurement no significant difference between the high accurate and the low-cost GPS receiver can be seen in the flight track plot as shown in Figure 23.

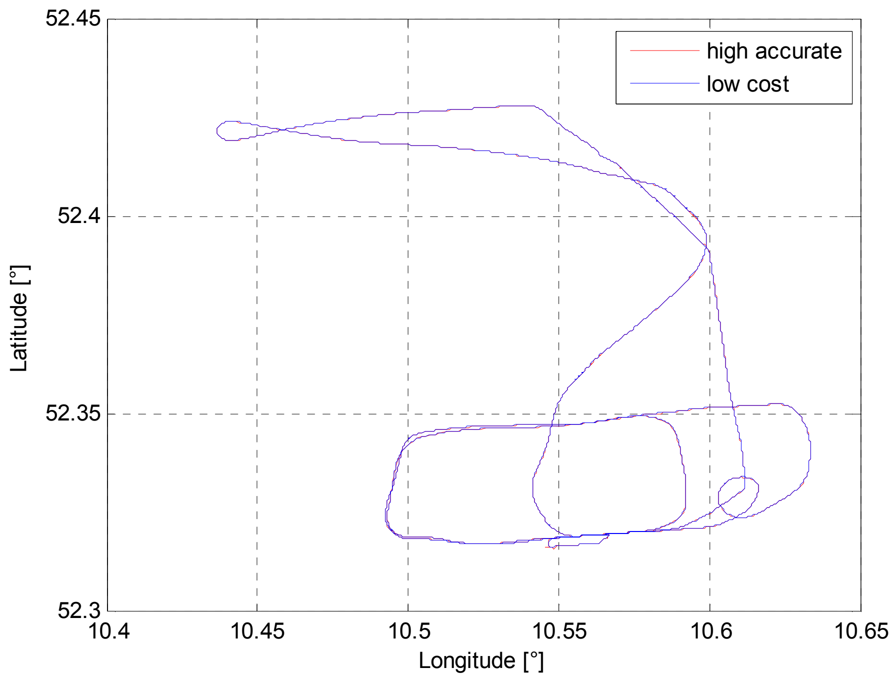


Figure 23: Comparison of GPS track

The result for the altitude is different. Between the high accurate and the low cost receiver a difference in the order of 50 ft plus a mean difference of 120 ft was found.

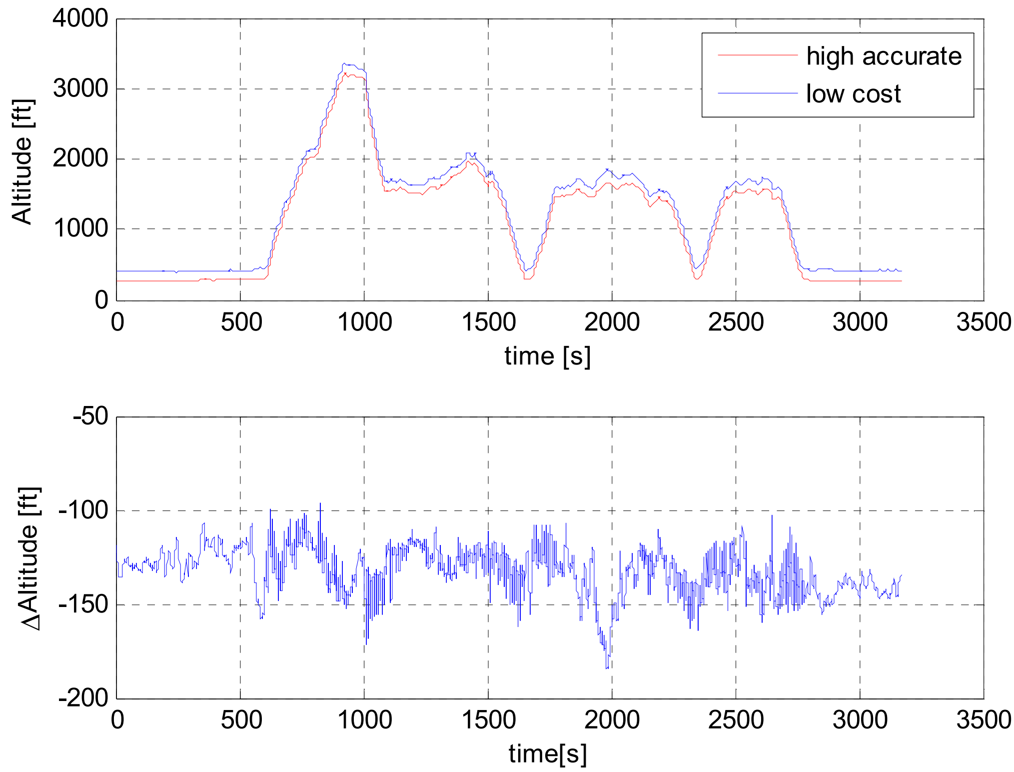


Figure 24: Comparison of GPS altitude

As mentioned before a camera was installed at the ceiling of the cabin. The perspective was set to the instrument panel only and not to the window to avoid high contrasts within the picture. With this setup pretty good results were achieved. Picture 23 shows a photo shot of this video camera. All indicators are clearly recognized. Not all numbers on the indicators are readable but this problem could be solved by taking a detailed photo of the installation. No problems with the contrast and focus of the camera arose by any light conditions during the trial flights – even with direct sun light from the front. Further tests with different light condition are necessary.

Figure 25: Picture of the video camera

As mentioned earlier some values which are not measured directly can be estimated and computed by using different quantities. As a first result the estimation of the angle of attack is shown. From the load factor n_z, the dynamic pressure q and some aeroplane specific quantities the angle off attack can be computed with the following equation:

$$\alpha = \frac{n_z \cdot m \cdot g}{q \cdot S \cdot C_{L\alpha}} + \alpha_0 \qquad \{4\}$$

The wing area S is a geometric value and g a constant (acceleration of the earth) while the lift increase coefficient $C_{L\alpha}$ and the offset α_0 have to be estimated for each type of aeroplane. The direct measurement of the aeroplane mass m would be challenging and therefore a typical load has to be defined. The result is shown in Figure 26. As reference the readings of the wind vane installed at the wing boom were taken.

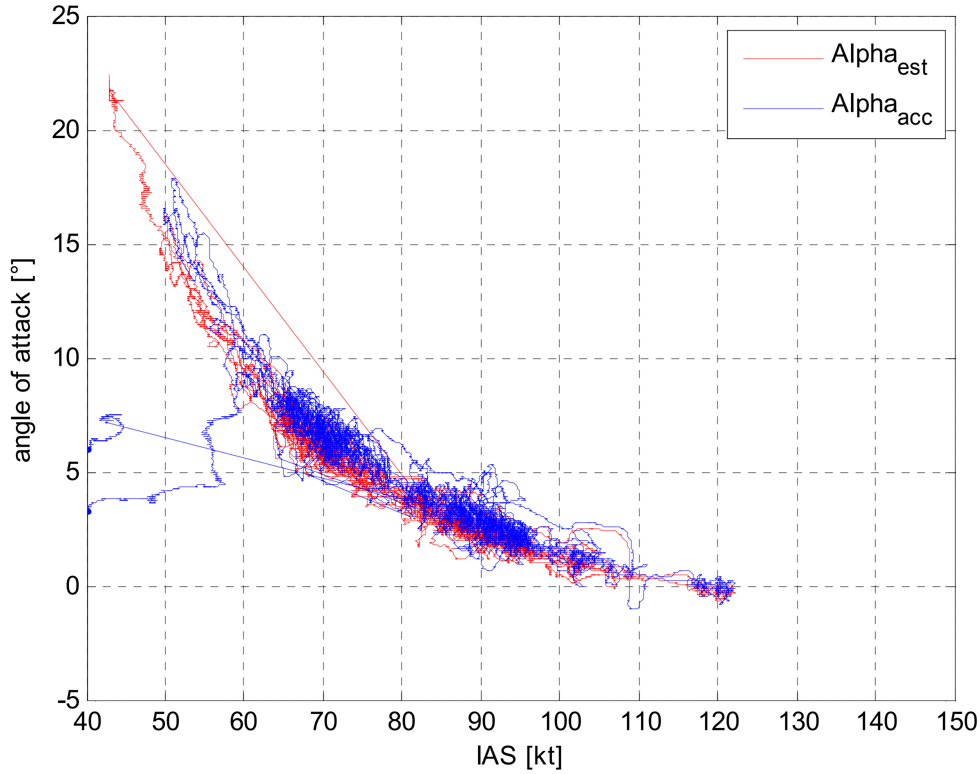


Figure 26: Comparison of angle of attack

A similar equation can be used for the estimation of the side slip angle.

$$\beta = \frac{a_y \cdot m}{q \cdot S \cdot C_{Y\beta}} + \beta_0 \qquad \{5\}$$

Instead of the vertical load the horizontal lateral acceleration is taken and another coefficient $C_{Y\beta}$ is used.

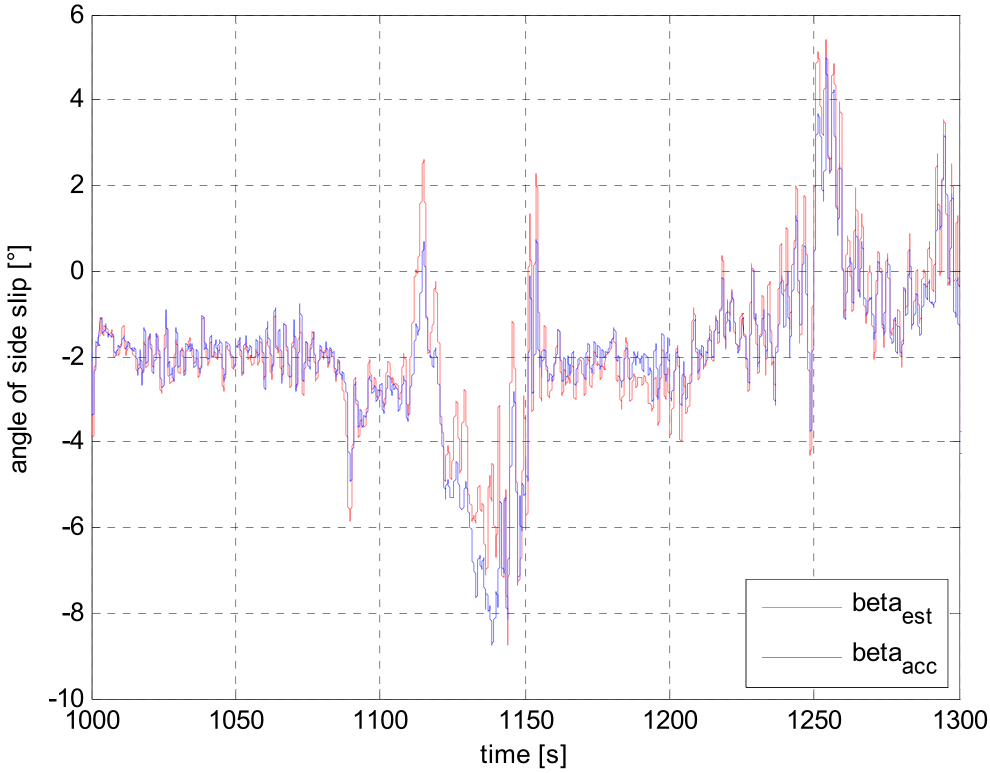


Figure 27: Comparison of angle of side slip

At least good results were achieved for this part of the flight. The deviation goes up to 5° but manoeuvres can be indentified.

Furthermore it was tested to estimate the control inputs. The aileron input can be obtained by using the angular rate on the longitudinal axis. The aileron deflection ζ can be estimated by the following equation:

$$\zeta = q \cdot p \cdot C_{\zeta} + \zeta_0 \qquad \{6\}$$

Here is:

- q dynamic pressure
- p angular rate of the longitudinal axis
- C_{ζ} and ζ_o are aeroplane specific constants to be calibrated

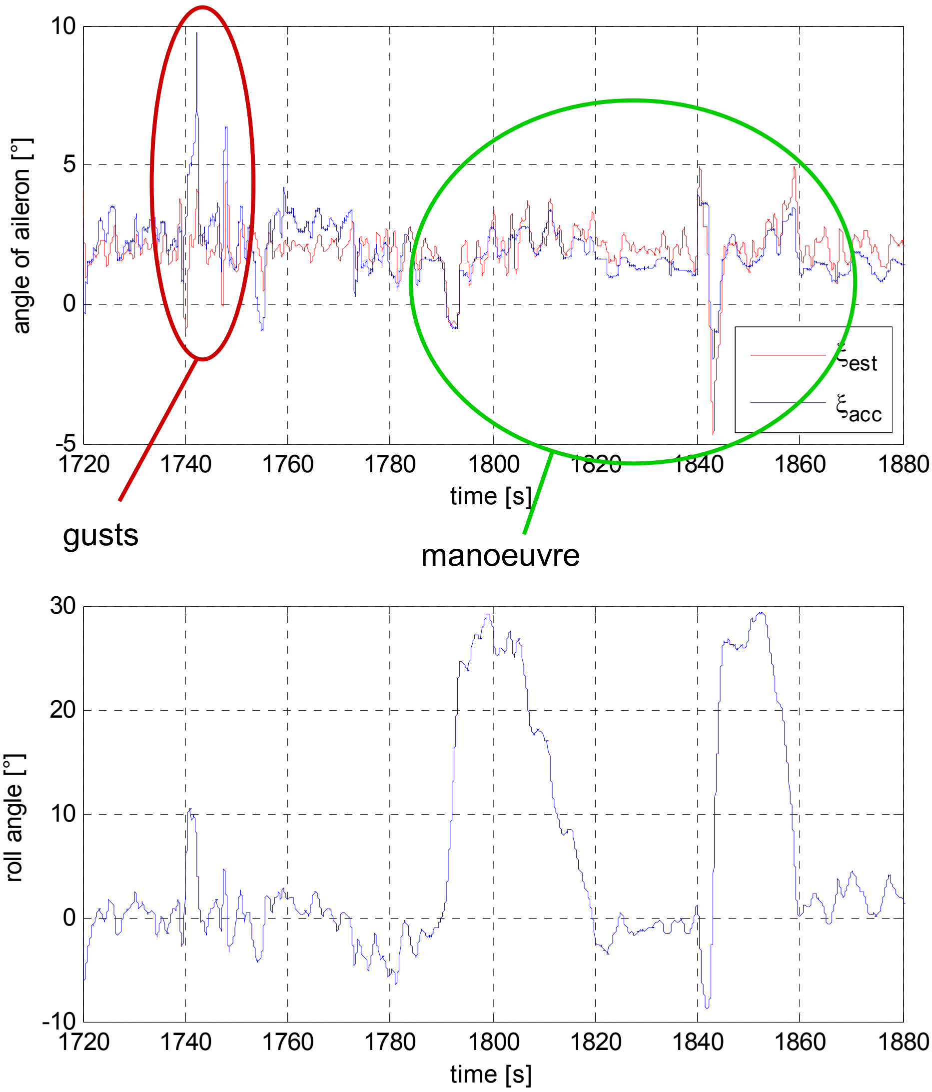


Figure 28: Estimation of aileron input

This method only works for manoeuvres and not for aileron inputs made to correct for gust influence. This is shown in 6. At the time of 1740 to 1750 the aeroplane was affected by gusts. The measured signal shows a short but hard input of up to 10° deflection while the estimated aileron deflection shows almost no input. In case of a manoeuvre both signals show almost equal values. This is shown at the time of 1790 to 1860 when the aeroplane performs two turns.

As final example a hard landing should be analysed. At first the manoeuvre is explained with the results of the high accurate sensors in Figure 29.

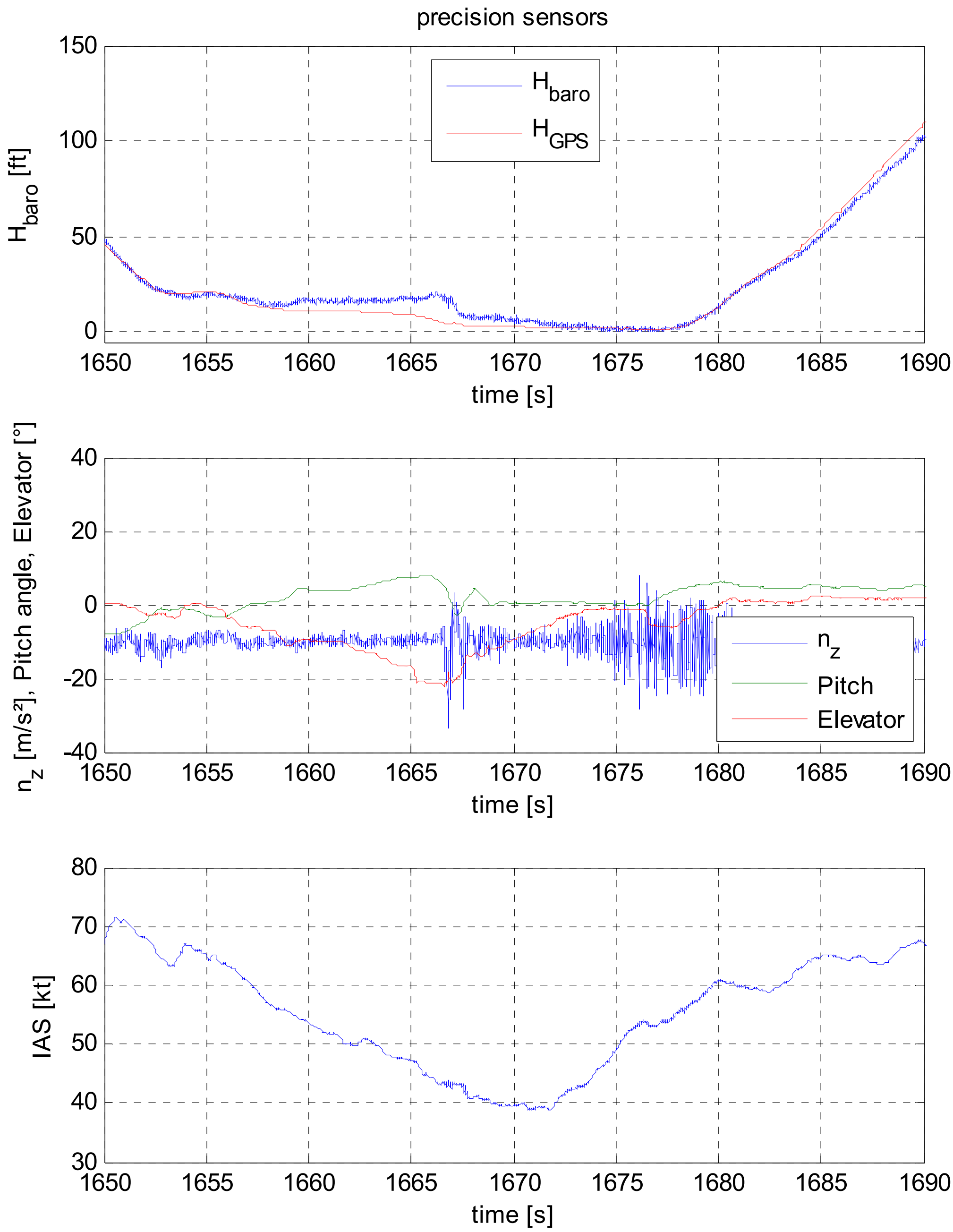


Figure 29: hard landing with high accurate sensors

The aeroplane is descending up to the time 1653 s when the flare starts at a height of 20 ft. In this phase the elevator is pulled more and more until it reaches its maximum deflection at 1665 s. At this point the aeroplane still has a height of 10 ft. Now the nose starts pitching down combined with an increasing vertical speed. At 1667 s the aeroplane hits the ground for the first time with an acceleration of 3 g. At 1677 s the aeroplane is pitched up by pulling the elevator and is taking off again. The barometric altitude is affected by the position error and the ground effect. This is obvious as the barometric altitude drops at 1667 s just after the aeroplane hits the ground.

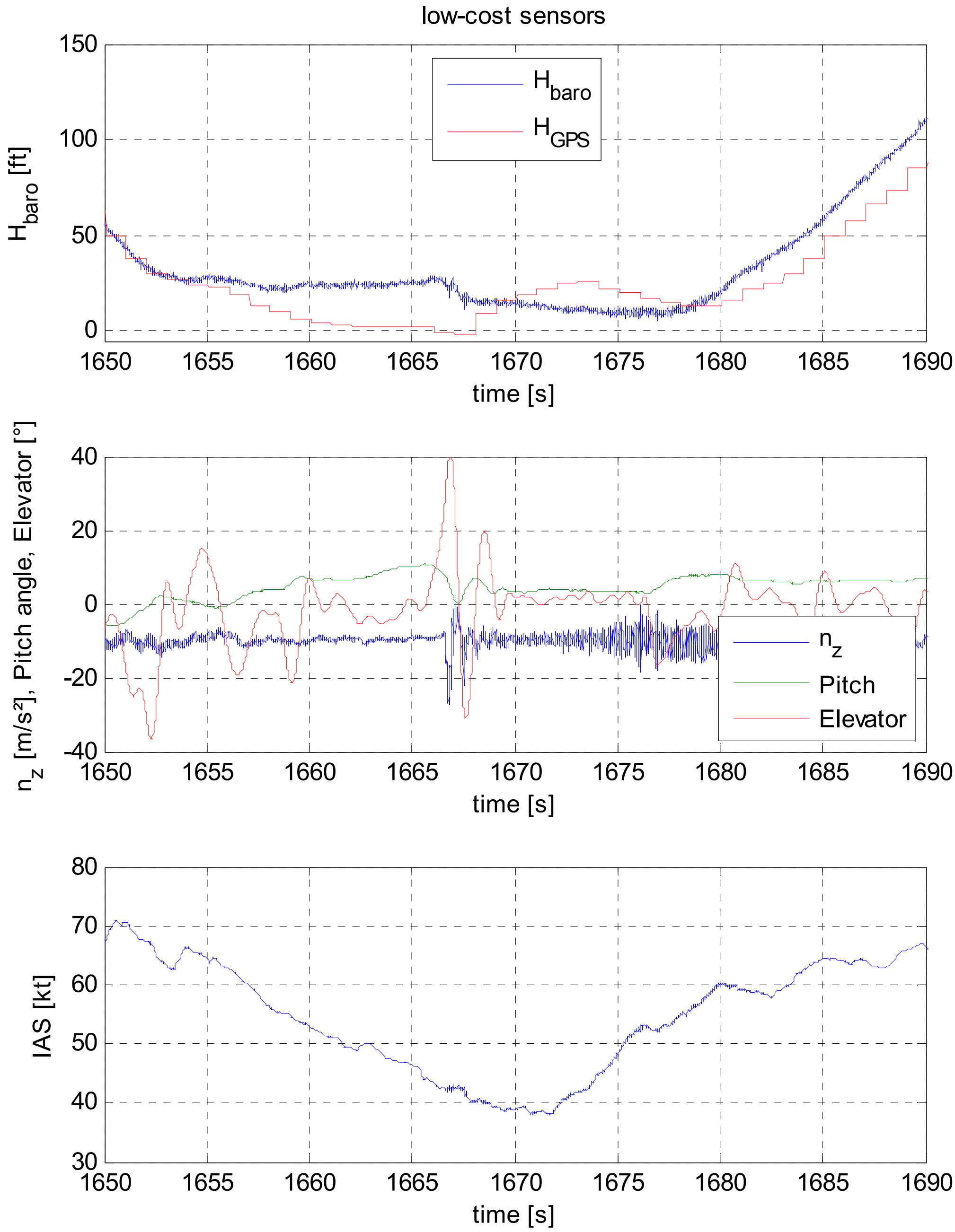


Figure 30: hard landing with low cost sensors

The results for the low cost sensors are depicted in Figure 30. The airspeed shows no significant difference for both sensors. The dropping pitch angle at 1665 s can be recognized also. The GPS altitude does not show the altitude seconds before the first ground contact correctly. The low cost receiver shows a good flare at less than 5 ft above ground which is too low. Another problem with the GPS altitude arises at 1668 s when it is increasing during the ground run up to 30 ft. This is definitively a measurement error with still unknown reason. The measured acceleration is comparable to the high accurate signal while the test of estimating the elevator deflection yields useless results. A direct measurement of the control inputs would be essential to analyse this kind of manoeuvre in detail.

7.8 Prototype design

In this section different design suggestions are made depending on the age / equipment of the aeroplane.

In chapter 7.3.3.3 four different categories are described as technical base of the installed avionic and instrument system. As aeroplane with digital / electrical avionic system and non electrical engine sensors are extremely rare this category II.a is neglected in the following. The expression “non electrical sensors and avionic” refers to instruments for speed, altitude, climb speed and attitude as avionic and engine sensors which have no electrical output useable for a data recording.

Three categories are remaining:

- I. all non electrical sensors for avionic and engine (most older aeroplane)
- II.b non electrical avionic and electrical engine sensors (mostly with digital output)
- III. glass cockpit with digital output for avionic and engine instruments

Due to the different technical base in category I, II.b and III three different prototype designs are suggested. With a maximum allowable cost of 5.000 € a FDM in category I would not fulfil all requirements of application B (maintenance). Since only an engine speed sensor can be realized within the cost limit, only the maximum engine speed limit exceedance can be observed. Other states of interest for maintenance like oil pressure or temperature won’t be available.

For category II.b and III all application scenarios could be realize within the cost limit.

7.8.1 Design 1 (older aeroplane)

Aeroplanes of category I. do not have any sensors or instruments which could be used for a FDM system. All sensors for the state which should to be recorded need to be installed in addition. Within the desired cost limit a full instrumentation of the engine is not possible. Only the engine rotational speed (RPM) and the manifold pressure can be realized. Therefore this system design has limitations for the use in application scenario B (maintenance).

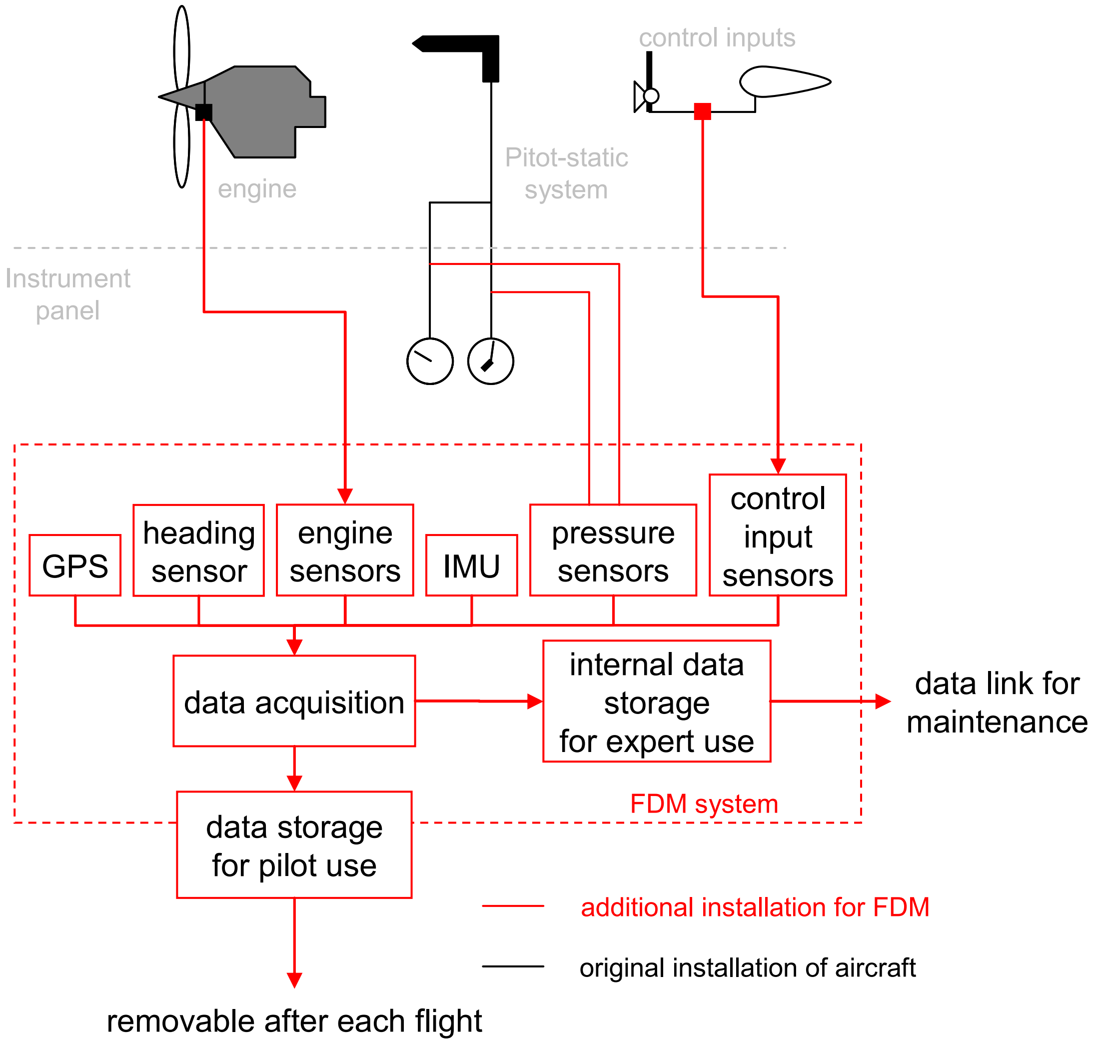


Figure 31: Block diagram for FDM system for older aeroplane without electrical sensor

All sensors and the data acquisition system can be installed in a small box that can be mounted in the instrument panel. Two different data storages are suggested for the different applications. One internal memory - which could be crash or fire proof – should record all data of the last two flight hours with high frequency and in addition the pre-processed data like mean values and the event triggered limit exceedance. This data storage should be readable for accident investigation experts and maintenance experts only.

The second data storage records data of the last flight at least with high frequency. The memory card must be reachable for the pilot for a fast access after the flight. So the pilot can put the memory card into a standard PC for his own analysis with adequate software or he can copy the data to a database for further investigation by experts.

7.8.2 Design 2 (aeroplane with electrical engine instruments)

The aeroplanes of category II b are equipped with electrical sensors for the engine states. These data are collected, digitized and visualized with the help of an indication module. Most of these systems are equipped with a digital output which could be used to transfer the data to the FDM system. The attitude and air data sensors do not have an electrical output. Therefore these sensors need to be included into the FDM system. The control input sensors also have to be included into the FDM system.

This system design is almost identical compared to design 1. In addition a digital data link of the engine instruments to the data acquisition of the FDM system is included. Therefore the additional engine sensors of design 1 are omitted.

For different types of engine instrument systems different software drivers are required. Compared to design 1 this system can record more engine states which are provided by the aeroplane instrumentation. The system and installation cost are reduced somewhat.

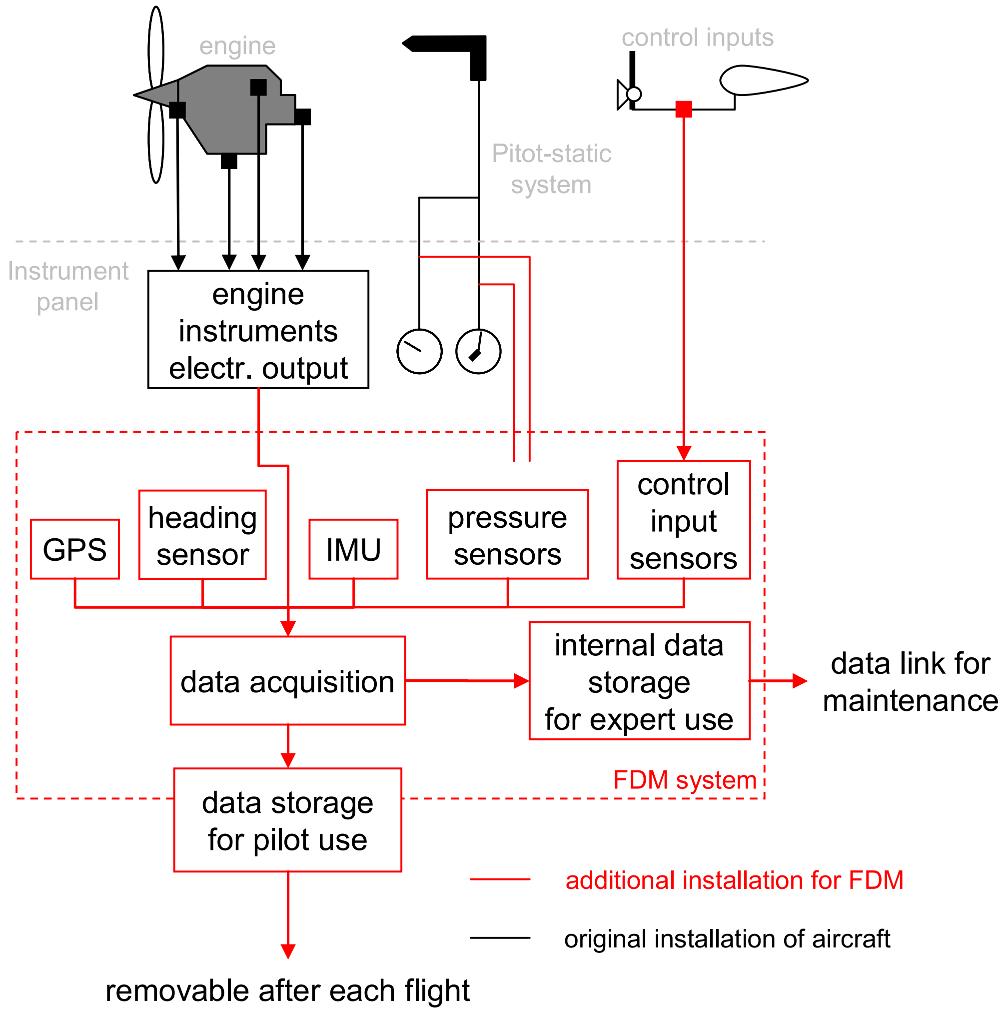


Figure 32: Block diagram for FDM system for aeroplane with electrical engine instrumentation

7.8.3 Design 3 (aeroplane with "glass cockpit")

The aeroplanes of category III include sensors for all required quantities in the glass cockpit system. All data are available in digital format. Therefore the FDM system is reduced to the data acquisition module and the data storage. The only additional sensors left are the control input sensors.

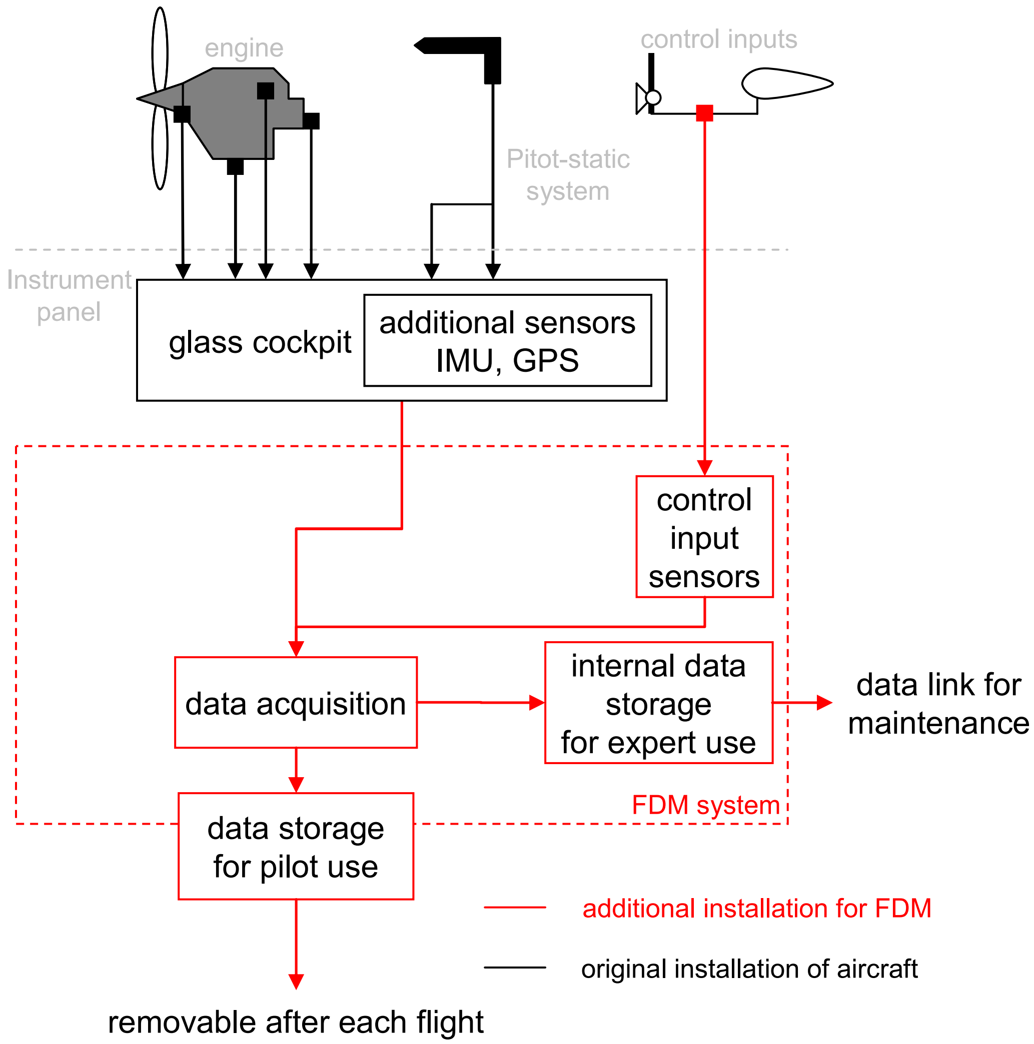
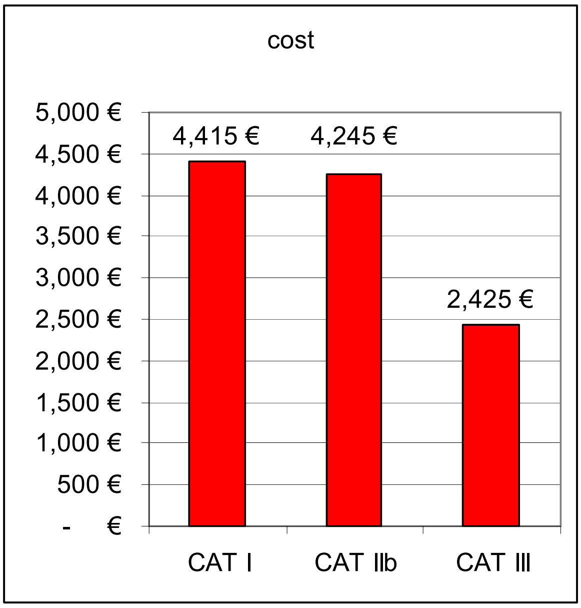


Figure 33: Block diagram for FDM system for aeroplane with electrical engine instrumentation and glass cockpit

7.8.4 Conclusion of prototype design

As the instrumentation of the aeroplane is too different, one design of an FDM system for all categories of aeroplane does not make sense. In category I all sensors have to be installed additionally. Therefore the cost of this design is the most expensive. As the desired cost limit of 5.000 € does not allow the installation of all engine sensors this design has some limitation with respect to maintenance. 37 observed states are possible for 4.415 €. Aeroplanes with electrical engine sensors (CAT IIb) allow the recording of all required engine states. As the installation effort is less compared to design 1 the system and installation cost are reduced a little to 4.245 € with an increase of the number of observed states to 48.



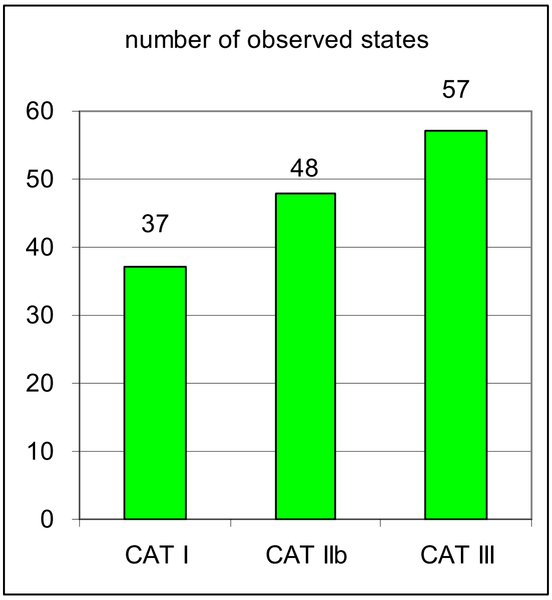


Figure 34: Comparison of cost and number of observed states

Aeroplanes of category III already have nearly all sensors which are required. Typically even more sensors are included so this design 3 can record 57 states at a significant lower price of 2.425 €.

8 Outcomes

The findings and results will be valuated in this chapter regarding the aims and objectives defined in chapter 4, in the following order:

Assessment of developed application scenarios and safety benefit assumptions	Ch. 8.1
Assessment of determination of sensor configurations	Ch. 8.2
Assessment of flight trials	Ch. 8.3
Assessment of prototype design	Ch. 8.4
Comparison with existing solution	Ch. 8.5
Assessment of safety benefit	Ch. 8.6

The value of this study is the development of a complete line of argumentation from the description of applications of FDM for light aeroplane to the possible technical conversion.

8.1 Assessment of developed application scenarios and safety benefit assumptions

Flight data monitoring (FDM) is mandatory and successfully applied in commercial operation of large aeroplane embedded in the safety management system (SMS), see Ch. 5.2. The common used definition of Flight Data Monitoring is:

"*Flight Data Monitoring (FDM) is the systematic, pro-active and non-punitive use of digital flight data from routine operations to improve aviation safety.*", see e.g. [29].

Although FDM is safety beneficial on it's own it should advantageously be embedded in a SMS. For commercial operators of light aeroplane it will be much easier to adapt FDM and SMS concepts from large aeroplane operation than for non-commercial operators. For this the available concepts must be carefully adapted considering the sports and leisure character of this operation.

The compiled application scenarios are safety-oriented applications, but no applications of supervision from the law enforcement agencies. Five application scenarios were found, see Ch. 7.1:

A. Quality improvement of flight operation and training

The in-flight stored data will be analysed by a third party to identify potential ineffective or hazardous procedures in training or other operation. Findings and results are sent to the pilot and the operator and handled according to the established operator's FDM regulations. It is based on the knowledge of standard operation procedures (SOP). The light aeroplane fleet is very heterogeneous compared to large aeroplane and it will be extensive to define SOP's for all types.

B. Maintenance

The attention of maintenance personnel is focused on technical conditions of the aeroplane engine and the airframe. The knowledge of the (pre)history of components since the last regular maintenance can help to identify urgent technical problems. The FAA approved *engine trend monitoring system* (ETMS), see [41], is an example of an established system.

C. Direct application in training and other operation

The direct application describes the primary use of recorded data for self-study. Automated limit exceedance checks or automated checks for derivation from standard operation procedures (SOP) may be included. The pilot is responsible for the usage of the data. No warnings or messages are generated to third parties. The pilot can reflect his actions and the use of this method can be a part of the whole training process.

D. Accident/Incident investigation

The accident/incident investigation of light aeroplane is not a FDM application in the above described meaning, because it is re-active and not pro-active. But data analysis and interpretation is similar to FDM. The regular provision of a basic set of aeroplane state data for accident/incident investigation will improve the quality and the outcomes.

E. Administrative needs

This application describes the statistical collection of air activity legislative purposes and purposes of flight operators (fleet statistics).

To be considered must be the legal force of such a system if it is installed, even if it is not intended to be used for this purpose. If on-board data is stored then not safety related requests will appear, e.g. from the law enforcements agencies or third parties (insurance companies, etc.). This will affect the user acceptance; but the user acceptance is an essential premise for beneficial application of FDM and SMS. Or with the words of others [39]:

> *It cannot be stressed enough that a Flight Data Monitoring (FDM) program is and must remain a safety program.*
>
> *1) non-punitive*
>
> *2) confidential*
>
> *3) trend monitoring and not a "policing" system*
>
> *"FDM is the pro-active and non-punitive use of flight data from routine operations to improve aviation safety". Mutual trust and confidentiality between all parties is essential.*

Everyone that is involved in this topic must be aware of this circumstance.
An ideal SMS would prevent all accidents and would decrease the number of incidents to a minimum, but commonly known no real existing system is perfect. The rate of deviation from the ideal state cannot be designated within this study.

The safety benefit of a stand-alone FDM system will be less compared to a FDM embedded in a SMS. A substantive quantification of that decrease is only possible using detailed planned or established FDM systems.

In Figure 1 and 2 it can be seen that the process of FDM is characterized by a cycle. It is obvious that a safety benefit is only possible, if this cycle is closed. The focus of this study is on the technical feasibility and not the development of a whole FDM system that is why a potential safety benefit is defined. In the context of this study it is assumed that, the *potential safety benefit* of the technical part of the FDM is not decreased by non-technical factors (e.g. human errors in handling the FDM).

The assumption of a *potential safety* benefit with known technical constrains changes the safety benefit related task of this study from "assessment of safety benefit" to the use of the "safety benefit as design criterion or optimization criterions". In Ch. 8.6 will be assessed if the derived system complies with the assumptions or if there are restrictions of application scenarios due to technical reason.

For the five application scenarios the scale of the *potential safety benefit* and the time horizon in which the safety benefit may appear is depicted. The result of the detailed discussion in Ch. 7.2 can be found in next the table.

Application scenario		Expected scale of safety benefit	Time horizon of effects (after adoption)
A	Quality improvement of flight operation and training	Potentially high	1 decade
B	Maintenance	High potential to minimize number of technical accidents/incidents	1 decade
C	Direct application in training and flight operation	Potentially high / Potentially medium	1..3 decades
D	Accident/Incident investigation	Low / Potentially high	1 decade
E	Administrative needs	Potential sustainability	1 decade

Table 21: Comparison of potential safety benefit

It is cognizable that the five described application scenarios do not only support the FDM but rather cover the whole bandwidth of on-board data related measures within a SMS.

Adverse effects of an on-board data collecting system must be considered. The user acceptance must be given in general. Each negatory attitude to FDM can reduce the safety benefit. The feeling of being observed by the FDM may cause uncertainness by the pilot, or reverse may give an unfounded feeling of safety.

That is why the benefit and the protection of data privacy for each pilot must be pointed out; costs must be kept within acceptable limits.

8.2 Assessment of determination of sensor configurations

One major task was to select the set of *states to observe* as a basis for the investigation of the technical feasibility. The heuristically based criterions gave no hard facts to exclude or include states and several non-technical and statistically difficult ascertainable aspects have exposed as not negligible. As several criterions are not independent from other they might better characterized as points of view on the topic.

All criteria were discussed in detail separately to understand the importance of each one. This is the base for the content based ranking of these criteria. The detailed documentation allows anyone to follow our conclusions for the afterwards ranking. The ranking of the discussed criteria sets the importance of them into relation.

The detailed discussion was part of the approach to bring the criteria together to a founded set of *states to observe*. Hereby a *multi criteria approach* was used. It is less a strict methodology than a scheme to handle the interdependencies of the criteria. As numerous conclusions (e.g. exclusion of states) may depend on the perception of the reader, most reasons were explained. Even if the reader has several heavily deviating opinions he may use the given structure to derive a system and its costs.

One major part of this open structure is the description of possible technical realisations and roughly estimated costs for the measuring of every state. The given costs shall be seen as substitute values to assess the relative costs and the scale of the overall costs. The result of this consideration is assessed in Ch. 8.5. More detailed cost estimation must be done from a potential commercial provider.

For all five application scenarios a system could be derived that achieves the goal of less than 5.000€ per installed system. A system that can serve all application scenarios was estimated to be 7.300€ worth some concessions had to done. As the use of the investigated system for maintenance purposes may save maintenance cost we assumed that this part of the system must not be included in the 5.000€-system. The price of the resulting, reduced system is approximately 4.400€.

If the state information, that are captured on video or audio, can be read out to timescale data with appropriate data rate and accuracy for low overall costs, then these two methods are to be taken into account as a substitute for direct sensors. As the investigation of video and audio devices was not proposed, these possibilities were included only conceptual.

8.3 Assessment of flight trials

The flight trials were made to demonstrate the possible use of low cost systems for a FDM system. This was made by comparing the low cost sensors (i. e. pressure transducer, GPS and IMU) with high precision sensors.

The sensor accuracy stated in ED-112 was not obtained with the low cost sensors. But the results were sufficient to give a good understanding of the flight and the manoeuvres. Especially the attitude accuracy depends on the dynamic of the flight. A low cost system is not able to provide reasonable results for aerobatic manoeuvres and uncontrolled flight conditions. A post processing might improve the accuracy but the effort would be too high for general use. In case of accident investigation the fact that an uncontrolled condition occurs is of primary interest, and not the exact characteristics of the whole flight path. Furthermore the high effort of a post processing is justifiable for accident investigation so finally a low cost system will meet the demands of accident investigation.

A strict definition of accuracy for quantities narrows the manufacturer for realising low cost sensors. A technical solution giving good results for most situations at low costs might be blocked through this. As an example the attitude is given. The IMU tested in the flight trials reached an accuracy of about 3° for level flight and smooth manoeuvres. For harder manoeuvres the error increased to about 5°. Though the maximum error is quite high this system showed up to give reasonable results to understand the flight. So a hard landing for example could be analysed clearly.

Based on the result by the flight trials the following accuracies are sufficient:

Sensor	Accuracy
static pressure	2 % full scale
dynamic pressure	1.5 % full scale
acceleration	0.3 m/s²
attitude	3° for level flight 5° for manoeuvres

Table 22: Recommended minimum accuracies

It might be useful to define manoeuvres which reflect a typical flight operation. New systems could be compared initially to a reference system.

The flight trials showed that the angle of attack and the angle of side slip can be estimated using the inertial data of the IMU and the air data with reasonable accuracy. The use of additional sensor for these quantities is not necessary.

The estimation of the control inputs gave no useful results. The quantities have to be measured with additional sensors.

The heading information of a system consisting of GPS and IMU with earth perpendicular coupling gave no sufficient accuracy. Here an additional sensor has to be used. This could be a two antenna GPS system or a magnetic sensor.

8.4 Assessment of prototype design

An FDM system based on low cost sensors is able to measure numerous states with adequate accuracy so the technical feasibility is given in general.
The technical equipment of the aeroplane shows a wide variety. This ranges from old aeroplanes with only mechanical sensors to modern aeroplanes with a “glass cockpit”. Following this it is impossible to find one design that fits all. Three major categories were found described in the chapter 7.8. A system for older aeroplanes with only mechanical instruments does not fulfil the requirements of all application scenarios. This affects the use for maintenance purposes. As financial advantages

might arise from using FDM in maintenance the owner of such aeroplanes might be willing to accept the higher costs.

Generally spoken the number of states observed by an FDM increases for more modern aeroplanes while the system and installation costs are reduced. This is based on the fact that modern aircraft include more sensors so they need not to be installed additionally.

The use of two independent data storages is recommended. An internal storage records all data as time series for at least the last two flight hours and pre-processed data. This storage is accessible by maintenance staff and accident investigation experts only. The second storage records all data as time series of the last flight. The pilot should have access to the memory card so a fast removal is required after the flight. These data can be transferred to a standard PC for further analysis and post processing or visualization (i. e. direct application in flight training).

As the cost of storage is low the requirements of ED-112 for the data rate should be considered as minimum. These requirements are mainly made for the accident investigation. The direct application in flight training would be improved by a higher data rate - especially the visualization. An output data rate of 10 Hz is suggested.
All sensors and the data acquisition system of a low cost FDM system can be installed into a small box that can be mounted in the instrument panel. The size might be smaller than 1000 cm^3 and the weight less than 0.7 kg. The power consumption is estimated to about 30 W. Especially the size will decrease with technical progress in the future. This would enable an installation onboard almost every general aviation aeroplane.

8.5 Comparison with existing solutions

Up to now and to our knowledge there is only one certified FDM system specially designed for the use in light aeroplane (Capacq: GA-FDM, [41]), but it is limited to the installation in one type of aeroplane only, the Cirrus SR 20/22.

The Cirrus already features a modern cockpit layout with displays and digital data format, which facilitates the implementation of a flight data recording system.

The GA-FDM does not only store the data on-board but additionally sends status-emails after a flight – a feature which can improve maintenance tasks greatly.

The overall costs for GA-FDM are approx. 9$/hr (based on 40 flight hours a month for 3 years) – but this includes installation and leasing of the system (it will not be sold outright); for after-flight data processing we estimate an hourly rate of 3$ which is already included in the total amount above.

For the „reduced system“ (shown in Table 19) there is a system price of 4.400 €. Under the same assumptions as above (40 hours each month for 3 years) there is an hourly rate of 3€, for data processing we estimate another 2€/hr, for a total of 5 €/hr (approx. 7 $/hr); the costs for the „combined system“ are estimated to 7.300 €, that is 5 €/hr plus 2€/hr data processing for a total of 7 €/hr (10 $/hr).

So the costs derived in Chapter 7.6.7 are realistic.

8.6 Assessment of safety benefit

As stated in Ch. 7.2 and Ch. 8.1 the assessment of the safety benefit is the assessment if the derived systems restricts the *potential safety benefit* for the five application scenarios due to technical reason.
The derived sensor configurations for every application scenario (Ch. 7.6.1-7.6.6) and the "Combined" sensor configuration (Ch. 7.6.7) do not bring out restriction for the application scenario because all necessary states are observed. The "Reduced" sensor configuration (Ch. 7.6.7) would restrict the application in maintenance because only 3 of the 12 engine states are observed, but engine states are definitely preferred by maintenance experts (Ch.7.3.2.3).

The "Reduced" system considers the most extensive situation without any on-board existing digital data source. **The proposed prototype design 1 (aeroplane category I) would serve all application scenarios except the maintenance application (B). If any digital data source is available the proposed prototype design 2 (aeroplane category II.b) and design 3 (aeroplane category III), that can serve all five applications scenarios, are applicable.**

The assumed application scenarios include nearly all thinkable, safety related possibilities for the use of on-board data. By definition it is no "policing" system. The following groups may benefit from the derived technical systems:

- All pilots: More safety by the possibility to implement a FDM system for light aeroplane
- All pilots: Possibility for self-analysis by self-study of flight data
- Especially student pilots but also all other pilots: Sustainable training
- Aeroplane owner/operator: Supervision of technical conditions of the aeroplane, possibly reduced maintenance costs
- Pilots, operator and owner: Safety increase by improved accident/incident investigation
- Aeroplane operator: Fleet statistics
- Legislation: Coherent data base for purposeful legislative work

.

9 Conclusions

- Flight Data monitoring (FDM) is a successful part of Safety Management Systems (SMS) in Commercial Aviation; it also can be adopted for the use in light aeroplane
- Because the demands for General Aviation (GA) are somewhat different compared to Commercial Aviation there must be especially suited FDMs and SMS for GA; light aeroplanes in commercial use should be treated like large aeroplanes
- There are different evaluation purposes for the on-board data (accident investigation, maintenance, training) which can be satisfied with only one single system
- Despite the different purposes there are common technical solutions
- Different types of data must be taken into account: additional sensors, digital sources (regular instrumentation), video and audio
- With low cost sensors the required accuracy according to ED-112 will not be reached
- The flight trials showed reasonable results with the use of low-cost sensors, so that manoeuvres could be indentified clearly
- It is possible to provide desired systems for a target price of less than 5.000 € and 2€/h DOC, without the use of a crash proof data storage
- In all cases potentially unauthorized misuse by policing parties must be precluded
- User acceptance is an essential necessity for a purposeful FDM.
- Broad user acceptance would be greatly improved if the system can be used for multiple tasks (e.g. maintenance and training; or TBO-elongation)
- Compared to a retrofit system for older aeroplane (additional sensors required) a modern aeroplane with only digital systems will facilitate the use of a FDM drastically

10 Recommendations

- With the use of a FDM as part of a SMS for light aeroplane there will be a significant safety benefit so it is recommended to be realised
- Two independent data storages are suggested: one internal for maintenance and accident investigation and one external (readily available) for flight training and pilot use
- The internal storage should be accessible by experts only during maintenance and for accident investigation tasks
- A crash proof storage would only be useful for accident investigation. As 85 % of unprotected storages survive an accident the use of crash proof data storage is not recommended to reduce the cost.
- A significant cost reduction of crash proof storage in the future due to technical improvement might enable the use
- Pre-processing of data (like histograms and mean values) for maintenance use and recording in internal storage
- An output data rate of 10 Hz is suggested
- An authoritative list of flight manoeuvres for in-flight calibration of new systems should be established
- All new electronic avionic and engine instrument system should have a common data output format so the data can be recorded by an FDM easily
- Three different types of FDM system are suggested to meet the different technical standard of existing aeroplanes:
  - non electrical avionic and engine instruments
  - non electrical avionic and digital engine instrument system
  - all digital “glass-cockpit”
- The first step should be a rather „soft“ implementation of a FDM (e.g. only for aeroplane with digital cockpit); after some years of experience with such a system the impacts should be reviewed and assessed
- The use of SMS must be combined with changes in pilot training procedures

- Different presentation tools must be developed:
    - Pre-processed data and specified diagrams for maintenance
    - Graphical presentations (e.g. virtual instrument panel) for flight training
- An open data format is suggested for the FDM so open source software projects are encouraged
- It should be investigated whether a governmental funding would improve the acceptance and implementation of FDM for light aeroplane

11 References

11.1 Abbreviations

A/C	Aeroplane
AFM	Aeroplane flight manual
bCOS	body fixed coordinate system
CAA	Civil Aviation Authority (UK)
CASA	Civil Aviation Safety Authority (Australia)
C/G	Centre of gravity
CS	Certification specification
CS-VLA	Certification specification for Very Light Aeroplane [16]
CVR	Cockpit voice recorder
DFDR	Digital Flight Data Recorder
DOC	Direct operating costs
EASA	European Aviation Safety Agency
ECCAIRS	European Coordination Centre for Accident and Incident Reporting Systems
ECU	Engine control unit
EUROCAE	European Organisation for Civil Aviation Equipment
ETMS	Engine trend monitoring system
FADEC	Full authority digital engine control
FDM	Flight Data Monitoring
FDR	Flight Data Recorder
FODA	Flight Operations Data Analysis
FOQA	Flight Operations Quality Assurance
FOM	Flight Operations Monitoring
GA	General Aviation
GNSS	Global navigation satellite system
ICAO	International Civil Aviation Organisation
IMU	Inertial measurement unit

MOPS	Minimum operational performance specification
MOR	Mandatory Occurrence Reporting
MCTOW	Maximum certified take-off weight
SMS	Safety Management System
SN	State number, see 7.4.2
SOP	Standard Operating Procedures
SSCVDFDR	Combined Voice and Data Solid State Digital Flight Data Recorder
SSDFDR	Solid State Digital Flight Data Recorder

11.2 Glossary

State:

All physical values or quantities that describe an aeroplane are states. In principle it's a very large number, e.g. strain at every point of the aeroplane structure.

State vector:

Not all physically possible values are useful for a FDM system. Within this study about 112 states were found to describe the aeroplane and the pilot's actions.

States to observe:

Not every state of the state vector is essential to fulfil the purposes of FDM. The *states to observe* are the essential ones, in the context of this study.

States to record:

Not every *state to observe* can be measured with low cost sensors but can be calculated. For any state in the list of *states to record* there must be a sensor.

Criterion and aspect:

These experessions are used to collect different points of view on the FDM topic. As they are at very different levels of abstraction (from single numbers to improper descriptions) it is difficult to find a single term.

11.3 Bibliography

11.3.1 General literature

[1] EASA: Specifications attached to the Invitation to Tender EASA/200/OP/18, 09/10/2007

[2] Kommission der Europäischen Gemeinschaft: Mitteilung der Kommission, Agenda für eine nachhaltige Zukunft der allgemeinen Luftfahrt und der Geschäftsreiseluftfahrt, KOM(2007)869, 11. Januar 2008

[3] Normstelle Luftfahrt: LN9300, Dez. 1970

11.3.2 Related working groups

[4] ONBASS – Onboard Active Safety System, Publishable final activity report, Revision 1.0, Euro Telematik AG, 18 4/18/2008

[5] ONBASS – Onboard Active Safety System, Application Domain Definition (D1.1), Revision 2.2, London Metropolitan University, August 2005

[6] ONBASS – Onboard Active Safety System, Principle of active system safety/ functional and reliability models (D1.2), Revision 0.3.4, London Metropolitan University, date?

[7] www.onbass.org, 01/12/2008

[8] Plantin de Hugues, P.: FLIGHT RECORDERS FOR LIGHTWEIGHT AIRCRAFT, presentation, 09/16/2008

[9] EUROCAE WG-77: Minutes of Meetings 1-4

[10] EUROCAE: Minimum operational performance specification for lightweight flight recorder systems, ED-155, draft 4, 2008

11.3.3 Regulations and specifications

[11] FAA: PART 121--OPERATING REQUIREMENTS: DOMESTIC, FLAG, AND SUPPLEMENTAL OPERATIONS, Subpart K--Instrument and Equipment Requirements, Sec. 121.343 Flight recorders, 01/01/2003

[12] EUROCAE: Minimum operational performance specification for crash protected airborne recorder systems, ED-112, March 2003

[13] ICAO: ADREP 2000 taxonomy, 01/04/2007

[14] Bundesministerium für Verkehr, Bau und Stadtentwicklung: Bekanntmachung der Bestimmung über die gewerbsmäßige Beförderung von Personen und Sachen in Flugzeugen (JAR-OPS1 deutsch) vom 10. April 2006, Bundesanzeiger Nr. 131a vom 15. Juli 2006

[15] EASA: CS-23, 11/14/2003

[16] EASA: CS-VLA, 11/14/2003

11.3.4 Accident reports and related literature

[17] Bundesstelle für Flugunfalluntersuchung: BFU-Jahresberichte 1999-2007

[18] BTRE Aviation Statistics – General Aviation 2006*

[19] UK Civil Aviation Authority: CAP673 Aviation Safety Review, May 1997

[20] Boeing: Statistical Summary of Commercial Jet Airplane Accidents Worldwide Operations 1959 – 2007, Aviation Safety - Boeing Commercial Airplanes, July 2008

[21] http://www.ntsb.gov/speeches/sumwalt/rls070919.htm, 10/18/2008

[22] EASA: Annual Safety Review 2007

[23] NTSB: Current Procedures for Collecting and Reporting U.S. General Aviation Accident and Activity Data, NTSB/SR-05/02, 07/29/2002

11.3.5 Training and AFM

[24] AC 61-21A Flight Training Handbook

[25] Cessna C172R Flughandbuch

[26] Aquila AT01 Flughandbuch

11.3.6 Literature about Flight Data Recording

[27] Kim, D. et.al.: Low-cost Lightweight Flight Data Recorders for General Aviation Aircraft, AIAA 2002-5800

[28] UK Civil Aviation Authority: CAP731 Approval, operational Serviceability and Readout of Flight Data Recorder Systems, 06/03/2006

11.3.7 Safety Management System (SMS) and Flight Data Monitoring (FDM)

[29] UK Civil Aviation Authority: CAP739 Flight Data Monitoring, 08/29/2003

[30] UK Civil Aviation Authority: CAP382 The Mandatory Occurrence Reporting Scheme, Information and Guidance, Nov 2005

[31] ICAO: Doc9859, Safety management manual, 2006

[32] Safety Management Systems Small Operator Pilot Implementation Project, Final Report; Transport Canada, Civil Aviation, Fall 2006

[33] FAA: Advisory circular AC120-92, Introduction to Safety Management Systems for Air Operators, 6/22/06

[34] Mitchell, K. et.al.: General Aviation Aircraft Flight Operations Quality Assurance: Overcoming the Obstacles, IEEE A&E SYSTEMS MAGAZINE, June 2007

[35] EASA: Position Paper on the compliance of EASA system and EU-OPS with ICAO Annex 6 safety management systems (SMS) standards and recommended practices for air operators. 12/20/2007

[36] http://www.caa.co.uk/default.aspx?catid=100&pagetype=70&gid=101&faqid=34,11/19/2008

[37] Bundesamt für Zivilluftfahrt BAZL, Switzerland: Implementation of Safety-Management-Systems (SMS), 8/16/2008

[38] UK Civil Aviation Authority, Safety Regulation Group: SAFETY MANAGEMENT SYSTEMS – GUIDANCE TO ORGANISATIONS, Oct 2008

[39] http://mail.beca.be/joomla/index.php?option=com_content&task=view&id=48&Itemid=35, 10/16/2008

11.3.8 Commercial provider of Flight Data Recording and Flight Data Monitoring

[40] www.ka-pi.de, 10/20/2008

[41] Capacg: GA-FDM (www.capacg.com, 02/10/2008)
Capacg: Safer Flights and lower Operating Cost for All Cirrus Aircraft
Capacg: General Aviation Flight Data Monitoring
Capacg: FDM – For General Aviation Fleets
Capacg: GA-FDM Introduction
Embry-Riddle/Capacg; Flight Data Monitoting for General Aviation, 2007

[42] www.ga-fdm.com, 10/21/2008

[43] www.jpinstruments.com, 21/10/2008

[44] Franz Aircraft Engines Vertriebs GmbH: Rotax-Flydat

[45] Dynon Avionics: EMS-D10, Engine Monitoring System

[46] http://www.teledyne-controls.com/productsolution/fdm/whyimplementfdm.asp, 10/16/2008

[47] Appareo: Aircraft Logging and Event Recording for Training and Safety

[48] https://www.swiss49.com/support_site/fdmPrinciples.html, 10/16/2008

[49] TL elektronic: TL-3424 User's manual Hradec Kralove, CZ, 2003

11.3.9 Literature for safety benefit analysis

[50] Rompe, K.: Bewertungsverfahren für die Sicherheit von Personenwagen : Kolloquium des Instituts für Verkehrssicherheit im TÜV Rheinland e. V., Direktionsbereich Kraftfahrzeugverkehr und Ford-Werke AG ; Veranstaltung der TÜV Akademie Rheinland am 1. Dezember 1983 in Köln-Poll

[51] Erke, H., Gstalter, H.: Handbuch für die Durchführung und Auswertung von Erhebungen, 1985

[52] Rompe, K.: Mehr Sicherheit durch Elektronik im Auto, TÜV-Kolloquium, Verlag TÜV Rheinland GmbH, 1987

[53] Eberstein, H. H.: Einführung in die Grundsätze des sicherheitstechnischen Rechts, Verlag Recht und Wirtschaft GmbH, 1987

[54] Grunow, D.: Sicherheitsbewertung von Personenkraftwagen, Berichte der Bundesanstalt für Straßenwesen, Fahrzeugtechnik, Heft F17,1996

[55] Niemann, H.: Geschichte der Straßenverkehrssicherheit im Wechselspiel zwischen Fahrzeug, Fahrbahn und Mensch / DaimlerChrysler, 1998

[56] Worthoff, Rüdiger H.: Anlagensicherheit in der Verfahrenstechnik, Shaker-Verlag, 2001

[57] Raths, H.-P.: Handbuch Betriebssicherheit : Vorschriften, Erläuterungen und Arbeitshilfen zu den Bereichen: Arbeitsschutz, Chemikaliensicherheit, Anlagensicherheit, Umweltschutz; Forkel, 2003

[58] Schlag, B.: Verkehrspsychologie, Mobilität – Sicherheit – Fahrerassistenz, Pabst Science Publisher, 2004

[59] Busch, S.: Entwicklung einer Bewertungsmethodik zur Prognose des Sicherheitsgewinns ausgewählter Fahrerassistenzsysteme, Fortschrittsberichte VDI, Nr. 588, 2004

[60] Internationale Strategien zur Unfallvermeidung; Hrsg.: DEKRA Automobil GmbH, 2005

[61] Fisi, W.: Handlungshilfen zur Gefährdungsbeurteilung; Verlag Forkel, 2007

11.3.10 Miscellaneous

[62] Schmand, C.: „Ground and Operational Communication for Electric Flight Bag Applications“, Technical University of Braunschweig, Institute of Flight Guidance, Diploma thesis , 2006

[63] http://www.vaisala.de/, 11/13/2008

[64] http://www.u-blox.de/, 11/13/2008

[65] http://www.micro-epsilon.de/ , 11/13/2008

[66] http://www.o-navi.com/, 11/17/2008

[67] http://www.buy-ei.com/, 11/17/2008

[68] Moore, Gordon E. (1965). "Cramming more components onto integrated circuits" 4. Electronics Magazine

[69] http://en.wikipedia.org/wiki/Moores_law, 11/19/2008

[70] http://www.aeec-amc-fsemc.com/aeec/projects/dfdr/index.html, 11/19/2008

[71] RTCA/DO-160E, RTCA Paper No. 111-04/SC135-645, Washington, DC 20036, 11/19/2008

[72] http://www.aircraftspruce.com/catalog/inpages/1105557.php, 11/19/2008

12 Appendixes

12.1 Detailed discussion of design criteria and aspects

12.1.1 Statistical/technical criteria

12.1.1.1 Analysis of Certification Specification (CS) and of Aeroplane Flight Manuals (AFM)

The analysis of the certification specification CS-23 [15] and CS-VLA [16] was done in two different ways:

The first approach assumed that any subsection of the certification specification can be expressed by a set of states. To detect a limit exceedance regarding this subsection all describing states must be recorded. The relative frequency of a state in a subsection state set was expected to be an indicator for the importance of this state.

But this is a wrong assumption because a very detailed formulated paragraph with several sub cases can pretend an importance that is not given by physically reality, see 6.1.1.

The second approach assumes a certified aeroplane. That means that all relevant data were within the prescribed limits during the certification process. It is not intended to use the FDM for certification flight trialing purposes.

So only limitations are considered which can be violated by the pilot. The following list can be used to check how many limit violations by the pilot the suggested system can detect. Two examples were analyzed:

Limitations according to CS-VLA (Certification specification for Very Light Aeroplane)		
1	CS-VLA 1	MTOW 750 kg day-VFR only
2	CS-VLA 3	only Non-aerobatic use (Stalls, Lazy eights, chandelles, steep turns up to 60° bank)
3	CS-VLA 29	center of gravity in limits (empty aeroplane)
4	CS-VLA 337	Limit maneuvering load factors: + 3,8; -1,5
5	CS-VLA 345	with flaps down: limit maneuvering positive load factor: +2,0
6	CS-VLA 1505	Never-exceed speed V_{NE} Maximum cruising speed V_{NO}
7	CS-VLA 1507	Maneuvering speed V_A
8	CS-VLA 1511	Flap extended speed V_F
9	CS-VLA 1519	Weight and center of gravity in limits
10	CS-VLA 1521	Power plant limitations: - maximum rotational speed - maximum allowable manifold pressure - time limits for engine states - maximum cylinder head temperature - maximum liquid coolant temperature - maximum oil temperature - minimum fuel grade
11	CS-VLA 1559	maximum landing gear operating speed V_{LO}

Table 23: Limitations according CS-VLA

Limitations according to CS-23 (Certification Specifications for Normal, Utility, Aerobatics and Commuter Category Aeroplanes; Commuter Category Aeroplanes will not be considered)		
1	CS-23.1	MTOW 5.670 kg
2	CS-23.3	Normal category: normal flying, stalls, lazy eights, chandelles steep turns up to 60° bank Utility category: all maneuvers of the normal category, spins (if approved), lazy eights, chandelles, steep turns or similar maneuvers with more than 60° up to 90° bank Aerobatic category: without restrictions (other than those shown to be necessary)
3	CS-23.29	center of gravity in limits (empty aeroplane)
4	CS-23.337	Limit maneuvering load factors: Normal: + 3,8; -1,5 Utility: + 4,4; - 1,76 Aerobatic: + 6,0; - 3,0
5	CS-23.345	with flaps down: limit maneuvering positive load factor: +2,0
6	CS-23.1505	Never-exceed speed V_{NE} Maximum cruising speed V_{NO}
7	CS-23.1507	Maneuvering speed V_A
8	CS-23.1511	Flap extended speed V_F
9	CS-23.1513	Minimum control speed V_{MC}
10	CS-23.1519	Weight and center of gravity in limits
11	CS-23.1521	Power plant limitations: - maximum crankshaft speed - maximum allowable manifold pressure - maximum ITT - time limits for engine states - maximum cylinder head temperature - maximum liquid coolant temperature - maximum oil temperature - minimum fuel grade
12	CS-23.1527	Maximum operating altitude
13	CS-23.1559	maximum landing gear operating speed V_{LO}

Table 24: Limitations according CS-23

The extracted paragraphs are represented in *aeroplane flight manuals* (AFM). The essential content of Aeroplane Flight Manuals (AFM) is defined in the according certification specification. Limitations to be attend by the pilot that can be found in two existing AFM are listed below:

CS-23 Aeroplane, e.g. Cessna 172 R		CS-VLA aeroplane, e.g. Aquila A210	
1	V_A	1	V_A
2	V_{FE}	2	V_{FE}
3	V_{NO}	3	V_{NO}
4	V_{NE}	4	V_{NE}
5	Maximum Speed with windows open (same as V_{NE})		
6	V_S	5	V_S
7	Max Engine RPM (Take off and continuous)	6	Max Engine RPM
		7	Max Engine RPM
8	Oil Pressure	8	Oil Pressure
9	Oil Temperature	9	Oil Temperature
10	Fuel Flow		
		10	Fuel Pressure
11	vacuum indicator		
12	weight and balance	11	weight and balance
13	allowed flight manoeuvres in normal/utility category	12	max/min load factor in normal/utility category
14	max/min load factor in normal/utility category	13	max/min load factor in normal/utility category
15	max. side slip time		
16	flap setting for take-off		
17	max. demonstrated cross wind component (no limitation)	14	max. demonstrated cross wind component (no limitation)
		15	Cylinder Head Temperature
		16	Voltmeter
		17	min/max outside temperatures for take off

Table 25: Comparison of essential AFM content of a C-172R and a A-210

Conclusions

The main limitations given by CS and AFM, which are prone to be violated by the pilot, are either specific speed limits or engine limitations.

While a exceedance of a speed limit solely will not in every case damage the aeroplane immediately, a flight with high speed while encountering severe turbulence can cause structural damage to the airframe; this damage can be assumed when looking at the load factors and thereafter maintenance action may be required. Without the recording and analysis of these data such damage may be masked until a complete breakdown will destroy the aeroplane.

The same spoken is valid for the engine states; short time exceeding of the max. RPM may be harmless to the engine but operation of the engine without oil pressure can yield to a catastrophic engine failure.

So for detecting possible violations of the limitations from CS and AFM at least the following states must be recorded:

- engine states (RPM, OP, OT)
- airspeed
- load factor

With these states the adherence to the majority of the limitations can be checked. Only some less important values are not implemented (e.g. aeroplane electrical system voltage).

12.1.1.2 Accident/Incident data review (ECCAIRS data)

The offer and the first approach (see 6.1.1) were based on the assumption that certain states are to prefer statically proven for FDM. Therefore it was contemplated to investigate statistically which states are necessary to describe accidents. Even if the aspired system would not be used for accident investigation but for FDM, the hazardous situations will be essential for the operation scenarios within FDM.

For this analysis the accident data of the *European Coordination Centre for Accident and Incident Reporting Systems* (ECCAIRS) seemed to be well suitable because of the differentiation and data collection, see [13]. The ECCAIRS is system that EASA uses to store and analyse accident and incident data. Such a data base is very suitable to determine frequencies of meaningful correlations and to quantify it. As this system is still in build-up this investigation is not possible.

The available data of the NTSB database is not suitable because of its sum up character. The needed detail information could be obtained only by exceeding effort.

As by-product the number of possible direct entries in the ECCAIRS system with the aspired system will be named.

Conclusion

The ECCAIRS system is well suited for the planned analysis. However it is in the build-up process and is not filled with sufficient detailed data for this purpose.

12.1.1.3 Accident/Incident data review (generalised view)

The definition of an accident according to ICAO Annex 13 is (condensed) if an aeroplane is substantially damaged or destroyed or if persons are seriously or fatally injured.

In all cases an accident occurs only if several malfunctions happen simultaneously or after each other; e.g. engine failure as primary reason, but a crash afterwards due to a stall in the final turn for landing; or a flight in bad weather conditions (main reason) but also a stall during a 180°-turn to fly out of the weather; engine failure during take-off (main reason), but because of a wet runway the braking action was poor and the aeroplane overshoot the runway. So the cause of an accident can be divided in multiple single reasons; in the statistics the main cause of an accident is only presented.

EASAs Annual Safety Report 2007 [22] gives an overview of light aeroplanes accident according CAST/ICAO Common Taxonomy Team (CICTT) categories. The following figures show a different category distribution for fatal and non-fatal accidents.

At the first look these statistics seem to be well suitable to derive different state subsets. But conditions of every accident are different. That’s why a system derivation will always start with the trajectory information to get some basic information. The next subclass that must be considered are engine data.

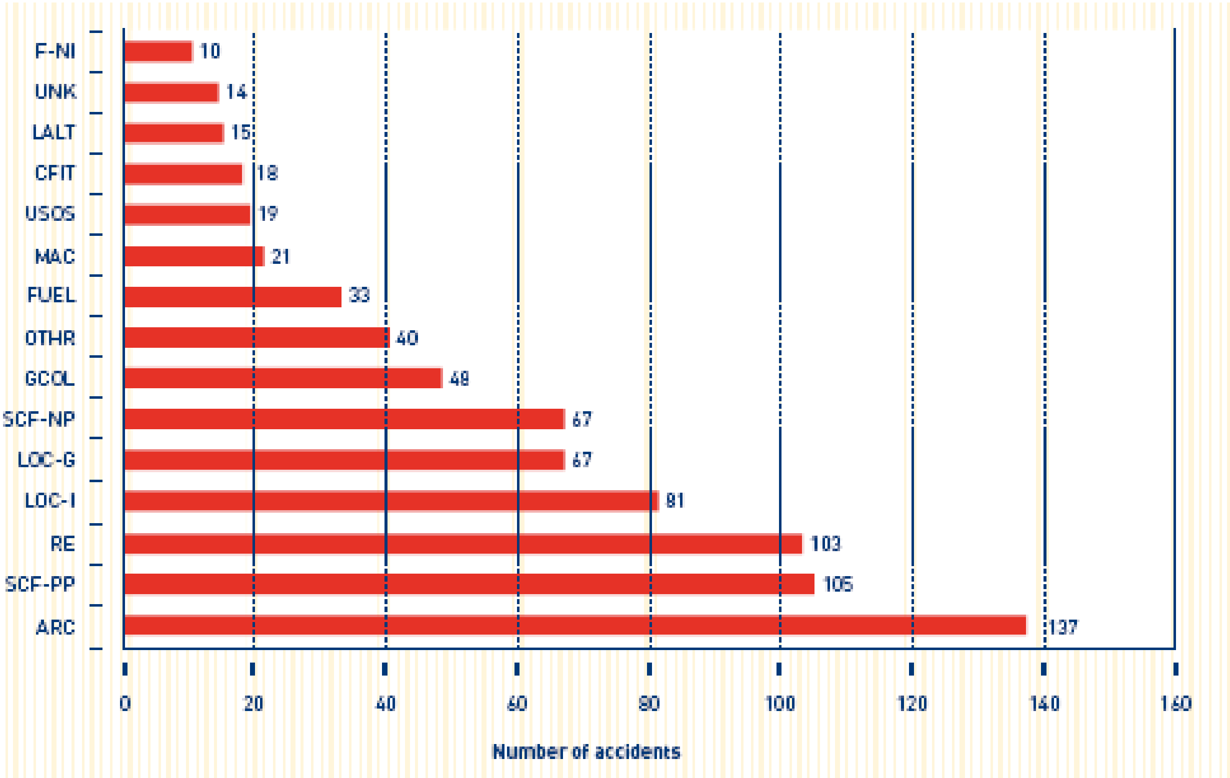


Figure 35: All accidents of aeroplanes below 2250kg, 2006

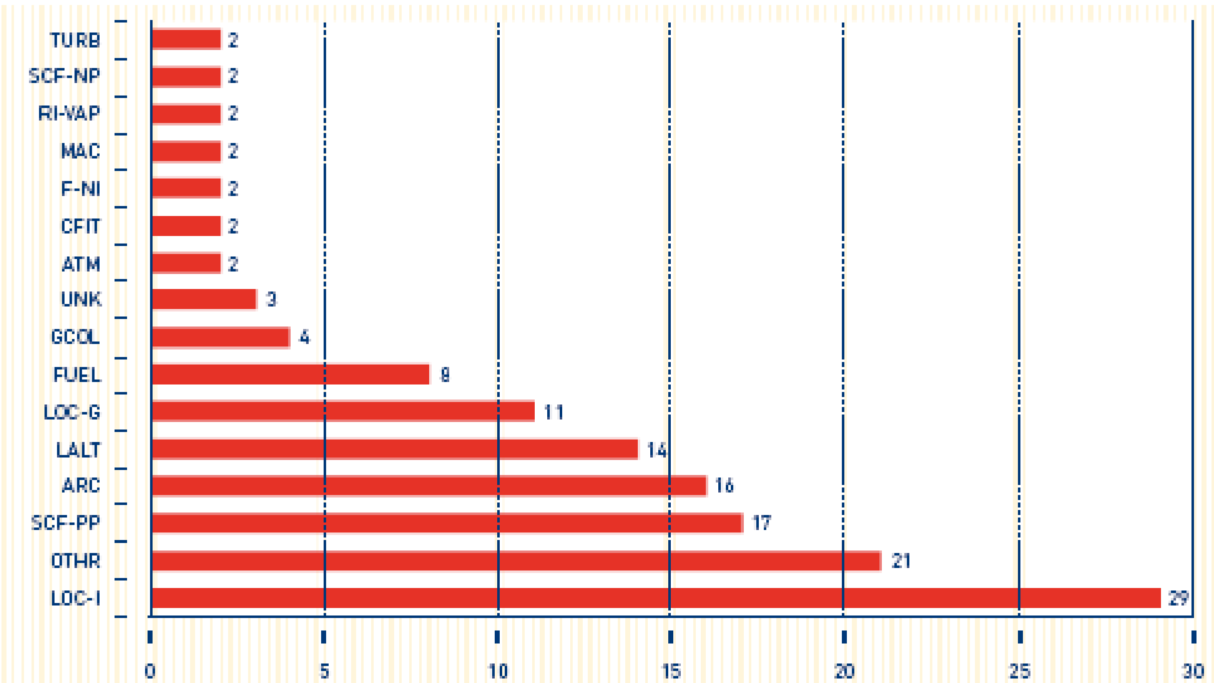


Figure 36: Fatal accidents of aeroplanes below 2250kg, 2006

Conclusions

- Many accidents are caused by human factors
- The definitely dominating source of technical problems is the engine
- Trajectory and attitude information are a bit more frequent relevant than engine data to describe accidents

12.1.2 Interviews / surveys

12.1.2.1 Interview of aeroplane accident investigation experts

Up to now there is no data recording required in light aeroplane. In several cases the installed GPS-receiver could be used to plot the flight path after an accident. If the aeroplane was equipped with an altitude transmitting transponder and radar-coverage was available during the accident flight, the aeroplane position and altitude could be adopted from this source.

No other states are normally stored onboard a light aeroplane. (Exemption: Some small experimental aeroplane and some new certified aeroplane incorporate an engine monitoring with data storage – Rotax engine with Flydat-system; other exemption are brand new aeroplane already equipped with an engine monitoring system – e.g. aeroplane with Thielert Diesel engines. See also 5.3.

When talking with flight accident examiners their generalized statement was: Every additional state which is recorded and can be retrieved after an accident will improve and speed up the investigation of accidents. Or short:

„Any information that helps to understand the situation around an accident/incident is useful. “

One examiner said: “If he had a picture of the cockpit every 30 seconds this would help a lot for accident investigation.” This case related statement demonstrates that a better knowledge of the overall situation and special detail information are expected from a light aeroplane Flight Data Recording device. Their wish list represents the aspiration for situational awareness. The following states are suggested in the mentioned order:

a) Position
b) Altitude
c) Airspeed
d) Accelerations (load factor)
e) Attitude

While this order is logically sorted from general to more detailed information about the aeroplane (seen as a rigid body), a decision whether the also suggested engine data or the rigid body state should be preferred was not answered definitely.

As mentioned in 12.1.1.3 one main cause for aeroplane accidents (single and light multi engine aeroplanes) are engine failures – that is why there is a strong need to measure and store the engine states.

In our understanding these data are needed to clarify what has happened – but if it is required to evaluate why something has happened some additional sensors or other equipment (like cockpit voice recorder) might be necessary. (e.g. up to now there is no way to find out why a pilot continued his flight despite worsening weather conditions).

Another – very important – demand noted by accident investigators was, that all data must be easily read out and analyzed by the investigation office (not like it is today where the evaluation of standard flight data recorders is very expensive and exhausting to get access to the data)

In [8] it is stated that the successful read-out rate of unprotected memory chips is about 85%. The destruction of the other 15% is mostly caused by fire. That means that, if there is no correlation between fire occurrences and known accident causes, it is less important to use crash protected data storage devices but very cost beneficial.

<u>Conclusions</u>

- o Rigid body state and air data preferred
- o Engine data are desired too
- o No criteria for an advanced state selection
- o Crash protection not essential

12.1.2.2 FDM for flight training

Generally flight training can be divided in 6 main tasks:

1 - Flight training for getting the license
2 - Advanced flight training
3 - Instrument flight training (that is IFR – training, and the so called CVFR-Training in Germany)
4 - Night flying training
5 - Aerobatic flight training
6 - Multi-engine flight training

Each of these tasks has its own requirements concerning kind of aeroplane, instrumentation, etc.

Up to now there is a mandatory number of flight hours which have to be absolved for gaining a specific flight license; only for the instrument flight rating (IFR) and some type ratings for bigger aeroplane the use of a training device like flight simulator is possible or in some cases even required. That is why today even with the use of a FDM during flight training there will be no financial advantage (e.g. like reducing the required flight hours for licensing).

Survey around flight instructors

To get a feeling whether the usage of a FDM would be accepted by flight instructors a survey was performed with almost 100 flight instructors. Before interviewing the instructors the possibilities of a FDM were briefly demonstrated, because no one of them had experience with such a system; thereafter they had to answer the following 5 questions:

1) Do you think that the use of data from a FDM will be useful for flight training purposes?
2) During which part of the flight training should FDM be used?
3) Which states should be recorded (and presented) and what is the ranking of these states?
4) In which way should the data from the FDM be presented to the student pilot?
5) What is your maximum price of such a complete system if you would use it for flight training?

The answers received concerning **question 1** were clear without ambiguity; 96% of the flight instructors found the use of a FDM useful for flight training.

But for **question 2** there were some differences; 64% would use such a system for advanced flight training, 40% for IFR-like training and only 30% for basic flight training (multiple answers were permitted).

For flight training such a device may be useful for discussing the flight with the student pilot and for highlighting the errors or problems in calm conditions after the flight on the ground; especially during IFR-training such a debriefing would be very helpful to demonstrate the errors – and possible improvements to the pilot. While airborne most student pilots are more or less mentally affected that is why a debriefing on the ground with actual flight data would be better than the somewhat hectic situation in the cockpit.

It will be essential to develop didactical concepts for the implementation and to train the pilot instructors. Otherwise an improper use of the FDM may lead to pilot conditionings that may cause new types of accidents.

Concerning the proposed states (**question 3**) there was a broad spectrum but a majority was found for the following values:

most essential:	aeroplane position, aeroplane speed, aeroplane altitude
second important:	engine states, heading, load factor
third important:	aerodynamic states like angle of attack or angle of sideslip

Table 26: Flight instructor's opinion about state importance

All (100%) would use the data for an offline-debriefing with suitable software on a PC at the flying school; none would use the data in flight (**question 4**).

For the costs (**question 5**) there was no agreement among the flight instructors:

up to 1.000€	1.000€ to 2.000€	2.000€ to 5.000 €	5 .000€ to 10.000 €	no opinion
36%	14%	11%	7%	32%

Table 27: Flight instructor's opinion about price of a FDM system for training

With regard to the financial limit of this task there was only a small group of flight instructors who were willing to spent approx. 5.000 € for a FDM system for flight training purposes only. But if a FDM system would be required nevertheless (for accident and maintenance purposes) all flight instructors would be interested to use the data for flight training also.

Conclusions

- o The preferred state groups are similar to the preferences of accident investigators with a bit less weight on engine data
- o The cost limit of 5.000€ might be acceptable if the system fulfills some more purposes than supporting flight training
- o It must be taken into account that the interviewed flight instructors are not familiar with flight data recording and analysis
- o Didactical concepts are needed for an beneficial use in training

12.1.2.3 Interview of maintenance experts

In a survey conducted for this study several members of the certifying staff of maintenance facilities were asked about their opinion to use FDM for maintenance purposes. The answers were all identical.

The most benefit for maintenance purposes would be the recording of engine states, in second place the airframe states; the suggested ranking order of the states is:

1. Engine speed (RPM)
2. Engine manifold pressure (MP) – if available (the engine performance arises from these two states, RPM and MP)
3. Oil pressure (OP)
4. Oil temperature (OT) (and/or coolant temperature for liquid cooled engines)
5. TIT (for turbocharged engines)

Thereafter in no specific order:

- o Cylinder head temperature (CHT)
- o Exhaust gas temperature (EGT)
- o Fuel Pressure (FP)
- o Fuel Flow (FF)

The desired states of the airframe for maintenance purposes are:

1. load factor (n)
2. air speed (V)

Additionally the accumulated flight time should be stored (especially a wish from aeroplane rental firms).

All states should be recorded in two different ways:

First: Whenever a limitation would be exceeded, the overrun should be recorded together with the duration and the time when this incident took place.

Second: To get information about the general condition of the engine/airframe - the states should be recorded continuously with a sampling rate of 1 per minute.

All data should be stored for a period of at least 100 flight hours or one year, because this is normally the time interval where major maintenance work is accomplished. There must be an easy access to the stored data and software tools to have a quick look for fast interpretation during the maintenance process.

Another maintenance wish (unique) was a lightning-strike sensor, because sometimes lightning strikes are not detected during flight but only if problems emerge many flight hours thereafter.

An interesting aspect of an engine data monitoring system would be the possibility to use this data for an extension of life time limits (e.g. TBO of engine, propeller). This would make the investment for a FDM somewhat easier (user acceptance)

Conclusion

- Engine data are definitely preferred by maintenance experts in a specific order
- load factor and airspeed are asked too

12.1.2.4 Charter demands

The demands from aeroplane charter businesses are a subset of maintenance demands and administrative needs. The legal force of such a system must be considerd if it is installed and accessible, even if it is not intended to be used for this purpose.

12.1.3 Other criteria

Various criteria, which will not fit into the two groups mentioned above are discussed in the following.

12.1.3.1 Existing specification (ED-112)

The relevant specification for flight data recording hardware is the ED-112 [12]. It contains all the experiences and knowledge of half a century of handling FDR in accident investigation. A list of states to be recorded, their minimum accuracies, minimum recording range and minimum recording solution is given, see [12](table II-A.1).

The core knowledge of this specification (data structure, test procedures, etc.) shall be kept, as some adoptions are necessary:

1. Crash protection: The necessity of crash protected data storing devices is discussed in chapter 12.1.2.1.
2. State selection: It is obvious that not all states stated in [12](table II-A.1) can be considered within an 5.000€ system. The selection of these states for maximising the safety benefit is one major task of this study.
3. Minimum data accuracy: The accuracies of states are strictly cost-related. This subject is discussed in 12.1.3.6. It is a key part of the investigation of the technical feasibility of the light aeroplane FDM.
4. Simplifications: Some simplifications are assumed to be advisable.

<u>Suggested simplifications:</u>

a. No differentiation in controls inputs/selections and control surface/flaps deflection/position: The reaction of the control surfaces/flaps corresponds to the control inputs with a derivation due to elastic deformation of the steering. The elastic deformation can be determined in dependencies of other states (e.g. dynamic pressure) at another number of the regarding type. A breakdown of the steering normally can be proven otherwise. If electrical steering will be realised this simplification is invalid.

b. Recorded values must not be the same as cockpit readings:

The requirement, that the cockpit readings are to be recorded is comprehensibly, but complicates the tasks enormously, since the majority of light aeroplane uses mechanical and electrical instruments, see 12.1.3.3. It is suggested to interpret this requirement as being worthwhile and not as an ultimate demand.

Conclusion

The ED-112 represents the knowledge of half a century of flight data recording and shall be applied as far as useful. Adoptions must be made concerning the number of states to be recorded and its accuracies. The crash protection of data storage devices must be questioned. Two simplifications are suggested. All adoptions are necessary due to cost.

12.1.3.2 Other working groups/studies

ONBASS study:

The ONBASS study (ONBoard Active Safety System)(see[4]-[7]) is dealing with the potential and the realisation of an active safety system for light aeroplane. The observed states are used to determine the situation of the aeroplane and to react in case of hazards. This approach to increase light aeroplane safety is much more challenging for the technical feasibility. System integrity and reliability are unlike more essential than for the object of this study. That’s why costs will be clearly higher than for a FDM.

Report D1.1 [5](p.86) lists four different selections of states. As stated in the report it is based on [11] whereas the most extensive selection is very similar to the ED-112 [12](table II-A.1). Reasons for the selection are not given in the available report parts nor state accuracies.

What can be learned from this study is the technical realisation of sensors and data treatment.

EUROCAE WG-77:

The working group 77 of the European Organisation for Civil Aviation Equipment (EUROCAE) is dealing with a related topic. According [8] the aims of this working group are:

- *Definition of minimum operational performance specification (MOPS) for «Robust» Recorder dedicated for lightweight aeroplane (Piston engines, Small Helicopters, Very Light Jets, Gliders, Balloons)*
- *Compromise between price & survivability*
- *Crash Protection based on ELT or ED-112?*
- *Information and advice for future developments*
- *Standardize the data formats*

The documents [9] available for us are show detailed considerations of the technical possibilities. Sound and picture recordings are regarded explicitly.

The problem of balancing different interests and needs is reported. As the aim of this WG-77 is the definition of MOPS (Minimum operational performance specification) similar to ED-112 [12] a focusing on accident investigation as minimum solution needs can be seen. This would reiterate the evolution of flight data recording in Commercial Aviation , where FDM was established later on base of FDR. The appellation of the aspired specification is ED-155 [10].

Several considerations are similar between WG-77 and our study, even the preliminary chosen set of states to be recorded. The detailed technical considerations of the WG-77 are worthwhile for the formulation of the specification and the realisation of a system suitable for daily use.

We see our work complementary to this working group as we are considering several application scenarios and try to find balanced principle solutions.

12.1.3.3 Technical perspective of light aeroplane (retrofit / new)

The retrofit of existing airplanes with a FDR is to be regarded explicitly. The technical conditions of modern airplanes and the products of the before-digital age are partly fundamental. The situation is analysed in the following.

Age of Aeroplane:

An exemplary statistic [18] shows a large part of very old aeroplane (single and small multi engine aeroplane), which are still in use; approximate ranges of age are:

up to 10 years	~ 10%
10 to 20 years	~ 10%
20 to 30 years	~ 35%
30 years and older	~ 45%

Table 28: Age of light aeroplane fleet acc. [18]

Since the technology has changed dramatically over this long period of time, there are a variety of different aeroplane types, especially if one considers the equipment with electronic systems like modern avionics. But for the basic aeroplane (structure and engine) there were significant changes only in the last 10 years. So nearly 90% of all aeroplane are of elderly design but partially with modern equipment.

Thus it must be differentiated between state of the art of

a) Engine
b) Avionics
c) Other sensors

To a) Engine:

To sample the engine data two different approaches must be considered:

<u>Older engines:</u> there are normally only sensors without additional electronic output and no digital engine control unit; so there is a requirement to install some kind of sensors which must have an output that can be used for FDR. Installation of new sensors into an otherwise certified aeroplane is considered as a not negligible change; this installation must be approved for every kind of sensor and for every type of aeroplane (STC required). This would surely exceed the cost limit for the FDM by far.

<u>Modern/updated engines:</u> Modern or updated engines are equipped with a digital *engine control unit* (ECU) or *full authority digital engine control* (FADEC) with digital output. For these aeroplane no additional sensors have to be installed for recording engine states, but an additional wiring to the recorder will be required.

To b) Avionics

Two fundamental situations encountered in cockpits:

Old-fashioned: there are normally only sensors without electronic output, and in a broad variety of technical layout (e.g. hydraulic, pneumatic, mechanical); so there is a requirement to install some kind of sensors which must have an output that can be used for FDR with the resulting advantages of retrofitting that are mentioned above.

New-fashioned: modern avionic is normally completely digital and that's why in case of an existing interface all data can be recorded easily.

To c) Other sensors

Normally no sensors are installed that do not serve the engine or avionic, so modern adapted systems can be applied if necessary. The cost relevant problem of retrofitting remains.

As other sensors will not dominate, four obvious combinations of technical situations can be appointed. These four combinations will be used as *type of aeroplane* in the context of this study.

type of a/c	engine sensors	avionic sensors
I.	analogue, no interface	pneumatic/mechanical/analogue no interface
IIa.	analogue, no interface	digital interface
IIb.	digital interface	pneumatic/mechanical/analogue no interface
III.	digital interface	digital interface

Table 29: Listing of basic technical conditions on A/C

The first situation (I.) will affect the most costs while the fully digital situation (III.) will be manageable with an inexpensive serial data recorder. If digital data sources are used, the requirements on data quality are shifted to that data sources outside the FDR.

It must be discussed if a modular system can be designed to fit to all four situations. If this is not possible graduated requirements are suggested.

Conclusions

- o Four different technical situations of light aeroplane can be determined
- o technical conditions are very different and may require adopted or modular solutions but not one system that fits all
- o retrofit costs are presumably much higher than new fit costs

12.1.3.4 Cost considerations

The tender specification [1] states that the costs shall not exceed 5000€ per installed system and shall be less than 2€ direct operating costs per flight hour. Detailed economic investigations cannot be carried out in the context of this study. Rather cost factors in principle are to be determined. The scale of costs is to be determined nevertheless, see 7.5 too.

Costs per installed system:

This consideration includes the onboard segment of the FDM. We assumed five different cost factors, from the development till installation, that represent the main costs. As the costs are allocated to a specific number of items, this number is an important difference in the cost factors:

	Cost factor	Number of items to allocate costs	Relative costs per installed system
1.	Development of the system	All light aeroplanes	Low
2.	Certification of the system	All light aeroplanes	Low
3.	Manufacturing	Per system	Direct
4.	Certification of installation (STC)	Number of aeroplanes per type	Dependent on number of aeroplanes per type
5.	Installation	Per system	Direct

Table 30: Expense factors from system development till installation

The largest effects of the system design at the costs are to expect within 3. - 5. While 1. and 2. depend primarily on the number of comprised aeroplane. Following findings can be derived:

To 1.+2.: The costs can be decreased with higher number of units. Somewhat more expensive sensors can be used to reduce development costs (sensor qualification, algorithms, etc.) and vice versa.

To 1.-3.: Integrity and reliability requirements, redundancy of hardware and software, built in hardware self test routines and so on may increase costs enormously.

To 3.: Costs per system can be reduced by mass production.

To 4.: This point can cause an unbalanced financial load to the light aeroplane fleet. This must be avoided.

4.+5.: The system must be designed minimally invasive. This may reduce these costs drastically.

To 5.: The costs of installation cannot be decreased by higher number of items.

Conclusions on costs per installed system:

- For the selection of states to be recorded the installation and certification efforts must be mentioned, better minimised.
- The complexity (integrity requirements,...) must be kept at a useful minimum

Direct operating costs (DOC):

As stated in table 2 these costs are almost not relevant for accident investigation (D) due to high other costs of such an unattractive situation. For all other purposes the following costs have to be considered:

1. Data transmission to public network
2. Data assessment
3. Feedback
4. Maintenance of the onboard system

To 1: As stated in 12.1.3.8 the most simple and inexpensive way for transmission data will be a mobile data storage device. Except accident investigation (A) and maintenance (D) the aeroplane operator is responsible for the execution of the data transfer. Any wireless solution is more convenient but related to additional costs. The market will bring up solutions that operators will be willing to pay.

To 2 and 3: As stated in chapter 5.2 there are several competitive providers of FDM services for Commercial Aviation . Some are offering FDM services for GA too, see e.g. [41]. The routine costs for data transmission and automated data assessment are low because costs for internet access and only little server capability are unimportant for the single user. We estimate an amount of 1€/flight hour. This contains data transfer costs via the internet and provision of a server infrastructure with running assessment software.

Punctual high costs will occur when manual engagement or extensive feedback are needed. Costs of 50€ per engagement are estimated. The main factor will be the manual assessment of the situation.

The average operational costs per flight hour will strongly depend on the numbers of occurrences.

To 4: It will probably be necessary to examine such a system regularly. This can be done during the annual examination at a maintenance company. While malfunctions can be detected with built-in test routines (increasing purchase costs) some sensors calibrations must be checked. The costs will strongly depend on the simplicity of this process. We estimate the time to maintain a well-engineered system of about 20 minutes or accordant costs of about 50€.

With the assumption of 100 flight hours and one occurrence per year the average operational costs will be 2€/flight hour:

1. Data transmission	0 €	-	
2. Data assessment	1€/flight hour	100 flight hours per year	1€/flight hour
3. Feedback	50€/occurence	1 occurrence per year	0.50€/flight hour
4. Maintenance	50€/examination	1 occurrence per year	0.50€/flight hour
sum		200€/year	2€/flight hour

Table 31: Direct operating costs of FDM

More detailed cost estimation needs detailed formulated requirements for the FDM system.

The above mentioned assumptions are representing one commercial approach to calculate the costs. A comparison with a commercial provider shows that the scale of assumptions is correct: The offer of GA-FDM [42] for a *Cirrus* like aeroplane is about 4.200$ p.a. for complete system incl. installation, assessment and monthly reports. Thereof 2.730$ p.a. are for hardware leasing and installation. For the analysis of assumed 40h per month an amount of 1.470$ p.a. is charged. This means that the assessment of one flight hour costs about 3$.

Of course cost can be increased by several convenient options:

To 1.: Wireless data transmission, dependent from data amount

To 2.: Advanced software with additional functions

To 3.: Intensity of feedback, e.g. see [42]: personnel mentoring

To 4.: Intensity of maintenance

<u>Conclusion on DOC:</u>

DOC within the one-digit Euro per flight hour range seems to be feasible for a basic FDM system.

12.1.3.5 Solutions for measuring or determination of states

For almost every quantity low-cost sensors are available on the market. Generally accuracy increases with the price. The question if suitable data can be obtained with low-cost sensors is discussed and answered in chapter 0. Quantities, which for there are no low-cost sensors or the installation costs are too high, can be observed by means of other measured quantities together with a dynamical model. Figure X shows the principle of such a state observer.

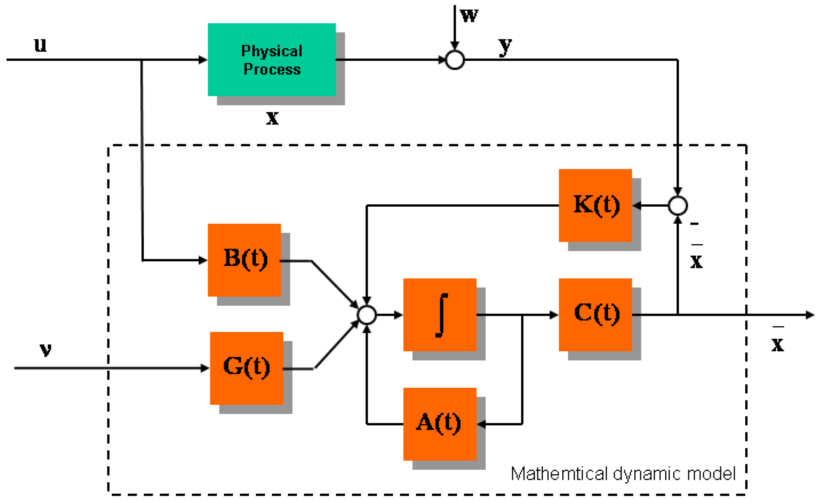


Figure 37: Principle of a state observer

The inputs causing a physical system to react are input to the state observer. The measured outputs of the physical system are compared to the outputs of the dynamic model and the deviation of these – also called innovations – causes a change in the estimated state. The model describes not only the input and the output states, it describes the internal states as well. A simple example; measuring the acceleration and position of a train using the acceleration as input to the model and the position as comparing measurement, the state observer will estimate a velocity as internal state. Obviously zero innovations implies the model and its states to be correct. To account for model errors and measurement noise (stochastically errors) a Kalman filter as state observer can be used. In this case the relation of the covariance for v and w dictates the gain of the feedback K. Measurements with high noise and a good model causes a low K – the results of the model is weighted higher than the measurement – and the other way around.

A state observer can be used for every dynamical system. Examples in aviation are engine properties, environmental influence like wind and the aeroplane motion itself. Using a model of the aeroplane all kinematic states i.e. position, velocity, attitude, angle of attack side slip angle can be estimated knowing the control inputs. Of course the other way around is possible as well; knowing the kinematical state of the aeroplane the inputs can be estimated. For applications of FDM where the load factor, angle of attack and the sideslip angle are all small (no aerobatics), simplified equations of motion can be used for a state observer. In some cases neglecting stochastically and non-linear effects the observer is reduced to an analytical equation. An example for the angle of attack is described in chapter 7.5.2.

12.1.3.6 Considerations on data qualities

The question which states to record leads directly to the questions of:

- accuracy
- recording rate
- recording range
- recording solution

The recording range can be retained as stated in ED-112 [12]. Recording rates presented in ED-155 draft 4 [10] shall be taken as a minimum. As costs of the storage medium are not a real problem, see 12.1.3.7, the exact recording rate is a minor problem. The recording resolution depends on the sensor accuracy. Given ratios in ED-112 of sensor accuracy to recording accuracy shall be kept.

The accuracies stated in ED-112 represent - without proof - the present technically surely attainable accuracies. ED-112 corresponds to systems used in large transport aeroplane. Normally these systems are onboard for flight guidance and control purposes. The costs of such systems are out of the question for light aeroplane.

The accuracy of a sensor stands usually in a proportional relation to its price. Using smart algorithms for certain low cost sensor configurations satisfying accuracies can be obtained, see 12.1.3.5. Considering the statement in 7.3.2.1 that „any information that helps to understand the situation is useful “, then reductions of accuracies are recommended in favour of a payable system.

It must be mentioned that accuracies depend usually on the operation scenario. E.g. the attitude determination of a typical utility aeroplane operation may be possible with a low cost system, but such a system will be not suitable for aerobatic attitude determination or similar a loss of control accident investigation. Recommendations for the applicable accuracies of the states to observe shall be made after flight trials.

The accuracies demanded in ED-112 are to be seen as aimed target values.

12.1.3.7 Data type and storage

"The complexity (Editor: of integrated circuits) for minimum component costs has increased at a rate of roughly a factor of two per year… Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years." [68]

Gordon E. Moore, 1965

Gordon Moore slightly altered the formulation of the law over time, bolstering the perceived accuracy of Moore's Law in retrospect. Most notably, 1975, Moore altered his projection to a doubling every two years. Today we know that the complexity of minimum component costs increases with a factor two every 18 months [69] somewhere in between Moore's first and altered statement. For Flash memory like solid state drive (SSD) using NAND memory this law applies as well, as can be seen in Figure 38.

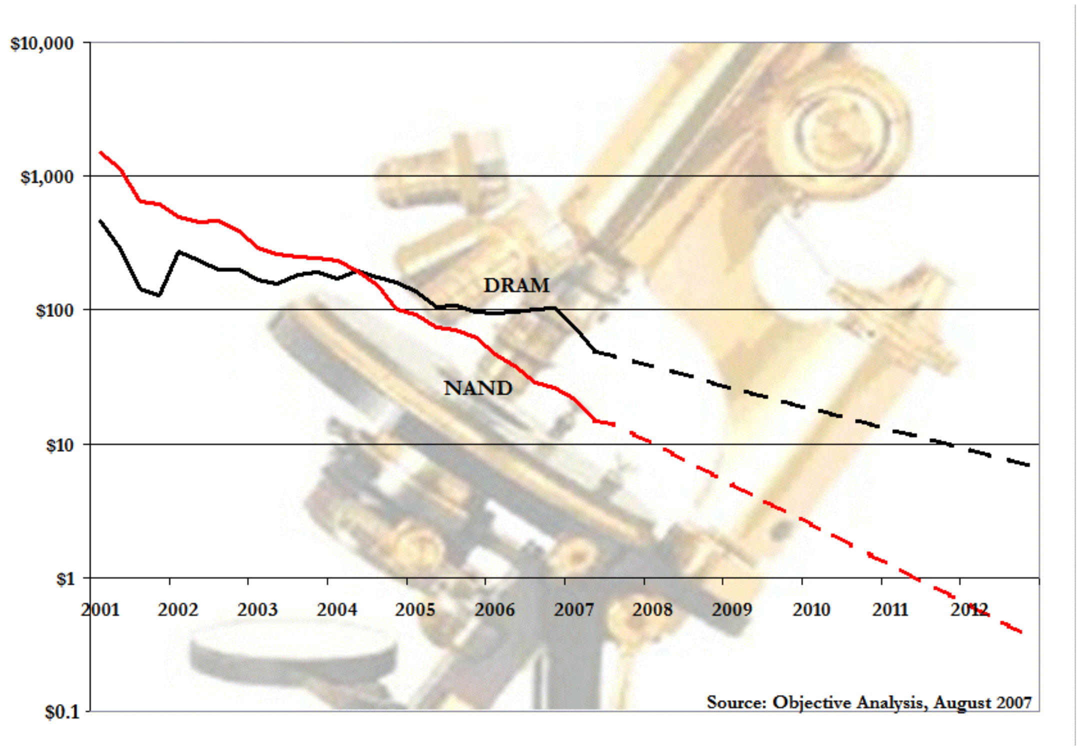


Figure 38: Prices per 1GB DRAM and NAND memory over time.

The development of memory cost over time relaxes the need of compressing or other means of reducing the memory storage demand of applications to reduce costs. An application where the price of the needed memory storage amount exceeds the financial limit by a factor of 10 will become profitable in about three years.

Storage medium:

An aeroplane is a harsh environment for memory storage. Commercial memory storage (Harddisk – HDD) used for desktop computers and laptops are not suitable for use in an aeroplane since vibrations, static pressure and temperature generally exceed its design limits. During the last years SSD flash storages have become more conventional and it is prognosticated to take over HDD position in the next years even in laptop and desktop computers. Industrial grade SDD storages have environmental limitations exceeding standard HDD partially with a factor of 10 and are appropriate for use in an aeroplane. In

Table 32 the features of different memory storages are summarized.

			
	Hitachi Travelstar 60GH	HDD Hitachi Endurastar J4K50 (Industrial)	SILICONDRIVE SSD-DXXXS(I)-4210 (Industrial)
Storage Type	2.5” HDD	2.5” HDD	2.5” SSD
Interface	ATA-5	ATA-6	Serial ATA
Temperature	5° C to 55° C	-30° C to +85° C	-40ºC to 85ºC
Humidity	8% - 90% % non-condensing	5% to 90% non-condensing	8% to 95% non-condensing
Altitude	--- [6]	-300 to 5,000 meters	Up to 24,000 meters
MTBF	300,000 Hours	330,000 Hours	2,000,000 Hours
Shock (half-sine)	150G (2ms)	250G (2ms)	1000G (0.5 ms)
Vibration	0.67G (5 - 500Hz)	Up to 3G (10-500Hz)	16.3gRMS, MIL-STD-810F
Reliabilty	1 per 10^{13} bits	1 per 10^{13} bits	1 per 10^{32} bits

Table 32: Specifications of different 2.5” size memory storages

[6] No information applied from manufacturer, normally up to 3000 Meters

Industrial hard disks HDD have environmental limitations somewhere in between commercial HDD and Industrial grade SDD. They are sufficient for most light aeroplane applications.

Data format to be recorded:

The acquisition and recording of data for later analyses can be performed in three, partly redundant ways:

1. direct acquisition of a state recorded on the storage as a value with timestamp
2. video acquisition recorded on the storage as motion pictures with timestamp
3. audio acquisition recorded on the storage with timestamp

For analyses the method 1 is the simplest, since time plot and other data auto and semi-automatic processing and presentation can be performed using the stored data directly, see chapter 12.1.3.9. Method 2 is a simple way of acquiring information i.e. by filming the cockpit instruments as described in the following chapter – other examples are discussed in chapter 7.5.

Processing and presentation of the data is more difficult with method 2 – to achieve measurement values a manual readout of the stored pictures is necessary. For application scenario D (accident/incident investigation) this is satisfactory. For the other application scenarios an automatic processing of the data using advanced image analyzing featuring an individual configuration for every aeroplane cockpit is necessary.

Analyses of the third method are similar to the second method; only a manual analysis is possible with the recorded data. For an automatic processing, advanced audio analyzing featuring aeroplane individual properties, is necessary. Examples of applications are engine speed and landing gear position (in/out). For other examples, see chapter 0.

The storage memory requirement per measured value is much smaller for method 1 than for the two other methods. On the other hand methods 2 and 3 makes it simpler (with less installation effort) to acquire some data and the methods makes it possible to acquire information not possible with method 1 i.e. cockpit voice and instrument malfunction.

Image Recording of engine states:

Because of the a.m. reasons there must be a monitoring system which will not need additional permanently installed sensors. To achieve an easy monitoring of the engine states we suggest an „Image recording“ with the help of a digital camera. The camera should be installed in such a way that the engine instruments can be easily observed.

This would provide the following benefits compared to the installation of additional engine sensors:

- simple installation
- no additional engine sensors required
- no interference with the normal engine sensors
- compatible to all aeroplane regardless of age and equipment
- much cheaper
- all information are provided in one picture and because the depiction is like in the real aeroplane, this would benefit the interpretation of the data for e.g. flight training purposes

Of course, there are some disadvantages:

- there will be a huge data file, if the pictures should be recorded for 100 flight hours or more
- lighting and shadowing effects must be considered as well as flights during nights
- to provide an automatically interpretation of the data (e.g. for maintenance purposes) this would require some highly sophisticated evaluation hard- and software
- there must be provisions to protect the privacy of pilot and passengers if they should become visible on the recording

The first results using image recording are described in chapter 0.

System Reliability:

To analyse the reliability of the storage for a data recording system, it is important to understand the processing of data. After the acquisition and possibly processing of the data, it is transported to the operating system for storage. The operating system (normally) caches the data to increase performance before sending it to the mass storage. The mass storage normally caches as well, before physically writing the data to a magnetic medium (HDD) or flash (SDD). As an extreme example the data from a complete flight might be kept in volatile memory (caches) until it is physically written to a medium. In case of power interruption or system breakdown all data will be lost. There are simple means to prevent this, like periodically purging the data to be written on medium or periodically closing and reopening the recorded file. In case of interruption only the data since the last purge is lost. Furthermore the file system might be corrupted in case of power interruption. In the past software methods reducing the vulnerable timeslots and power buffers in hardware, assuring operations to be completed were used to cope with the problem. A cost efficient method of resolving the problem is to use lately developed journaling filesystems were a journal of planned and successful operations are kept. In case of a power interruption the file system is checked quickly during the next boot and outstanding operations are finished.

The reliability of reproducing the data after it has been physical written to the medium is shown in
Table 32. The reliability of SSD exceeds the one from HDD with a factor of 10^{19}.

Data Recording Format and Data File Format:

The ED-112 [12] defines recording format, range, interval, accuracy and resolution to be used by a FDR together with other attributes like robust multi-word storage of data. It does however not define the format of the recorded file to be used. Actually, currently there is no standardization of the data file formats used by FDR witch could be adopted for the FDM application. Work in progress is preparation of specification ARINC 657: Airborne Recorder File Format from the Digital Flight Data Recorder (DFDR) Subcommittee [70]. The goal of the subcommittee is to ensure that aeroplane flight data recording system standards meet airline operational needs and evolving regulatory requirements. In accomplishing this goal, the subcommittee considers issues such as including health monitoring of aeroplane systems and components, flight operations quality assurance (FOQA) initiatives, and current and impending regulatory requirements. A standardized data format would allow instant import of the data file and provide consistency with the use of a standardized documentation file format, as described by Specification 647A (FRED files). A standardized data format will reduce the amount of readout equipment required for FDR data transcription. The structure is necessary to support newer recording requirements for flight data, data link, audio, and image recording. This structure is intended for use with all civil recorders and should support use with military recorders

Considerations on compliance to ED-112 [12] and ED-155 Version4 [10]:

It is challenging if not impossible to fulfill all the requirements in ED-112 "The minimum operational performance specification for crash protected airborne recorder systems" using low-cost and commercial of the shelf products. None of the here presented data storage mediums comply with the ED-112. From the specifications listed in

Table 32 all mediums fail to comply with shocks and temperatures above category A [71]. Other challenging environmental capabilities as the penetration resistance, high temperature and fluid immersion fire can only be achieved by expensive capsulation of the FDM in appropriate material. Furthermore the ED-112 requires all aeroplane to install a Recorder Independent Power Supply (RIPS) to support a flight recorder to allow for continued operation for 10 minutes applied in all cases when aeroplane power to the recorder is removed. This demand implies that sensors used by the FDM system should be powered directly from the FDM and that the FDM should contain an Uninterruptible Power Supply. The crash protection and RIPS requirements in the ED-112 affect the FDM scenario A Accident/Incident investigation only and make the FDM significant more expensive. To fulfil the predetermined budget of less than 5000 Euro per installed system, either the system does not comply with a standard, or the requirements of the standard need to be lowered. The requirements in ED-155 "The minimum operational performance specification for Lightweight Flight Recorder Systems" are lower than in ED-112 but still (in version 4) not low enough for FDM with the predetermined budget.

Technical solution:

Off the shelf Industrial grade HDD and flash memory storage (as SSD) can be used for storing the measurement data in the aeroplane for FDM although they do not fulfill the requirements of ED-112 or ED-155 version 4. The price of memory storage is falling exponentially with a factor of about 10 in three years. To rise the system reliability a journaling filesystem should be used. Storage of measurement values are easier to handle in auto- and semi-automatic processing and presentation of the data. Video and audio acquisition and storage enables a cost efficient way of storing a great amount of data satisfactory for application scenario A incident/accident investigation. The ED-112 defines recording format, range, interval, accuracy and resolution to be used by a FDR which should be adopted by FDM. Currently there is no standardization of the data formats used by FDR witch could be adopted for the FDM application. Work in progress is preparation of specification ARINC 657 which should be considered to be used for FDM to be compatibility to future FDR software tools.

Conclusion

Off the shelf Industrial grade HDD and flash memory storages (as SSD) can be used for storing the measurement data in the aeroplane for FDM although they do not fulfill the requirements of ED-112 or ED-155 version 4. The high storage memory requirement is reduced by a factor of 10 every 3 years. Standardizations of data recording format and data file format either exist or are currently in work and should be considered to be used for FDM.

12.1.3.8 Data transmission

The different application scenarios have different demands for data transmission. The main differences in demand are the type of data transmission medium and timeframe for which the data is relevant. Obviously the recorded data during a training flight has a short timeframe of relevance – typically used to support the debriefing shortly after the flight. For procedure improvement of flight operation and training the same kind of data is useful even a long time after the flight. There are three data types; time domain data (large amount of data), statistical data (small amount of data) and warnings. A warning is a short message signaling that the FDM has detected something that needs attention from operator of the aeroplane or the pilot. Transmission mediums are put in four categories; “Wireless non aviation” i.e. mobile phone technology GSM/UMTS and WLAN/WMAN/WiMAX, “Wireless aviation” i.e. ADS-B and VDL Mode2, “mobile storage mediums” i.e. USB-sticks, CF-Cards etc. and the last category “readout of onboard storage”

“Wireless non aviation” data transmission must be considered non-continuously. It is currently not possible to guaranty a communication world-wide since these wireless technologies have coverage mainly in urban areas. Furthermore these technologies are intended and optimized (i.e. coverage footprint) for land based application causing a limited coverage in air. Even with these restrictions the technology is interesting for applications were an occasionally communication is sufficient since the investment and usage costs of this technology are low compared to “wireless aviation” technology.

In commercial aviation an increasing number of aeroplane use an online wireless transmission with a global coverage for air traffic management (ATM), Communication Navigation and Surveillance (CNS) and there are plans to implement several services in the near future such as Auto Downlink of Aeroplane States (ADAP), see [62]. If an integer wireless data link is needed for FDM for light aeroplane, commercial solutions already exists.

The cheapest data transmission method is the “readout of onboard storage” where the onboard storage data is transmitted to a PC using a cable connection. Drawbacks of this method are as follows; the need of a PC in the aeroplane, the aeroplane power must be turned on to perform the data transmission and the time needed for the transmission possibly occupying the aeroplane.

The last data transmission method “mobile storage medium” relaxes the drawbacks using the “readout of onboard” method. There is no need for a PC in the aeroplane since the mobile storage medium is connected directly to the FDM. When the mobile storage medium is “plugged-in” to the FDM pre flight as described later in application scenario B “Direct application in training and flight operation” the data transfer does not cause any extra waiting time, since the data is stored on the medium during the flight.

In the following the specific data transmission demands of each scenario is described and an abstract table characterising the transmission is given.

<ins>A – Quality improvement of flight operation and training</ins>

Since this application scenario involves analyzing all time domain data the amount of data to transfer is large. The time frame in which the is are useful is long term allowing the transmission to be performed within the maintenance.

Timeframe relevant:	Long term
Data type:	Time domain data, statistical data, Warnings
Transmission Type:	Readout of onboard storage, Mobile storage medium

B – Maintenance

For the maintenance a data transmission within the regular maintenance intervals seems reasonable. By connecting to a standard PC the data could be transferred form the on board FDM to a database in the maintenance facility for further use. Warnings can be used to signal a need of maintenance between the regular intervals.

Timeframe relevant:	Medium term
Data type:	Statistical data, Warnings
Transmission Type:	Readout of onboard storage, Mobile storage medium

C – Direct application in training and flight operation

The use of a FDM system for flight training requires a data transmission after each flight. For this scenario a removable memory would be the best solution. This could be USB-sick or SD-/CF-cards. Additionally to storing the flight measurement data on an on-board storage the FDM stores information on a “plugged-in” mobile storage. Each pilot could insert his private memory in the FDM prior to the flight and could take the data with him after the flight for further analysis in the debriefing. Since each pilot has his own mobile storage medium, there will be no waiting time caused by data transfer from the FDM to a debriefing utility.

Timeframe relevant:	Short term
Data type:	Time domain data
Transmission Type:	Readout of onboard storage, Mobile storage medium

D – Accident/Incident investigation

For the case of accident investigation there is no need for a special data transmission. In case of an accident the crash proof memory can be collected from the wreck for analysis in a laboratory with equipment required. The timeframe relevant is long term since the reason for an accident never becomes uninteresting.

Timeframe relevant:	Long term
Data type:	Time domain data
Transmission Type:	None (onboard storage)

E – Administrative needs

The data relevant for "Administrative needs" is an extract of all time domain data. In application scenario C these data are transmitted for "Procedure improvement of flight operation and training". In C as well as for the administrative needs the timeframe relevant is Long term. This allows the transmission to be performed within the regular maintenance intervals.

Timeframe relevant:	Long term
Data type:	Time domain data
Transmission Type:	Readout of onboard storage, Mobile storage medium

Technical solution:

The data transmission for all of the application scenarios can be solved using readout of onboard storage or a mobile storage medium causing low costs. Today a wide variety of different data storage cards such as USB, SD and CF-cards exist and most likely every pilot and maintenance facility have access to this technology including a PC for visualization and analysis of the data. Furthermore the technology for a wire less data transmission exists today - world-wide coverage (continuously communication) using aviation wireless technology as well as cheaper mobile phone technology at the cost of lower coverage (non-continuously communication).

Conclusion

The data transmission for all of the application scenarios can be solved using readout of onboard storage or mobile storage medium at low costs

12.1.3.9 Data presentation and analysis

The way of presenting the flight data depends on the application and may vary. The relevant time basis of the data varies also with the application. For training purposes the trend of the states over time are relevant. These data does not interest the maintenance staff since analyzing all time series data since the last maintenance of the aeroplane would be a cumbersome task. For the maintenance descriptive characteristics of the states are relevant. It might be helpful to sort the data into flight phases and generate different presentation for each flight phas to check the different values of its operational range as suggested in ED-112. Data presentations which are relevant to the application of FDM can be put into five main categories:

1. Statistical values
2. Statistical figures
3. 2 dimensional plots
4. Virtual instruments
5. Text reports

Both of the statistical presentation types described (1 and 2), belong to the discipline of descriptive statistics – used to describe the basic features of the data gathered from an experimental study in various ways.

Statistical values as mean value, median value, max and min are characteristic values of a time series. They can be calculated using the time series (large amount of data), allocate a very low amount of memory independent of measuring time and in certain applications this information on the measured state is sufficient.

Statistical figures i.e. histogram and pie chart visualizes and characterizes a time series state in more detail than the statistical values on the cost of some more memory – still independent of measuring time though. A typical application is histogram showing running time of the engine within different rotation speed intervals.

2 dimensional plots; any kind of plot with two axis i.e. quantity over time (low and high sampling rate), crossplots using two quantities, polynomial fitted curve of the crossrelation between two measurements and Fast Fourier Transformation (FFT). Some of these presentations like an altitude over time plot need time series data requires much memory storage increasing by the measurement time, other plots, like a crossplot of oil pressure versus engine rotation speed need not necessarily be recorded as time series data. The memory storage requirement can be reduced without significant loss of information by pre-processing the data in the FDM onboard unit generating a polyfit curve with uncertainty information. This yields FFT plots as well; instead of recording the time series data the shape of the resulting FFT curve can be stored.

Virtual Instruments any graphical presentation with moving graphical components, either models of real instruments or other visualizations i.e. a moving map or a 3D model of the aeroplane showing the attitude in advanced flight modes as for example spin. For training purposes virtual instruments can be used to replay the flight during the debriefing. To be able use this kind of visualization, the measurements must be recorded with a medium to high sampling rate (~8 Hz).

Text reports are presentation of events in textual form triggered by some measurement value or calculation i.e. the time of exceeding a preset limit of an engine state.

All the described presentation types can be applied using the time series data with high sampling rate. Thus time series data is the most basic information in the system. The only reason of any effort to pre-process the data in the FDM onboard unit would be to enable other types of presentation with less memory storage requirement and reducing the data amount to be handled in the analyses. If such a memory reduction is used and a sorting of the measurement data in flight mode is needed, this must be performed by the FDM onboard unit since the flight mode information can not be derived from the memory reduced recorded data. Another means of reducing the amount of recorded data is event triggered storage of time series data. When an event is detected (i.e. engine rotation speed exceeded) the time series data some time before the event and some time after the event are recorded. In the following examples of presentations for the different application scenarios are given.

The accident investigations bureaus have there own tools for analysis and visualization so there is no further need for presentation.

For maintenance (application scenario B) a presentation in form of charts and histograms is required. The charts could be analyzed and interpreted by the maintenance experts directly. These data need to be prepared during the flight in form of data reduction (e.g. by computing mean values for a time interval of one minute). For the presentation itself more calculation might be necessary on a remote PC – like computation of histograms. This presentation has a technical focus and is made for specialists with adequate education.

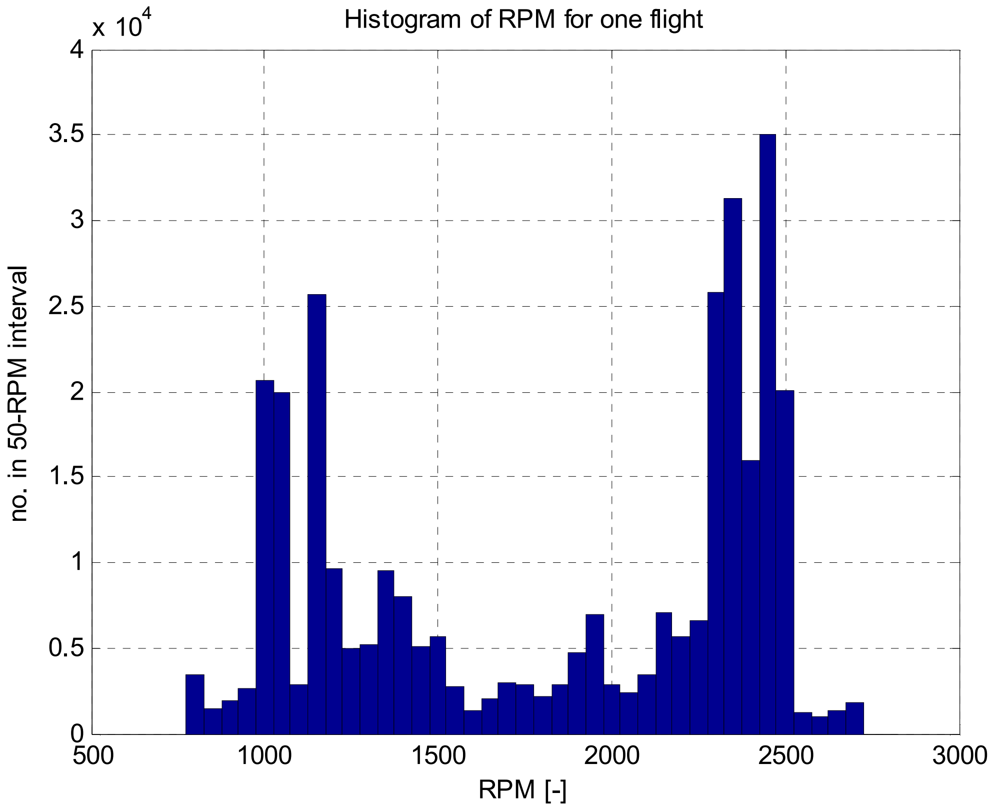


Figure 39: Example of histogram for RPM

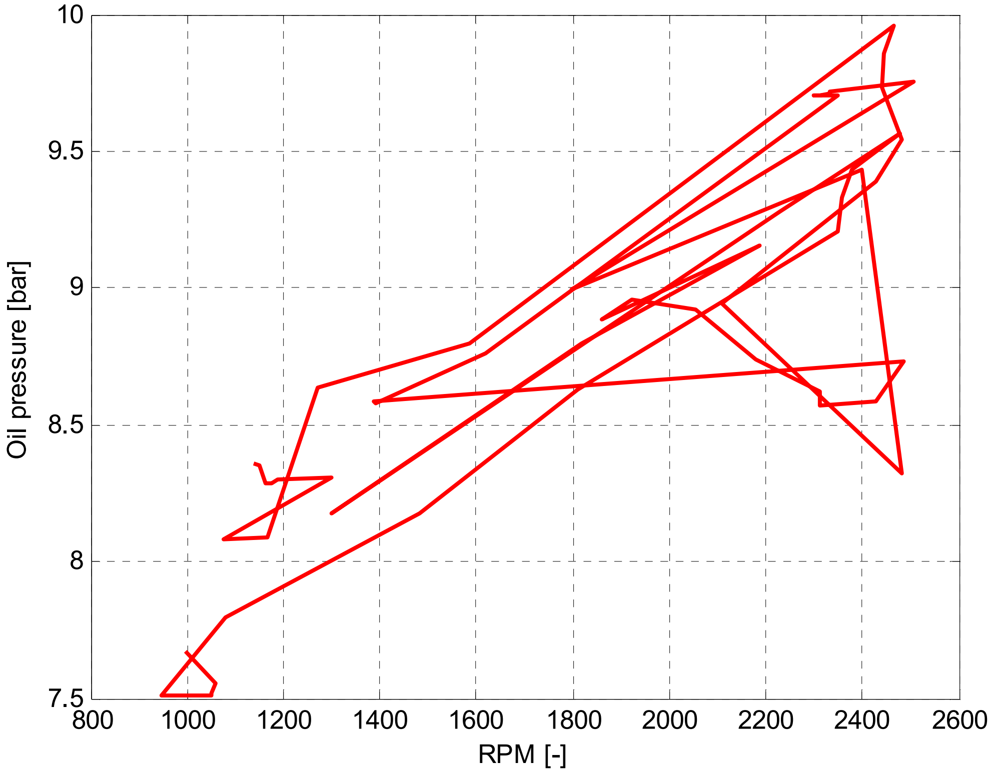


Figure 40: Example of plot of oil pressure versus RPM

Additionally the maintenance experts need the exceedance of special quantities in form of events. These should be presented in form of table such as the following example:

date	time	quantity	maximum value	limit	time over limit [s]
02.09.2008	13:45:14	RPM	2750	2700	2
02.09.2008	13:51:25	RPM	2780	2700	120
02.09.2008	13:56:02	load	3.7	3.4	4
05.09.2008	09:31:14	CHT	183	180	150
05.09.2008	09:56:47	IAS	150	155	23

Table 33: Example for limit exceedance presentation

The presentation of the data for flight training (C) is different. Normally the raw data of the last flight will be analyzed. As the pilots are non professionals the presentation must be easy to understand. Therefore it is useful to show the data in form of an environment as close as possible to the surrounding the pilot is used to.

An important information is the flight track which could be shown on a VFR chart.

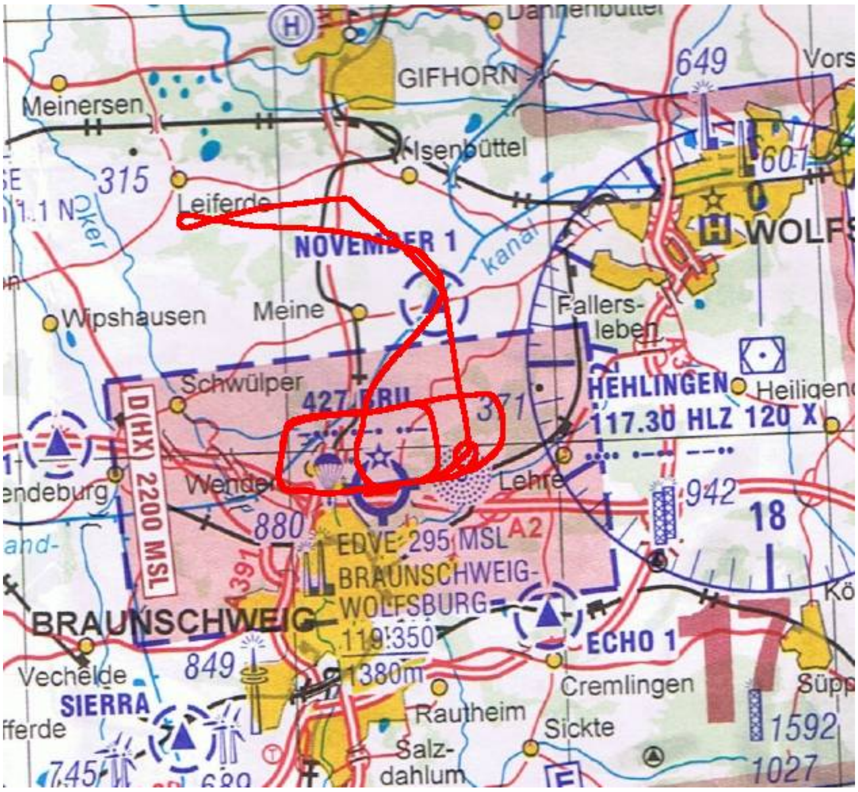


Figure 41: flight track on standard ICAO VFR chart

Other quantities should be shown in form of virtual instruments. Such software could rebuild the original instrument panel quite realistic so that the pilot finds the instruments in the order he is used to. Additional information such as angle of attack could be included in a virtual cockpit.

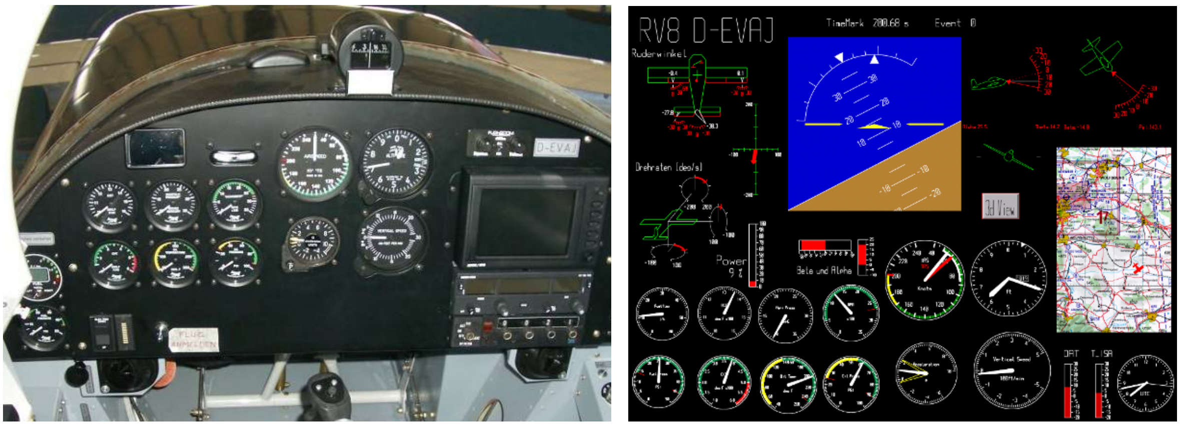


Figure 42: Original instrument panel (left) and virtual instrument panel

This presentation gives a good overview of the flight condition as well as detailed demonstration of single maneuvers. For some question a time plot of different quantities for the whole flight is more useful. As example the altitude keeping performance of the pilot should be mentioned.

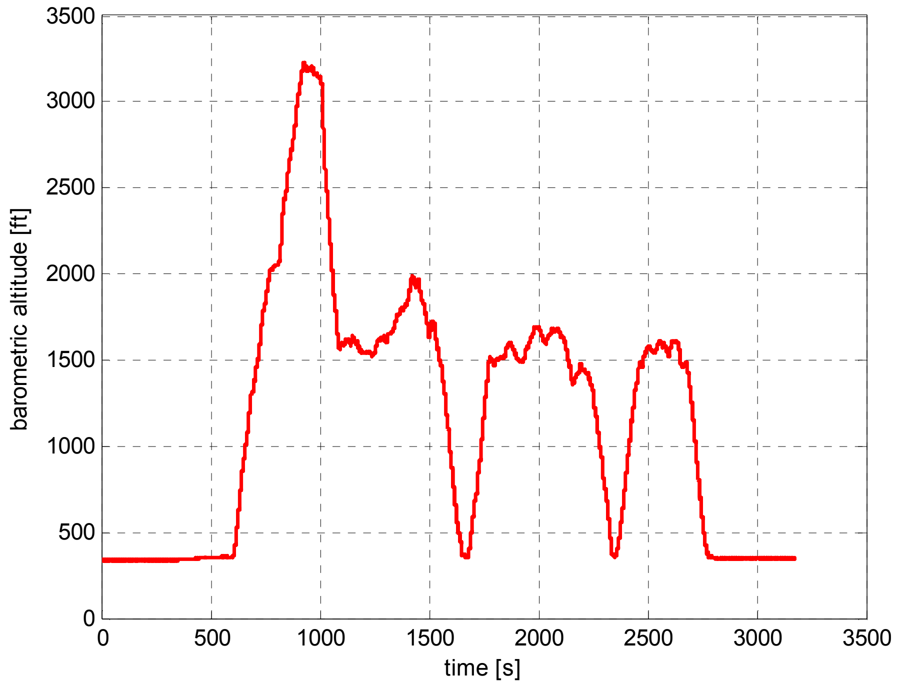


Figure 43: Barometric altitude as time plot for a flight with traffic pattern

After a short training a non professional pilot should be able to interpret the different phases of the flight.

The presentation of data for statistical purposes (E) depends on the specifications for this analysis. As this is not defined no further suggestions are made in this study.

For different applications commercial solutions exist for FDM-visualization. These are mainly made for commercial use. But it will be possible to adapt this software to non commercial use. If the data format is open to the public it can be expected that open source projects will emerge giving free alternative software to the community. This could lead to a cost reduction of professional products as well.

<u>Conclusion:</u>

The different scenarios have different demands on the presentation of the flight data. No demand for special presentation tools can be found for accident investigation as these bureaus already have their own existing tools. For maintenance and statistical purposes demonstration in form of charts, tables and diagrams with a technical focus is needed. For flight training a graphical visualization of virtual instruments and VFR charts are useful. For both areas commercial versions already exist which can be adapted. If the data format is open to the public it can be expected that open source projects will emerge giving free alternative software to the community. To reduce the amount of measurement data to be handled without significant loss of information, a pre-processing can be performed in the FDM onboard system.

12.2 Compiled state vector

In the following the compilation of the maximum state vector is presented, see chapter 7.4.2. For this the number of entries of states in every source can be seen in the green fields. 12 datasets were analysed. The remark “direct” for ECCAIRS system means that these values could be entered directly in the system, if these values are observes by the aspired system.

bCOS – body fixed coordinate system

Category	Con't No.	symbol	description	LN9300 [3]	ED-112 [12]	CS-VLA (short) [16]	CS-23 (short) [15]	Maintenance 7.3.2.3	AFM Aquila A210 [26]	AFM C-172R [25]	ECCAIRS direct [13]	ONBASS mini [5]	ONBASS enhanced [5]	ONBASS full [5]	ONBASS future [5]
			Total number of entries:	38	74	20	21	14	16	16	54	6	11	18	59
1. General															
	1	t	time	1	1	1	1	1	1	1	5	1	1	1	1
	2	DATE	date		1										
	3	V	velocity	1											
	4	H	altitude	1			1				1	1	1	1	
	5	HRADIO	radio altitude		1										1
2. Air data															
	6	p_{stat}	statik pressure	1	1						4				1
	7	q	dynamic pressure	1	1	4	5	1	1	1	2	1	1	1	1
	8	α	angle of attack	1	1										1
	9	β	angle of side slip	1	1					1					
	10	OAT	outside air temperature		1				1		2				1
	11	DEW	dewpoint								1				
	12	ρ	density	1											
	13	a	speed of sound	1											
	14	Ma	mach number	1											
3. Inertial data															
	15	a_x	acceleration in x-bCOS	1	1								1	1	1
	16	a_y	acceleration in y-bCOS	1	1										1
	17	a_z	acceleration in z-bCOS	1											
	18	n_{az}	load factor z-bCOS	1	1	2	2	1	1	1		1	1	1	1
	19	p	angular rate x-bCOS	1											
	20	q	angular rate y-bCOS	1											
	21	r	angular rate z-bCOS	1											

4. Trajectory and attitude															
	22	Ψ	heading	1	1						1	1	1	1	1
	23	Θ	pitch attitude	1	1	1	1		1	1	2		1	1	1
	24	Φ	roll attitude	1	1	1	1		1	1	4		1	1	1
	25	χ	azimuth	1	1						1				1
	26	γ	vertical track angle	1											
	27	γ_a	vertical airverctor angle	1											
	28	V_k	track velocity	1							9				
	29	GS	ground spped		1										
	30	TAS	ture airspeed								1				
	31	LAT	latitude		1						1				1
	32	LON	longitude		1						1				1
	33	POS	position								3				
	34	APPROACH	approach errors												1
	35	GPSCOR	GPS correction in use		1										
5. Wind data															
	36	χ_w	wind azimuth	1											
	37	γ_w	vertical windvector angle	1											
	38	V_w	wind speed	1	1				1	1	10				1
6. Weight and Balance															
	39	T/W	takeoff weight			2	1		1	1					
	40	L/W	landing weight						1	1					
	41	m_F	fuel mass								1				
	42	xCG	center of gravity x-bCOS	1	1	2	2		1	1					1
	43	yCG	center of gravity y-bCOS	1											
	44	zCG	center of gravity z-bCOS	1											
7. Aerodynamic controls															
	45	δ_i	deflection of a control surface (general)	1											
	46	ξ	airlon deflection	1	1									1	1
	47	η_K	landing flap deflection	1	1	1	1			1				1	1
	48	η	elevator deflection	1	1								1	1	1
	49	ζ	rudder deflection	1	1									1	1
	50	η_t	elevator trim tab deflection	1	1										1
	51	ζ_t	rudder trim tab deflection	1	1										1
	52	ξ_t	airlon trim tab deflection		1										1
	53	δ_{SB}	speedbrake position		1										1

8. Pilot inputs									
54	FCONTROLS	all cockpit flight control input forces	1						
55	SCONTROLS	primary flight controls pilots input	1					1	1
56	FLAPSET	flap setting	1					1	1
57	ETATSEL	trim selection elevator	1					1	1
58	KSITSEL	trim selection airlon	1						1
59	ZETATSEL	trim selection rudder	1						1
60	PWRSEL	power selection	1						1
61	PPSEL	propeller pitch selection	1						
62	SPSEL	speed brake selection	1						1
63	L/R-BRAKEPRES	left and right brake pressure	1						1
64	L/R-BRAKEPED	left and right brake pedal position	1						1
9. Pilot inputs (discrete)									
65	FS	fuel cut off lever position	1						
66	PRIMER	primer							
67	GEARSELECT	landing gear selection	1						1
68	COM	radio transmission keying	1			1	1	1	1
69	NAVF	selected Frequencies each NAV-Receiver	1						1
70	STALLPROT	stall Protection	1						
71	NAVL	NAV-lights			1				
72	EVENT	eventmarker	1						
73	AUTOP	autopilot/autothrottle status	1						1
74	DEICESEL	deicing selection	1						1
10. Cockpit displays									
75	ILS/MLS	vertical / horizontal beam deviation / marker beacon passage	1		2				1
76	DME	DME indication	1		1				1
77	BAROSET	selected barometric setting	1						1
78	EFISSET	EFIS setting	1						1
79	ENGDISPSET	Engine display setting	1						1
11. Cockpit operation									
80	OSP	operational stall protection	1						1
81	PNAV	primary NAV	1	1					
82	HYDPRESS	hydraulic pressure	1						

12. Cockpit warnings															
	83	WARN	Warnings		1										1
	84	HYDPRESSWARN	low hydraulic pressure warning		1										
	85	PNEUPRESSWARN	low pneumatic pressure warning		1					1					
	86	TCASWARN	TCAS/ACAS		1										1
	87	WINDSHEARWARN	windshear warning		1										1
	88	ENGVIBWARN	engine vibration warning		1										1
	89	ENGOVERSPWARN	engine warning overspeed		1										1
	90	CABPRESSWARN	loss of cabin pressure		1										1
	91	OILPRESSWARN	engine warning oil pressure low												1
13. Engine data															
	92	F	thrust	1	1								1	1	1
	93	n	rotation speed		1	1	1	1	1	1					
	94	p_{MF}	manifold pressure		1	1	1	1							
	95	POIL	oil pressure					1	1	1					
	96	FF	fuelflow		1			1		1					
	97	FP	fuel pressure					1	1						
	98	CTemp	carb. temperature												
	99	CHeat	carb. heating												
	100	EGT	exhaust gas temperature		1			1							
	101	CHT	cylinder head temperature		1	1	1	1	1						
	102	TOIL	Oil temperature			1	1	1	1	1					
	103	TCOOLANT	coolant temperature			1	1	1							
	104	ITT	ITT				1	1							
	105	AEP	additional engine states		1										1
	106	TR	position thrust reverser											1	1
14. Electrical system															
	107	UNET	onboard voltage		1				1						1
	108	IBATT	accumulator charging current		1										1
	109	LIGHTSTRIKEDET	lightning strike detector					1							
15. Landing gear															
	110	GEAR	gear position		1										1
16. Cabin															
	111	CO	carbon monoxide in cabin								1				
	112	DOORS	door state												

Table 34: Compiled of state vector

12.3 Overview of detailed solution analysis

Description see chapter 7.5.17.

Category	con't No.	Symbol	Description	AVIONIC „analogue“	AVIONIC „digital“	ENGINE „analogue“	ENGINE „digital“	OTHERS only retrofit
		Not realisable / not	definite defined / simplification					
		External sorce						
		Probaly solution						
		Computable with cer	tain input					
1. General								
	1	t	time	GNSS	Avionic			
	2	DATE	date	GNSS	Avionic			
	3	V	velocity	Not defined	Not defined			
	4	H	altitude	Not defined	Not defined			
	5	HRADIO	radio altitude	Video	Avionic			
2. Air data								
	6	p_{stat}	statik pressure	Sensor/Video	Avionic			
	7	q	dynamic pressure	Sensor/Video	Avionic			
	8	α	angle of attack	Computable	Avionic			
	9	β	angle oof side slip	Computable	Avionic			
	10	OAT	outside air temperature	Ext. source	Ext. source			
	11	DEW	dewpoint	Ext. source	Ext. source			
	12	ρ	density	Computable	Avionic			
	13	a	speed of sound	Computable	Avionic			
	14	Ma	mach number	Computable	Avionic			
3. Inertial data								
	15	a_x	acceleration in x-bKOS	IMU	Avionic			
	16	a_y	acceleration in y-bKOS	IMU	Avionic			
	17	a_z	acceleration in z-bKOS	IMU	Avionic			
	18	n_{az}	load factor z-bKOS	IMU	Avionic			
	19	p	angular rate x-bKOS	IMU	Avionic			
	20	q	angular rate y-bKOS	IMU	Avionic			
	21	r	angular rate z-bKOS	IMU	Avionic			
4. Trajectory and attitude								
	22	Ψ	heading	Magn./GNSS	Avionic			
	23	Θ	pitch attitude	GNSS + IMU	Avionic			
	24	Φ	roll attitude	GNSS + IMU	Avionic			
	25	χ	azimuth	GNSS	Avionic			
	26	γ	vertical track angle	GNSS	Avionic			
	27	γ_a	vertical airvector angle	Computable	Avionic			
	28	V_k	track velocity	GNSS	Avionic			
	29	GS	ground spped	GNSS	Avionic			
	30	TAS	true airspeed	Computable	Avionic			
	31	LAT	latitude	GNSS	Avionic			
	32	LON	longitude	GNSS	Avionic			
	33	POS	position	GNSS	Avionic			
	34	APPROACH	approach errors	GNSS	Avionic			
	35	GPSCOR	GPS correction in use	GNSS	Avionic			
5. Wind data								
	36	χ_w	wind azimuth	Computable	Avionic			
	37	γ_w	vertical windvector angle	Computable	Avionic			
	38	V_w	wind speed	Computable	Avionic			
6. Weight and Balance								
	39	T/W	takeoff weight					Costs
	40	L/W	landing weight					Costs
	41	m_F	fuel mass					Costs
	42	xCG	center of gravity x-bKOS					Costs
	43	yCG	center of gravity y-bKOS					Costs
	44	zCG	center of gravity z-bKOS					Costs
7. Aerodynamic controls								
	45	δ_i	deflection of a control surface (general)					Simplification
	46	ξ	airlon deflection					Simplification
	47	η_K	landing flap deflection					Simplification
	48	η	elevator deflection					Simplification
	49	ζ	rudder deflection					Simplification
	50	η_t	elevator trim tab deflection					Simplification
	51	ζ_t	rudder trim tab deflection					Simplification
	52	ξ_t	airlon trim tab deflection					Simplification
	53	δ_{SB}	speedbrake position					Simplification

8. Pilot inputs							
54	FCONTROLS	all cockpit flight control input forces					costs
55	SCONTROLS	primary flight controls pilots input					Sensor/Video
56	FLAPSET	flap setting					Video
57	ETATSEL	trim selection elevator					Video
58	KSITSEL	trim selection airlon					Video
59	ZETATSEL	trim selection rudder					Video
60	PWRSEL	power selection					Video
61	PPSEL	propeller pitch selection					Video
62	SPSEL	speed brake selection					Video
63	L/R-BREAKPRES	left and right brake pressure					costs
64	L/R-BREAKPED	left and right brake pedal pos.					costs
9. Pilot inputs, discree							
65	FS	fuel cut off lever position					Video
66	PRIMER	primer					Video
67	GEARSELECT	landing gear selection					Video
68	COM	radio transmission keying					Video
69	NAVF	selected Frequencies each NAV-receiv.					Video
70	STALLPROT	stall Protection					Video
71	NAVL	NAV-lights					Video
72	EVENT	eventmarker					Video
73	AUTOP	autopilot/autothrottle status					Video
74	DEICESEL	deicing selection					Video
10. Cockpit displays							
75	ILS/MLS	vertical / horizontal beam deviation / marker beacon passage	Video	Avionic			
76	DME	DME indication	Video	Avionic			
77	BAROSET	selected barometric setting	Video	Avionic			
78	EFISSET	EFIS setting	Video	Avionic			
79	ENGDISPSET	Engine display setting	Video	Avionic			
11. Cockpit operation							
80	OSP	operational stall protection					Video/interface
81	PNAV	primary NAV	Video	Avionic			
82	HYDPRESS	hydraulic pressure					Video
12. Cockpit warnings							
83	WARN	Warnings	Video/CVR	Avionic			
84	HYDPRESSWARN	low hydraulic pressure warning	Video/CVR	Avionic			
85	PNEUPRESSWARN	low pneumatic pressure warning	Video/CVR	Avionic			
86	TCASWARN	TCAS/ACAS	Video/CVR	Avionic			
87	WINDSHEARWARN	windshear warning	Video/CVR	Avionic			
88	ENGVIBWARN	engine vibration warning			Video/CVR	ECU	
89	ENGOVERSPWARN	engine warning overspeed			Video/CVR	ECU	
90	CABPRESSWARN	loss of cabin pressure	Video/CVR	Avionic			
91	OILPRESSWARN	engine warning oil pressure low			Video/CVR	ECU	
13. Engine							
92	F	thrust			computable	ECU	
93	n	rotation speed			Video/CVR/sensor	ECU	
94	p_{MF}	manifold pressure			Video/sensor	ECU	
95	POIL	oil pressure			Video/sensor	ECU	
96	FF	fuelflow			Video/sensor	ECU	
97	FP	fuel pressure			Video/sensor	ECU	
98	CTemp	carb. temperature			Video/sensor	ECU	
99	CHeat	carb. heating			Video/sensor	ECU	
100	EGT	exhaust gas temperature			Video/sensor	ECU	
101	CHT	cylinder head temperature			Video/sensor	ECU	
102	TOIL	oil temperature			Video/sensor	ECU	
103	TCOOLANT	coolant temperature			Video/sensor	ECU	
104	ITT	ITT			Video/sensor	ECU	
105	AEP	additional engine states			Video/sensor	ECU	
106	TR	position thrust reverser			Video/sensor	ECU	
14. Electrical system							
107	UNET	onboard voltage					video
108	IBATT	accumulator charging current					video
109	LIGHTSTRIKEDET	lightning strike detector					sensor
15. Landing gear							
110	GEAR	gear position					video
16. Cabin							
111	CO	carbon monoxide in cabin					sensor/video
112	DOORS	door state					costs

Table 35: Overview of detailed solution analysis

12.4 Overview of detailed cost analysis of onboard unit

Description see chapter 7.5.17.

	Symbol	Description	Probably Solution	Costs - Sensor	Installation	Additional	Comments additional costs
1. General							
1	t	time	GNSS receiver	100 €	200 €	500 €	data acquisition unit (DAU)
2	DATE	date	GNSS receiver	-	-	-	-
3	V	velocity	not defined	-	-	-	-
4	H	altitude	not defined	-	-	-	-
5	HRADIO	radio altitude	Video	400 €	150 €	-	Only hardware costs
2. Air data							
6	p_{stat}	statik pressure	sensor A	70 €	150 €	-	-
7	q	dynamic pressure	sensor A	-	-	-	-
8	α	angle of attack	computable	-	-	-	-
9	β	angle oof side slip	computable	-	-	-	-
10	OAT	outside air temperature	-	-	-	-	-
11	DEW	dewpoint	sensor B	260 €	150 €	500 €	housing
12	ρ	density	computable	-	-	-	-
13	a	speed of sound	computable	-	-	-	-
14	Ma	mach number	computable	-	-	-	-
3. Inertial data							
15	a_x	acceleration in x-bKOS	IMU	1.000 €	150 €	-	-
16	a_y	acceleration in y-bKOS	IMU	-	-	-	-
17	a_z	acceleration in z-bKOS	IMU	-	-	-	-
18	n_{az}	load factor z-bKOS	IMU	-	-	-	-
19	p	angular rate x-bKOS	IMU	-	-	-	-
20	q	angular rate y-bKOS	IMU	-	-	-	-
21	r	angular rate z-bKOS	IMU	-	-	-	-
4. Trajectory and attitude							
22	Ψ	heading	Sensor	150€	150€	-	-
23	Θ	pitch attitude	GNSS + IMU	-	-	-	-
24	Φ	roll attitude	GNSS + IMU	-	-	-	-
25	χ	azimuth	GNSS receiver	-	-	-	-
26	γ	vertical track angle	GNSS receiver	-	-	-	-
27	γ_a	vertical airvector angle	computable	-	-	-	-
28	V_k	track velocity	GNSS receiver	-	-	-	-
29	GS	ground spped	GNSS receiver	-	-	-	-
30	TAS	true airspeed	computable	-	-	-	-
31	LAT	latitude	GNSS receiver	-	-	-	-
32	LON	longitude	GNSS receiver	-	-	-	-
33	POS	position	GNSS receiver	-	-	-	-
34	APPROACH	approach errors	GNSS receiver	-	-	-	-
35	GPSCOR	GPS correction in use	GNSS receiver	-	-	-	-
5. Wind data							
36	χ_w	wind azimuth	computable	-	-	-	-
37	γ_w	vertical windvector angle	computable	-	-	-	-
38	V_w	wind speed	computable	-	-	-	-
6. Weight and Balance							
39	T/W	takeoff weight	costs	-	-	-	-
40	L/W	landing weight	costs	-	-	-	-
41	m_F	fuel mass	costs	-	-	-	possibly fuel flow sensor
42	xCG	center of gravity x-bKOS	costs	-	-	-	-
43	yCG	center of gravity y-bKOS	costs	-	-	-	-
44	zCG	center of gravity z-bKOS	costs	-	-	-	-
7. Aerodynamic controls							
45	δ_i	deflection of a control surface (general)	Simplification	-	-	-	-
46	ξ	airlon deflection	Simplification	-	-	-	-
47	η_K	landing flap deflection	Simplification	-	-	-	-
48	η	elevator deflection	Simplification	-	-	-	-
49	ζ	rudder deflection	Simplification	-	-	-	-
50	η_t	elevator trim tab deflection	Simplification	-	-	-	-
51	ζ_t	rudder trim tab deflection	Simplification	-	-	-	-
52	ξ_t	airlon trim tab deflection	Simplification	-	-	-	-
53	δ_{SB}	speedbrake position	Simplification	-	-	-	-

8. Pilot inputs							
54	FCONTROLS	all cockpit flight control input forces	costs	-	-	-	-
55	SCONTROLS	primary flight controls pilots input	sensor C	450 €	250 €	-	-
56	FLAPSET	flap setting	Video	-	-	-	-
57	ETATSEL	trim selection elevator	Video	-	-	-	-
58	KSITSEL	trim selection airlon	Video	-	-	-	-
59	ZETATSEL	trim selection rudder	Video	-	-	-	-
60	PWRSEL	power selection	Video	-	-	-	-
61	PPSEL	propeller pitch selection	Video	-	-	-	-
62	SPSEL	speed brake selection	Video	-	-	-	-
63	L/R-BREAKPRES	left and right brake pressure	costs	-	-	-	-
64	L/R-BREAKPED	left and right brake pedal position	costs	-	-	-	-
9. Pilot inputs, discrete							
65	FS	fuel cut off lever position	Video	-	-	-	-
66	PRIMER	primer	Video	-	-	-	-
67	GEARSELECT	landing gear selection	Video	-	-	-	-
68	COM	radio transmission keying	Video	-	-	-	-
69	NAVF	selected Frequencies each NAV-Receiver	Video	-	-	-	-
70	STALLPROT	stall Protection	Video	-	-	-	-
71	NAVL	NAV-lights	Video	-	-	-	-
72	EVENT	eventmarker	Video	-	-	-	-
73	AUTOP	autopilot/autothrottle status	Video	-	-	-	-
74	DEICESEL	deicing selection	Video	-	-	-	-
10. Cockpit displays							
75	ILS/MLS	vertical / horizontal beam deviation / marker	Video	-	-	-	-
76	DME	DME indication	Video	-	-	-	-
77	BAROSET	selected barometric setting	Video	-	-	-	-
78	EFISSET	EFIS setting	Video	-	-	-	-
79	ENGDISPSET	Engine display setting	Video	-	-	-	-
11. Cockpit operation							
80	OSP	operational stall protection	Video/interface	-	150 €	-	price for interface cable
81	PNAV	primary NAV	Video	-	-	-	-
82	HYDPRESS	hydraulic pressure	Video	-	-	-	-
12. Cockpit warnings							
83	WARN	Warnings	Video+CVR	200 €	150 €	-	price for CVR
84	HYDPRESSWARN	low hydraulic pressure warning	Video+CVR	-	-	-	-
85	PNEUPRESSWARN	low pneumatic pressure warning	Video+CVR	-	-	-	-
86	TCASWARN	TCAS/ACAS	Video+CVR	-	-	-	-
87	WINDSHEARWARN	windshear warning	Video+CVR	-	-	-	-
88	ENGVIBWARN	engine vibration warning	Video+CVR	-	-	-	-
89	ENGOVERSPWARN	engine warning overspeed	Video+CVR	-	-	-	-
90	CABPRESSWARN	loss of cabin pressure	Video+CVR	-	-	-	-
91	OILPRESSWARN	engine warning oil pressure low	Video+CVR	-	-	-	-
13. Engine							
92	F	thrust	computable	-	-	-	
93	n	rotation speed	Sensor D	-	150 €	10 €	signal conditioning
94	p_{MF}	manifold pressure	Sensor E	-	150 €	10 €	signal conditioning
95	POIL	oil pressure	video	-	-	-	-
96	FF	fuelflow	video	-	-	-	-
97	FP	fuel pressure	video	-	-	-	-
98	CTemp	carb. temperature	video	-	-	-	-
99	CHeat	carb. heating	video	-	-	-	-
100	EGT	exhaust gas temperature	video	-	-	-	-
101	CHT	cylinder head temperature	video	-	-	-	-
102	TOIL	oil temperature	video	-	-	-	-
103	TCOOLANT	coolant temperature	video	-	-	-	-
104	ITT	ITT	video	-	-	-	-
105	AEP	additional engine states	video	-	-	-	-
106	TR	position thrust reverser	video	-	-	-	-
14. Electrical system							
107	UNET	onboard voltage	Sensor F	5 €	-	-	inside DAU
108	IBATT	accumulator charging current	Video	-	-	-	-
109	LIGHTSTRIKEDET	lightning strike detector	Sensor G	50 €	150 €	-	-
15. Landing gear							
110	GEAR	gear position	Video				-
16. Cabin							
111	CO	carbon monoxide in cabin	Sensor H	20 €	-	-	inside DAU
112	DOORS	door state	costs	-	-	-	-

Table 36: Overview of detailed cost analysis of onboard unit

12.5 Overview of system configurations

Description see chapter 7.6.6.

IMU	Computable
Accelerometer	Video
GNSS	Sensors

	symbol	description	A 4.855 €	B 3.485 €	C 3.840 €	D 3.440 €	E 850 €	Combined 7.315 €	Reduced 4.415 €
1. General									
1	t	time	850 €	850 €	850 €	850 €	850 €	850 €	850 €
2	DATE	date	-	-	-	-	-	-	-
3	V	velocity	-	-	-	-	-	-	-
4	H	altitude	-	-	-	-	-	-	-
5	HRADIO	radio altitude	-	-	-	550 €	-	550 €	550 €
2. Air data									
6	p_{stat}	statik pressure	220 €	220 €	220 €	220 €	-	220 €	220 €
7	q	dynamic pressure	-	-	-	-	-	-	-
8	α	angle of attack	-	-	-	-	-	-	-
9	β	angle oof side slip	-	-	-	-	-	-	-
10	OAT	outside air temperature	-	-	-	-	-	-	-
11	DEW	dewpoint	910 €	-	-	-	-	910 €	-
12	ρ	density	-	-	-	-	-	-	-
13	a	speed of sound	-	-	-	-	-	-	-
14	Ma	mach number	-	-	-	-	-	-	-
3. Inertial data									
15	a_x	acceleration in x-bKOS	1.150 €	-	1.150 €	1.150 €	-	1.150 €	1.150 €
16	a_y	acceleration in y-bKOS	-	-	-	-	-	-	-
17	a_z	acceleration in z-bKOS	-	250 €	-	-	-	-	-
18	n_{az}	load factor z-bKOS	-	-	-	-	-	-	-
19	p	angular rate x-bKOS	-	-	-	-	-	-	-
20	q	angular rate y-bKOS	-	-	-	-	-	-	-
21	r	angular rate z-bKOS	-	-	-	-	-	-	-
4. Trajectory and attitude									
22	Ψ	heading	300€	-	300€	300€	-	300€	300€
23	Θ	pitch attitude	-	-	-	-	-	-	-
24	Φ	roll attitude	-	-	-	-	-	-	-
25	χ	azimuth	-	-	-	-	-	-	-
26	γ	vertical track angle	-	-	-	-	-	-	-
27	γ_a	vertical airvector angle	-	-	-	-	-	-	-
28	V_k	track velocity	-	-	-	-	-	-	-
29	GS	ground spped	-	-	-	-	-	-	-
30	TAS	true airspeed	-	-	-	-	-	-	-
31	LAT	latitude	-	-	-	-	-	-	-
32	LON	longitude	-	-	-	-	-	-	-
33	POS	position	-	-	-	-	-	-	-
34	APPROACH	approach errors	-	-	-	-	-	-	-
35	GPSCOR	GPS correction in use	-	-	-	-	-	-	-
5. Wind data									
36	χ_w	wind azimuth	-	-	-	-	-	-	-
37	γ_w	vertical windvector angle	-	-	-	-	-	-	-
38	V_w	wind speed	-	-	-	-	-	-	-
6. Weight and Balance									
39	T/W	takeoff weight	-	-	-	-	-	-	-
40	L/W	landing weight	-	-	-	-	-	-	-
41	m_F	fuel mass	-	-	-	-	-	-	-
42	xCG	center of gravity x-bKOS	-	-	-	-	-	-	-
43	yCG	center of gravity y-bKOS	-	-	-	-	-	-	-
44	zCG	center of gravity z-bKOS	-	-	-	-	-	-	-
7. Aerodynamic controls									
45	δ_i	deflection of a control surface (general)	-	-	-	-	-	-	-
46	ξ	airlon deflection	-	-	-	-	-	-	-
47	η_K	landing flap deflection	-	-	-	-	-	-	-
48	η	elevator deflection	-	-	-	-	-	-	-
49	ζ	rudder deflection	-	-	-	-	-	-	-
50	η_t	elevator trim tab deflection	-	-	-	-	-	-	-
51	ζ_t	rudder trim tab deflection	-	-	-	-	-	-	-
52	ξ_t	airlon trim tab deflection	-	-	-	-	-	-	-
53	δ_{SB}	speedbrake position	-	-	-	-	-	-	-

8. Pilot inputs									
54	FCONTROLS	all cockpit flight control input frcs.	-	-	-	-	-	-	-
55	SCONTROLS	primary flight controls pilots input	-	-	700 €	-		700 €	700 €
56	FLAPSET	flap setting	300 €	-	300 €	-	-	300 €	300 €
57	ETATSEL	trim selection elevator	-	-	-	-	-	-	-
58	KSITSEL	trim selection airlon	-	-	-	-	-	-	-
59	ZETATSEL	trim selection rudder	-	-	-	-	-	-	-
60	PWRSEL	power selection	-	-	-	-	-	-	-
61	PPSEL	propeller pitch selection	-	-	-	-	-	-	-
62	SPSEL	speed brake selection	-	-	-	-	-	-	-
63	L/R-BREAKPRES	left and right brake pressure	-	-	-	-	-	-	-
64	L/R-BREAKPED	left and right brake pedal position	-	-	-	-	-	-	-
9. Pilot inputs, discrete									
65	FS	fuel cut off lever position	-	-	-	-	-	-	-
66	PRIMER	Primer	-	-	-	-	-	-	-
67	GEARSELECT	landing gear selection	-	-	-	-	-	-	-
68	COM	radio transmission keying	-	-	-	-	-	-	-
69	NAVF	selected Frequencies each NAV	-	-	-	-	-	-	-
70	STALLPROT	stall Protection	-	-	-	-	-	-	-
71	NAVL	NAV-lights	-	-	-	-	-	-	-
72	EVENT	Eventmarker	-	-	-	-	-	-	-
73	AUTOP	autopilot/autothrottle status	-	-	-	-	-	-	-
74	DEICESEL	deicing selection	-	-	-	-	-	-	-
10. Cockpit displays									
75	ILS/MLS	vertical / horizontal beam dev…	-	-	-	-	-	-	-
76	DME	DME indication	-	-	-	-	-	-	-
77	BAROSET	selected barometric setting	-	-	-	-	-	-	-
78	EFISSET	EFIS setting	-	-	-	-	-	-	-
79	ENGDISPSET	Engine display setting	-	-	-	-	-	-	-
11. Cockpit operation									
80	OSP	operational stall protection	-	-	-	-	-	-	-
81	PNAV	primary NAV	-	-	-	-	-	-	-
82	HYDPRESS	hydraulic pressure	-	-	-	-	-	-	-
12. Cockpit warnings									
83	WARN	Warnings	-	-	-	350 €	-	350 €	-
84	HYDPRESSWARN	low hydraulic pressure warning	-	-	-	-	-	-	-
85	PNEUPRESSWARN	low pneumatic pressure warning	-	-	-	-	-	-	-
86	TCASWARN	TCAS/ACAS	-	-	-	-	-	-	-
87	WINDSHEARWARN	windshear warning	-	-	-	-	-	-	-
88	ENGVIBWARN	engine vibration warning	-	-	-	-	-	-	-
89	ENGOVERSPWARN	engine warning overspeed	-	-	-	-	-	-	-
90	CABPRESSWARN	loss of cabin pressure	-	-	-	-	-	-	-
91	OILPRESSWARN	engine warning oil pressure low	-	-	-	-	-	-	-
13. Engine									
92	F	thrust	-	-	-	-	-	-	-
93	n	rotation speed	160 €	160 €	160 €	-	-	160 €	160 €
94	p_{MF}	manifold pressure	160 €	160 €	160 €	-	-	160 €	160 €
95	POIL	oil pressure	160 €	160 €	-	-	-	160 €	-
96	FF	fuelflow	160 €	160 €	-	-	-	160 €	-
97	FP	fuel pressure	160 €	160 €	-	-	-	160 €	-
98	CTemp	carb. temperature	-	160 €	-	-	-	160 €	-
99	CHeat	carb. heating	-	160 €	-	-	-	160 €	-
100	EGT	exhaust gas temperature	-	160 €	-	-	-	160 €	-
101	CHT	cylindar head temperature	160 €	160 €	-	-	-	160 €	-
102	TOIL	oil temperature	160 €	160 €	-	-	-	160 €	-
103	TCOOLANT	coolant temperature	-	160 €	-	-	-	160 €	-
104	ITT	ITT	-	-	-	-	-	-	-
105	AEP	additional engine states	-	-	-	-	-	-	-
106	TR	position thrust reverser	-	-	-	-	-	-	-
14. Electrical system									
107	UNET	onboard voltage	5 €	5 €	-	-	-	5 €	5 €
108	IBATT	accumulator charging current	-	200 €	-	-	-	-	-
109	LIGHTSTRIKEDET	lightning strike detector	-	200 €	-	-	-	200 €	-
15. Landing gear									
110	GEAR	gear position	-	-	-	-	-	-	-
16. Cabin									
111	CO	carbon monoxide in cabin	-	-	-	20 €	-	20 €	20 €
112	DOORS	door state	-	-	-	-	-	-	-

Table 37: Overview of system configurations