Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

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RNLAF/F-16 LOADS AND USAGE MONITORING/MANAGEMENT PROGRAM

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0. SUMMARY

Structural load monitoring of the RNLAF/F-16 fleet is carried out by NLR as a routine program since the early nineties.

A more sophisticated electronic device capable of in flight data reduction of a strain gage signal replaced the ex factory mechanical strain recorder. A representative sample of each squadron was instrumented and final results were extrapolated to each individual aircraft to gain insight in the severity of operational usage. Later hardware upgrades made it possible to record some flight and engine parameters as well.

In recent years a completely new monitoring system has been developed. Main features are an increase to five strain gage locations, a flexible selection of flight, engine, and avionics parameters available via the MUX-BUS and fleetwide implementation. A relational database was developed for storing, managing and processing the raw measured data combined with flight operational data obtained from the RNLAF computerized maintenance/debriefing system.

Most recently the resulting fleet management information for the end users by means of an interactive interface becomes feasible.

1. INTRODUCTION

Load monitoring on the F-16 fleet of the Royal Netherlands Air Force (RNLAF) has been performed since the introduction of the aircraft in 1979. Through the years several monitoring systems were used. However, the main load parameter monitored was the strain measured at one of the major carry through bulkheads in the centre fuselage (figure 1). The strain at this location is an accurate measure for the wing root bending moment, which is a representative figure for the operational loads and can therefore be used as an indicator for the usage severity.

The original on-board load monitoring device evolved from a relative "simple" mechanical strain recorder to the advanced FACE system nowadays. Main features are the increase to five strain gage locations, a flexible selection of flight, engine, and avionics parameters available via the MUX-BUS and in-flight data reduction. Along with the development of the load monitoring equipment itself it was decided that for the second half of the operational life of the RNLAF F-16 fleet fleetwide implementation of the FACE system would be favourable. In chapter 2 a brief overview of this development and a description of the FACE instrumentation package will be given.

Switching over from a sample load monitoring program to fleetwide individual load monitoring combined with the flexible way of measuring a wide range of additional flight parameters required a different approach of handling the data. This resulted in a tailor made information system built by NLR for storing, managing, analyzing the collected measured flight data (MFD) with the on-board FACE system together with the administrative flight data (AFD) from each aircraft obtained from the RNLAF computerized maintenance/debriefing system CAMS. By making use of such a centralized information system efficient data handling is achieved. As well as for ad hoc analysis as for generating routine status reports for fleet management purposes. Recently the resulting fleet management information by means of an interactive interface with the use of the OLAP-tool (On-Line Analytical Processing) PowerPlay is becoming feasible. In chapter 3, the load monitoring program and information system will be described in more detail.

2. LOADS AND USAGE MONITORING INSTRUMENTATION

2.1 Overview development instrumentation

The first F-16 was introduced into the RNLAF in 1979. From the very beginning loads and usage monitoring has been taken care of. For this purpose a sample of the fleet was ex factory instrumented with a Flight Loads Recorder (FLR) for Loads Environment Spectrum Survey (L/ESS) recordings and a Mechanical Strain Recorder (MSR) was installed on each aircraft for individual aircraft tracking (IAT). The results however were not very satisfactory in terms of reliability and quality. Together with long turn around times, cassettes of both the systems had to be read out by the USAF, it was inevitable to abandon this way of loads and usage monitoring.

After the first update of the Fleet Structural Maintenance Plan (FSMP) for which L/ESS data was recorded with the FLR in 1985, the FLR was completely removed from the fleet. Note that by doing so the RNLAF had no L/ESS capability anymore. For replacing the MSR, the RNLAF and NLR decided that it should be replaced by a full strain gage bridge at the same location as the MSR (FS325) and to do this only on a (representative) sample of the fleet. Also a choice had to be made for the on-board electronic device. Selected was an instrument capable of recording the strain gage signal according to the peak-and-trough data reduction algorithm. The Spectrapot system produced by Spectralab in Switzerland was chosen for this purpose. In 1994 the one channel version of the Spectrapot was replaced by a four-channel version through which a limited L/ESS capability was obtained. This meant that besides the strain at FS325 also speed, altitude and vertical acceleration or engine RPM was recorded.
Within each squadron three to four aircraft were continually equipped and in total ten aircraft had “provisions for” to fly with a Spectrapot. This was necessary to keep the number of measured flights on an acceptable level in case of long time maintenance.

When in 1994 the updated 4-channel version of the Spectrapot was introduced it was already clear that this would and should only be a temporary solution. Since 1990 serious exchanges of views between the RNLAF and NLR took place about what would be the most favourable load monitoring program for the second half of the operational life of the F-16 fleet.

Two major modification projects were foreseen, Falcon Up and the Mid Life Update (MLU). The Falcon Up project is mainly a structural modification of the four main carry through bulkheads whereas MLU is basically an avionics upgrade of the aircraft. As a result of the structural upgrade it was expected that the mid fuselage section would give less fatigue problems in the future. Consequently, other parts of the structure would become fatigue critical. The main indicator for the loading experience of the aircraft, the strain gage bridge at main bulkhead FS 325, would therefore not be sufficient enough for monitoring the fatigue experience in other parts of the aircraft like outer wing, fuselage and stabilizers. Moreover some fatigue cracks were already found in these other parts. It was concluded that an increase of the number of strain gage bridges would be needed.
The number of strain gages is increased to five in the current program. Besides the strain gage on carry through bulkhead at FS 325, strain gage bridges are located at the lower skin of the outer wing at BL 120, at the keelson in the centre fuselage at FS 374, at one of the aft fuselage bulkheads at FS 479 and at one of the attach fittings of the vertical tail at FS 462, see figure 3.
A special measuring program was carried out with two instrumented aircraft. During 330 operational flights the signals of ten strain gage bridges were recorded and analyzed. The locations of these ten bridges were chosen in close co-operation with LM Aero.

One of the basic assumptions for the sample program was that aircraft in the same squadron flew more or less the same mission mix. This was certainly true for the first years of operation of the RNLAF F-16. In later years aircraft started to switch more often from squadron to squadron and the number of "out of area operations" increased with a significant difference in usage and loading experience. It was obvious that a sample program would not be sufficient enough and the decision was taken to go for a fleetwide implementation of a load monitoring system.

In that same period the RNLAF was also looking for an independent pilot debriefing system. RADA Electronic Industries in Israel could offer their Autonomous Air Combat Evaluation System (ACE) to do this task. The ACE system compiles a relevant selection of flight data from the aircraft's MUX-BUS and inserts these onto the airborne video system. A ground station capable of handling a maximum of a large number of tapes synchronizes the data offering a graphic and a video replay of the flight manoeuvres for debriefing and evaluation.
During test flights carried out with the ACE system in 1993 the idea came up to investigate the possibility of combining the autonomous debriefing system with the need for a new extended load monitoring system. NLR was contracted to specify the requirements for the "Fatigue Analyzing" part of the combined system and to codevelop with RADA the so to be called Fatigue Analyzer & Air Combat Evaluation system (FACE). A testflight carried out in 1994 showed that it was indeed possible to combine the pilot debriefing and load monitoring function. In 1995 the RNLAF signed the contract to implement the FACE system fleetwide and shortly after the first test flights took place. During this development and test phase close contact was kept with Lockheed Martin to ensure a proper installation of the FACE system. Special

attention was given to the connection with the MUX-BUS, hard- and software and the wiring for the MLU configuration. The first operational flight with the FACE system took place in 1997. At this moment about 80% of the fleet is instrumented with FACE.

2.2 FACE instrumentation

As mentioned before the FACE system combines the pilot debriefing and the load/usage monitoring function. The combined airborne part consists of four components:

- Flight Monitoring Unit (FMU)
- Data Recording Unit (DRU)
- Data Recording Cartridge (DRC)
- Strain Gage Amplifiers

On the ground both functions are completely separated. At each squadron two ground stations are located. The Operational Debriefing Station (ODS) offering the pilots a synchronized graphic and video replay and a PC-based Logistic Debriefing Station (LDS). The LDS offers readout of the flight recorded data from the DRC (after every 10 flight hours nowadays), storage of flight data and Setup Configurations Files for the airborne FMU (figure 4).

The FMU collects data from a number of data sources (figure 5) depending on the loaded Setup Configuration File (SCF). The SCF dictates which processes/signals are to be measured, which data reduction algorithms have to be used and onto which storage devices the results finally are to be recorded:

- *input:*

The FMU can interface with MUX-BUS channels as a monitor, analogues, discretes and serial channels. Via the MUX-BUS channels data like flight parameters, attitude, accelerations and store configuration are available to record. For engine monitoring data is required from the Digital Electronic Engine Controller/Engine Diagnostic Unit (DEEC/EDU) which are made available via the MUX-BUS. In this way all digital engine data can be recorded, such as RPM, pressures and temperatures. Both, MUX-BUS channels and DEEC/EDU handle in total a few hundred of signals. The strain gage signals for load monitoring are an example of analogue input. In total 15 analogue input signals can be monitored if required. Further some discrete values are monitored. The last group of input signals into the FMU are the video signals for debriefing purposes

- *output:*

Three types of output devices can be distinguished. The Data Recording Cartridge (DRC) which is used for collecting the data for loads and usage monitoring of the airframe and the engine. Nowadays every 10 flight hours a cartridge is changed. A Video tape is used for debriefing and mission evaluation. Additional data from the MUX-BUS channels is written onto the tape for the ODS to produce a graphic display of the actual flight. Video tapes are normally removed after each flight. As a third storage device the Voice And Data Recorder (VADR) will be installed. The VADR will only be used for mishap investigation. It remains on-board and recorded data is cyclic overwritten.

In the FMU a choice has to be made which signals are to be monitored and which data reduction algorithm is to be used for those selected signals. For this purpose an input file, the so called Setup Configuration File (SCF), is uploaded into the FMU. An SCF can easily be generated on the LDS via a user friendly interface. Next step is to upload the SCF into the FMU with a Software Load Data Recording Cartridge (SLDRC). If no new SCF is uploaded the FMU uses the resident SCF.
Up to a total of 15 processes can be specified which are monitored simultaneously. A master and a number of slaved signals define a process. Per master signal a maximum of 50 slaved signals can be selected. In total 200 master/slave combinations are possible. The master signal is the signal on which the reduction algorithm will be applied. At the same moment of finding a sample in the master signals, the momentaneous values of selected other signals are taken as "slaved" signals.

For each process a suitable, depending on the specific usage of the recorded data, data reduction algorithm has to be selected. Three main types of data reduction algorithms are possible:

- *Peak And Trough (PAT):*

The PAT algorithm searches the master signal for peaks and troughs. A specified range filter is used to filter out small cycles. In this way only cycles which are of importance for fatigue are stored in their actual sequence (figure 6). This algorithm is used for all the strain gage signals.

- *Time At Level (TAL):*

In the TAL algorithm crossings of specified levels are recorded in their actual sequence (figure 7). Up to 100 levels can be specified. As a result the time spent between two levels can be calculated. For example, the use of the after burner during a flight. Note that no slaved signals are possible with this algorithm.

- *SAMPLE:*

The SAMPLE algorithm (equidistance in time) gives the possibility of a constant sample rate by skipping a number of samples in the master signal before the next recording takes place (figure 8).

One has to bear in mind that the available sample rates for the different signals in the aircraft is not the same. On the MUX-BUS channels the highest sample rate of a signal available is 50 Hz. This for example is the case for accelerations and roll-, pitch- and yaw-rates. DEEC signals however are at the most sampled with 4 Hz.
For the analogue signals the highest sample rate possible is 1000 Hz which is used for the strain gage signals.

Data reduction is further possible by selecting the flight mode: ALL, AIR or GROUND during which the recording should take place. Also a time slot during a flight can be specified or a combination of two signals with a specified range for both signals. For example: only record if the Mach number is between 0.8 and 0.9 and if the altitude is between 500 an 1000 ft.

Taking the above mentioned into consideration it should be clear that every RNLAF F-16 instrumented with the FACE system can more or less be used as a fully instrumented test aircraft. And that besides for the airframe and the engine a lot of data can be made available for health monitoring of the avionics systems.

3. F-16 MONITORING PROGRAM AND INFORMATION SYSTEM

Load monitoring of the F-16 fleet of the RNLAF is carried out as a routine program by the National Aerospace Laboratory NLR since 1990 when the Spectrapot capable of processing in flight the signal of a strain gage bridge replaced the previous Mechanical Strain Recorder. In both cases the direct strain measured at main carry through bulkhead FS 325 is representative for the wing root bending moment.

At the time, the F-16 fleet was monitored on a sample basis. The information gathered with three to four aircraft per squadron was thought to be representative for the loads and usage experience of that squadron assuming that all aircraft belonging to a specific squadron flew more or less the same mission mix. Additional operational flight administrative data such as flight duration, mission type and external store configuration were taken from a special debriefing form and since 1995 directly extracted from the Core Automated Maintenance System (CAMS) of the RNLAF. Combining the load data from the sample measuring load program and the CAMS data from all F-16 flights it was possible to provide the RNLAF information on the experienced load severity per tail number. From the sample measuring program the severity per mission type, per squadron and per time period is available. By combining this information with the actual mission mix per individual tail number for the same period an individual damage indication can be calculated.

As a damage indicator, the Crack Severity Index (CSI) is in use. This CSI, developed by NLR, is a relative figure: for the F-16 a value of 1.0 means fatigue damage according to the reference usage and loading environment used to generate the current inspection schedule (Fleet Structural Maintenance Plan FSMP). The CSI method takes into account interaction effects between large and small load cycles (or between severe and mild flights). The fatigue damage of a flight is therefore dependent on the severity of the flights flown before.

At first glance one could say that an upscaling of the sample load monitoring program took place; an increase of one to five strain gage bridge locations and fleetwide implementation. However as discussed in chapter 2, the FACE system is fully integrated with other aircraft systems through which by far more flight parameters for airframe , engine and avionics monitoring are available. Moreover the set of measured parameters is not a fixed set, but can easily be changed via the Setup Configuration File (SCF). Figure 9 shows the default SCF used for airframe- and engine monitoring.

In order to cope with the large amount of loads and usage data a drastic change had to be made in collecting, storing and analyzing in comparison with the sample program with a fixed selected set of measured parameters and number of instrumented aircraft. The whole process of data handling has been automated to a large extent. Every night read out measured flight data from one squadron, collected from the Data Recording

Cartridges (DRCs) at the squadron's logistic debriefing station (LDS), is automatically sent to NLR. Once a week the relevant operational flight administrative data of all flights is directly extracted from CAMS. Special care has been taken to ensure "secure" data communication.

For storing, managing and processing the recorded raw measured FACE and CAMS administrative data NLR built a tailor made database application with the Oracle relational database package. In the design of the database special attention was given to the flexible way of FACE's handling of a large amount of different signals which was a base requirement for the database as well. Before storing the actual data a large number of checks is performed. Next recorded flights (FACE) are linked to realized flights (CAMS). One must realise that the number of recorded flights will always be less than the number of realized flights even after fleetwide implementation. A 100% data capture is an illusion. It is inevitable that sensors break down, memory cartridges lose data, wiring problems occur etc. Besides the real loss of data it may take a while before actual recorded data becomes available. Initially a DRC was only changed after 25 flying hours, which meant a delay of several weeks in processing the data. Nowadays the DRC is changed after 10 flying hours.

The database became operational with a limited functionality end 2000. In the base functionality <u>all</u> recorded FACE data is stored together with the operational flight administrative data and automatic calculation of the damage severity indicator CSI per tail number for strain gage location FS 325 is implemented. This is done according the sample program methodology since not all aircraft are equipped yet though the number of used measured flights is significantly higher and still increasing. For the remaining four strain gage locations discussions with LM Aero are still going on about correct determination of the reference load sequences, which are needed to calculate the correct CSI for these locations. As mentioned before the CSI is a relative figure between the <u>actual</u> measured and the <u>reference</u> usage and loading environment that was used as input by LM Aero for generating the current inspection schedule. Therefore the CSI can be used as an indicative measure for ASIP (Aircraft Structural Integrity Pogram) control points.

Making the measured loads and usage data in combination with the flight operational data easy accessible for routine and ad hoc analysis is one. Another base requirement of the database is that routine status reports for the RNLAF for fleet management purposes should be made available in an “on line” interactive form on a weekly basis. For this specific purpose use is made of the so-called OLAP-tool PowerPlay (On Line Analytical Processing). Characteristic for these kind of tools is the possibility of presenting different sets of results at different levels to the end users, for example air staff, air force bases and squadrons. The end user has the possibility to carry out a limited analysis of the final results to find out why a change took place in for example the usage severity by simply “drilling through” the data. In 2001 a pilot project has started with the RNLAF air staff in presenting the results in such a way for replacing the “old” routine CSI status reports. During this start up phase it has already become clear that in the near future more results will be presented via this way. NLR and the RNLAF discuss on a regular basis how to fully exploit these possibilities for fleet management support.
For the routine engine monitoring program the F-16 Loads and Usage Monitoring Information System functions as the data source for the measured engine parameters

and operational flight data. Processing the signals and calculation of the usage severity results is done with separate software tools developed at NLR.

4. CONCLUDING REMARKS AND WHAT'S NEXT

- An overview has been presented of the development of the loads and usage monitoring instrumentation for the F-16 of the RNLAF from the ex factory FLR and MSR to the advanced fully integrated FACE system.
- The change from sample based monitoring to fleetwide individual monitoring with FACE has been described and the impact this had on managing, storing data and making final results available.
- As soon as the proper reference load sequences for the remaining four strain gages are released by LM Aero 5 damage severity indicators per aircraft will be presented (indicative for about 40 ASIP control points).
- On short term a switch will be made from the "sample load monitoring methodology" to use of individual measured data per aircraft. A "gap filling" procedure is still needed for replacing lost or not yet available data of the flights concerned.
- During the second half of this year a start will be made with collecting new L/ESS recordings for a new update of the Fleet Structural Maintenance Plan by making use of FACE.
- For engine monitoring more detailed recordings are planned and engine results will also be made available via the F-16 Loads and Usage Monitoring Information System.

5. REFERENCES

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3. Spiekhout, D.J., Load Monitoring of F-16 Aircraft of the RNLAF with a Smart Electronic Device, AGARD Conference Proceedings CP-506, Fatigue Management, Bath, United Kingdom, May 1991.

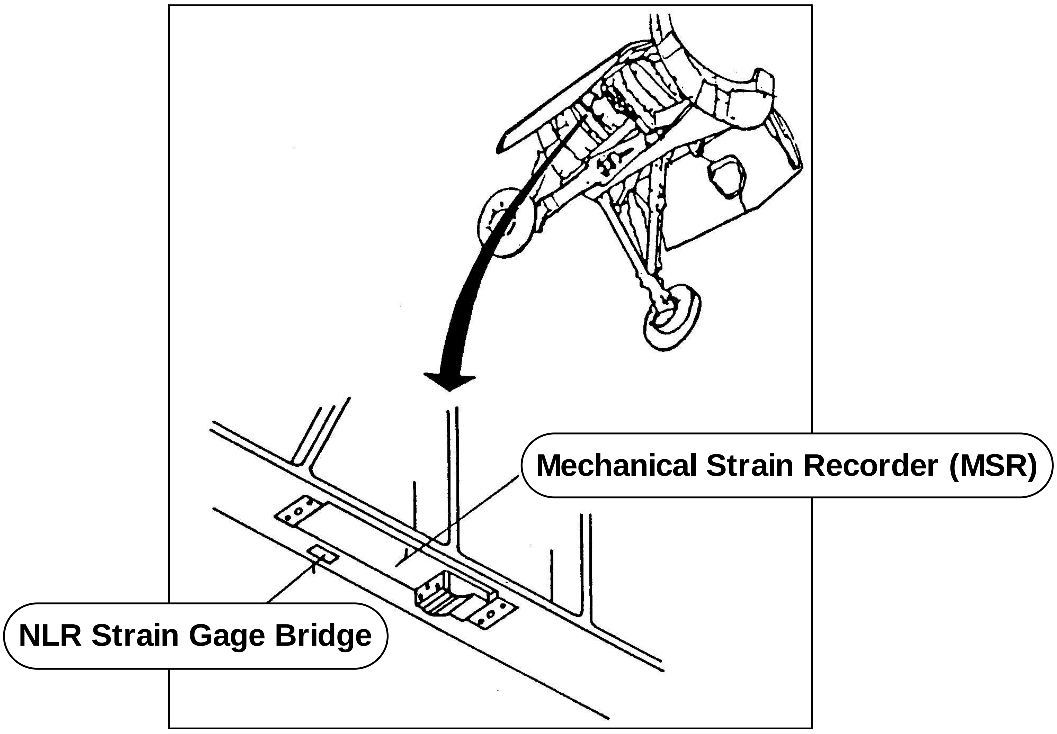

Figure 1: Strain gage bridge and MSR location FS 325.8

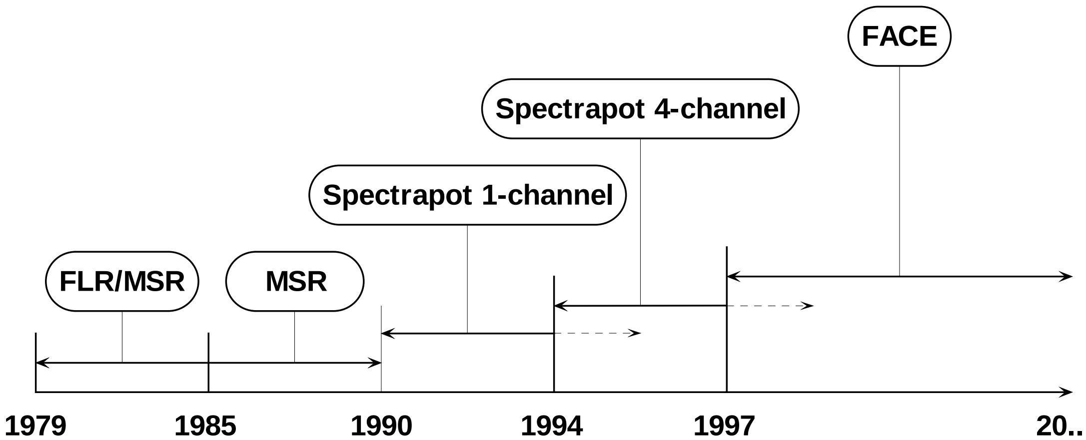

Figure 2: Timeline monitoring instrumentation trhough the years

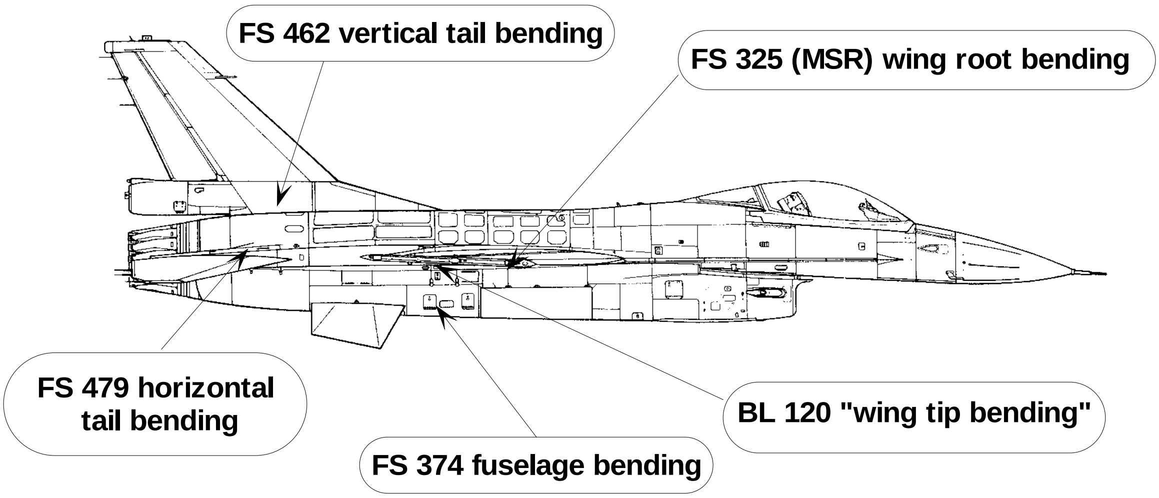

Figure 3: Strain gage bridge locations

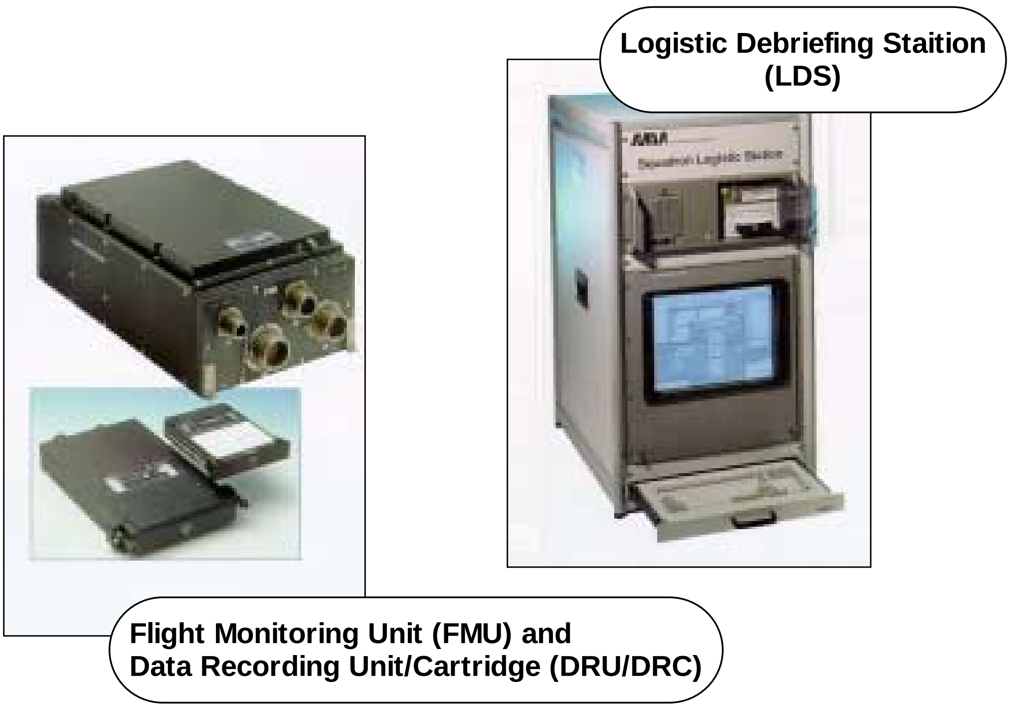

Figure 4: FMU, DRU/DRC, and LDS

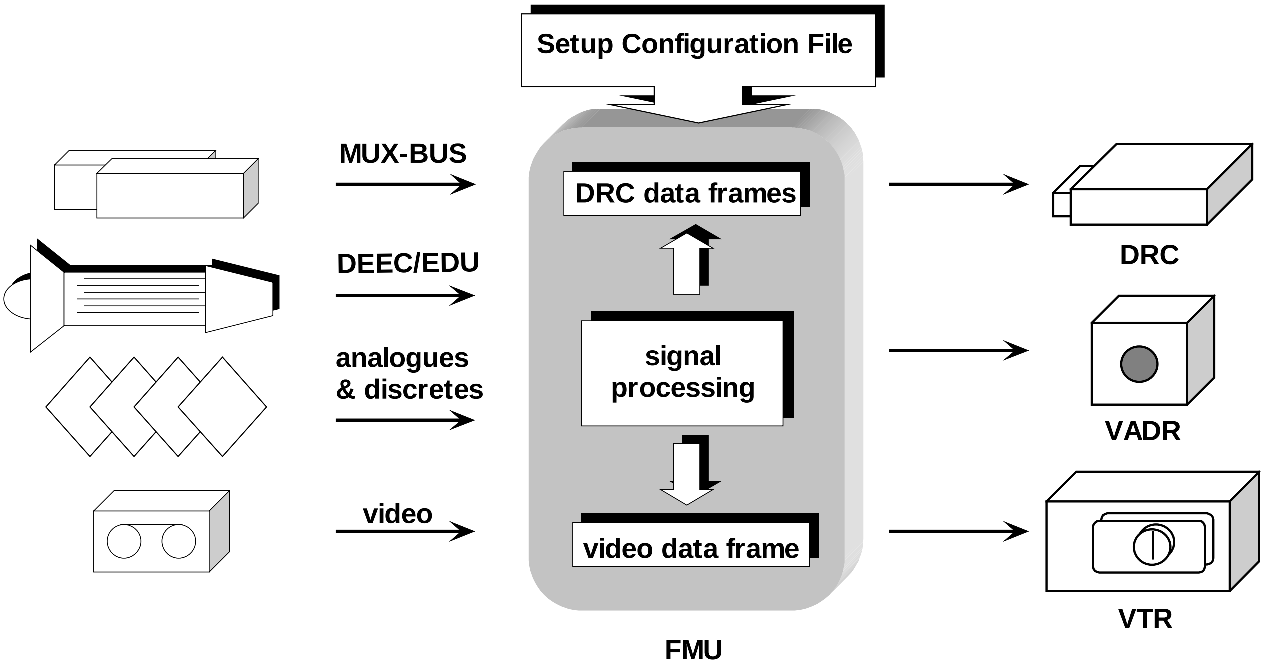

Figure 5: Schematic overview FACE system structure

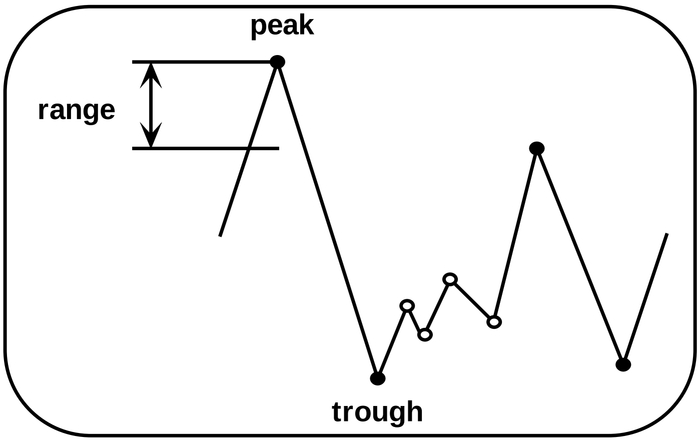

Figure 6: Peak and Trough data reduction algorithm

- *recognized as peak/trough*

○ *<u>not</u> recognized as peak/trough*

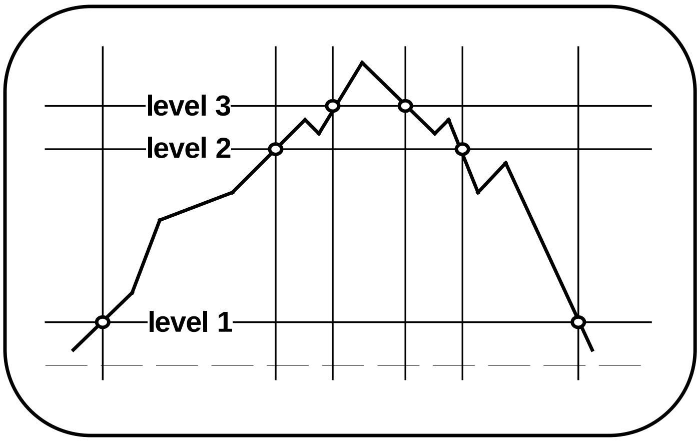

Figure 7: Time at level data reduction algorithm

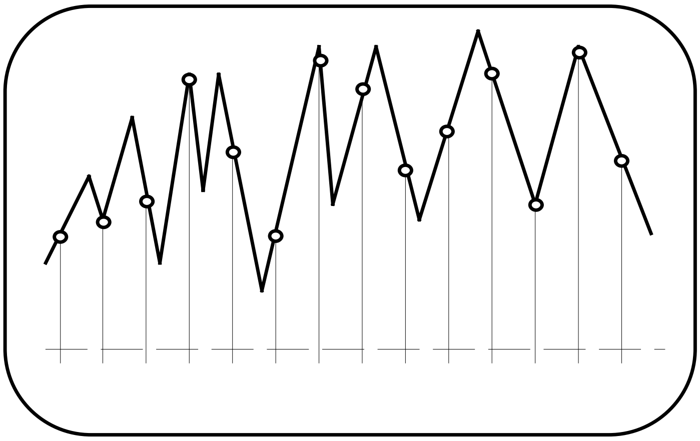

Figure 8: Sample data reduction algorithm (equidistance in time)

proces	master	slaves	processing algorithm
0	NORMACCEL normal acceleration	-	PAT range filter 0.5G
1	LATACCEL lateral acceleration	-	PAT range filter 0.1G
2	FS325 strain gage center fuselage bulkhead	-	PAT range filter 10 MPa
3	FS374 strain gage keelson center fuselage	-	PAT range filter 10 MPa
4	FS462 strain gage vertical tail attachment	-	PAT range filter 10 MPa
5	FS479 strain gage aft fuselage bulkhead	-	PAT range filter 10 MPa
6	BL120 strain gage outer wing	-	PAT range filter 10 MPa
7	N1 fan speed	-	PAT range filter 2%
8	N2 high compressor speed	-	PAT range filter 2%
9	PLA power lever angle	-	PAT range filter 2%
10	PLA power lever angle	-	TAL level1 17 deg, level2 89 deg
11	NORMACCEL normal acceleration	25	SAMPLE reduction factor 250, NORMACCEL on MUX available with 50 Hz → SAMPLE frequency 0.2 Hz

no	parameter	description	no	parameter	description
1	LATACCEL	lateral acceleration	14	AOA	angle of attack
2	LONGACCEL	longitudinal acceleration	15	Mach	Mach number
3	FS325	strain gage FS 325	16	CAS	calibrated airspeed
4	FS374	strain gage FS 374	17	MMCFDRMW1	configuration
5	FS462	strain gage FS 462	18	FUELWGT	fuel weight
6	FS479	strain gage FS 479	19	Ph	pressure altitude
7	BL120	strain gage BL 120	20	N2	high compressor speed
8	roll	roll-angle	21	PLA	power lever angle
9	pitch	pitch-angle	22	TFAT	true free air stream temp
10	TRHDG	true heading	23	FTIT	fan turbine inlet temp
11	FCCROLLR	roll-rate	24	TT2	inlet total temperature
12	FCCPTHR	pitch-rate	25	N1	fan speed
13	FCCYAWR	yaw-rate			

Figure 9: Default Setup Configuration File

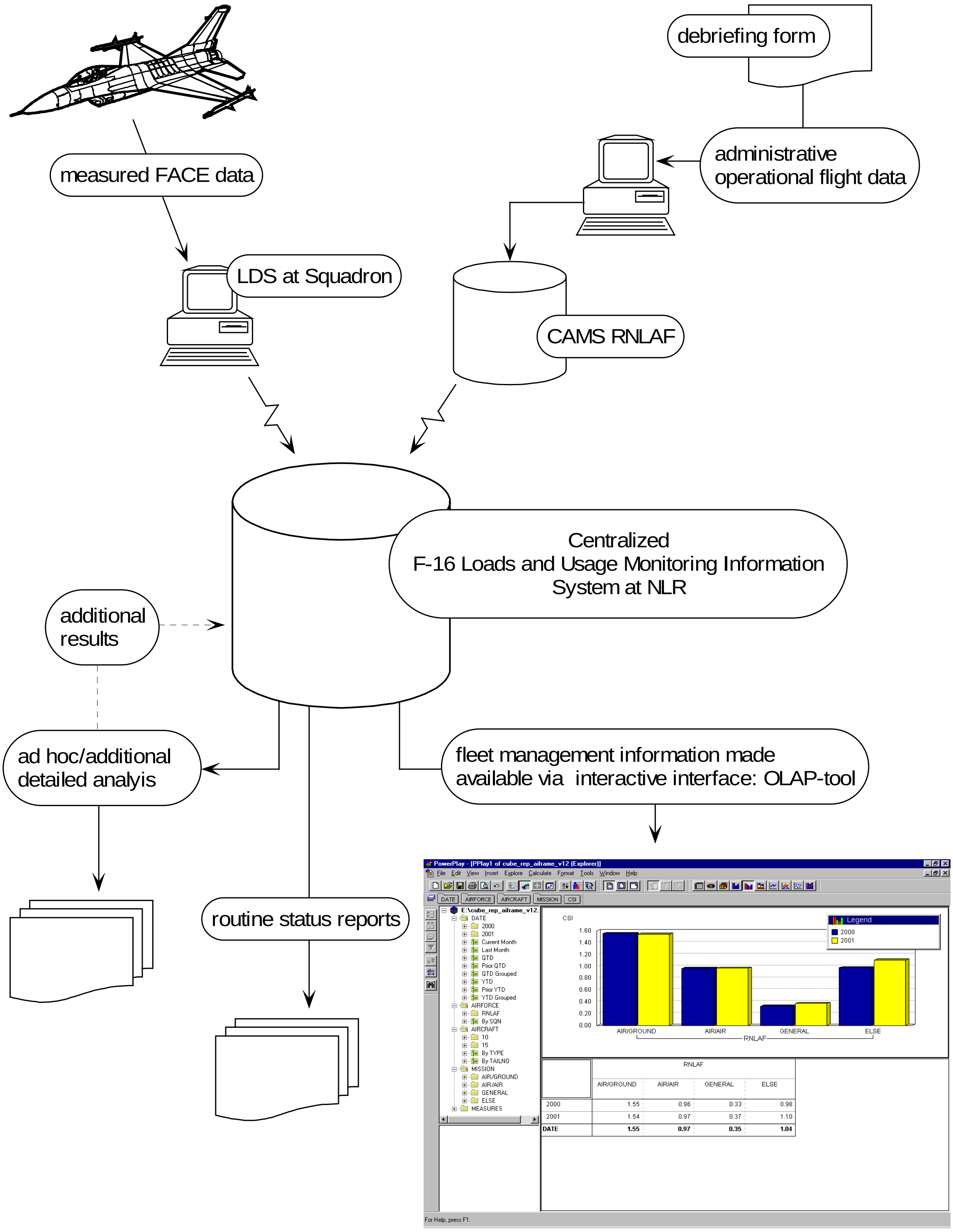

Figure 10: Overview data/information flow