Use of Recorders in Future Aircraft Operations

Edward A. Driessen,[*] Hendrik C. Vermeulen,[†] and Karel H. Ledeboer[‡]
KLM Royal Dutch Airlines, Schiphol Airport, Netherlands

Since 1959 KLM Royal Dutch Airlines, together with the Dutch National Aero- and Astronautical Research Institute, has been engaged in the development of a prototype airborne digital recorder. The experiments with this recorder have been directed at evaluating the applicability of flight recorders for performance purposes. This recorder, installed in one of KLM's DC-8 aircraft, has logged over 1000 flying hours in 1962 and 1963. This paper discusses the project development, gives a short description of the recorder, and presents the sequence of tests performed in 1962 and 1963. Regarding the data reduction and analysis, a brief outline is given on accuracy and repeatability, aircraft operation analysis, and engine analysis. From the experience with this recorder program, KLM's ideas with regard to system analysis and data reduction are given. Finally, some thoughts regarding a future aircraft integrated data system are presented. The information from such a system must be applicable in trouble shooting, component life prediction, performance discipline, flight planning, crash and incident analysis, etc.

Nomenclature

RAT = ram air temperature
SAT = static air temperature
TAS = true air speed
IAS = indicated air speed
PA = pressure altitude
M = Mach number
EPR = engine pressure ratio
EGT = exhaust gas temperature = Tt_7
FF = fuel flow = W_f
FQT = fuel quantity totalizer
N_1 = low-pressure rotor speed
N_2 = high-pressure rotor speed
δ = ambient pressure ratio
θ = ambient temperature ratio
δt_2 = Pt_2/P_0 = total pressure ratio at engine inlet
θt_2 = Tt_2/T_0 = total temperature ratio at engine inlet

Historical Background of KLM's Flight Recorder Project

Ever since airline people became interested in aircraft performance recording, a number of parameters proved to be essential. The human observer was usually sufficiently capable of writing down the required information. For general flight testing of aircraft by the manufacturer, more sophisticated methods were needed and the automatic film camera was developed for this purpose. Besides that, photographic trace recorders came into use. It was not until the era of the jet-propelled passenger aircraft, however, that applications of recording techniques for general airline use were considered.

In 1959 KLM's interest in this matter had reached such a point that approval was given for evaluating any suitable flight recorder that might be available. At the same time, the Dutch Aero- and Astronautical Research Institute (NLR) considered the purchase of a recorder deck in order to extend their facilities for flight testing of prototype aircraft by means of magnetic tape recording. KLM's ideas and those of the NLR could be combined, and therefore it was decided that the NLR should develop and build a recorder that could be tested in one of KLM's DC-8 aircraft. The fact that the equipment used in this flight recorder was designed for general flight test purposes had important consequences on its design. In the mechanical construction and the electronics design, versatility for flight test application in many cases prevailed over minimum-space considerations and case of maintenance. Nevertheless, it is felt that the principles used do provide a sound basis for the further development of flight recorders and flight-test equipment in general. The specimen used by KLM has given opportunity to investigate the applicability of flight recorders in large jet-propelled aircraft on a routine basis.

KLM's Research Department was responsible for the parameter selection, but a rather severe restriction was imposed on it by KLM's management. For all information required,

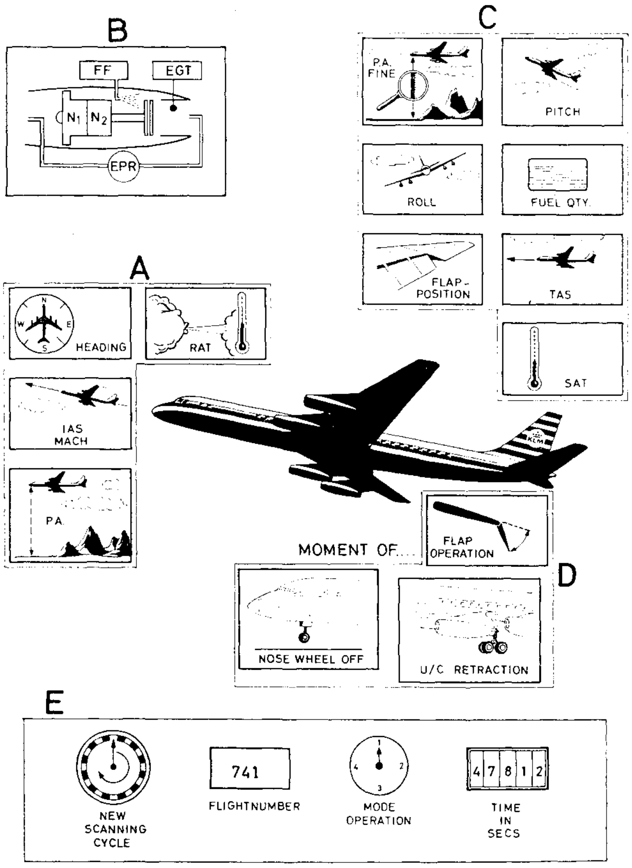

Fig. 1 Selected parameters.

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[*] Director of Research. Member AIAA.

[†] Project Engineer.

[‡] Maintenance Engineer.

use could only be made of the signal transducers already available in the aircraft. No extra transducers could be used in general, except for altitude, *IAS*, and *RAT*.

At that time, 1960, it was felt that, for a first investigation in the field of flight recording, aircraft performance and engine performance were the most interesting areas. This led to selection of the following parameters (see Fig. 1):

1) General flight condition parameters: a) pressure altitude, b) ram air temperature, c) Mach number, d) indicated airspeed, and e) heading.

2) Engine parameters (per engine): a) revolutions per minute of high-pressure compressor, b) revolutions per minute of low-pressure compressor, c) fuel flow, d) exhaust gas temperature, and e) engine pressure ratio.

3) Additional aircraft performance parameters: a) pressure altitude during take-off, b) pitch angle, c) roll angle, d) fuel quantity, e) flap position, f) true airspeed, and g) static air temperature.

4) Special procedure parameters: a) the moment at which the flaps move from or to their retracted position, b) the moment at which the main undercarriage is retracted, and c) the moment at which the nosewheel lifts off the ground.

5) Parameters for identification purposes: a) start of a new scanning cycle, b) number of the flight, c) scanning mode operation, and d) time.

KLM's Research Department was also in charge of all programs to be developed for data reduction. This data reduction was done by means of IBM 1401 and 705 computers.

Early in 1962 the recorder equipment was ready for installation, and on May 12, 1962, PH-DCH "Orville Wright" took off with a fully operative, digital flight recorder on board. This was, as far as we know, the first commercial airliner to do so. For a continuous period of 850 flying hours, the equipment remained on board and produced a mass of valuable data on the aircraft performance and engine condition.

In 1963 a second series of tests was performed. This time no general information was required, but the tests were directed at one specific problem that KLM encountered. The information recorded with this recorder has proved to be of very high quality and has been of great assistance.

Short Technical Description of the Recorder System Used in KLM's Evaluation Program[1]

The major problem that an airline has to face when considering automatic flight recording for general purposes is the mass of data to be analyzed. The only practical way of doing this is by means of electronic computers. This more or less decided the type of recording medium, magnetic tape, and the form (digital) in which the information should be stored. The NLR developed the recording equipment from a flight-test point of view and, in that respect, required accuracies of 0.2%. KLM felt that, in order to be able to find certain phenomena, the recorder accuracy should at least be a factor better than the transducer accuracies. This meant almost the same 0.2% accuracy for a number of channels. Such high precisions can only be attained if the measuring quantities are digitized in the aircraft. This was another reason to record the required data on the magnetic tape in digital form. The code used was a cyclic, progressive, decimal binary code, in which each of the three decimals consists of five bits plus a parity bit.

As stated in the previous section, KLM's management restricted the inputs of the recorder to the transducers already available in the aircraft. This requirement posed three problems on the NLR for the design of the input circuits: 1) they have to be adaptable to all types of measuring signals used in the aircraft; 2) they had to be designed so that they could not in any way influence the proper functioning of the normal aircraft systems to which they were connected; and 3) the precision of the flight recorder should not be decreased by the fluctuations in voltage and frequency occurring in normal aircraft electrical supplies.

The types of input from the parameters mentioned previously were three contact switches 28-v d.c., eight tachometers (a.c. voltages of variable frequency), eight a.c. voltage ratios (ratios of input voltage to the voltage of the 400 cps aircraft supply), two d.c. voltage ratios (ratios of input voltage to the 28-v d.c. aircraft supply), four absolute d.c. voltages (independent of the aircraft supply voltage), four synchro outputs (normal type), and six synchro outputs (Kollsman Synchrotel).

The various incoming signals were converted to a common type of analog signal, and this signal was digitized. After ample consideration, the NLR decided that pulse duration modulation (PDM) would be the best intermediate analog signal, but the a.c. signals were first converted to a d.c. with subsequent filtering before they were converted to PDM.

To reduce the bulk of the equipment as much as possible, the NLR designed the system in such a way that all signals of one type of input could be treated by a common conversion circuit. Therefore, the incoming signals were sent directly to the scanner before any signal modification took place. Of the four types of scanners considered, namely, the rotating switch, the stepping switch, the transistor scanner, and the relay scanner, the latter was chosen because of its safety, reliability, versatility, and switching characteristics.

The scanner ran at a speed of 5 inputs/sec with a maximum number of inputs of 48 in 1 cycle. The sequence in each scanning cycle (mode) could be altered by means of a patchboard.

KLM's interest centered on three distinct phases of flight: 1) engine start; 2) takeoff, first climb, and landing; and 3) cruise. For each phase, different repetition rates were required, which could be complied with by means of different scanning cycles. In mode 1, 8 parameters (*EGT* and N_2) had to be measured every 2 sec, 12 others every 10 sec. In mode 2, the *IAS* had to be measured every 2 sec, 35 others every 10 sec. In mode 3, pitch and pressure altitude were recorded every 2 sec, *EPR* every 5 sec, and the other parameters once in a cycle of 10 sec. This would be repeated every 100 sec.

This latter routine resulted in a considerable increase in recording time of the magnetic tape and a reduction in time required for data analysis. The duration of one roll of tape could then be increased by a factor of 4 to 5. Switching from one mode to another was done automatically. Normal checklist switches were used to operate modes 1 and 2. Mode 3 would override mode 2 at altitudes above 10,000 ft, whereas mode 3 could run continuously after a button on the flight engineer's panel was pushed by the flight engineer (mode 4). This would be done when special tests were performed during cruise.

Comprehensive safety measures had to be taken as this recorder was connected to the normal aircraft measuring circuits. Even in case of a recorder malfunctioning, no disturbances in the cockpit indications should be caused. The fact that almost all information went straight to the scanner added to the safety of the recorder. The power lines from the aircraft could be cut off by circuit breakers in the cockpit, and as an extra safety measure, all cables entering the flight recorder through one large connector could be disconnected from the recorder. None of these safety measures was applied during the operating time of the recorder. In Fig. 2, a block diagram is given which shows the recorder equipment as installed in the DC-8 together with test equipment in the aircraft and in the test car.

The airborne equipment of this experimental recorder was divided in two racks: an electronics rack that was mounted beneath the forward three seats of the lounge, and a recorder rack mounted beneath the two rear seats of the lounge. The electronics rack, measuring 58 × 26 in., contained 8 boxes, measuring 18.5 × 8 × 4.5 in., holding the electronics of the flight recorder and two boxes of slightly different dimensions

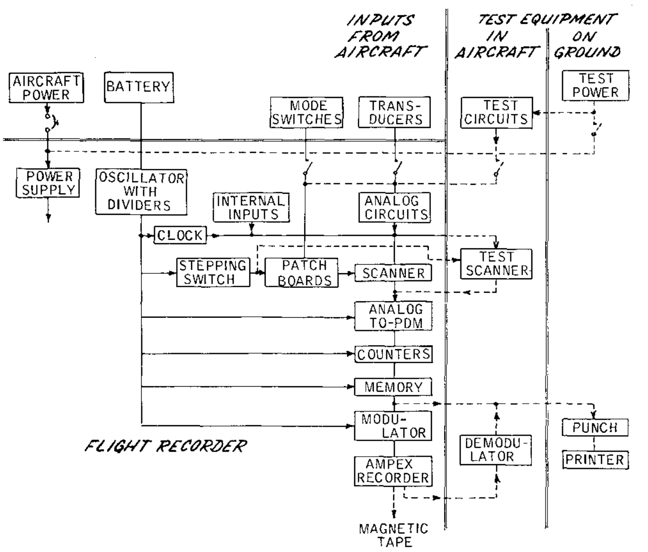


Fig. 2 General diagram of recorder equipment.

for the relay scanner and the test transducers. Figure 3 shows the electronics rack the way it was mounted in the DC-8. The recorder rack (Fig. 4) contained the Ampex AR-200 recorder and two boxes, 18.5 × 8 × 4.5 in., holding the power supply and test circuity. Weight of this experimental recorder was 300 lb. Magnetic tape used was of the mylar type. One reel contained 2500 ft which, with a tape speed of $1\frac{3}{4}$ in./sec, offered $4\frac{3}{4}$ hr of recording time. Tape width was 1 in., 14 traces, but since only 7 traces were used, the total recording time per reel could be doubled by switching the tape after recording one side. In this way some 45 hr of flying time could be recorded on one reel.

The DC-8 used was in normal airline operation during the experimental period. Therefore, any checks on the installed equipment had to be made during the rather short stops at Schiphol Airport. With this in mind, the NLR developed a semiautomatic test procedure. Part of the test equipment was mounted on the two racks in the aircraft. At Schiphol Airport, a test car was available which could produce all of the power required for the performance tests. Also in the test car were a paper punch and punched tape read/write unit.

Four test phases could be selected: phase A, over-all test of the equipment; phase B, response to fixed inputs; phase C, check on *A* (analog) to *D* (digital) conversion; and phase D, internal testing, time check. For any detailed checking of circuits in phases A and B, the test scanner could be stopped at any scanner position.

Since this experimental evaluation program was set up for assessing the feasibility of a flight recorder for airline purposes, no special ground equipment was developed. Use was made of the computer equipment available.

The magnetic tape from the recorder was played back at the NLR and translated into a punched paper tape. This latter tape was handled by KLM's IBM 1401 computer. For more detailed programs, KLM's IBM 705 was used. Figure 5 shows the analysis sequence.

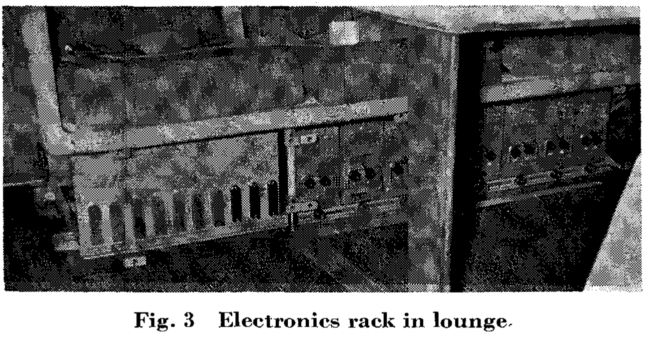


Fig. 3 Electronics rack in lounge.

Flight Recorder Tests of 1962 and 1963

The basic philosophy behind the recorder experiments was this: The recorder should never be less accurate than any sensor; consequently it should never raise questions as to whether an error could be attributed to the recorder.

The test phase was meant to produce enough recorder data mainly to 1) evaluate recorder behavior over a sustained period of normal airline operation over a wide range of environmental conditions; 2) check and retrim individual channel performance of the complete system (i.e., sensing + recording) to obtain the required accuracy, repeatability, and dependability; 3) evaluate aircraft system behavior and over-all aircraft performance over a sustained period of time and a wide range of environmental conditions; and 4) evaluate data reduction methods.

A schematic diagram of the recorder and computer operations is shown in Fig. 5. Many people might criticize this complicated way of doing things, but anyone who has tried to accomplish research programs during regular airline operation will know that such a program seldom gets as simple and efficient as a project engineer might wish.

In this case we did not like to increase the costs unnecessarily, and therefore we used the existing data processing system and shop equipment, simultaneously making the connection with the NLR equipment as smooth and simple as possible.

As shown in Fig. 2, the aircraft equipment consisted of normal aircraft sensors, NLR-designed signal conditioning (analogue circuits) and digitalization circuits, and an Ampex tape-recorder deck.

The first 850 hr of flight testing lasted from May until mid-August 1962, when passenger traffic was at its summer peak. Although initially we had some problems in program debugging, the operation of checking, calibrating, keeping log on line maintenance operations and on the aircraft systems, etc., worked quite smoothly.

Ultimately, all information was put on a dozen IBM computer tapes, and some flights were analyzed with the designed programs. Some of them will be discussed below.

The major problems of the operation of the system in practice were some cases of failure of the crew to change the right tape at the right moment, a tape-belt break, and a failure in the synchro channels of the recorder system causing misreadings. This last failure was detected very quickly because the data showed that the fuel quantity increased during cruise.

Reading the quality of the data, we had to suspect the following channels: 1) the *RAT* (ram air temperature), 2) the fuel flow, and 3) the altitude. The *RAT* was one of the exceptional parameters for which we installed a special transducer, namely, a Rosemount probe.

The reason for suspicion was, in the first place, a marked deviation from the flight engineer's readings (Lewis system), and secondly, the remarkable behavior of engine performance when reduced to standard sea-level conditions at various temperatures and altitudes.

This problem was not completely solved in the first test period, but was tackled again in the 1963 series. The fuel flow problem was of the same nature except that we had, in this case, more cross checks available to be sure that some difference existed between actual and recorded fuel consumption. This problem was not solved in the 1962 period. However, it indicated very strongly that the accuracy of the system should be high. If the system is not or cannot be calibrated accurately, it might lead to unjustified conclusions regarding aircraft system condition and might set back recorder development for a long time.

The authors' strong conviction is that the accuracy of a recorder system in the test phase should be better than the accuracy of the transducers. From the results of this test phase, requirements should be set for the production recorder in order to balance production costs vs system performance.

The third suspect item was the altimeter. In this case the altimeter, which was also one of the three exceptions where a special transducer with electrical output was used, showed, after analysis, to have failed in the second half of the 1962 test period. Precautions were taken so that this would not happen again in the 1963 test period.

The other parameters recorded in the 1962 period did not indicate that they should be suspected to the same degree because a high repeatability was found, and the data were very close to other manual checks made.

Based on these findings, which became more evident after analysis in early 1963, it was decided to run a second series of tests with the aim of solving the fuel flow and *RAT* problems and running these tests under more controlled conditions, which involved 1) provision of an airborne calibration check built into the recorder system, 2) a test program for fuel flow and *RAT* channels, and 3) turbine engine checks under controlled engine bleed conditions as far as possible.

This program was carried out successfully in 1963 solving our *RAT* and fuel flow problems. In this test phase, the recorder was not used continuously, but the rate of recording was determined by the test program.

Before going into more detailed analysis of both the 1962 and 1963 test periods, some basic ideas on maintenance and performance recorders should be emphasized. Every research program into a new area of technology requires basic knowledge of the functions and parameters, which are bound to be of importance. So far, for many systems, the airline depends on ground tests under sea-level conditions or simulated altitude conditions, having taken system components out of their normal operational environments. If the advances in a new area of technology will be applicable, more knowledge must become available about standard system behavior in normal day-to-day operation. The initial testing phase should be carried out with such accuracy as to be able to know from each individual system its normal operating performance level.

Only then can deviations from this level become meaningful and make it possible for the maintenance and performance people to draw firm conclusions about system failure, system condition, operational discipline, etc. The aim of the program carried out by KLM and the NLR was primarily meant to test this basic concept.

When successful, this would hold great promise for the data reduction problem too, because then a reliable base would have been provided for "management by exception." Also this would lead to a better judging of the possibility of accomplishing this latter concept in a very early phase of the data reduction.

From the following it might be learned that so far we were reasonably successful.

Some Results of the Test Periods

As already indicated in the previous paragraph, one of the major problems that had to be solved in the test periods was the determination of the actual accuracy and repeatability of the recordings. Factors affecting the determination of the accuracy of the recording are, subsequently, 1) the degree of stability of the aircraft system involved under normal operations; 2) quality and characteristics of the transducers; and 3) quality and characteristics of the recording process, which includes conditioning, *A* to *D* conversion, and transfer to tape.

The first factor is dependent on system characteristics and condition, and therefore can only be determined by comparison with other equal systems, e.g., cross checking four jet engines.

The second factor can be evaluated by ground tests under simulated conditions but still might give some problems when the transducer is installed in its normal operational environment. Where required and possible, careful calibration of these transducers was executed previous to, during, and after the tests. Regarding the normal environmental conditions that might influence the input signal too, some precautions have been taken, but the influence was found more or less as a by-product of the measures taken to evaluate the third factor.

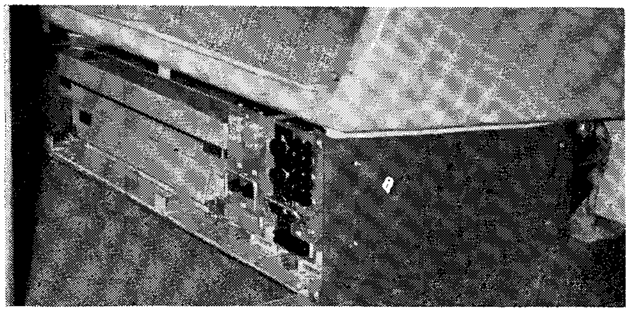


Fig. 4 Recorder rack in lounge.

To judge the quality and accuracy of the recorder system itself (third factor), a number of calibration cycles were provided for in the second test series. Some of the most important parameters of the calibration or test cycles are 1) aircraft a.c. frequency (400 Hz), 2) *RAT* (− 30°C), 3) fuel flow per engine (2100 kg/hr), and 4) compressor revolutions per minute (71.4% rpm).

Beyond these four types of test indications, there were a number of others that either indicated the quality and characteristics per specific parameter or per type of input signal.

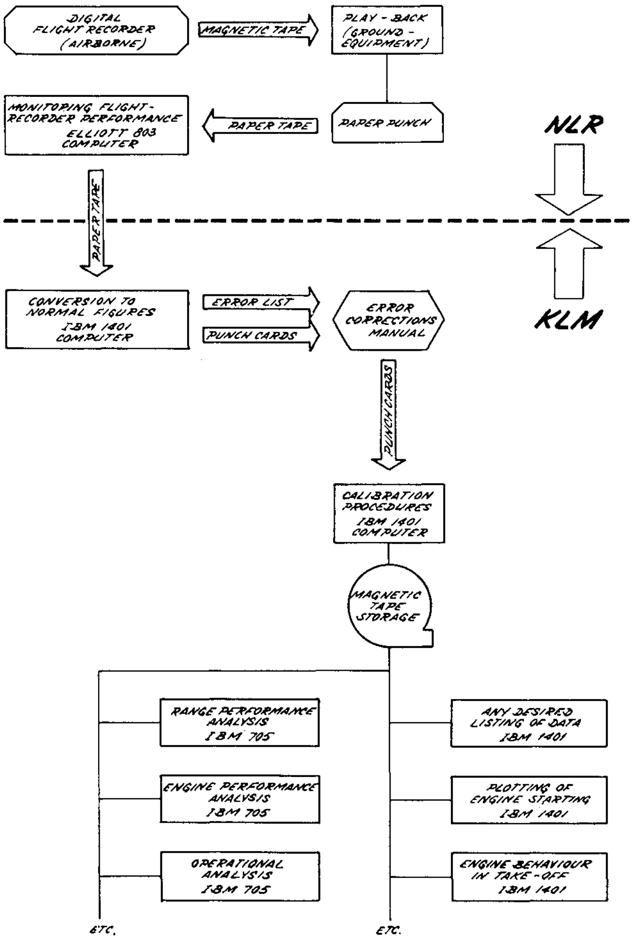


Fig. 5 Analysis sequence.

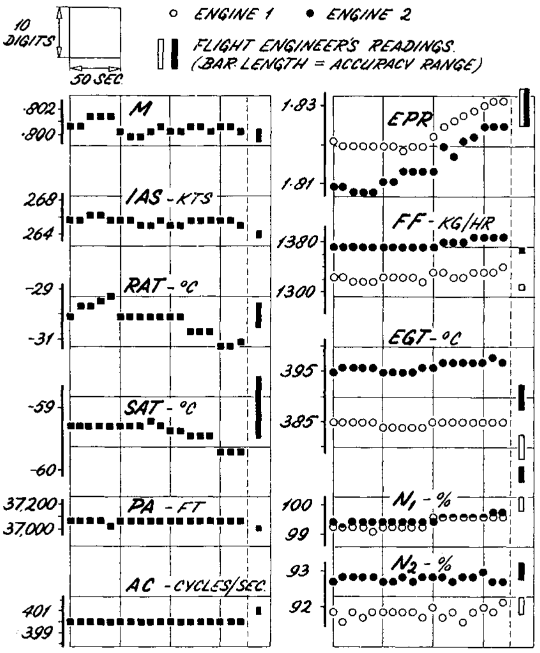


Fig. 6 Flight recorder vs flight engineer's readings.

These test points were produced partly by feeding the recorder with fixed input signals with values representative for normal operating conditions in cruise, or by recording voltages or voltage ratios. Deviations of the aircraft a.c. frequency (item 1) could be used to correct synchro outputs.

When the flight is executed with the four aircraft generators coupled, which is the normal procedure, this a.c. frequency will practically never change more than $\frac{1}{2}\%$ (see Table 1).

With the use of the *RAT* test cycle (item 2), we succeeded in getting accurate and repeatable *RAT* indications because any drift would automatically be indicated. The fuel flow test points (item 3) were chosen at 2100 and 4400 kg/hr, respectively. This calibration test was very helpful in adjusting the calibration or decoding characteristics for the digital output to get the accuracy within the design limits. In Table 1, the test cycle stability for a number of flights is shown. The tachometer test cycle performance (item 4) is also shown in Table 1, indicating the very high stability and accuracy of this signal.

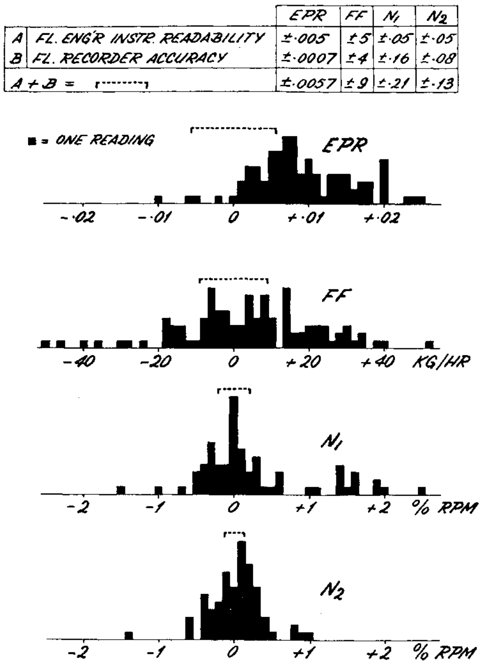
Table 1 Testpoint deviations

Test-channel	Freq. of testpoint deviations[a] −3	−2	−1	0	+1	+2	+3	Value of one digit
Synchro	...	1	8	77	26	3	...	0.5 Hz
RAT	...	...	...	10	4	7	5	0.2°C
FF	...	...	...	21	6	...	...	8 kg/hr
Tacho	...	...	...	27	...	...	...	8.7 rpm N_1 13.5 rpm N_2

[a] Zero is equal to digit value of test value.

Returning to the possible influence of environmental conditions, it will be clear that this would show up in deviations of the test readings when compared to the fixed test values. In practice, this influence proved to be of minor importance. It might be of interest at this point to give some idea of the stability of the readings under normal cruise operation.

In Table 2, the first column shows the standard deviation of the differences between each pair of subsequent recorded values. This standard deviation was chosen to be able to use a simple computer routine calculation in which the influence of nonsignificant transients in the time series of data is negligible. Thus an idea occurred to us concerning the stability of the data acquisition equipment. Assuming total stochastic independence of two subsequent measurements (or assuming that the recorder does not oscillate with a frequency of the order of the scanning cycle frequency), the second column gives the standard deviation of the recorder data.



		EPR	FF	N_1	N_2
A	FL. ENG'R INSTR. READABILITY	±·005	±5	±·05	±·05
B	FL. RECORDER ACCURACY	±·0007	±4	±·16	±·08
A + B = ┌┄┄┐		±·0057	±9	±·21	±·13

Fig. 7 Spread of flight engineer's readings around flight recorder readings.

Table 2 Frequency of digit change in cruise

Input	Parameter	σ^a	$\sigma/2^{1/2}$	Value of one digit
a.c.	*FF* eng. 1	1.31	0.93	8 kg/hr
	FF eng. 2	1.04	0.74	8 kg/hr
	FF eng. 3	0.99	0.70	8 kg/hr
	FF eng. 4	1.16	0.82	8 kg/hr
	Fuel Q. total	0.61	0.43	820 kg
	Pitch angle	1.98	1.40	0.11°
	Roll angle	2.50	1.77	0.11°
Tacho	N_1 eng. 1	0.95	0.67	8.7 rpm
	N_1 eng. 2	0.83	0.59	8.7 rpm
	N_1 eng. 3	0.82	0.58	8.7 rpm
	N_1 eng. 4	0.80	0.57	8.7 rpm
	N_2 eng. 1	1.36	0.96	13.5 rpm
	N_2 eng. 2	1.31	0.93	13.5 rpm
	N_2 eng. 3	1.04	0.73	13.5 rpm
	N_2 eng. 4	1.36	0.96	13.5 rpm
d.c.	*EGT* eng. 1	1.36	0.96	1°C
	EGT eng. 2	1.32	0.93	1°C
	EGT eng. 3	1.43	1.01	1°C
	EGT eng. 4	1.42	1.00	1°C
	RAT	1.05	0.74	0.2°C
Synchro-tel	*EPR* eng. 1	1.32	0.94	0.0014
	EPR eng. 2	1.33	0.94	0.0014
	EPR eng. 3	2.79	1.97	0.0014
	EPR eng. 4	1.28	0.90	0.0014
	IAS	1.09	0.77	0.58 knots
	PA	0.91	0.64	34.9 ft
Synchro	Heading	1.29	0.91	0.18°
	Doppler	3.14	2.22	0.5 knots
	Mach number	2.01	1.42	0.0004
	SAT	0.78	0.55	0.08°C

[a] σ = Standard deviation in digits.

The stability differences between systems or components can be seen specifically by comparing the standard deviations of, for instance, fuel quantity and pitch angle.

Another possibility of checking the functioning and, to a certain degree, the accuracy is by comparison of recorder readings with the flight engineers' observations. To get synchronization between the recorder and the flight engineer, the latter was asked to switch to mode 4 (increased scanning rate) when he took his log readings.

An example of such a comparison is shown in Fig. 6. Each parameter point of the recorder is shown for a period of 170 sec together with the flight engineer's readings. For a number of flights these readings were plotted vs the recorder outputs and these are shown in Fig. 7.

Because both observations, those of the recorder and those of the flight engineer, are taken from the same transmitter, the results should be such that the readings of the flight engineer have a normal spread around the recorder value. However, in some cases, deviations can be found since the recorder bypasses the indicator and human reading error. We experienced that this particularly is the case for *EPR* readings if no system calibrations (*EPR* + transmitter) were performed, and even then we encountered small deviations because of the difficulty in calibrating a pressure ratio system like this over its full range. This latter type of deviation, however, could be evaluated by investigation of total aircraft system accuracy. This was done for the jet engine but it seems more logical to include this in the next section.

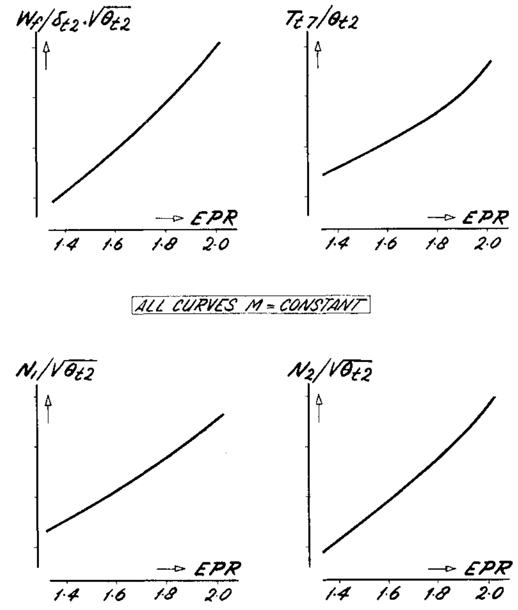


Fig. 8 Engine gas generator curves.

Engine Analysis

The engines installed in the DC-8 used for the recorder tests are Pratt & Whitney JT3D-3 fan engines. The performance data for these engines are presented in the Pratt & Whitney Aircraft (P&WA) engine specification and in the P&WA operating instruction OI-214. In this operating instruction (Fig. 8), P&WA presents the engine performance data in nondimensional form, called gas generator curves.

The chart shows that for each flight condition at a given *EPR* the fuel flow W_f, low and high rotor speeds N_1 and N_2, and exhaust gas temperature *EGT* are fixed. The chart is valid for a bare engine without bleed or power extraction.

In our second series of recorder tests, we used a special program to insure that we could determine the quality of the total recording relative to P&WA type of performance data. The following program was carried out on a number of subsequent flights.

1) The flight engineer was instructed to shut off the bleed subsequently on each engine and set the engine at various *EPR*'s to get readings over the full cruise thrust range.

2) The recorder was operated in mode 4 during these tests.

3) The tests were carried out at various altitudes under normal airline operation.

4) The most important transducers were calibrated before and after the tests.

5) A separate photographic trace recorder was used for measuring the regulated bleed flow to exclude any doubt with respect to bleed load.

6) An IBM computer program was used which calibrated and reduced all recorded data to the form used in P&WA's operating instruction. The parameters used in this program are *PA*, *M*, *IAS*, *RAT*, *EPR*, N_1, N_2, *EGT*, and W_f. These parameters were reduced to the following form:

EPRc = engine-pressure ratio, calibrated
$W_f/(\theta t_2)^{1/2}\ \delta\ t_2$ = fuel flow, nondimensional
$N_1/\theta t_2^{1/2}$ = low-pressure rotor speed, nondimensional
$N_2/\theta t_2^{1/2}$ = high-pressure rotor speed, nondimensional
$T_{t_7}/\theta t_2$ = exhaust gas temperature, nondimensional

The gas generator curves of the operating instruction (Fig. 8) indicate that, in the normal cruise range, namely, *EPR*'s from 1.50 to 1.80, the functions are practically linear.

Based on this phenomenon, the correlation with, and standard deviations respective to, a function $x = ay + b$ were calculated for each pair of engine parameters, for all data points sampled during these tests. The data points from the flight recorder were fed into the computer, and the computer program calculated the function $x = ay + b$ through these points, using the least squares method. Thus, instead of using the P&WA curve, a new relationship was found. The resulting correlation coefficients and standard deviations are shown in Table 3 for one of the four engines. *A* shows the values that apply to all altitudes ranging from 28,500 to 37,000 ft. *B* gives the values that apply to altitudes ranging from 28,500 to 35,000 ft. The standard deviations are expressed in *EPR* to make them comparable.

The table of standard deviations shows distinctly that the quality and repeatability characteristics of the recorder and the transducers must be high, especially with respect to *EPR*, fuel flow, and N_1. The higher values for the N_2 must be

Table 3 Correlation coefficients and standard deviations

	Correlation coefficients					Standard deviations expressed in *EPR*				
	EPR	$W_f/\delta t_2(\theta t_2)^{1/2}$	$N_1/\theta t_2^{1/2}$	$N_2/\theta t_2^{1/2}$	$Tt_7/\theta t_2$	*EPR*	$W_f/\delta t_2(\theta t_2)^{1/2}$	$N_1/\theta t_2^{1/2}$	$N_2/\theta t_2^{1/2}$	$Tt_7/\theta t_2$
EPR	...	0.999	0.998	0.992	0.996*A*	...	0.0062	0.0069	0.0145	0.0097*A*
$W_f/\delta_2(\theta t_2)^{1/2}$	0.999	...	0.998	0.992	0.996	0.0058	...	0.0063	0.0147	0.0103
$N_1/\theta t_2^{1/2}$	0.998	0.999	...	0.994	0.997	0.0062	0.0054	...	0.0128	0.0082
$N_2/\theta t_2^{1/2}$	0.991	0.991	0.993	...	0.992	0.0148	0.0149	0.0135	...	0.0142
$Tt_7/\theta t_2$	0.997 *B*	0.997	0.997	0.992	...	0.0085 *B*	0.0089	0.0080	0.0145	...

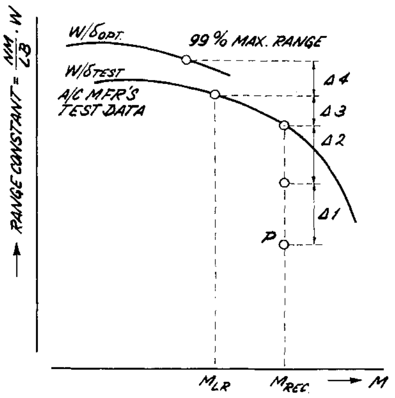


Fig. 9 Range constant vs Mach number.

partly due to floating of the high rotor speed, because the measuring system is equal for both low and high rotor speeds.

Another conclusion is that there is some altitude effect on the engine performance which is shown by the decreasing standard deviations when the altitude range is decreased. This altitude effect seems to be a function of engine condition and/or deterioration. Once the quality and repeatability are known, it is worthwhile to see what this means in case we use recording for engine maintenance. In the first place it will be evident that transducer malfunctioning can be directly detected because this would immediately be indicated in a diagram such as Table 3. For instance, *EPR* transmitter malfunctioning would be indicated by all standard deviations related to the *EPR*.

Deterioration would be indicated by increasing standard deviations, decreasing correlation coefficient, and/or changing equation constants (function $x = ay + b$). The sensitivity of the recorder to indicate deviations in engine performance is shown in Table 4, indicating minimum standard deviations during the recorder tests. The standard deviations in Table 3 are calculated for all relationships of one single engine for a number of subsequent flights. In Table 4, however, the standard deviations are the minimum values ever found with respect to each relationship between two parameters. As can be derived from this table, this sensitivity is quite high and well within the maximum accuracy attainable by dial readings on the aircraft system.

Range Constant

The list of parameters given previously shows that an analysis program for a check on the aircraft operational performance could be developed. This was done using the method indicated by the aircraft manufacturer, namely, the range constant method (Fig. 9). In this figure the aircraft performance (manufacturer's) is shown for the test W/δ. The point P is the reduced recorder data point at the same W/δ and Mach number $M_{\rm rec}$. The computer program calculates the deviations Δ1, Δ2, Δ3, and Δ4, which are deviations due, respectively, to Δ1, engine performance; Δ2, aircraft performance; Δ3, pilot + instrument performance relative to company speed schedules, and Δ4, air traffic control (deviations from optimum altitude).

We derive the conclusion that the air traffic control, aircraft performance, and pilot discipline were well within limits. This analysis indicated, however, a fluctuation in aircraft performance which so far could not be explained by aerodynamic theory. For instance, from the recorded weight, altitude, and speed, the required thrust setting is determined and compared with the manufacturer's charts. The results of these IBM calculations are plotted vs time. They show a reasonable agreement over certain periods of a flight, but at other periods high positive or negative differences occur. These deviations do not correlate with other measured parameters on this airplane. For this reason, the performance might well be more affected by vertical air movements than is known today. If this can be proven to be so, recording will be a powerful tool in finding the characteristics thereof in order to optimize the flight path. Fuel savings involved are estimated at least at 1%. A study concerning the flight technical error, based on the recorded data, was made by the NLR in order to deliver a positive contribution to the vertical separation problem.

System Design Influence on Data Reduction

Previous paragraphs have shown the basic structure on which the data reduction has to be based, namely, an accurate and reliable record, having automatic calibration, by which it is possible to separate recording system errors from any other malfunctioning or deterioration. From a recording system offering this quality, reliable, normal aircraft system operating levels can be derived. Having derived the operating levels, deviations from these levels indicate the degree of malfunctioning or deterioration of the aircraft system, the system components, or transducers. The higher the sensitivity of the recorder system, the faster the reaction can be on existing or developing malfunctions.

One of the most important factors, however, which brings us now to the data reduction itself, is that the more accurate and reliable the record is, the less data points will be required. What we wish to see is a definite indication of failure, malfunctioning (existing or developing), and the degree of deterioration. Of these, failure is apt to give the least problems, whereas malfunctioning tends to require more information.

It is evident that, without any failure or malfunctioning, mainly the accuracy and repeatability of the recorder will determine the number of data points required for a reliable analysis of a certain operating level or change thereof. But at a once determined operating level, the number of data points required to analyze failures and malfunctioning will be less for the more accurate and self-checking system. Thus, by increasing the quality of the record and providing self-checking ability, the extent of the data reduction process will be reduced. Many parameters that are related to other parameters will need some type of integration to determine the operating level. An example is shown in the previous paragraph for the jet engine $[W_f/(\theta t_2)^{1/2}\ \delta t_2]$. Once this level is known, accuracy and repeatability will make more simplified data reduction methods possible.

Achievement of these simplification techniques will be reflected in the size and complexity of electronic analysis equipment for short term maintenance purposes at line stations and/or computer devices aboard the aircraft (see next paragraph).

Another area where quality is directly related to size of equipment is the number of parameters to be recorded. Reliable and accurate information will give the aircraft system engineer more chance to optimize the number of parameters he needs for failure, malfunctioning, or deterioration detection. The less accurate and repeatable the record, the more he will safeguard himself against insufficient information by increasing the number of parameters to be recorded.

Summarizing, it can be stated that a high quality record reduces the amount of data to be analyzed, makes more simplified data reduction methods possible, reduces the number of parameters to be recorded, and makes the

Table 4 Minimum standard deviations expressed in EPR

	$W_f/\delta t_2(\theta t_2)^{1/2}$	$N_1/\theta t_2{}^{1/2}$	$N_2/\theta t_2{}^{1/2}$	$Tt_7/\theta t_2$
EPR	0.0051	0.0039	0.0097	0.0067
$W_f/\delta_2(\theta t_2)^{1/2}$	...	0.0054	0.0115	0.0077
$N_1/\theta t_2{}^{1/2}$	...	...	0.0102	0.0061
$N_2/\theta t_2{}^{1/2}$	...	...	...	0.0132

system adaptable to introduction of airborne computing methods.

The problem of the rate of sampling to be used is of quite a different nature. It has evident consequences regarding the extent of the data reduction process. When for each selected parameter the required sampling rate is determined individually, the total result will be that a range of sampling rates will be required. Careful analysis of each parameter (taking into account the system stabilities in the various flight regimes and individual system operating regimes, with simultaneous intelligent use of modern electronic techniques), can separate the parameters in a number of categories, each requiring a certain sampling rate. The recorder system then should be flexible enough to accept different groups of parameters and different operating regimes.

The experience with the NLR recorder with the use of different operating modes and different sampling rates (see previous paragraph) has indicated that intelligent sampling rate selection will result in reduction of the number of data points per flight and simplification of the data reduction. This general concept is illustrated in Fig. 10.

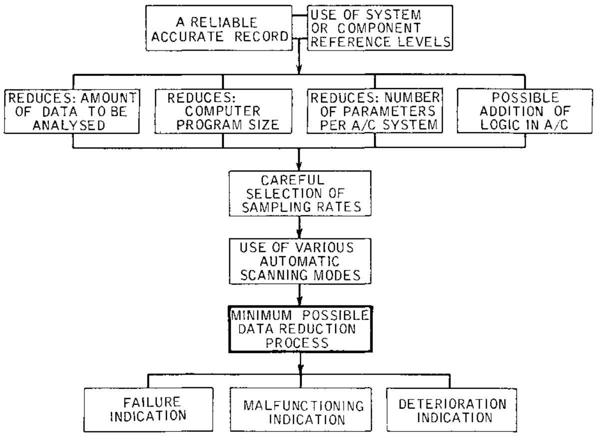


Fig. 10 Data reduction concept on a digital aircraft integrated data system.

Future Use of Digital Recorders in Airline Operation

Flight recorders may prove to be of value as performance checking devices, but their greatest advantages will be in the field of aircraft maintenance. At present, KLM's maintenance schemes are divided into five types of inspection: 1) after each flight, 2) after each return to main base with a ground time of more than 4 hr, 3) after 50 flying hr (dependent on aircraft type), 4) after 400 flying hr (dependent on aircraft type), and 5) after 3600 flying hr (dependent on aircraft type).

The scheduled ground time for inspections 1 and 2 is short, and therefore the amount of maintenance to be done is limited. For 3, 4, and 5, longer periods of time are available. This should be reflected in the type of analysis to be done on the recorded information. All that is required in checks 1 and 2 is to know whether any system has operated beyond its normal operating limits. In the other checks, developing trends should also be incorporated in the decisions regarding the work to be done. In the type 1 check, only the information regarding the last flight is of interest. For types 2 and 3, the behavior of the systems during the flights from main base and back need to be considered. For 4 and 5, the characteristics over a longer period must be taken into account. Thus a pattern develops in which distinction can be made between short- and long- term maintenance. For the long-term maintenance, all analysis can be done at one location, for instance, the main base. For the short-term analysis, some sort of equipment must be available at each airport at which the aircraft lands. This also has its influence on the parameter selection. For short-term analysis, one or two parameters per system (or part thereof) may be sufficient to indicate whether any limits have been surpassed. For long-term analysis, a more detailed knowledge of the system will be required in order to indicate whether the condition of the total system is still within acceptable limits. This will also be necessary to find component deterioration. Thinking along these lines, one may need some 300 parameters for long-term analysis purposes and 60 parameters for short-term checks.

The equipment required at the outstations will then only need a capacity for reading some 60 channels. Now, considering *KLM*'s network where some 70 stations are served by 40 aircraft, it might be worthwhile to have a simple unit in the aircraft itself instead of a very infrequently used, read-out unit at each airfield.

Hereby some form of logic is built into the recorder system and a display may immediately tell the crew (and after landing, the ground engineers) whether any parameters have surpassed their limits. If any serious effects are noted, the recorded information regarding those specific systems should be sent to the central processing unit for detailed analysis via telex lines, which are already present. This means that no corrective actions can be taken until an answer is received from the main base. Since some telex lines are very extensive, subcenters at logical stations, capable of doing the analysis just mentioned, might be required. For KLM's network, the main center could be at Schiphol Airport, covering all Europe and with subcenters at New York for the U.S.A., Canada, and Mexico; at Curaçao for South and Central America; at Bangkok for Asia; and at Johannesburg for Africa. Perhaps a second European and Near-East center might be necessary at Rome. There is also a further possibility that other airlines might be interested in using the analysis equipment in these outstations, which would make it a more economical proposition.

The functions of the central processing unit at the main base will be more extensive than those at the outstations. These latter units will deal only with the short-term analysis. The main base unit should be capable of doing both short-term and long-term analysis, as well as special performance or operational checks.

Considering a fleet of 40 aircraft, 20 long range and 20 medium/short range types, some 2000 flying hr will be accumulated during a week's time. During one week each aircraft will have returned to the main base at least once. Using the same principle of reduced recording rate during cruise, as applied in the experimental flight recorder, some 600 hr recording time will be produced. Assuming a playback rate of 40 times the recording rate, the read-in time for this material will be 15 hr. An estimate of the required computer time for the various calculations to be made is 8 to 10 times the read-in time, and therefore from 120 to 150 hr of computer time per week. This would mean that the main computer will be in service all day to analyze all the material recorded in detail. The results of this analysis should be produced in a practical form and be meaningful for maintenance and operational personnel.

What kind of recorder system do we envisage for this task? The system as developed by the NLR was capable of handling inputs of various sources. It now will be possible to build modules of small size, capable of taking some 30 odd inputs, multiplexing and converting them to a common analog signal. This common analog signal should then be fed into one analog-to-digital converter coupled to a recorder unit. As suggested previously, some form of logic might be required. This should be put after the A to D converter. This split-up of the airborne part of the recording system will allow the location of separate units in strategical parts of the aircraft, together with one central A to D converter and tape deck. Such strategical points might be (in a four-engine aircraft) between

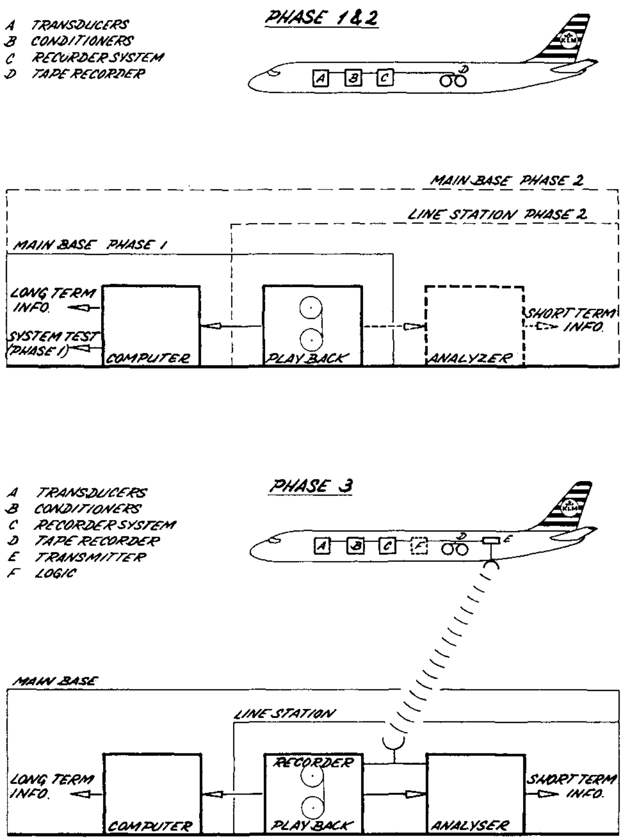


Fig. 11 Flight recorder in future use.

two engines, in the nose, in the tail, or near the c.g. The advantages of such a system are its reduced wire weight and the possibility of extending the total recording capability by adding modules.

For crash-recording requirements it may be necessary to make provisions for the tape to be recovered after a crash. However, with a 300-channel magnetic tape recorder, this may be a rather difficult job, keeping in mind that for maintenance purposes the tape should be easily changeable and accessible. Also the fact that the mandatory requirements are not speaking in terms of 300 parameters makes it a waste of effort to protect everything. Therefore, a separate recorder taking only the mandatory parameters could be installed in a suitable location (possibly the tailzone). Another possibility that we are considering is telemetering of the data prior to landing and during takeoff and climb.

The majority of accidents occur in the first or last phases of the flight. If transmission of data to the ground station, together with recording on the ground and in the aircraft, could be effected in those periods, a major improvement in retrieval of valuable data will be possible. After completion of the flight and storage of the flight-recorded data, the ground-recorded data can be destroyed. Figure 11 depicts our general views, whereby a development in several phases is envisaged.

What effects will these methods have on our present maintenance procedures? This depends largely on the extent of the analysis to be performed with the recorded data. Considering the types 1 and 2 inspections, the value of the system exists only where it can immediately indicate system failures. Therefore, the analysis should be directed at that goal. Should one succeed in attaining this, then a minimum turn-around time at a station would be the result. No input of nondefect components to the workshops will be necessary, which is an extra advantage.

In the types 3 and 4 inspections, a different attitude toward periodical change of components will be required. At present, items are removed after an arbitrary number of flying hours. If the condition of these items is known, they need only be replaced when the performance has deteriorated to a predetermined level. This will result in a more even workload on the maintenance sections as well as on the repair shops. Furthermore, the amount of spare parts can be diminished since the items are in longer use.

Considering the influence on operational procedures and aircraft performance, a tool will be given to the ground personnel to better instruct the flight crews on optimal cruise procedures, climb-out- and landing procedures, etc. The state of the art at present, however, does not present us with accurate ways of assessing the advantages envisioned for the future.

Great efforts will be required from the manufacturers to produce hardware that is reliable, accurate, easily installable, extendable, and maintainable. But the major efforts will be required from the airlines, which must investigate all possibilities in detail, test the most promising applications, adapt their maintenance behavior, and learn to live with flight recording systems as integrated units in their operation.

Reference

[1] Bosman, D., Pool, A., and Willekens, A. J. L., "A digital airborne recording system," Ingr. **50,** L55–L63 (December 14, 1962).