ICAS-86-3.3.3

# TEST AND FLIGHT EVALUATION OF PRECISION DISTANCE MEASURING EQUIPMENT

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## Abstract

The International Civil Aviation Organization has described a new type of precision distance measuring equipment (DME/P), that will be an integral part of the coming microwave landing system. It is based on two modes for the initial approach and final approach phases. Compared to the conventional Distance Measuring Equipment accuracy is increased by almost an order of magnitude while the immunity against multipath reception is significantly improved. New developed ground and airborne DME/P equipment is introduced and laboratory results on the instrumentation accuracy and the measured multipath immunity are discussed.

For flight testing of the DME/P a novel avionics flight evaluation system was employed providing high precision reference positions of the test aircraft. Some typical flight test results are presented and commented on.

## 1. Introduction

In 1982 the All Weather Operations Panel (AWOP) of the ICAO (International Civil Aviation Organisation) completed the evaluation of the concept and operational characteristics for DME/P (Precision Distance Measuring Equipment). DME/P is an integral part of the future MLS (Microwave Landing System), which will replace the conventional ILS (Instrument Landing System).

In Germany ground and airborne DME/P equipment has been under development since 1981. In parallel, the Avionics Flight Evaluation System (AFES) was developed. AFES provides very high positioning accuracy and has the capability of on-line (during flight) recording and off-line evaluation of positioning errors and other relevant system parameters. Both development programmes were sponsored by the BMFT (German Ministry of Research and Technology).

In the following the new developed DME/P as the system under test and AFES, the flight test system, are described briefly and characteristic test results are presented and discussed.

## 2. DME/P - The System under Test

The technical concept of DME/P is based on two operational modes. One mode, the Initial Approach Mode (IAM) is fully compatible with the conventional DME/N, but provides for higher accuracy. The second mode, termed Final Approach Mode (FAM), is a new mode, which is designed to achieve very high accuracy during the last few miles of approach even under severe multipath conditions.

Table 1 presents in a short form the DME/P system accuracy requirements as specified by AWOP(1). The distance measuring errors are defined in terms of path following error (PFE) and control motion noise (CMN). The PFE represents the low

| Distance to Groundstation | Operating Mode | PFE | CMN |
|---|---|---|---|
| 22 NM to 7 NM | IAM | ± 250 m reducing linearly to ± 85 m | 68 m reducing linearly to 34 m |
| 7 NM to 2 NM (reference datum) | FAM | ± 85 m reducing linearly to ± 30 m | 18 m |
| At MLS reference datum and through runway coverage | FAM | ± 30 m | 18 m |
| Throughout back azimuth coverage volume | FAM/IAM | ± 100 m | 68 m |

Notes : 1. The DME/P ground station is assumed to be located 2 NM behind the MLS reference datum point.
2. If FAM is not operational, IAM only shall be used (reduced accuracy).
3. Level of echo signals is up to -3 dB in case of FAM and up to -6 dB in case of IAM.

TABLE 1: SYSTEM ACCURACY REQUIREMENTS FOR DME/P

frequency error components leading to guidance errors while the CMN describes the high frequency components of the error (see (1) for detailed definition of PFE and CMN data evaluation filters).

Implementation of the DME/P concept requires technical changes to the conventional DME/N transponder and airborne unit. These include measures to generate short rise time transmit pulses and, for the FAM, the use of a broad band receiver section and a special low threshold trigger circuit. By these means an excellent suppression of errors caused by multipath propagation is achieved when the equipment operates in the FAM. The drawback of FAM broadband operation and low thresholding is a lower signal-to-noise ratio, since, due to spectral requirements, the ground transmit power for the steep rise pulses is limited. Thus, the range of the FAM operation reduces to some 7 NM.

The DME/P ground and airborne equipment developed by SEL are described in detail in (2). Figures 1 and 2 present the units used for the bench and flight tests. For bench tests special DME/P test instrumentation (new developed transponder and interrogator simulators) was used.

## 3. Bench Tests and Results

Prior to field tests or flight tests, the new developed DME/P system components - ground transponder/monitor as well as the airborne unit - had to undergo extensive laboratory tests. One major point of interest was the accuracy, especially under multipath condition. The test echoes characterized by amplitude, RF phase and delay time with respect to the direct signal were generated by simulators. These echo tests on the bench are essential for the evaluation of the echo resistivity of the DME/P design.

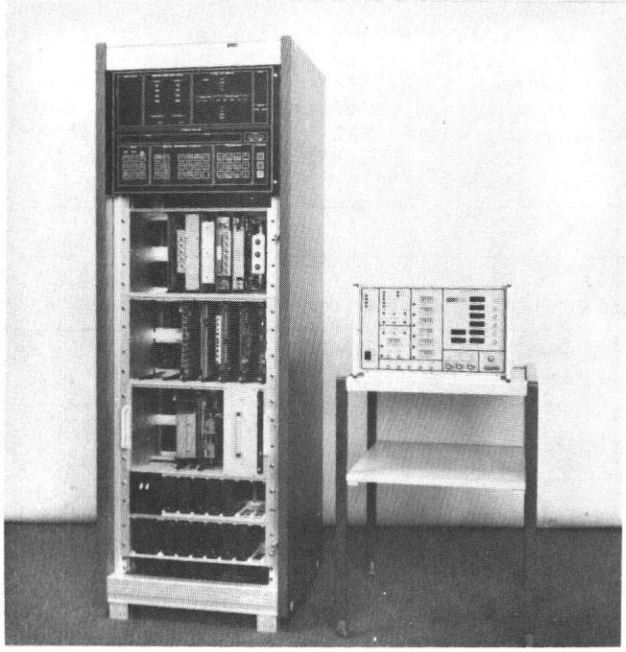


Fig. 1 DME/P Ground Transponder (Laboratory model) Interrogator-Simulator (right)

It has to be verified that the aforementioned accuracy of DME/P - FAM will be fulfilled even with the specified maximum multipath amplitude superimposed on the direct signal. In the following the kind of tests and the most essential results are described in brief.

### 3a. Test of the DME/P Airborne Transceiver

Test procedures and test limits to be applied refer to the design specifications, which together with the main characteristics of the airborne unit are summarised in table 2.

For performance testing of the airborne unit a new developed DME/P simulator/tester was employed, being tailored to the requirements of the new DME/P standard. Compared to a conventional DME simulator it has an instrumentation accuracy of better than 30 ns (or 5 m) and permits simulation of multipath by adding of echo replies to the direct reply pulses. Amplitude, delay and RF-phase change rate of the echo pulses are pre-settable. Besides it permits testing of the dynamic features of the interrogator unit, such as distance change rate. acceleration, and allows simulation of approach flights for verification of the IAM to FAM transmission properties in conjunction with various test parameters such as receive field strength, ground reply efficiency, or interfering signals like on channel - or off channel - interfering signals.

Figure 3a shows the PFE plot over 500 output data words. The measurements were taken in FA mode at the lowest specified receive level for that mode, with no multipath signal superimposed. As can be seen the mean PFE is at about + 7 meters bias (which also includes the above mentioned instrumentation error of the simu-

Fig.2 DME/P Interrogator Unit (partly disassembled) Background: DME/P Transponder-Simulator

| Design Characteristics: | | |
|---|---|---|
| DME/N function | TSO C66a, ARINC 709, DO 160 | |
| DME/P function | AWOP-WP 401 (12/82); (RTCA/SC 149 current issues) | |
| Technical Particulars: | | |
| Form factor (dimensions) | 4 MCU (123 x 194 x 318 mm) | |
| Weight | approx. 6 Kg | |
| Power Consumpt. | 115 V / 400: 50 W | |
| Transmitter Power | 500 Wp | |
| | FAM | IAM |
| Receiver Sensitivity | -73 dBm | -83 dBm |
| Instrumentation Error (Std. 1 applies) | | |
| a) with no multipath | | |
| PFE | 15 m | 30 m |
| CMN | 10 m | 15 m |
| b) with short delay multipath signal superimposed | M/D= -3dB | M/D= -6dB |
| Degradation PFE | 10 m | 37 m |
| Degradation CMN | 8 m | 20 m |

**TABLE 2: CHARACTERISTICS OF THE DME/P INTERROGATOR**

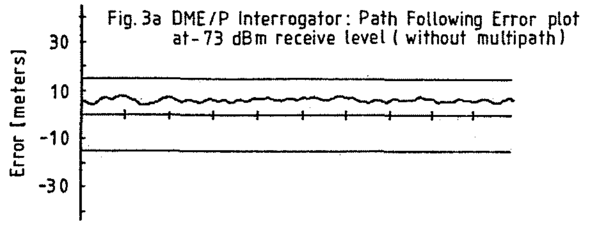


Fig. 3a DME/P Interrogator: Path Following Error plot at -73 dBm receive level (without multipath)

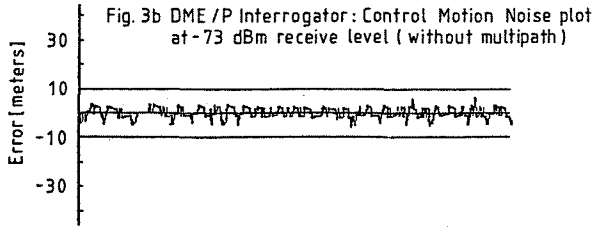


Fig. 3b DME/P Interrogator: Control Motion Noise plot at -73 dBm receive level (without multipath)

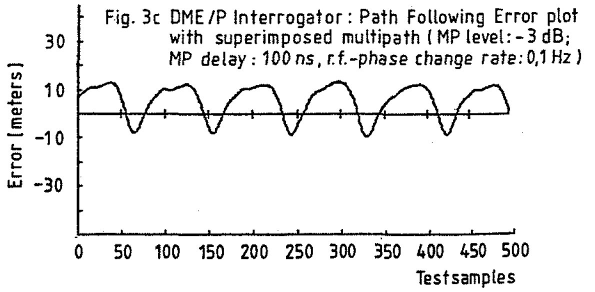


Fig. 3c DME/P Interrogator: Path Following Error plot with superimposed multipath (MP level: -3 dB; MP delay: 100 ns, r.f.-phase change rate: 0,1 Hz)

Fig. 3a - 3c DME/P INTERROGATOR UNIT IN FAM
-Instrumentation Error-
Laboratory Test Results

lator). The corresponding plot for the CMN is shown in figure 3b: due to the high pass characteristics of the CMN-filter the bias error is suppressed. The resulting error variance reflects essentially the variation of the 3.6 meter LSB (least significant bit) of the distance output data word. The specified error limits for PFE and CMN are shown as solid lines. Figure 3c shows corresponding measurements, but with the strongest specified multipath signals superimposed which is 3 dB below the level of the direct received signal. Delayed by 100 ns with respect to the latter it occurs at the most susceptible timing region of the low level trigger function, used in FAM for timing of DME/P replies. With the phase change rate of the echo carrier frequency preset to 0.1 Hz the plot visualises also the variation of the echo induced PFE between the upper and lower error extremes. The measured plot is in fairly good coincidence with the theoretically predicted error curve.

## 3b Test of the DME/P Ground Transponder

As for the airborne unit also for the new developed ground transponder, thorough bench testing was applied in order to prove compliance with the required design characteristics which are summarised briefly in the table 3.

| Design Characteristics: | | |
|---|---|---|
| AWOP - WP/401 (12/82)<br>FAA - E - 2721/3b (3/85)<br>EUROCAE WG25 (4/85) | | |
| Technical Particulars: | | |
| Transmitter Power | 300 W ERP | |
| | FAM | IAM |
| Receiver Sensitivity | -63 dBm | -74 dBm |
| Instrumentation Error (Std. 1 applies) | | |
| a) with no multipath | | |
| PFE | 10 m | 15 m |
| CMN | 8 m | 10 m |
| b) with short delay multipath signal superimposed | M/D= -3dB | M/D= -6dB |
| Degradation PFE 1) | 15 m | 60 m |
| Degradation CMN 1) | 10 m | - |
| 1) worst case max. static errors | | |

**TABLE 3: CHARACTERISTICS OF THE DME/P TRANSPONDER**

For laboratory tests a new DME/P interrogator simulator was available, which permits simulation of airborne interrogators by feeding carrier modulated test interrogation pulses to the transponder under test whilst measuring delay accuracy and reply efficiency and other relevant characteristics of the transponder output signal.

Figure 3d shows the measued PFE and CMN values for the delay accuracy in FA mode. The r.f. interrogation level is at -63 dbm which is the minimum senstivity level specified for that mode ("threshold sensitivity"). The measurements are safely within the upper and lower limits, (shown as solid lines).

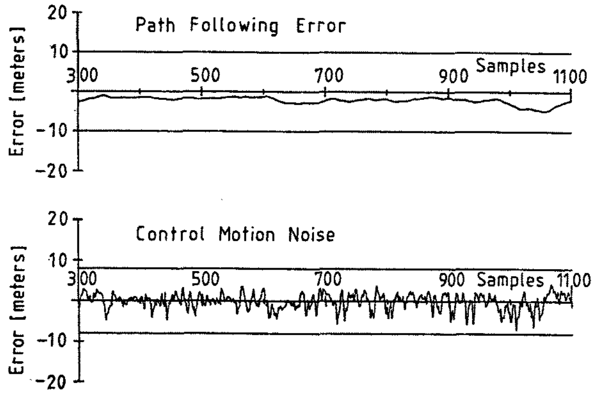


Fig. 3 d DME/P Transponder: PFE and CMN plots in Final Approach Mode at -63 dBm interrogation level

Figure 3e shows the PFE and CMN error measured for IAM operation, again at threshold sensitivity, which is specified to - 74 dBm for that mode.

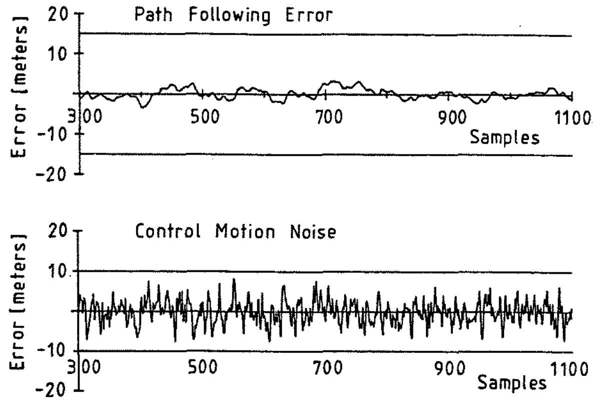
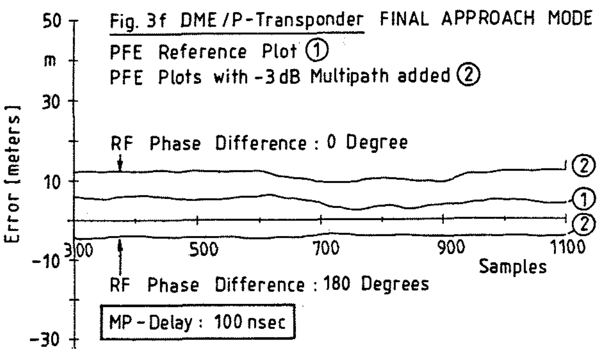


Fig. 3e DME/P Transponder: PFE and CMN plots in Initial Approach Mode at -74 dBm interrogation level

The accuracy degradation of the transponder due to superimposed multipath can be seen for FAM in Figure 3f and for IAM in Figure 3g, with the multipath error plots taken at the most critical values (i.e. 0 degrees and 180 degrees) for the r.f. phase differences (between the direct and the multipath signal). The delay of the echo was preset to the most susceptible value, which is 100 ns for FAM and some 600 ns for IAM. The amplitude of the echo was preset to the highest specified value, i.e. - 3 dB for FAM and - 6 dB for IAM.



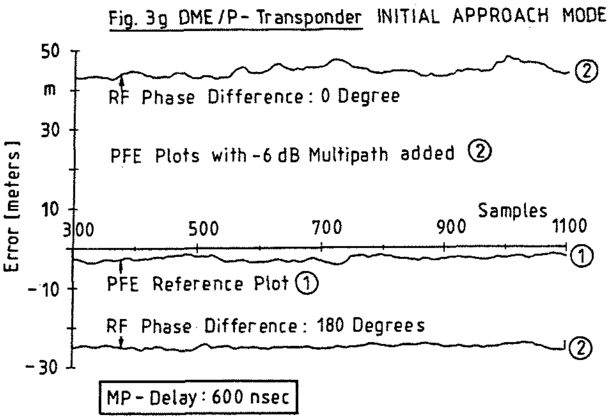


Fig. 3f + 3g DME/P Transponder: PFE-Plots with superimposed multipath signals

The resulting accuracy degradation due to multipath can be seen by comparing the respective reference plot (taken with the echo signal switched off) against the corresponding error plot at 0 degrees and 180 degrees. The measured values for FAM and IAM are well within the specified limits, demonstrating the superior echo immunity of the new FA mode.

It should be noted that, in FAM, echoes delayed by more than 300 ns will cause virtually no distance errors.

## 4. AFES - The Avionics Flight Evaluation System

AFES has been designed for flight test of new navigation systems by the Institute for Flight Guidance of the DFVLR (Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt - German Aerospace Research Establishment) in cooperation with the Institute for Telecommunication of the Technical University in Braunschweig.

The determination of high-precision reference positions of a test aircraft is of central importance, in particular for the investigation of the error characteristics of navigation systems. AFES uses a system incorporating a laser tracker and a tracking radar on the ground and an inertial navigation system on board the test aircraft (hybrid system). The navigation data obtained in the test aircraft

and on the ground are exchanged by means of telemetry. The data are combined and optimized on board the test aircraft by Kalman filtering.
High-speed processors are used both in the test aircraft and on the ground in order to permit on-line (real time) evaluation. All elements of AFES are connected together via an efficient data transmission system. (see figure 4).

The error behaviour of radio navigation systems depends largely on interferences caused by multipath propagations of the r.f.-signals. AFES, therefore, is prepared for incorporation of a subsystem for measuring those propagations. A further subsystem is able to simulate artificial traffic load.

Altogether AFES consists of the following subsystems:

- central control station
- reference system
- data transmission system
- multipath measurement system
- traffic load system.

The interconnections of the subsystems are shown in Figure 4.

The central control station of AFES performs the following tasks:

- provision of data and voice links with the various subsystems,
- storage and processing of flight test data,
- display of results (on-line).

The key instrumentation for generating the reference positions are the Carousel IVA inertial navigation system, the tracking radar DIR (RCA-digital instrumentation radar) and a laser tracker built by DFVLR.

The position data from the ground installation (laser tracker, tracking radar) are transmitted to the test aircraft as "reference positions", where they are used to correct the navigational data of the inertial navigation system with the aid of the Kalman filter calculations. The corrected position data are transmitted to the central control station via a telemetry channel; this channel is also used for transmission of data from the on-board DME/P equipment under test.

The most important data describing the AFES are listed in table 4.

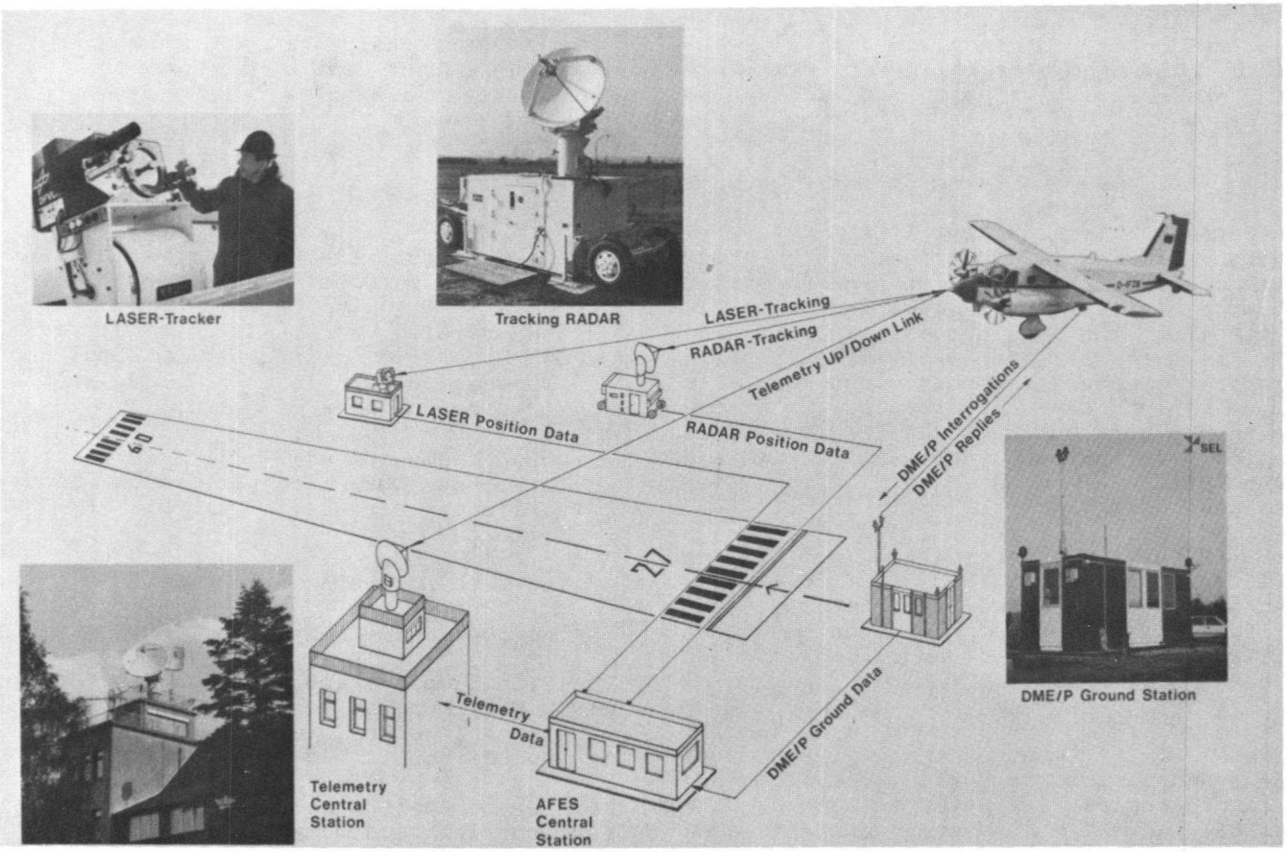


Fig. 4 Flight Test of the DME/P System
Using the Avionic Flight Evaluation System (AFES)
of DFVLR at Braunschweig Airport

| | |
|---|---|
| Maximum Range | 234 km |
| Position Accuracy ($1\sigma$)<br>(Reference point = laser tracker) | |
| Angular Accuracy | |
| up to 10 km range | 0.005° |
| above 10 km range | 0.01° |
| Distance Accuracy | |
| up to 10 km range | 0.3 m |
| above 10 km range | 2.0 m |
| Update rate of reference positions and flight test data | 20 Hz |

**TABLE 4. PERFORMANCE DATA OF AFES**

For evaluating the accuracy of the DME/P system the positions determined by the reference system have to be converted in reference distances with respect to the location of the DME/P ground station.

As test aircraft for testing DME/P a Dornier DO 28 was used with the airborne DME/P antenna belly-mounted.

For thorough investigation of unforeseeable effects during test, not only the aircraft data but also the data from the DME/P ground station were fed to the central control station via digital data link. The main data which were available in the central station are listed in Table 5.

## 5. Flight Tests of DME/P

Before starting flight tests several ground tests were carried out to check the correct function of DME/P system components and AFES equipment and to establish the data processing software. To test the IAM operation also at small ranges on ground a special test mode "IA Mode only" was incorporated into the airborne unit which permits IA mode operation at any distance inhibiting the automatic IA to FA transition for distances below 7 NM.

The flight tests were carried out during winter 1984/1985 at the airport of Braunschweig/Federal Republic of Germany. The flight time required for about 60 test flights amounted to approximately 30 hours.

Since DME/P is a subsystem of a landing system (MLS) most of the flights were approach flights at various elevation and azimuth angles. However, to check the signal coverage, several constant level flights of various azimuth angles and altitudes were performed.

The main results of the flight trials were documented by the DFVLR in form of plots showing

- the flight track on a grid for reference purposes (see figure 5a)
- the receive power of the airborne DME/P (providing information about the propagation path loss including ground and airborne antenna gain)
- the (unevaluated) distance error (airborne DME/P output value minus reference distance) without PFE/CMN filtering
- the path following error (PFE)
- the control motion noise (CMN)

Additional plots and strip chart records could be generated to present other parameters of interest, e.g. reply efficiency, decode counts and transmit counts.

Figure 5b to 5e present typical results for an approach flight carried out on Dec. 5th, 1984. The approach direction was 90° the glide path angle 3°. No traffic load was simulated.

Figure 5e shows the DME/P system error as such without PFE or CMN filtering. The

| Ground Data |
|---|
| Time |
| Receive Power Level |
| Count of IAM Interrogations |
| Count of FAM Interrogations |
| Counts of various Transmit Signals |
| Various Internal Parameters and Status Signals |

| Aircraft Data | |
|---|---|
| Time | |
| Reference Position | |
| DME/P - Raw Distance | 1) |
| DME/P - Distance | 2) |
| AGC - Voltage | 3) |
| Reply Efficiency FAM/IAM | |
| Various Internal Parameters (Trigger Counts, etc.) | |

Notes: 1) Internal data, not filtered
2) Output data of airborne unit
3) Is related to receive power level

**TABLE 5: MAIN DATA AVAILABLE IN CENTRAL STATION**

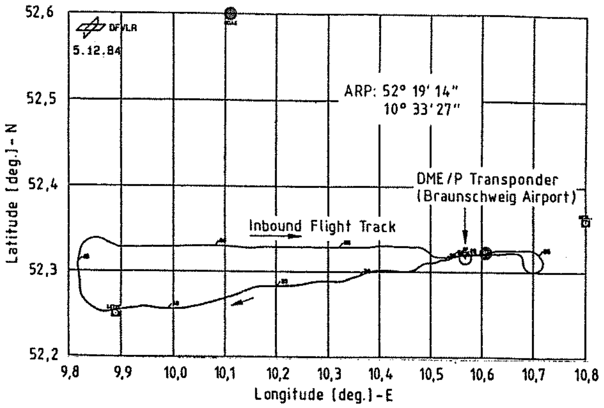


Fig. 5a Flight Track Reference Plot

curve at the bottom indicates the active mode ("low" for IAM, "high" for FAM).

It is evident that with transition from IAM to FAM at about 7.5 NM the error plot becomes considerably smoother. This behaviour is reflected by the PFE- and CMN-plots, presented in figures 5c to 5d. Thus, these plots demonstrate the excellent accuracy of the FAM. The errors during IAM operation can be explained by multipath effects. In the PFE and CMN plots for comparison the system error limits according to AWOP ‹1› (see table 1) are given, too. It can be seen that the measurement results are well within their limits. The IA to FA transition is smooth and shows no transitional effects. However, it should be noted that the margin of the CMN is less than that of the PFE.

This is in accordance to the bench test results and indicates that the more stringent accuracy parameter of the DME/P is the control motion noise.

Figure 5b shows the field strength at the airborne interrogator. The relative minimum at 2.5 NM results from the antenna pattern of the ground transponder. At approximately zero-distance all error plots indicate a sudden peak, which is caused by short out-of-track-condition of the airborne set due to the abrupt change from negative to positive distance rate.

The results of another typical flight at slightly different approach angles (85° azimuth, 5° elevation) are presented in Figures 5f to 5i.

In principle, the results are similar to that of the previous example. The accuracy again is better during FA-mode operation, i.e. at less than 7.5 NM. However, besides the peak at zero-distance, two further error peaks at about 1 NM and 3.5 NM occur, especially in the CMN plot. A look to Figure 5f, the airborne receive power level gives an explanation of this effect: at the critical distances the power significantly breaks down far below the specified minimum

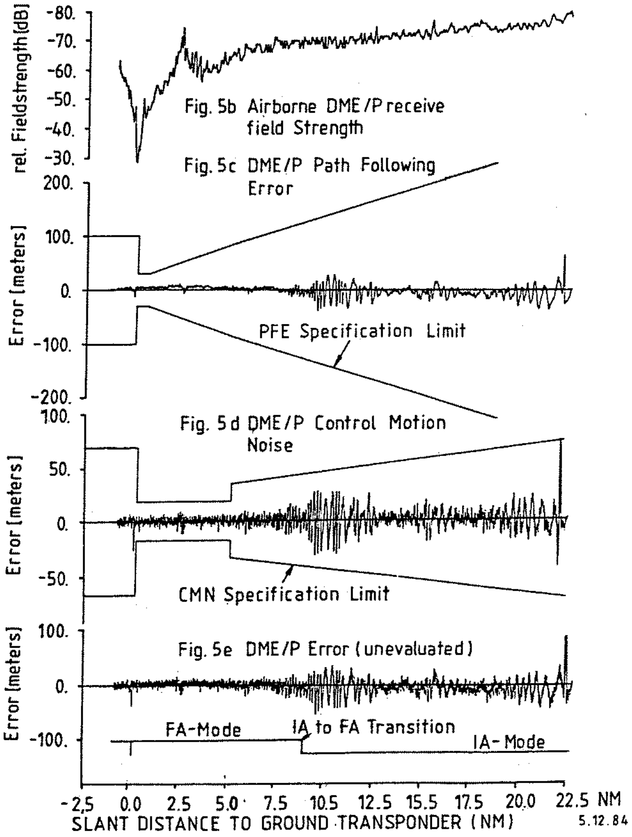


Fig. 5b to 5e DME/P Centerline Approach Flight
(Appr. Angle 90°, Glide Slope 3°)
at DFVLR Braunschweig

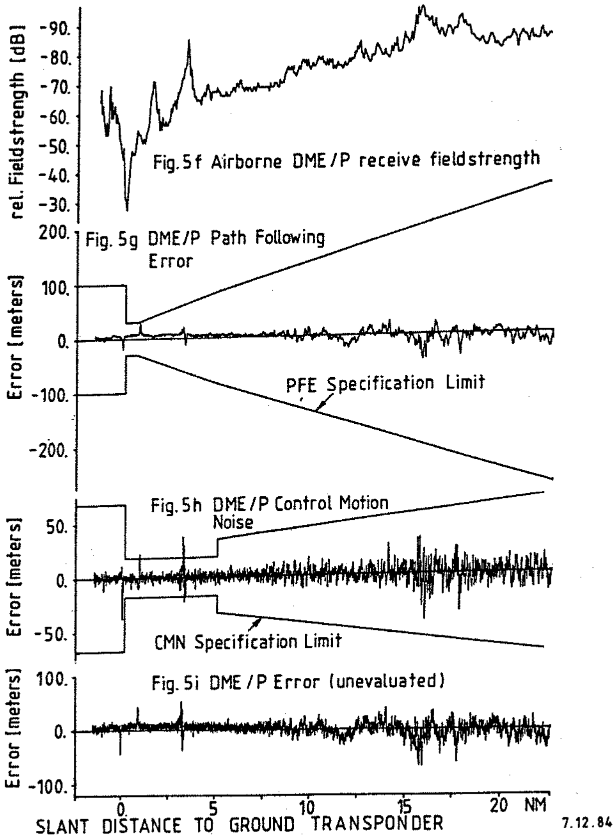


Fig. 5f to 5i DME/P Approach Flight
(Appr. Angle 85°, Glide Slope 5°)
at DFVLR Braunschweig

levels. Investigation of the radiation pattern of the ground antenna (taking ground reflections into account) indicated at this distance and at 5° elevation (flight path) strong minima of the radiation pattern.

It should be mentioned that a conventional en-route DME ground antenna was used for these flight tests. Their radiation pattern is optimized for low elevation angles, i.e. less than 3°. The test results call for a special DME/P antenna design.

To summarize the flight test results the following can be stated:

- DME/P ground and airborne equipment developed by SEL has successfully demonstrated the expected accuracy of the two-mode DME/P concept defined by AWOP (1).
- The AFES, developed by DFVLR, has proven its excellent capabilities as a tool for positioning and flight evaluation.
- The power budget of DME/P was recognized as a critical parameter. Special DME/P ground antennas are required.

It is planned to continue with the flight evaluation of DME/P during Spring 1986 with emphasis on the investigation of traffic loading effects on accuracy.

## 6. Operational Benefits of the DME/P and Outlook

Laboratory test and flight evaluation in so far have demonstrated the projected guidance accuracy and integrity of the new DME/P.

Collocated with the MLS azimuth ground station the DME/P will add the precision distance function to the precision guidance angles, azimuth and elevation, thus allowing complete, 3 dimensional position determination for approach and landing. In conjunction with the large proportional coverage volume of MLS the DME/P is the key to fully exploit the operational advantages of the MLS by enabling

- curved or segmented approaches
- offset approaches with derivation of lateral and vertical guidance
- MLS angle guidance coordinate conversion including translation of the azimuth, elevation or distance information coordinate reference point
- height and height rate computation for flare guidance
- Sensitivity modification of MLS azimuth and elevation signals.

Compared to other navigation systems such as e.g. GPS*) (providing nav. information) the DME/P conception is indeed tailored to the requirements of a <u>landing</u> system satisfying not only the requirements on accuracy and dynamics and necessary update rates (for autopilots / coupled approaches), but also the integrity demands for an instrument landing system.

During the most critical phase of flight the DME/P per se fulfills the required integrity of the guidance signals by

- dualized DME/P transponder/monitor configuration on the ground
- direct monitoring of the DME/P ground installation
- spontaneous, quick alarms to the pilot (between 1 to 10 seconds depending on category of operation) upon occurrence of malfunction
- reacquisition and track with full accuracy within 1 to 2 seconds after total loss of signal or measurement history.

### References

(1) ICAO (1982)
Report of the AWOP 9th Meeting Document 9400, All Weather Operations Panel-9, Montreal, Canada, Nov. 1982.

(2) Becker, K., Müller, A., Vogel, H.:
Precision Distance Measuring Equipment for the Microwave Landing System.
Electrical Communication 58,3 (1984), 336-343.

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*) Global Positioning System