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# A CONCEPT FOR 4D-GUIDANCE OF TRANSPORT AIRCRAFT IN THE TMA

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## Abstract

The four dimensional (4D) guidance of aircraft in the TMA allows for precise control of the minimum separation and thus efficient use of the available approach capacity of the respective airport. At the DFVLR Institute of Flight Guidance at Braunschweig a concept for the 4D-guidance of transport aircraft has been developed and a corresponding control mode has been integrated in an automatic flight control system for transport aircraft. This was tested on the DFVLR's HFB 320 test aircraft. The 4D mode is based on usual radar vector guidance technique of air traffic control and, therefore, is characterized by a succession of flight sections with constant values for indicated airspeed, heading and descent rate. The time-of-arrival is controlled by altering the path via a delay fan. The algorithm for the calculation of the commanded 4D flight path takes into account suitable wind models up-dated by actual wind data. In the paper the 4D mode is described and first flight test results are discussed.

## Symbols and abbreviations

| | |
|---|---|
| x,y | components of the flight path |
| h | altitude |
| $\psi$ | heading |
| $\phi$ | bank angle |
| $\Theta$ | pitch angle |
| $l_v$ | angle between aircraft track and heading |
| vw | magnitude of the wind |
| $\alpha_W$ | direction of the wind |
| $\chi$ | track angle |
| $u_g$ | ground speed |
| $v_{TAS}$ | true airspeed |
| $v_{IAS}$ | indicated airspeed |
| L | straight flight path segment |
| t | variable time parameter |
| T | constant time segment |
| $T_z$ | relativ time-of-arrival at the gate |
| g | gravity constant |
| a,b | coefficients for the calculation of the true airspeed |
| p,q | exponent and factor of the physical wind model |
| $r_i$ | coefficients of wind models (i = 1,2,3) |
| $a_i,b_i,c_i,d_i$ | coefficients of a cubic spline function (i = 1,2,3,4) |
| FP | waypoint at the beginning of the fan |
| GT | waypoint at the gate |
| $CP_i$ | intercept waypoints on the centerline (i = 1,2,3) |
| GPI, CPA | boundary waypoints at the fan |
| FMS | flight management system |
| FCC | flight control computer |
| TCC | thrust control computer |
| STAR | standard arrival route |
| FL | flight level |
| VHF COM | voice communication |
| 2D, 3D, 4D | n-dimensional |
| ATC | air traffic control |
| AFCS | automatic flight control system |
| TMA | terminal maneuvering area |
| TOA | time-of-arrival at the gate |
| d | differentation |
| $\Delta$ | difference |
| E | index for east components |
| N | index for north components |
| | index for a first value |

## I. Introduction

The increase in air traffic during the last decades and the restrictions with regard to noise went along with a considerable increase in flying time. Long and time-consuming take-off and approach procedures and a limited speed below FL 100 became necessary. Every day the limit of airport capacity is reached or exceeded for several times at large international airports as, for example, at Frankfurt. Therefore congestion and uneconomic delays occur (1,2).

Nominally the aircraft is supposed to follow the predefined standard arrival route (STAR) and the corresponding altitudes published for the respective airport (3). During traffic peaks, however, a STAR is often deviated from, and this means that the pilot then receives individual instructions via VHF COM from the controllers. The aircraft motion is displayed on the controller's radar screen and on the basis of the radar picture the controller allocates courses and speeds (radar vectors) as well as altitudes to the individual aircraft, in order to guide it to the centerline at a suitable separation.

There is a minimum separation margin between successive aircraft which must not be violated. The minimum separation margins ought to be achieved at the gate at the latest, i.e. shortly before the glidepath is intercepted. For safety reasons the controller has to keep a reserve in separation taking into account deviations due to effects from:

- delays in the transmission and execution of VHF COM commands
- deviations from the planned flight path

- inexact knowledge of the wind situation in the TMA.

The air traffic controllers can be supported in their difficult task by increased use of digital computers. On the one hand computers can be applied for planning tasks on the ground and on the other hand airborne computers can guide and control the individual aircraft precisely in space and time. This leads to an automated 4D terminal area guidance system which can offer several advantages as for example:
- the maximum use of the approach capacity of the respective airport by means of precise control of minimum separation margins,
- a reduction of work load for pilots and controllers and
- in general, an increased efficiency of air traffic.

This paper is addressing a concept for such a system which is developed by the DFVLR Institute of Flight Guidance at Braunschweig and which is undergoing its first flight tests during this year.

## II. Some conceptional features and assumptions

The 4D system is intended to be used during the terminal area flight spanning from the metering fix of the terminal area to the gate on the approach centerline. At this point the aircraft is supposed to have assumed a given state in speed and altitude at a given time slot. The TOA error at the gate should be less then 5 seconds ($2\sigma$).

### II.1 Share of sub tasks between the ground based and the airborne systems

The ground based computers can carry out rough planning on the basis of aircraft position measurements from the ground radar system and informations about aircraft data. Resulting from these algorithms, each aircraft is allocated to a certain time slot. By early monitoring the aircraft time errors can already be reduced outside the TMA by means of appropriate procedures. Therefore holding procedures within the TMA (below FL 100), where fuel consumption increases, are reduced to a minimum.

When entering the TMA the aircraft has reached a flight level below FL 100 and an indicated air speed of less than 250 kts. The ground based ATC planning algorithm computes a conflict-free flight path from the TMA entering point (metering fix) to the gate, taking into account individual requests for fuel-saving or cost-saving speeds and altitude profiles. For most of the civil transport aircraft with their relatively similar aerodynamic behaviour the aircraft should maintain their altitude and speed as long as possible close to FL 100 and to the maximum permitted speed of 250 kts, respectively.

On the basis of the computed flight path the individual aircraft receives corresponding guidance commands for indicated airspeed, altitude and lateral control. The data flow between ground and airborne systems is shown in Fig. 2.1. In accordance with conventional procesures, aircraft without a FMS obtain conventional radar vector and altitude information from the ground in the usual way, all this information is derived from the ATC planning algorithm. It is part of the pilot's responsibility to follow these commands as accurately as possible by what ever means, for instance by use of automatic systeme like FCC/TCC.

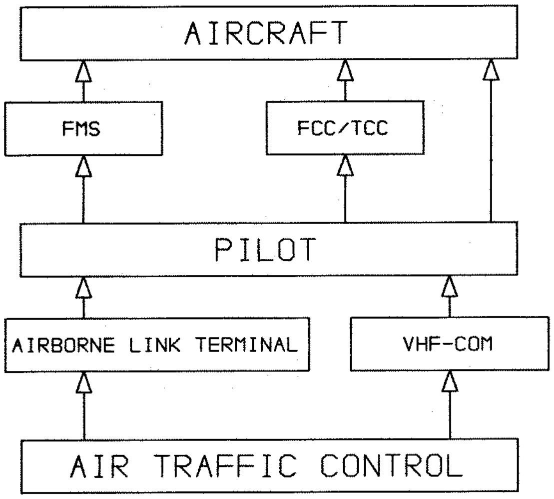


Figure 2.1 Data flow between the ground based system and the airborne system

Those aircraft which are equipped with a FMS can autonomously follow 4D commands of the ground planning. They obtain a coded information from the ground indicating the constraints for the horizontal flight path, the TOA at the gate, the altitude and the speed to be maintained during intermediate approach and at the gate. In addition, information is given about the wind in the TMA.

The FCC/TCC guides the aircraft on this path and controls the altitude and airspeed. The tracking of the lateral flight path is based on a control mode by which lateral flight path is based on a control mode by which lateral deviations can be automatically brought to zero and changes for a new radial at a 4D waypoint can be carried out by a turn with constant bank angle. In addition, the TOA error is monitored and the wind model is up-dated by means of wind measurements obtained from aircraft sensors. If the expected TOA error exceeds certain limits a correction of the original flight path becomes necessary.

The knowledge of the wind is of great importance for the planning computations if precise TOA control is desired. For this reason it is assumed that the ground computer processes general meteorological data and the wind data which are measured by the aircraft sensor system and transmitted to the ground by data-link. A 3D map of the wind profiles in the TMA is produced on the ground (windmapping) from which the magnitude and the direction of the wind can be derived for each individuall approach path.

At present ATC guidance commands are still transmitted by VHF COM. However, in future it is planned to use a data-link with an appropriate airborne receiver (airborne link terminal), equipped with a data display, so that these guidance commands can directly transfered to the aircraft and then be fed into the FMS after acknowledgment by the pilot.

## II.2 The principle of time-of-arrival control

TOA control is achieved basically by stretching or shortening the length of the flight path. It compensates for deviations, for instance resulting from discrepancies between actual wind and modelled wind during approach. For this purpose the intercept waypoint CP can be moved along the centerline (Fig. 2.2). All possible flight paths are forming a fan area, which is limited by two boundary waypoints CPI and CPA. In case the fan does not provide sufficient delays for TOA control because of extraordinary deviations of the command in TOA an appropriate number of holdings must be performed. The TOA error is continously computed and if it exceeds previously defined limits a new computing cycle for the 4D flight path is started again resulting in a new flight path. The initial waypoint $UP_1$ (Fig. 2.2) of the new flight path corresponds to the actual position of the aircraft and a new intercept point on the centerline is determined.

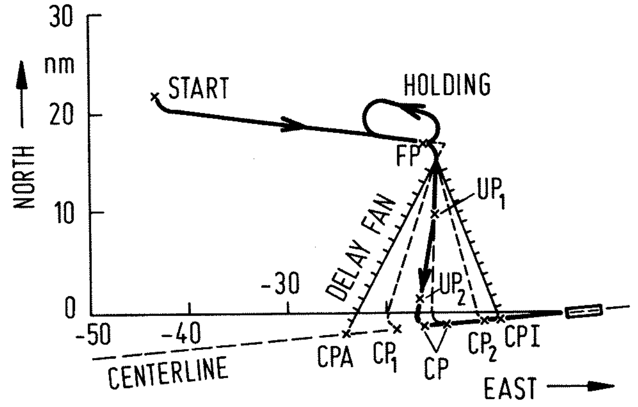


Figure 2.2: Horizontal flight path

Once the aircraft has reached the waypoint $UP_2$ situated close to the centerline path corrections are no longer possible. At this stage speed control is applied, but only by shifting the point where the speed reduction is started down to final approach speed.

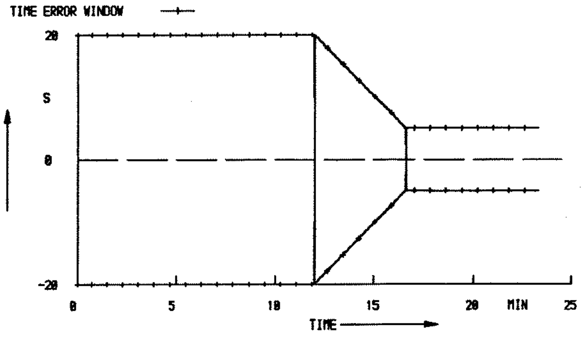


Figure 2.3: Time error window for flight path up-date

Fig. 2.3 represents the switching function for the flight path up-date a so-called time error window as a function of time. The acceptable TOA error is 20 seconds when starting the 4D mode. In any case, flight path computation take place at the fan waypoint FP and at waypoint $UP_2$ which is located approximately one minute before the centerline is intercepted. The path correction is entered by setting the switching function to zero. Between both waypoints the time error window linearly decreases from 20 seconds down to 5 seconds.

## II.3 Selection of the guidance commands

The selection of suitable guidance commands is of great importance for operational response and for the integration with a partly or fully automatic flight control system. The commands to be transmitted to the aircraft - in particular in case of VHF COM transmissions - should correspond to the standardized guidance commands for current 3D flight path control systems. Thus altitude or vertical speed, indicated airspeed and heading have to be used as command parameters.

The commanded 4D flight path consists of straight-line and circular-arc segments. For the circular-arc segements a constant bank angle is commanded, i.e. the geometry of these path segments with respect to the ground is affected by the wind. The straight-line segments simply represents radials to flight path waypoints. All this does not create any compatibility problem with regard to current autopilot systems.

When the 4D approach is initiated the aircraft assumes the $v_{IAS}$ command assigned to it by ATC at that time. Then, this command is executed. The reduction in speed takes place at a constant deceleration rate. In level flight a higher deceleration rate is possible than during descent. If a FMS is available and the deceleration profile can possibly be determined for an idle approach, this can be taken into account in the 4D flight path algorithms.

Fig. 2.4 shows a plot of a typical 4D approach command profile. At the beginning of the approach the aircraft decelerates to an intermediate speed and at the same time descends to an intermediate flight level. After about 3 minutes a new flight level, for example, FL 60, is commanded by the ATC controller. Altitude and speed, assigned for the time when the aircraft is supposed to reach the gate are commanded for the time when the aircraft intercepts the centerline.

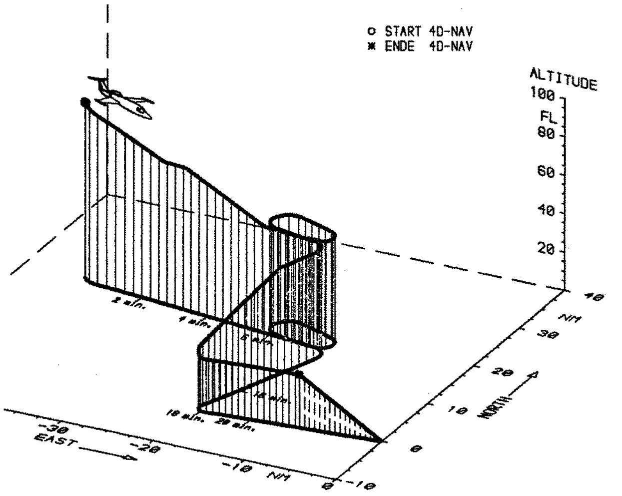


Figure 2.4: Typical simulated 4D approach

## II.4 Wind modelling

One essential task in flight-testing the 4D mode is to examine different wind models with regard to their suitability for predicting wind profiles of the altitude range associated to the 4D approach. For this purpose different wind models and up-date algorithms are used.

Using common airborne sensors of a transport aircraft a measurement of the wind at the actual aircraft position in terms of magnitude and direction is taken continuously. On the basis of this measurement wind data are entered into the computation of the 4D flight path as a function of altitude. Additional wind measurements available on the ground or onboard of other aircraft flying ahead are of great importance in order to up-date the wind models. The followind types of wind modelling are considered with regard to how the wind measurement data are processed:

- interpolation of a reference wind measurement at runway level or at certain altitude and wind data measured by airborne sensors. The interpolation algorithm corresponds to analytical relationships
- interpolation of several wind measurements at different altitude stages by mathematical functions
- short-time wind prediction based only on airborne measurements.

## III. The determination of the 4D flight path

### III.1 The horizontal flight path

Only iterative and fast-converging computation procedures are suitable for calculating the horizontal flight path because this task has to be executed real time during flight. Fig. 3.1 illustrates the basic geometric problem which has to be solved.

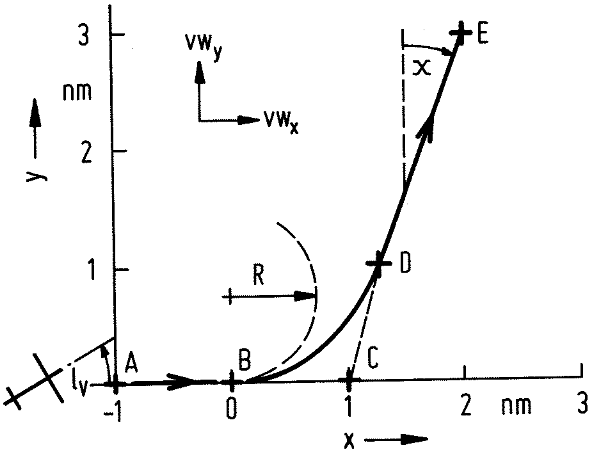


Figure 3.1: Connection of straight-line and circular-arc segments

The following equations apply for the circular-arc path segments affected by the wind:

$$x = R \cdot [\sin(\Delta\psi - l_V) + \sin(l_V)] + \int_0^t vw_E \cdot dt \tag{3.1}$$

$$y = R \cdot [\cos(l_V) + \cos(\Delta\psi - l_V)] + \int_0^t vw_N \cdot dt \tag{3.2}$$

$$R = v_{TAS}^2 / g \cdot \tan\phi \tag{3.3}$$

The basic task to be carried out first is to link a radial from the 4D waypoint E to the bent path segment by means of putting up a tangent. The following equation applies at the point D where the straight-line segment begins and the bent segment ends:

$$\begin{aligned} m_1 &= (dy/d\chi) \;/\; (dx/d\chi) \\ m_2 &= (y_E - y_D) \;/\; (x_E - x_D) \end{aligned} \tag{3.4}$$

i.e. the direction $m_2$ of the straight-line segment from D to E must be equal to the direction $m_1$ of the tangent at the point D.

If the derivatives of equations (3.1, 3.2) are inserted into equation (3.4), the result is a non-linear, transcendent equation which can be solved numerically by using an iterative procedure. Since the initial value $\Delta\psi_0$ of the iteration can be precisely determined because of the simple geometry of the flight path, 2 to 3 iterations are sufficient to determine the course angle to the waypoint D, i.e. with an accuracy of about 0.01 degress.

If two bent segments have to be linked by a common tangent it is possible to transfer this task to the basic problem described above. Again only 3 iterations are sufficient to solve this kind of problem. The same procedure is used to calculate a holding flight path and to determine a flight path up-date. These procedures characterized by a particularly fast convergence were proposed in (7,8).

## III.2 The 4D flight path

Based on the horizontal flight path, the corresponding TOA at the gate is calculated with reference to the altitude and the speed profile. For this purpose the known profile of the $v_{IAS}$ is used to calculate the $v_{TAS}$ using the equation (3.5). The influence of air density as a function of altitude is covered by an approximation:

$$v_{TAS} - v_{IAS} \cdot [1 + a \cdot h + b \cdot h^2] \qquad (3.5)$$

The ground speed can approximately be calculated by use of the track angle $\chi$. $v_{TAS}$ and the wind described by the wind model. According to the wind triangle shown in Fig. 3.2 Eq. (3.2) applies:

$$u_g = v_{TAS} - 0.5 \cdot vw^2 \cdot \sin(\chi - \alpha_W)/v_{TAS} + \\ + vw \cdot \cos(\chi - \alpha_W) \qquad (3.6)$$

The calculation of the flight time elapsed on a leg $\Delta L$ requires an integration of the time-dependent ground speed:

$$\Delta T = \int_0^{\Delta L} dL/u_g(t) \cdot dt \qquad (3.7)$$

This cumbersome integration can be avoided by means of a numerical trick. To do this $u_g(t)$ is numerically integrated until the integral reaches the value $\Delta L$. The number of steps required multiplied by the time interval of the integration then gives the desired value $\Delta T$. Relatively large time segments are possible because an interpolation calculation is made after the last step.

If equation (3.7) is applied for the circular-arc segments too, the value of $\Delta L$ would correspond to the length of the bent segment. In order to avoid calculations of great time consumption the turn rate $\psi$ and the change of the heading angle $\Delta\psi$ are used instead of $u_g$ and $\Delta L$.

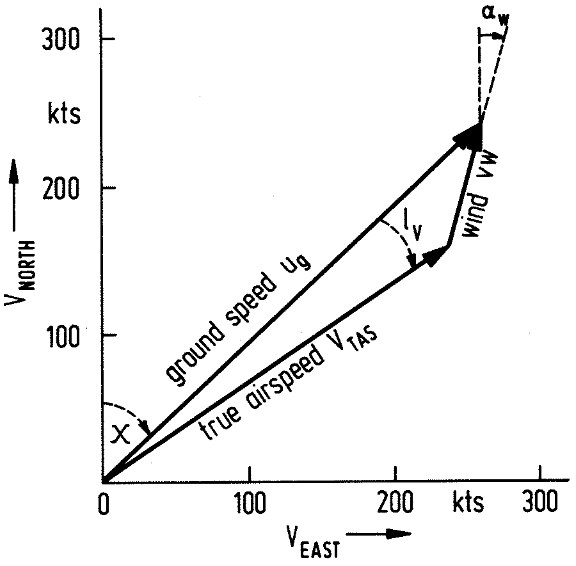


Figure 3.2: Wind triangle

$$\begin{aligned} \Delta T &= \int_0^{\Delta\psi} d\psi/\psi(t) = \\ &= \int_0^{\Delta\psi} d\psi \cdot g \cdot \tan\phi / v_{TAS} \cdot dt \end{aligned} \qquad (3.8)$$

The time $\Delta T$ again is obtained from the number of steps $\Delta\Psi$. Finally, the flight time for the complete 3D flight path including the altitude profile is obtained by adding up the flight times of the individual segments of the flight path.

The calculation of a 4D flight path, however, requires the inverse procedure, i.e. the flight path must be determined for a given TOA at the gate. However this direct way includes complicated numerical procedures, and for this reason an iterative method is used again: The TOA's of 2 different flight paths $T_1$ and $T_2$ are calculated, for example, for the corresponding distances of the intercept waypoints $\Delta CP_1$ and $\Delta CP_2$ from the gate. Because of the smooth relation between $\Delta CP$ and the desired TOA the desired distance $\Delta CP$ can be obtained by linear interpolation in accordance with equation (3.9):

$$\Delta CP = \Delta CP_1 + \\ + (\Delta CP_2 - \Delta CP_1)(TOA_1 - TOA_2) \cdot TOA \qquad (3.9)$$

At the beginning of the 4D approach the inner and outer boundary waypoints CPI and CPA are selected for $\Delta CP_1$ and $\Delta CP_2$ respectively since the corresponding flight paths have to be calculated anyway in order to determine the minimum TOA and the number of holdings, if necessary. For the 4D flight path up-date to compensate for TOA errors, it is sufficient to locate $\Delta CP_1$ and $\Delta CP_2$ approx. 500 m apart of the actual intercept waypoint in order to receive a high level of accuracy for the interpolation.

### III.3 Vertical wind models

During the flight experiments of the 4D mode the wind measurement is carried out by the aircraft inertial navigation system (INS) and the digital air data computer (DADC).

### III.3.1 Interpolation of wind data by analytical relationships

The wind profile can be described by the equation (3.10):

$$vw = v_0 \cdot (h/h_0)^p \quad ; \quad h \geq h_0 \qquad (3.10)$$

The value of p varies between 0 and 1 depending on the air turbulence, the distribution of the static pressure, temperature and humidity of the air, the structure of the earth surface etc. as described in (11). The value of 0.25 is most commonly used. If the wind is known not only at one (reference) altitude but also at the actual flight altitude, p can be calculated by re-arranging the equation (3.10).

A linear interpolation was selected for the wind direction $\alpha_W$. The factor q can be calculated by two wind measurements, too.

$$\alpha_W = \alpha_{W0} + q \cdot (h-h_0) \quad ; \quad h \geq h_0 \qquad (3.11)$$

In order to check this wind model, data from weather balloons launched by the aeronautical meteorological office at Hannover Airport were used. These data showed adequate correspondance in most cases. The mean value of the deviations was 1 kt with a standard deviation of 4 kts. However, this relatively simple wind model did not give an adequate description of the measured wind profils on days when inversions were observed.

Fig. 3.3.1 and Fig. 3.3.2 compare the measured and modelled wind profiles for 2 different days. The modelled wind profil corresponds to the equations (3.12, 3.13). Whereas in Fig. 3.3.1 the wind model gives an adequate description of the measured data, deviations of up to 20 kts occur in Fig. 3.3.2. On the 4th of June 1979 the wind magnitude even partly decreases during the climb of the balloon. This clearly demonstrates the problems involved in finding analytical relationships for wind profiles: although from the statistical point of view these relations give an adequate description of the wind profiles on average, possible large deviations on particular days can cause unacceptable TOA errors.

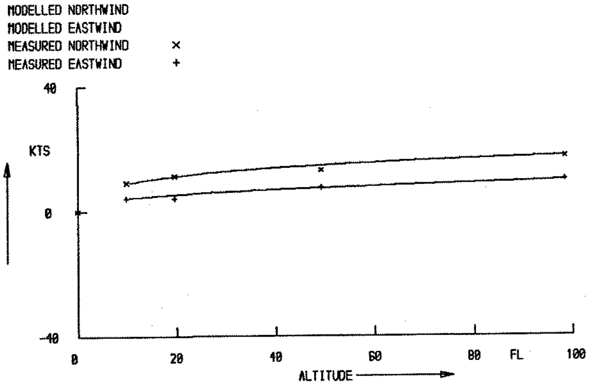


Figure 3.3.1: Comparison of measured and modelled wind profiles for the 16th of June, 1979

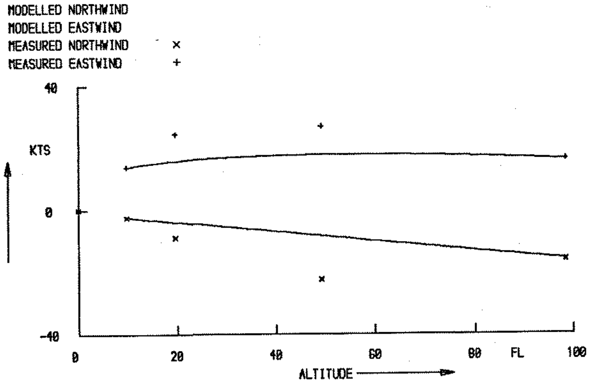


Figure 3.3.2: Comparison of measured and modelled wind profiles for the 4th of June, 1979

### III.3.2 Interpolation of wind data by a spline function

Interpolation of wind data by a spline function is based on a number of wind measurements by ground based sensors or by aircraft flying ahead. In the 4D system presented here a cubic spline function was used (Fig. 3.4). The full range of altitude during the 4D flight is broken up into 4 sections and for each section a total of 4 coefficients are assigned. To ensure a smooth function the determination of these coefficients for each segment is based on the boundary value of the preceeding and the following section. The result is a wind model as described for the east component of the wind by equation (3.12):

$$vw_E = a_L + b_L(h-h_1) + c_L(h-h_2)^2 + $$
$$+ d_L(h-h_3)^3 \; ; \; h_L \leq h \leq h_{L+1}$$
$$L = 1,\ldots,N$$
$$a_L = vw_{E/L} \quad ; \qquad L = 1,\ldots,N$$

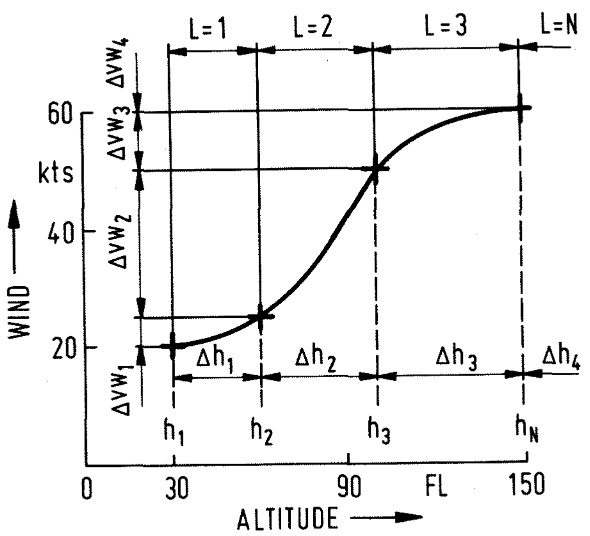


Figure 3.4: Cubic spline function

$$b_L = -\Delta h_L \cdot c_L + \Delta vw_L/\Delta h_L - \frac{1}{3}\Delta h_L (c_{L+1} - c_L) \quad ; \; L = 1,..,N-1$$

$$b_N = 2(\Delta h_{N-1} + \Delta h_N) - \Delta h^2_{N-1}/b_N$$

$$c_L = (d_L - \Delta h_L \cdot c_{L+1}) \quad ; \; L = 1,.., N-1$$

$$c_1 = c_N = 0$$

$$d_L = \frac{1}{3}(c_{L+1} - c_L)/\Delta h_L \; ; \; L = 1,.., N-1$$

$$d_N = 3(\Delta vw_N/\Delta h_N - \Delta vw_{N-1}/\Delta h_{N-1}) - \Delta h^2_{N-1}/b_{N-1} \qquad (3.12)$$

During the flight tests the wind data are derived onboard the test aircraft itself, which measures and stores wind data already during climb before initializing the 4D mode. After the 4D mode is engaged actual wind data up-date the coefficients of the spline function.

The advantage of this method lies in the fact that the wind is modelled exactly if it changes slowly. However, this method does require a ground-to-air data-link by the relevant spline coefficients or certain set of wind data have to be transmitted.

### III.3.3 Short-time prediction of wind profiles

The short-time wind prediction - on the basis of actual wind measurements - takes into account the fact that extremely accurate wind values are needed for the last path correction. In this case, the wind has to be predicted for the time of approx. one minute necessary for the last 1000 ft altitude change down to the altitude at the gate. All previous wind measurement data of the entire 4D approach flight are taken into account in order to achieve the most accurate wind prediction.

The prediction can be brought about by extrapolation of the wind profile as a function of the deviations observed in comparison with the wind profile used before. Here, an extrapolation polynom is used which is based on the measured wind gradients. For the east component of the wind equations (3.13) apply:

$$vw_E = vw_{OE} + g_{1E} \cdot (h - h_O) + g_{2E} \cdot (h - h_O)^2$$

$$g_{1E} = d(vw_E)/dh \quad ; \quad h = h_O$$

$$g_{2E} = 0.5 \cdot d^2(vw_E)/dh^2 \; , \; h = h_O \qquad (3.13)$$

## IV. Realization of the experimental 4D guidance system

### IV.1 The flight control system

An integrated digital flight control system (Fig. 4.1) implemented in the HFB 320 test aircraft of the DFVLR is used for the 4D guidance experiments. It was developed by the companies MBB, VFW and BGT and the DFVLR (14, 15, 16).

This system has got a hierarchical structure for the flight control modes corresponding to the level of automation. The basic control mode is the control wheel steering mode, by which the pilot can intervene the automatic system at any time. By operating the control wheel he commands changes in vertical speed and bank angle, respectively. The autopilot/autothrottle control modes are activated by pressing buttons on the AFCS control panel. Also guidance commands are keyed in on this panel. Automatic control modes for longer flight phases, such as the 4D mode, work on the autopilot/autothrottle control modes. The flight control algorithms correspond to a coupled multivariable control system with open loop and feedback control. The controls are rudder, ailerons, elevator and the throttle.

The software of the flight control computer (HONEYWELL 316) is modular in structure. Each control mode corresponds to a software module. The entire software which has been developed for 4D path control is stored in the 4D NAV computer (NORDEN 11/34M).

### IV.2 Algorithm sequence and CPU time of the software modules

Fig. 4.2 shows the basic structure of the algorithms necessary for 4D flight path guidance. The total program is composed of individual software modules.

The strict partitioning of the software into individual modules offers the following advantages

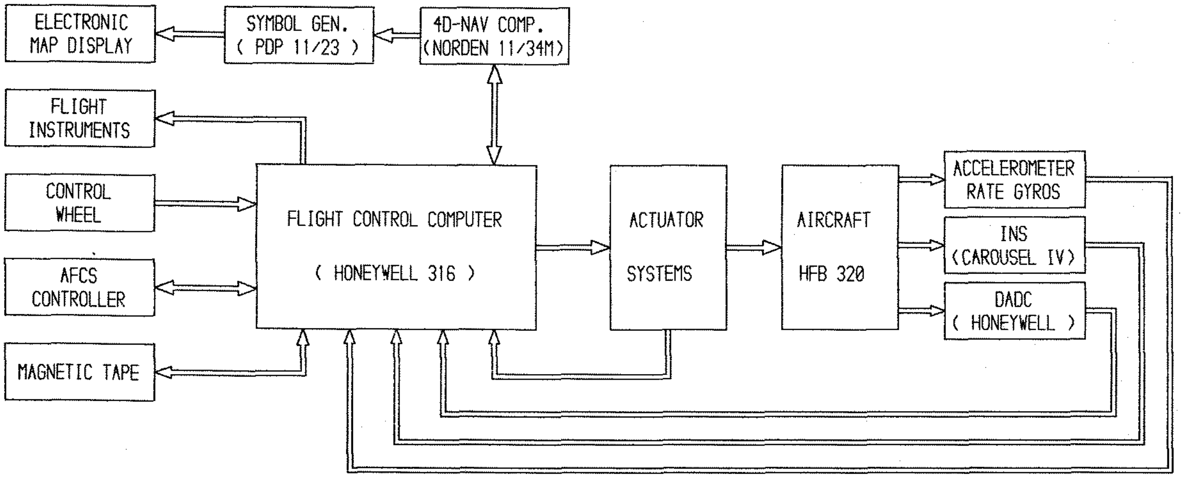


Figure 4.1: Structure of the digital flight control system

- the pilot can immediately observe a corresponding reaction when any input is made on the AFCS controller panel
- a clear program structure is obtained which makes the testing much easier and is especially suitable for optimization with regard to minimum CPU time.

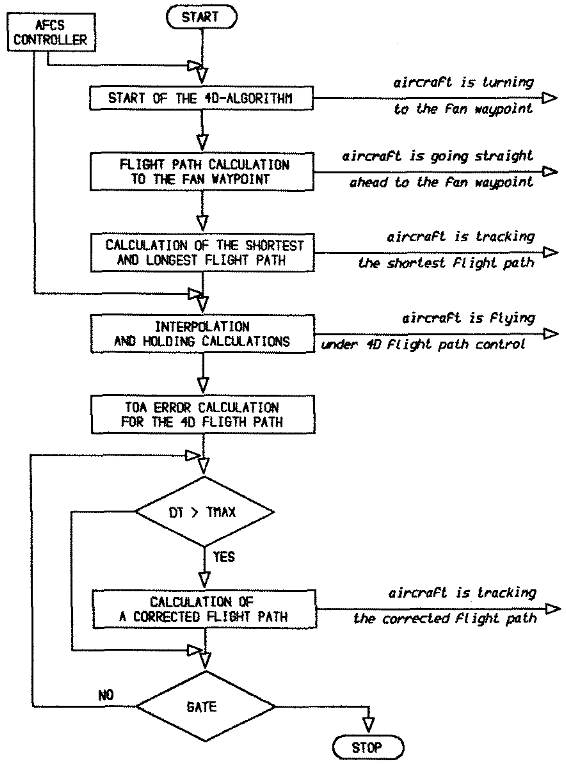


Figure 4.2: Algorithm sequence and structure of the software modules

The CPU time for each indvidual moduls as required in a NORDEN 11/34 M computer when programmed in FORTRAN IV is listed in Fig. 4.3:

| | | |
|---|---|---|
| A | first pre-calculation | 3.5 s |
| B | TOA error computation | 0.3 s |
| C | flight path correction | 3.0 s |
| | turn to the fan waypoint | 0.04 s |
| | direction to the fan waypoint | 0.06 s |
| | horizontal flight path | 1.0 s |
| | holding | 0.5 s |

Figure 4.3: CPU times of the individual software modules

In particular, three values of CPU time are important, namely those for:

- the pre-calculation of the complete 4D flight path (part A),
- the continuous calculation of the TOA error (part B) and
- the determination of a corrected flight path (part C)

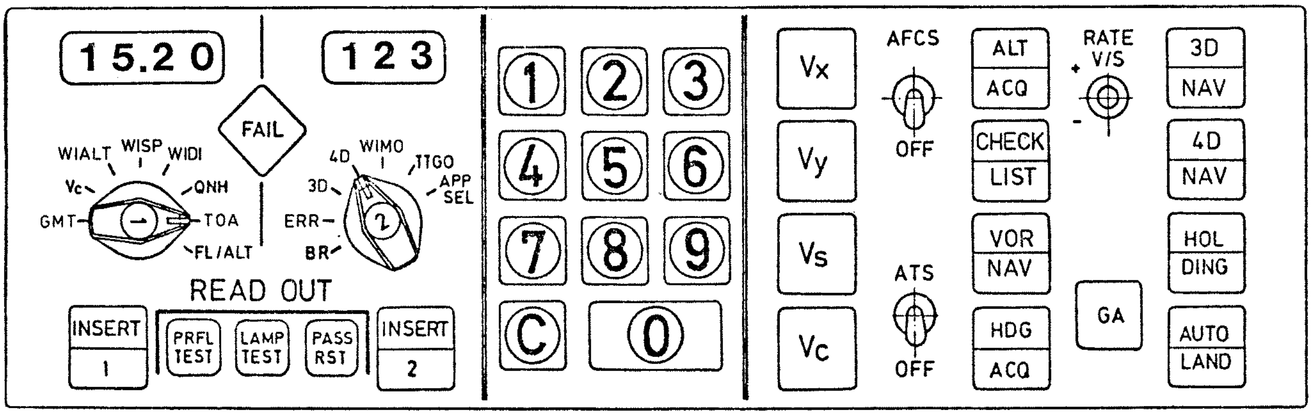
A total of 3.5 seconds are required for part A. If no holding is necessary, only 3 seconds in total are sufficient to determine the complete 4D flight path. The entire program consists of approx. 2000 FORTRAN statements stored in a 40 kbyte memory.

## IV.3 Operation of the 4D mode

The pilot inputs are made on the data entry panel of the AFCS controller panel shown in Fig. 4.4.

The actual procedure for a typical test flight is as follows:

1. Before take off the number of the wind model used for flight-testing has to be keyed in. The following numbers are available:



TMA2 : code of the STAR
GMT : actual time in absolute numbers
TTGO : time-to-go in minutes
ERR : error code
WIDI : direction of the reference wind
WISP : magnitude of the reference wind
WIALT : altitude of the reference wind
FL/ALT : commanded flight level
VC : commanded speed
TOA : desired TOA at the gate in absolute numbers

Figure 4.4: Front panel of the AFCS controller

1: wind model corresponding to the Eq. 3.10, 3.11
2: wind model corresponding to the Eq. 3.12
3: wind model 1 including wind prediction (Eq. 3.13)
4: wind model 2 including wind prediction (Eq. 3.13)

2. The pilot keys in the altitude and speed assigned by ATC. These commands are fed into the automatic flight control modes altitude aquire (ALTACQ) and speed control (VC)

3. The reference wind data are fed in.

4. The code for the type of the horizontal flight path to the gate and the altitude and speed for the intermediate approach are keyed in.

5. The 4D mode will be initiated by pressing the 4D-NAV button and the aircraft immediately starts the 4D approach by tracking the shortest 3D flight path.

6. The time-to-go corresponding to the minimum TOA is now displayed and the pilot feeds in the desired TOA with the left selector switch on position TOA.

7. If an altitude change for the intermediate approach is assigned by ATC the corresponding flight level has to be fed in. A descent rate of 1000 ft/min is automatically assigned. This descent rate can be changed by means of the RATE V/S toggle switch.

In addition to the conventional instrumentation on the instrument panel and the AFCS control panel the experimental system was equipped with an electronic map display shown in Fig. 4.5.

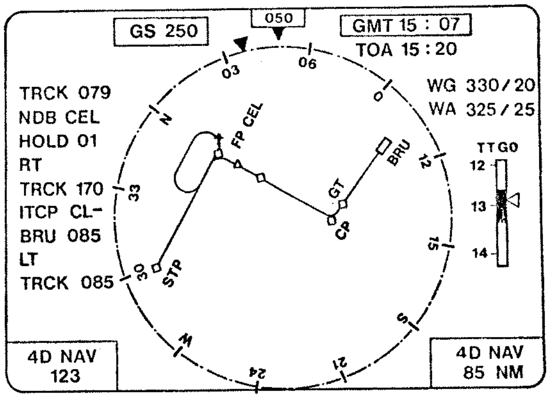


Figure 4.5: View of the electronic map display

The following parameter are displayed
- code of the type of the horizontal flight path
- mode of the flight control computer
- track angle
- heading
- ground speed
- actual wind data
- TOA error and its switching function
- absolute and relative times
- important waypoints
- symbols for the actual aircraft position

- number of holdings
- symbols for descent and speed reduction
- description of the pre-calculated flight path for manual flying
- a list of the data keyed in by the pilot can be displayed on request.

All signals required for flight path control are provided by the onboard sensor system in a suitable filtered form. The amount of signals as well as their quality meets the standard of modern transport aircraft. The essential signals are provided by a digital air data computer (HONEYWELL DADC), an inertial navigation system (CAROUSEL IVa INS) and rate gyros and accelerometers mounted in the body-fixed coordinate frame. For the flight tests the area navigation capability is established by the unaided CAROUSEL IV INS. The position errors are limited by means of a careful alignment phase and relative short mission time of approx. 30 minutes. The CAROUSEL IV position error is about 200 m at the gate. This corresponds to a TOA error of about 2 seconds. This sufficiently complies with the accuracy requirement in TOA control of less than ± 5 seconds. With regard to the area navigation systems for operational use in 4D guidance it becomes apparent, that no higher precision level is necessary in position determination.

## V. Flight test results

First flight tests of the 4D-NAV mode took place in the Hannover and Braunschweig area in May 1982. A large number of flight tests are planed in order to investigate various TOA, speed and altitude profiles and wind models in varying weather conditions.

The flight test selected for this presentation took place on May 25th, 1982. On this day an interesting wind profile was observed with a minimum magnitude of approx. 10 kts at FL 60 and a value of 20 kts at FL 100 and FL 30. The 3D flight path and the wind profile are shown in Fig. 6.1.

The 4D approach was started approx. 45 nm off the gate. The fan waypoint is located at a NDB radio station. Flight path command up-dates are performed by means of small course changes during intermediate approach. The desired TOA at the gate keyed in the AFCS controller panel by the pilot was too late to enter the fan directly, i.e. a holding had to be flown that was planned to take exactly 5 minutes flight time.

Fig. 5.2 shows the commanded speed and altitude profiles associated to this approach. The descent took place in two steps and the speed was reduced by the previously defined deceleration rates of 1 kts/s for level flight and of 0.2 kts/s during decent.

In Fig. 5.3 the ground speed and the course angle are plotted. The ground speed reflects the commanded steps of speed

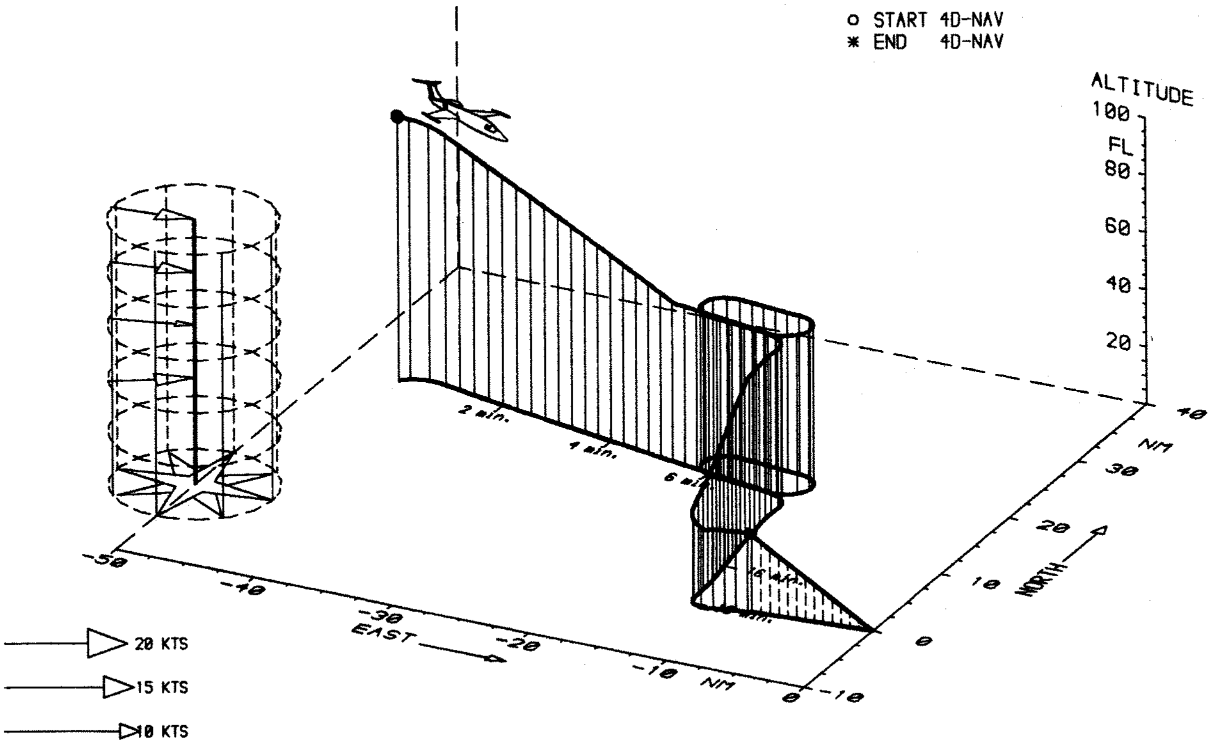


Figure 5.1: 3D flight path of flight test 12/2

reduction and, depending on the value of the course angle and flight altitude, illustrates the influence of the wind, acting on the aircraft from various directions for example while the holding is performed.

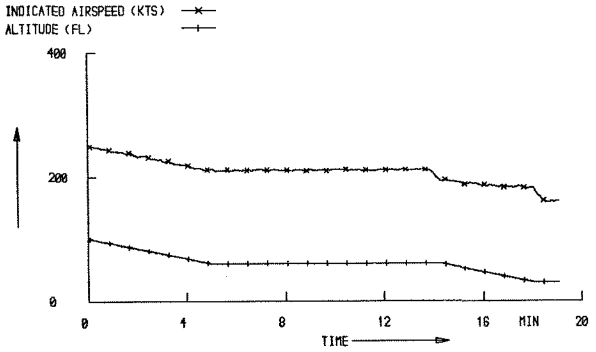


Figure 5.2: Speed and altitude profiles of flight test 12/2

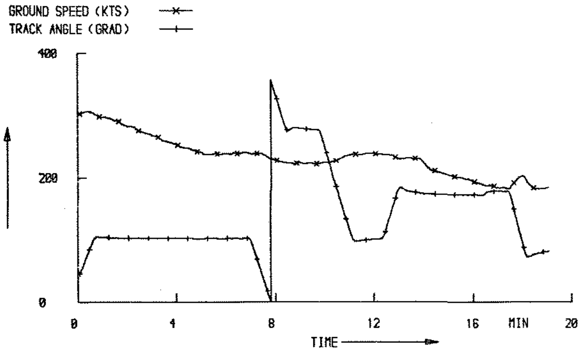


Figure 5.3: Ground speed and course angle of flight test 12/2

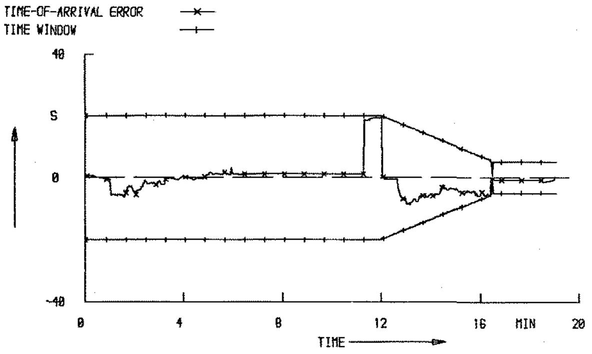


Figure 5.4: TOA error and time window for flight test 12/2

The TOA error for the selected 4D approach is shown in Fig. 5.4. The holding was executed at FL 60, at which a deviation of approx. 10 kts was observed between the wind model and the actual wind profile. This led to a relative TOA error of 20 seconds when the holding procedure was finished. At the fan waypoint a up-date computation took place taking into account the corrected wind profile. The last up-date compensates for a relative TOA error of approx. 5 seconds. By the time the gate was reached the TOA error was reduced down to about -1 second.

## VI. Conclusions

For the best use of airport approach capacity the 4D guidance system is an essential and promising element of TMA flight guidance automation. The system presented in this paper was developed for use during TMA flight from the metering fix to the gate located above the runway centerline about 12 nm of the runway threshold. At this point the aircraft is supposed to have assumed a given state in speed and altitude at a given time. First flight test results have shown that the TOA error at the gate meets an accuracy requirement of 5 seconds.

Flight path stretching or shortening via a delay fan is applied almost exclusively for time control and indicated airspeed is used for speed commands as conventional. This allows for manual flying of the commanded 4D flight path and to maintain a fuel-saving state of the aircraft as long as possible. The speed and altitude profiles are composed of a sequence of constant values corresponding to the usual radar vector guidance commands. The altitude is assigned by ATC. Different wind models are beeing investigated, in order to find the one best suited for the actual wind profiles. The accuracy levels achievable in experimental 4D systems above all depend on the precise knowledge of the wind profile along the pre-calculated flight path.

Iterative and fast-converging algorithms were developed for the calculation of the flight paht, TOA error computation, path correction calculations and holding computations. The hard- und software components were tested on the ground by means of the precise simulation of the HFB 320 test aircraft.

First test flights were started in May, 1982 and a typical 4D approach from this test series is shown in order to illustrate the principle features and the performance of the 4D system.

## VII. References

[1] Völckers, U., et.al, Analysis of two air traffic samples on the Frankfurt/ Main airport terminal area, August 4th, 1978, DFVLR, Institut für Flugführung, Braunschweig, ESA-TT-739, Translation of DFVLR-Mitt. 81-12, March 1982.

[2] Schubert, M., et.al., Analysis of two air traffic samples on the Frankfurt/Main airport terminal area, August 3th, 1979, DFVLR, Institut für Flugführung, Braunschweig, ESA-TT-740, Translation of DFVLR-Mitt. 81-17, March 1982.

[3] Schwarzott, P., Strategien der Flugsicherung zur Abwicklung des Luftverkehrs im Flughafen-Nahbereich, DGLR/DGON - Symposium "Fliegen im Flughafen-Nahbereich", Hamburg, April 1979.

[4] Terminal Configurated Vehicle Program Test Facilities and Experimentator's Guide, NASA Langley Research Center, Oct. 1975.

[5] Modlinger, A., Air Traffic Optimum Flow Control System (ATOFCS), VFW Bremen, Aug. 1981.

[6] Sundermeyer, P., Untersuchungen zur Verlagerung der Pilotentätigkeit auf eine höhere hierarchische Stufe der Flugführung, Technische Universität Braunschweig, Sonderforschungsbereich 58, FB 80-12-01.

[7] Pecsvaradi, T., Four-Dimensional Guidance Algorithms for Aircraft in an Air Traffic Control Environment, Ames Research Center, NASA TN-D7876, Febr. 1975.

[8] Homer, O., et.al., 4D Area Navigation System Description and Flight Test Results, Ames Research Center, NASA TN D-7874, Aug. 1975.

[9] Foundriat, E.C., A General Algorithm for Relating Ground Trajectory Distance, Elapsed Flight Time, and Aircraft Airspeed and its Application to 4D Guidance, Langley Research Center, NASA TN-D7876, Febr. 1975.

[10] Hotop, H.J., Probleme bei der bordseitigen Bestimmung der Windverhältnisse mit Optimalfiltern, DGLR/ DGON - Symposium "Fliegen im Flughafen-Nahbereich" Hamburg, April 1979.

[11] Böer, W., Technische Meteorologie, Edition Leipzig, 1964.

[12] Hemesath, N.B., et al., Three and Four Dimensional Area Navigation Study, FAA Report, RD-74-150, Final Report.

[13] Heimbold, R.L., et.al., Development of Advanced Avionics Systems Applicable to Terminal-Configured Vehicles, NASA Report 3280, 1980.

[14] Griem, H., Some Aspects of Advanced Flight Management Systems and their Application to Modern Transport Aircraft, 12th ICAS-Congress, München, Oct. 1980.

[15] Adam, V., et.al., Control Law Design for Transport Aircraft Flight Tasks, AGARDograph No. 251, Theory and Application of Optimal Control in Aerospace Systems, July 1981.

[16] Adam, V., et.al., Erhöhung der Führungsgenauigkeit durch den Einsatz eines integrierten digitalen Flugführungssystems, DGLR/DGON-Symposium "Fliegen im Flughafen-Nahbereich", Hamburg, April 1979.

[17] Lechner, W., et.al., Flugerprobung von Trägheitsnavigationssystemen, Beschreibung der Meß- und Auswertetechniken, DFVLR, Institut für Flugführung, Mitteilung 81-14, 1981.

[18] Stoer, J., Einführung in die numerische Mathematik, Springer-Verlag, Berlin, 1979.