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SOME ASPECTS OF ADVANCED FLIGHT MANAGEMENT SYSTEMS AND THEIR APPLICATION TO MODERN TRANSPORT AIRCRAFT

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Paper presented at the 12th ICAS-CONGRESS
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L I S T   O F   C O N T E N T S

L I S T   O F   F I G U R E S

1. Introduction

The take-off, landing approach and landing phases are flight phases of maximum stress for both cockpit crew and ATC-personnel with maximum accident frequency. This is due, on the one hand, to the flight path transitions from a ground-based to a wind-based coordinate system and vice versa, accompanied by rapid sequences of configuration changes and, on the other hand, to the frequently encountered high traffic densities in the terminal area.

Pilot stress is characterized by:

- communications with ATC;
- proceeding on complex lateral and vertical navigation profiles, including glide path intercepts;
- frequent velocity changes;
- configuration changes (extending flaps, landing gear, etc.) and configuration monitoring;
- frequency management.

The traffic density problem shall be demonstrated using the example of the Frankfurt/Main terminal. Figure 1 shows a ten-minute segment of traffic events at Frankfurt/Main. During this period, 8 runway manoeuvres, numerous holding manoeuvres (3 at the RÜD radio beacon, 4 at the GED radio beacon and 3 at the PS radio beacon), in addition to approach and take-off manoeuvres in the 4 approach lanes were observed.

A striking feature in this segment are the tracks of aircraft controlled via radar vectoring. Depending on the prevailing situation, these must be selected by the air traffic controller and reselected for each new situation. Another striking feature are the area violations in the holding patterns. In this respect, evaluations are available which cover manoeuvres recorded over extended periods of time; area violations by a factor of 10 are not unusual at this terminal.

One possibility to improve this situation in the future is automatic aircraft control on three-dimensional, ground-based flight paths while maintaining specified times. These flight paths must meet the following requirements:

- safe flyability for different types of traffic on these flight paths under any possible boundary conditions and adequate compliance with set-values;
- adequate separation potential under high traffic densities;
- simple monitoring and control of traffic on these flight paths by ATC-personnel;
- minimum cost-effectiveness constraints.

These ground-based flight paths have the advantage of reproducibility and, consequently, predictability which allows

on the ground	-	computer-controlled optimization of different traffic situations and appropriate allocations to the traffic, for instance, in the form of a time at which a certain aircraft must overfly a certain point; and
airborne	-	independent computation and implementation of set-values for flight path and velocity profiles on the basis of allocations by ATC.

The following presentation covers the airborne part of a system meeting these requirements. This system was developed, integrated and tested under the boundary conditions of an HFB 320 S 1 aircraft which was available for flight testing, including its equipment. The system functions and test results shall be communicated below.

2. Definition of Separation Flight Paths

The separation flight paths used for automatic control in the terminal area must meet the terminal area configuration for the individual terminals, i.e. the runway geometry, approach and take-off procedures, locations and types of the different radio beacons, landing aids, location and separation of holding patterns, approach lane geometry etc. must be taken into consideration. In addition, the selected flight path pattern must ensure adequate spatial and time separation of the different aircraft.

These requirements are met, in principle, by the possible approach flight path patterns shown in Figure 2 for the example of the Frankfurt/Main terminal.

These approach flight paths are based on the principle that the aircraft approaching for a landing are threaded into glide paths at equal distances and time intervals. The separation required for this purpose is accomplished via detour flight paths where the aircraft, proceeding at a specified mean velocity, are separated via detours to achieve time intervals of 1.5 minutes when this is required. The best-suited detour flight path is determined independently on board the aircraft, depending on its current position and the time specified by ATC at which the aircraft must pass the transfer-of-control point. After confirmation of the selected flight path by ATC, the automatic flight control system is engaged , and the aircraft proceeds on the prescribed flight path. The time schedule is precision-matched to the destination terminal by reducing or increasing the velocity profile for the time to go.

The organization of different traffic by ATC on the basis of specified times for individual aircraft and review of the flight paths reported by individual aircraft as well as the required additional information for processing and display on the ground, including consideration of the different velocity classes, is the subject of a traffic flow study now in progress.

A subdivision into two velocity classes as follows is conceivable:

	1.3 v_s / full flaps max. landing weight	
A 300 B 4	137, 5 kts	140 ± 4 kts
Bo 747	140	
Bo 767	144	
DC 10	136	
Bo 737/300	137	
A 310	132	128 ± 4 kts
Bo 727/200	126	
Bo 737/200	130	
DC 9	124	
L 1011	132	

The system presented in this report has been developed and tested, using an exemplary flight path pattern for the Braunschweig terminal (cf. Figure 3), in order to test and demonstrate the airborne equipment and its performance characteristics with respect to flight path control accuracy, compliance with the specified times and requirements with respect to displays and operator skills. Adaptation to the patterns of different terminals can be accomplished easily at any time. Moreover, the results acquired with the aid of exemplary patterns can be generalized.

3. Test System Used

The HFB 320 S 1 flight test system of the German Aerospace R&D Establishment (DFVLR) was used for these studies (cf. Figure 4). This system was equipped, in addition, with a digital flight control computer including interfaces and the software required for the newly developed automatic flight control system. In addition, a digital autopilot control unit meeting the space requirements of this flight test system was developed and integrated.

The resulting flight test system shall be described below.

3.1 Sensor System

All the measured variables required by the flight test system are produced by a sensor system in a filtered form suitable for flight control (cf. Figure 5). The signal quality of the individual sensors meets the standards to be expected for the next generation of transport aircraft.

An air data and navigation program processes the signals generated by the digital air data computer, the inertia platform and the radio navigation receivers into a set of filtered signals. The vertical channel of the inertia platform is referenced to barometric altitude so that very smooth altitude and rate-of-climb signals are available.

The long-time errors of the inertial navigation system are reduced via analog stabilization by means of a reference position. This reference position can be computed from the signals of an MLS or VOR-DME station. The long-time accuracy of this referenced inertial navigation system is equivalent to the long-time accuracy of the reference signals; however, the high-frequency noise in the reference signals is smoothed.

This means that navigation signals of constant quality equivalent to the short-time accuracy of the platform are available for all automatic modes used in the terminal area.

3.2 Control System

The flight test aircraft is equipped with fly-by-wire control in all three axes, engine control and flaps control, operated from the right-hand pilot seat. All actuators also accept electrical flight control signals without any authentication limits. In the event of errors, the control is returned to the basic mechanical control system.

3.3 Mode Concept and Control System

The newly developed digital flight control system includes a mode concept of hierarchic structure, depending on the degree of automation. It is subdivided into three groups:

- control wheel steering,
- automatic modes,
- modes including the automation of more complex flight control functions.

The following modes are provided:

• CWS ϕ • CWS H	controller-supported control wheel steering
• ALT HOLD / ACQ • HDG HOLD / ACQ • V_c • NAV • Modes including control of the aerodynamic state	automatic modes
• DEC. APPR. • AUTOLAND • GO AROUND • TMA	modes including automation of more complex flight control functions

Control wheel steering is the basic mode. The pilot can operate his control wheel at any time to select changes in pitch attitude or rate of descent (when the thrust control is activated) and the roll attitude. The higher-level automatic modes and functions are de-activated immediately, and the controller computes flight control deflections to stabilize the selected new flight attitude. This results in high manoeuvrability at reduced pilot stress.

In addition to the conventional autopilot modes for altitude selection, course preselection and VOR navigation, the autothrottle mode for speed preselection has been implemented in the same computer. Additional new modes serve to control the aerodynamic flow state, for instance, a desired multiple of the aircraft's stalling speed.

The modes named above can be used by higher-level functions for the automatic control of longer flight phases.

The control system has been designed as a coupled multiple-variable system where all significant sensor variables and control variables are coupled to all actuators. Control actuators include the three axes control surfaces and the thrust control unit. The flaps are not controlled but can be operated manually or via program, for instance, in the case of automatic go-around or landing approach with delayed flap operation (decelerated approach).

On the other hand, the selected controller structure (cf. Figure 6) allows independent shaping of the guidance-, disturbance- and inherent behaviour of the controlled system. Direct compensation of disturbances makes it possible to adjust the actuators on the aircraft at an early time so that most of the interference effects on aircraft manoeuvres are eliminated.

Since this is equivalent to pure anticipatory control of actuators, the system's inherent and control characteristics remain unchanged. External interference effects to be taken into consideration include, in addition to vertical and horizontal air movements, the aircraft configuration changes such as extension of flaps or landing gear.

Moreover, high flight control accuracy is achieved when the control signals affect the actuator values not merely via a comparison of set-values and actual values but also directly via dynamic anticipatory control derived from a flight control model. This applies, for instance, to the aileron and rudder deflections when a coordinated turn is initiated, or to pulling the elevators and increasing the thrust in steady-state banking flight. The control loops merely eliminate the remaining deviations due to inaccuracies in anticipatory control and in the compensation of interference variables.

3.4 Displays and Operation

In addition to the basic displays for flight attitude, flight path attitude and power state, an autopilot control unit has been developed for this digital flight control system (cf. Figure 7). This control unit allows mode selection via push-button control and the input of set-values via a numerical keyboard. The proper allocation of set-values is accomplished via two rotary switches of eight switch positions each. The selected set-values are displayed on a digital display to ensure an accuracy check by the pilot prior to transfer of the selected values to the flight control system.

With reference to automatic flight control in the terminal area with specified touch-down time, the following pilot activities are required:

- Set switch No. 2 to position TMA 2
  → Input of destination terminal codes
  These codes define:
  - runway geometry, approach direction;
  - coordinates of fan point and transfer-of-control point.

- Set switch No. 1 to position ALT
  → Input of target altitude at the transfer-of-control point.

- Set switch No. 2 to position TTGO (time to go)
  A plausibility check of the data input up to this time is made. These data are used to determine the time which would be required on a direct path to the transfer-of-control point under most economical flying conditions; this time is indicated on the second display and counted down continuously.

- Set switch No. 2 to position TACQ
  → Input of the time specified by ATC.

- Depress the TMA 2 mode selector key
  → If the selected time is plausible, mode TMA 2 is engaged , and the autopilot modes
  ALT ACQ / HOLD
  NAV
  V_C
  are fed the required set-values.

- Set switch No. 2 to position OTN
  The number of the selected detour flight path is indicated on display panel No. 2 and can then be reported to ATC.

After this procedure, it is possible, for instance, to continue with an automatic landing which is no longer subject to the laws of time but to the laws of safety. The time to touch-down is very accurately known if the wind parameters are known; it can be included in the overall time schedule.

3.5 Set-Value Computation

In order to compute the set-values for the lateral and vertical flight paths and for the velocity, the overall flight profile is subdivided into elements which are easy to compute, as follows:

with respect to lateral motion
- into arcs of constant radius of turn, and
- into linear segments;

with respect to vertical motion
- into horizontal flight segments,
- into segments of constant flight path inclination, and
- into transition segments between the two, with constant vertical acceleration;

with respect to velocity
- into segments of constant velocity, and
- into segments of constant deceleration.

These individual segments merge smoothly into each other without any kinematic or dynamic instabilities. Route markers are defined between neighbouring segments which are identified by a fixed geometric position and allocated times at which the aircraft must pass the route markers.

In order to achieve constant radii of turn at all potential velocities, the bank attitude for a turn is controlled as a function of velocity, in accordance with the following law:

$$\tan \varphi = \frac{v^2}{g \cdot R},$$

where φ = bank attitude
v = forward velocity
g = gravity acceleration
R = constant radius of turn.

The specified velocity profile along the flight path is first computed in the form of ground speed and subsequently converted into indicated airspeed, taking into consideration the current wind velocity and air density which decreases with increasing altitude; this indicated airspeed can then be processed by the speed controller.

In the event of deviations between specified and required times, time control according to the following principle has been provided:

The time of an independent clock (represented by the quartz-controlled computer clock) is compared to the time to go which is determined from the current aircraft position. The time difference derived from this comparison is fed to a controller network which computes a quantity which can differ from 1.0 by ± 2.5 %. This time factor is multiplied by the specified velocity and, consequently, introduced into the speed control system.

Control of a ground speed velocity profile has the advantage of being unique and independent of the wind. All procedures which make allowance for the wind require a wind prediction. One possibility of allowing for the wind is to stipulate that the wind force and direction measured upon initiation of the procedure remain constant throughout the procedure, possibly with an altitude-dependent reduction on the basis of a specified model. Using this wind model, the velocity profile must be modified so that, in place of ground speed, an indicated airspeed is controlled which takes into consideration this particular wind. Deviations of the actual wind from the model are compensated by the velocity control system. The algorithms for this situation have been developed and tested in simulations. As might be expected, it was found that, for instance, in a holding pattern, the indicated airspeed exhibits a constant profile if the wind is constant so that accordingly different ground speeds result. In keeping with this procedure, the headwind and tailwind thrust remains constant, but the ground flight path and the specified time for the holding pattern are maintained with sufficient accuracy.

3.6 Flight Control Computer

The heart of this flight control system is the MUC 161 computer by VFW, shown in Figure 8. All the information required for flight control is fed to this computer which computes the specified flight path and controls the entire automatic flight control sequence.

The MUC 161 computer has a word and instruction length of 16 bits. Its advanced design, using highly integrated MSI and LSI circuits made in TTL and TTL low-power Schottky technology, allows high operating speeds (such as: cycle time 200 nanoseconds, addition/subtraction 500 nanoseconds, storage reference 1,000 nanoseconds). The memory capacity is 32 kilowords of 16 bits each; CMOS modules can also be used for this memory. The computer has a power requirement of 15 W and is supplied from the 5 V system. It is especially due to its high computation speeds that the MUC 161 is extremely well suited for highly complex flight control functions.

The software provides for a basic 10 Hz cycle for

- sensor data interrogation,
- status interrogation,
- control computations,
- actuator outputs, and
- outputs to instruments.

The one-time predictions of the specified flight profiles, which require relatively long computation times, are executed during the remaining times in the individual cycles. It is of no significance whether this requires 10 or 20 cycles.

4. Test Results

After testing the system in simulations with hardware in the loop, it was retro-fitted into the aircraft. Figure 9 shows the AFCS computer, interface unit, computer control console and input peripherals after installation. Figure 10 shows the AFCS control console in the cockpit. After additional dynamic system testing on the installed equipment with connected peripherals (sensors, actuators, instruments) (cf. Figure 14), eight test flights were implemented. The most important test results have been compiled below.

4.1 Test Flight Implementation

Approaches to the Braunschweig terminal were made after coordination with local ATC. The procedure was started at a distance of approximately 85 km north-west of Braunschweig, using initial conditions such as the following:

air speed	170 kts IAS
altitude	12,000 ft
heading	90° north
configuration	clean.

Different touch-down times were specified so that approaches on different detour flight paths with and without holding pattern resulted. One example of approach is shown in Figure 12. The wind force was low during all flight tests (May/June 1980).

The important measured variables required for flight test monitoring were transmitted to the ground via telemetry and viewed on a quicklook station. In addition, more than 200 variables were recorded on magnetic tape and available for evaluation.

4.2 Flight Path Control Accuracy

As an example for control accuracy in the vertical plane, Figure 13 shows a selected flight path segment with the following events:

- airspeed reduction to 150 kts IAS,
- altitude change from FL 120 to FL 110,
- 25° flap extension

The altitude deviations from the specified flight path noted during this flight path segment were as follows:

$$\Delta h = \pm \; 10\,\mathrm{m} \text{ maximum}$$
$$\Delta h = < \; 4\,\mathrm{m} \text{ mean deviation.}$$

This means that the deviations are extremely small even in the event of flight attitude changes, manoeuvres and malfunctions, and the flight path control accuracy in the vertical plane can be considered positive without limitations.

The speed parameters have been plotted in Figure 14 for the same flight path segment. The ground speed is executed with programmed accuracy. Consequently, the indicated airspeed varies by its wind component.

The deviations from the selected indicated airspeed were:

$$v_{IAS} \approx 2 \text{ kts.}$$

The importance of the accuracy in executing the selected speed can be measured via the accuracy of maintaining the specified time for passing the transfer-of-control point (refer to Section 4.3, below).

Lateral flight path control is characterized by the variables of motion shown in Figure 15, using the example of one complete holding pattern. One striking feature are the lateral flight path deviations encountered in turns which were

$$\Delta L \cong 450 \text{ ft.}$$

In straight and level flight, the deviations remained within the allowable limits at

$$\Delta L \lesssim \pm 100 \text{ ft.}$$

The major deviations in turns were due to the control equation initially selected for these flight tests:

$$\varphi c = 15^{\circ} + K \cdot \Delta L.$$

This control equation does not take into consideration the velocity-dependent value of the selected roll angle which is required for constant, velocity-independent radii of turn. In addition, the integral of lateral flight path deviation, which would compensate for steady-state deviation, has not been taken into consideration.

Therefore, simulations were used to study the following control equation:

$$\varphi c = \left(\frac{v_{IAS}}{v_{IASO}}\right)^2 \cdot 15^{\circ} + K_1 \Delta L + K_2 \Delta L + K_3 \int \Delta L \, dt$$

It was found that the lateral deviations from the specified flight path amounted to

$$\Delta L \leq 100 \text{ ft.}$$

The factor $(v_{IAS}/v_{IASO})^2$ has the result that the roll angle is matched to that value which is required in order to achieve the radius of turn which is established at 15° bank attitude and v_{IASO} (for instance, 170 kts).

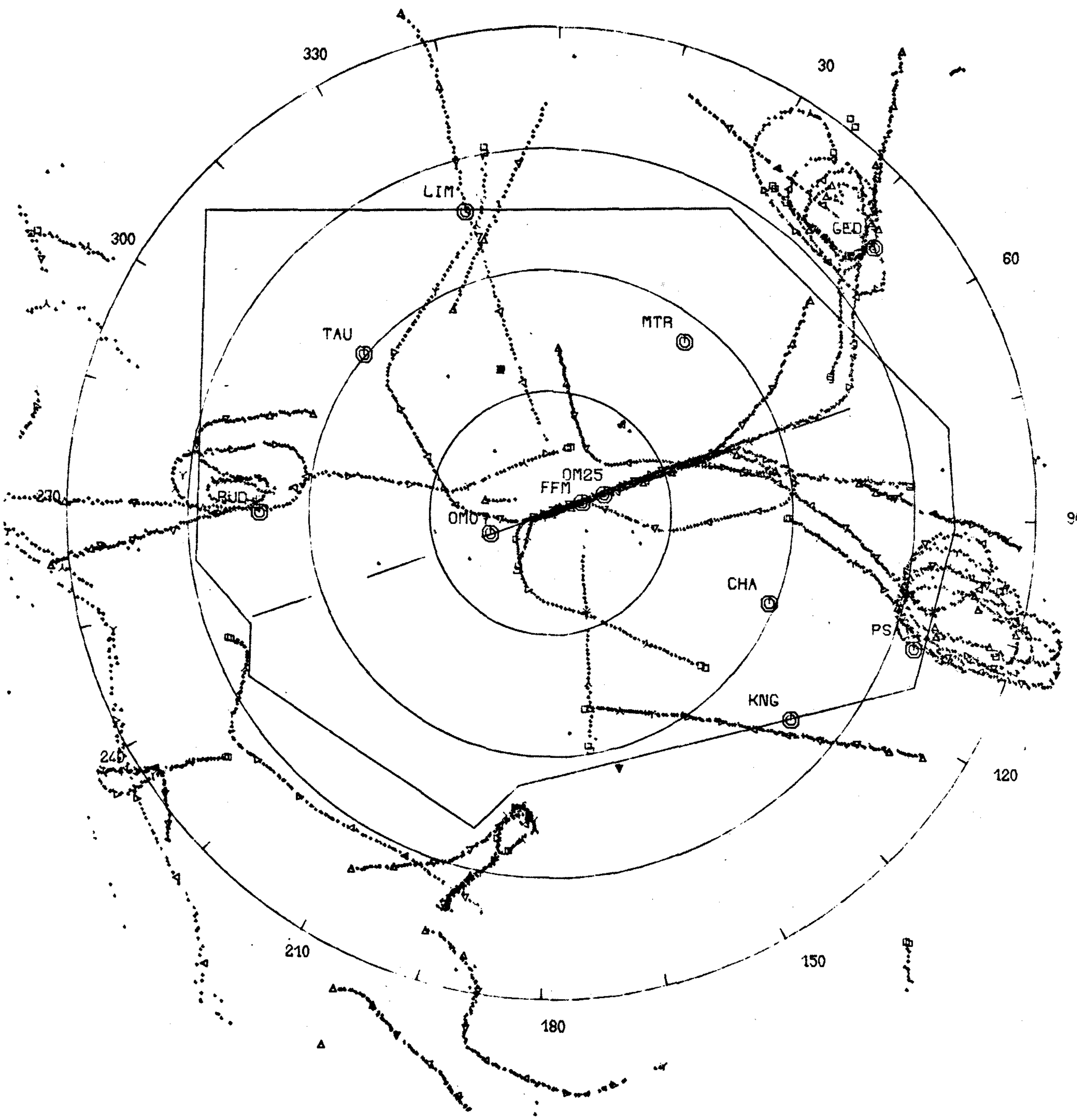
4.3 Time Accuracy

One important criterion for the evaluation of system performance is the accuracy in maintaining the specified times at every specified point on the flight path. In all the flight tests implemented, this accuracy was

$$t \leq 10 \text{ sec.}$$

This value includes errors due to the procedure, inaccuracies of the signal processing hardware, velocity measurement errors, and is valid under the moderate wind conditions encountered during these flight tests. The velocity measuring error is minimized by combining two cross-referenced measuring systems, ground speed measurement via the (referenced) inertia platform and the velocity generated by the airdata system.

The ground speed determination can only be as accurate as the determination of the position by the referenced navigation system. This condition is considered satisfied within the scope of the results communicated here. Improved accuracy of the reference system will also improve the accuracy of the transfer-of-control point. This will not degrade compliance with the time tolerances named above.



MASSTAB IN (NM)

0 2 4 6 8 10 12 14 16 18 20

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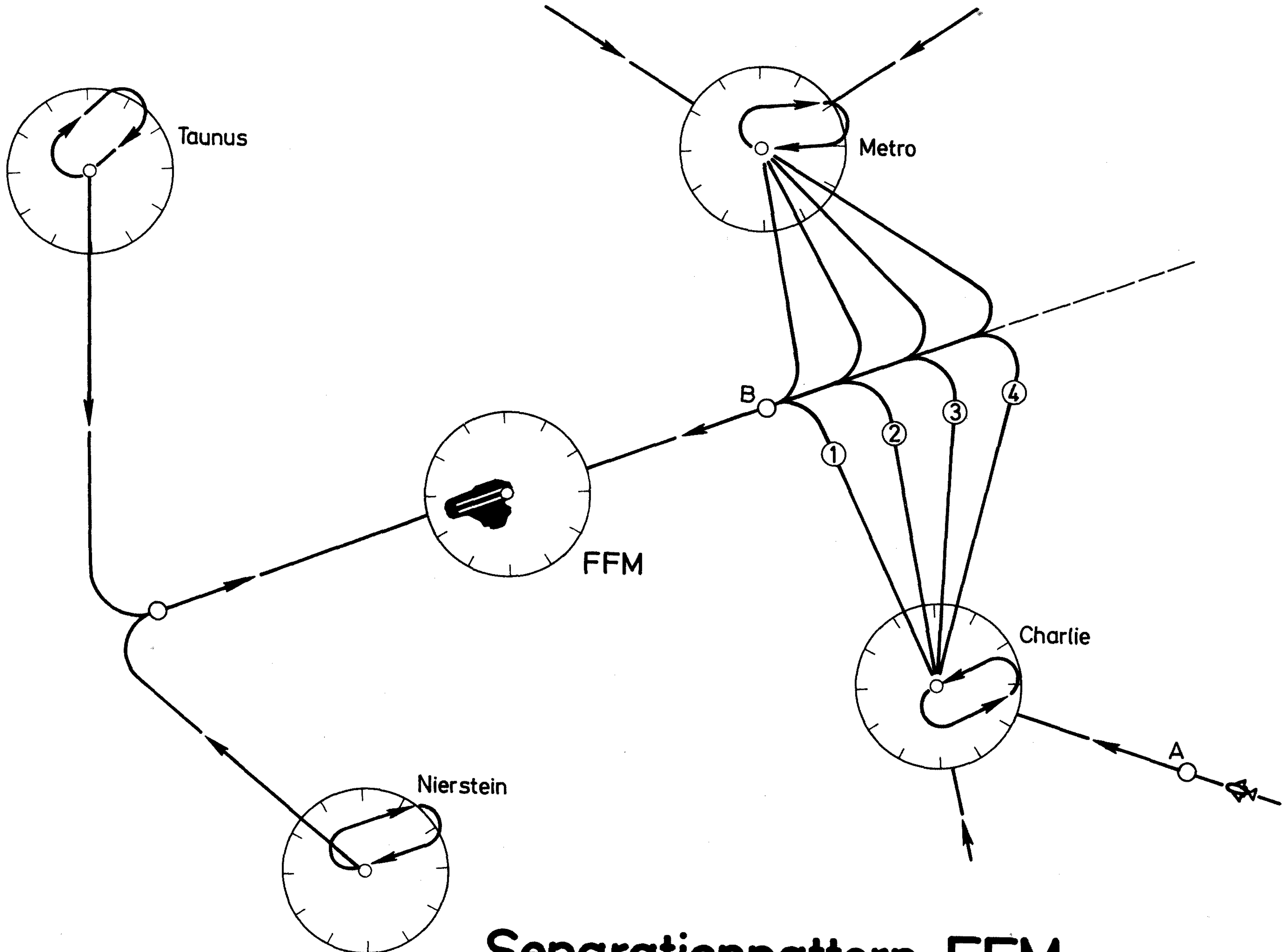
VON 11:38:57 02:08:79

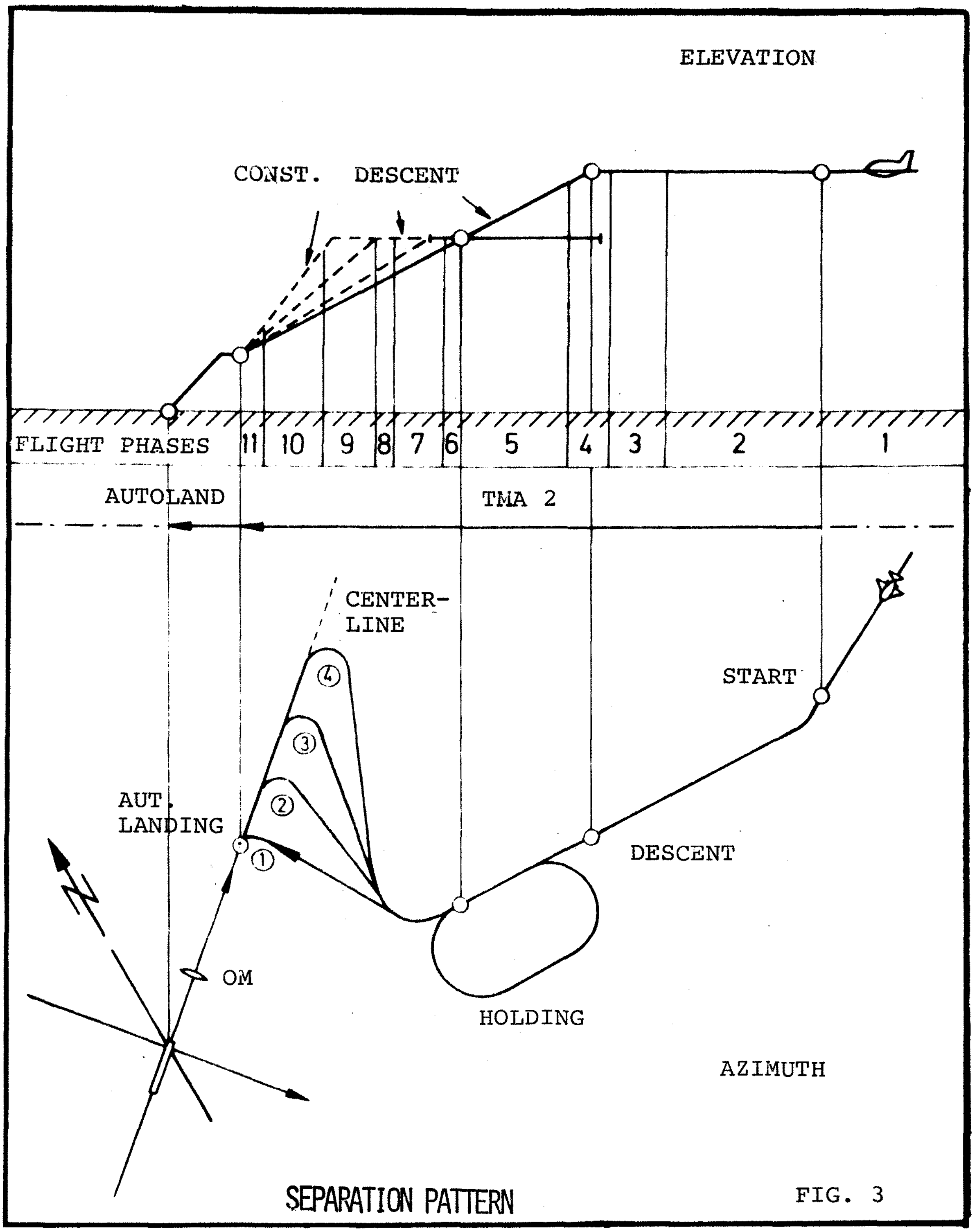
BIS 11:48:55

FIG. 1



Separationpattern FFM

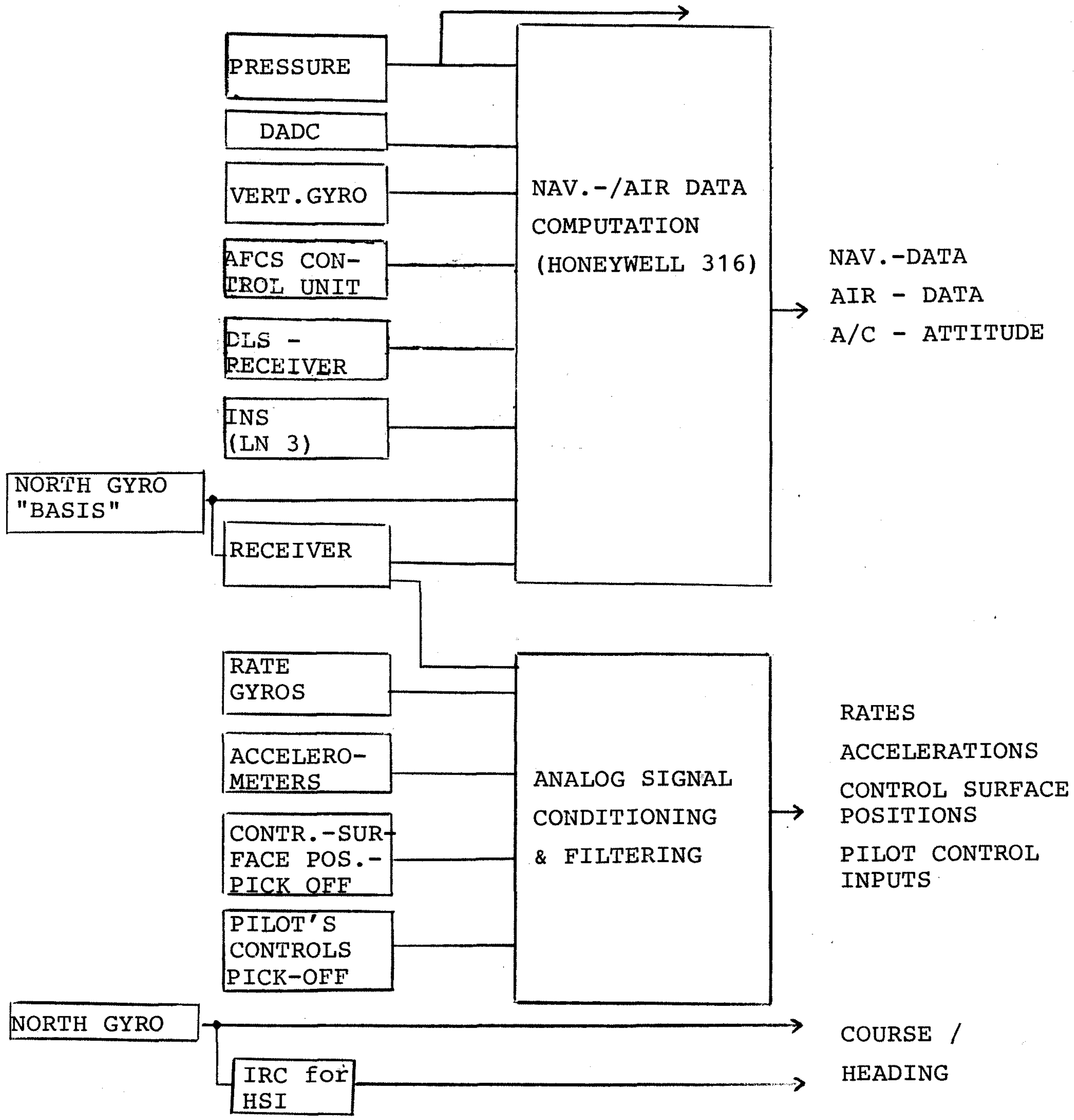
FIG. 2



SEPARATION PATTERN

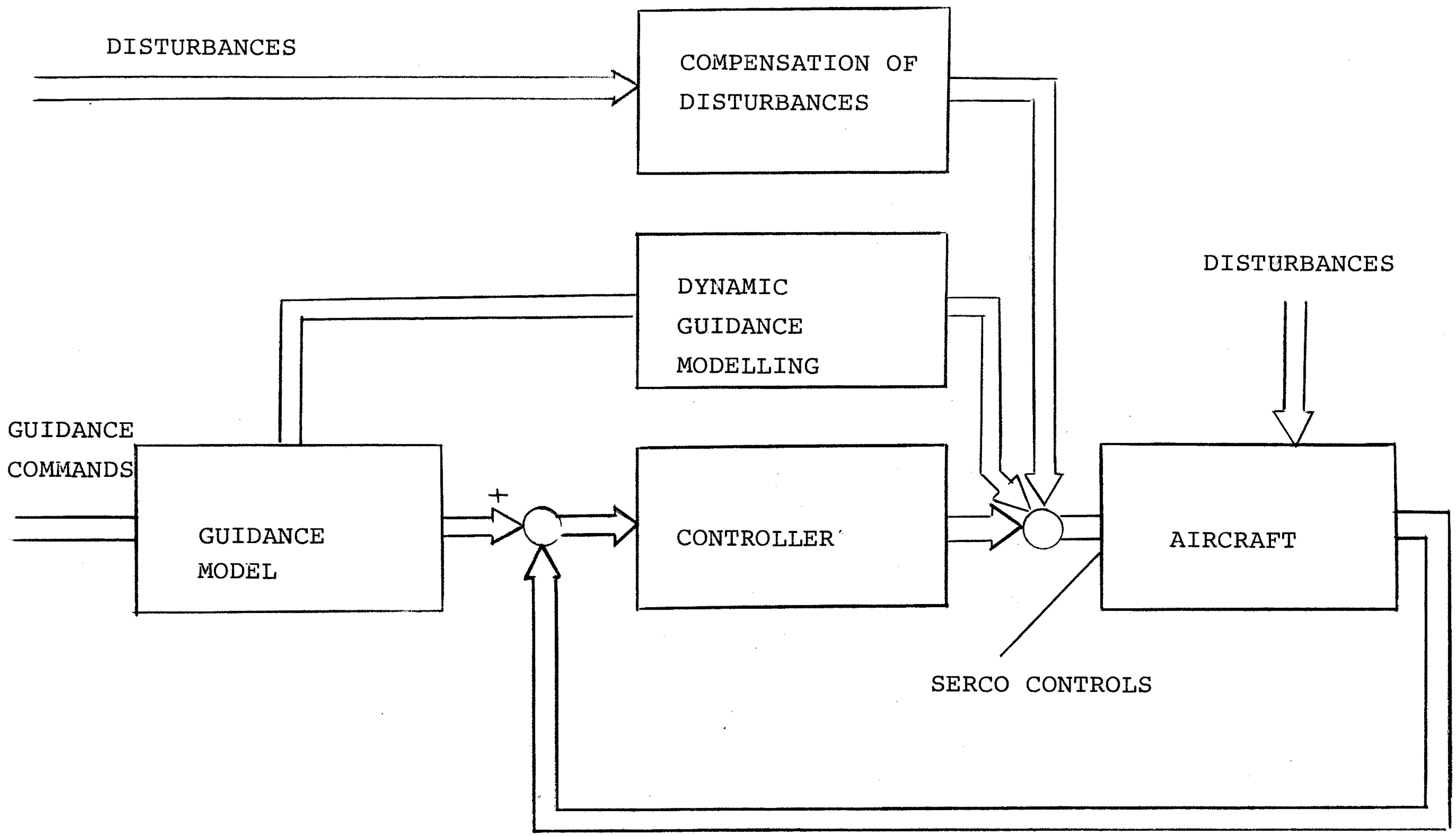
FIG. 3

FLIGHT TEST AIRCRAFT FIG. 4



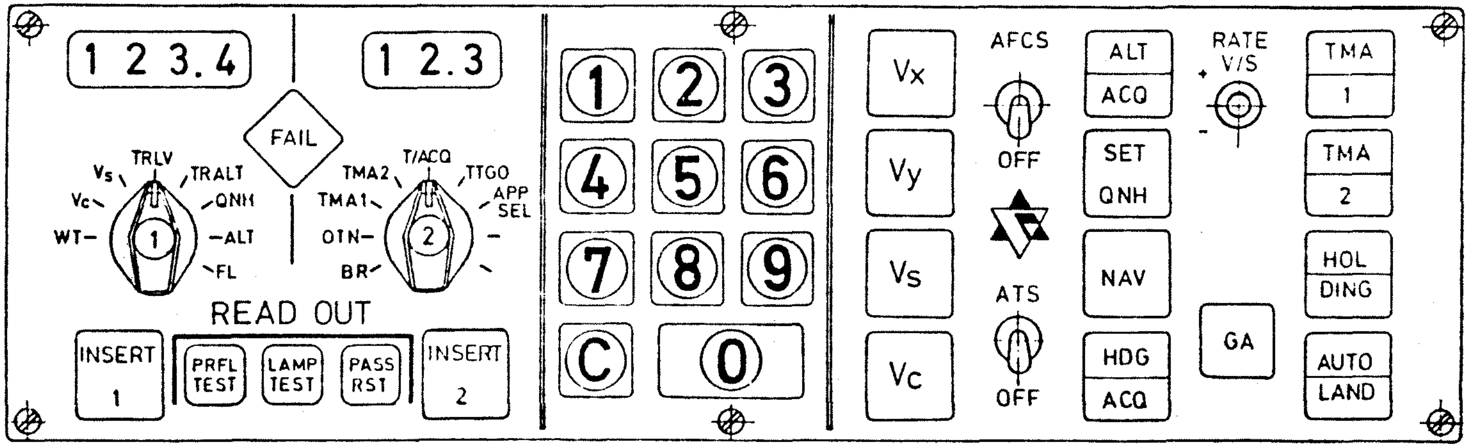
SENSORSYSTEM FLIGHT TEST A/C

FIG. 5

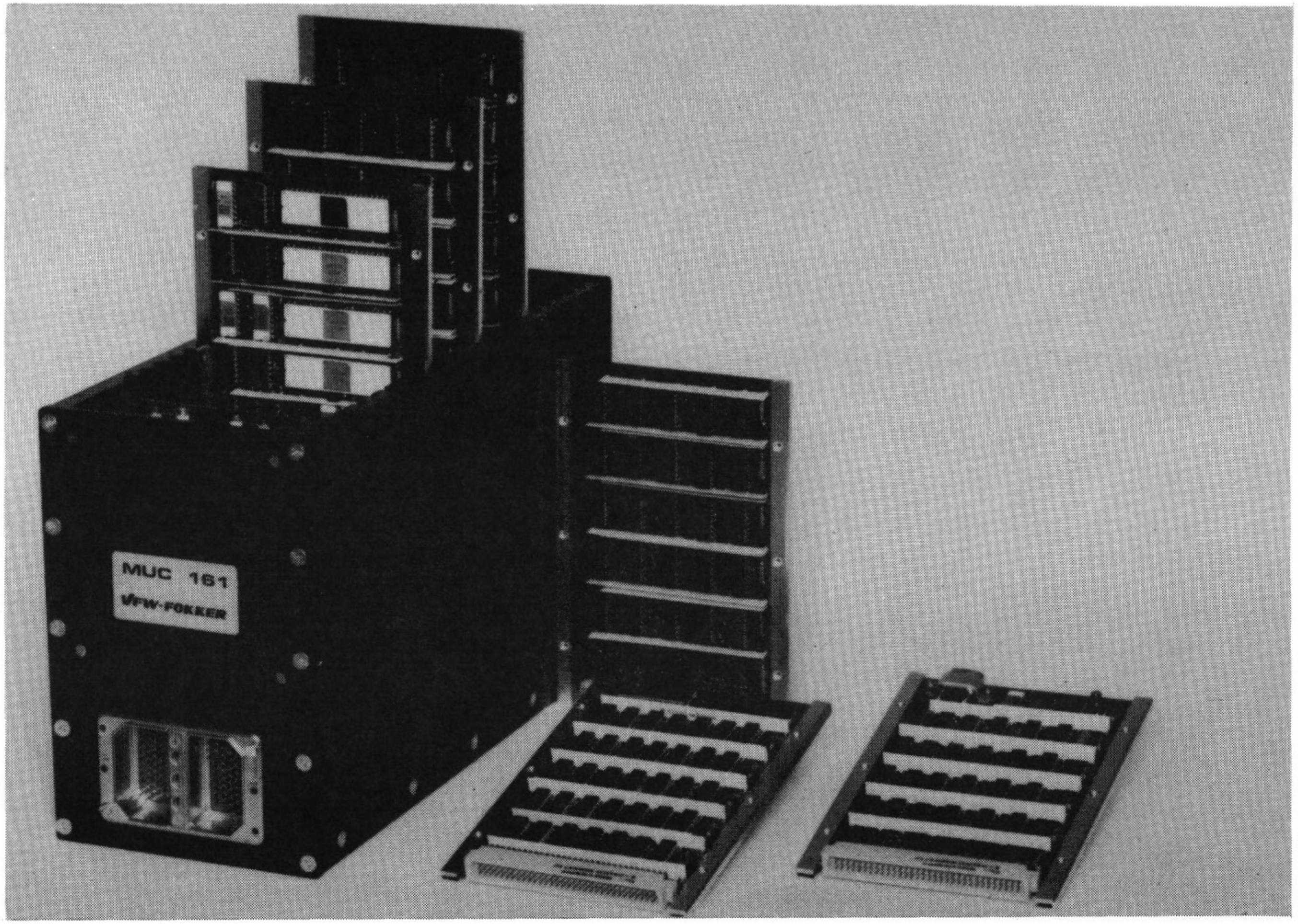


A F C S - STRUCTURE

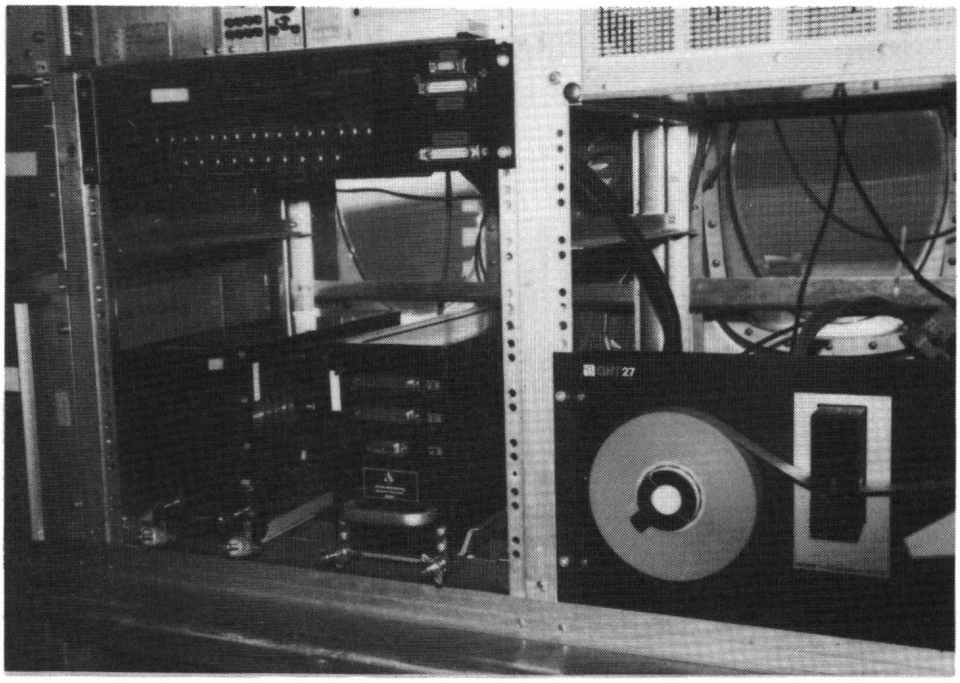
FIG. 6



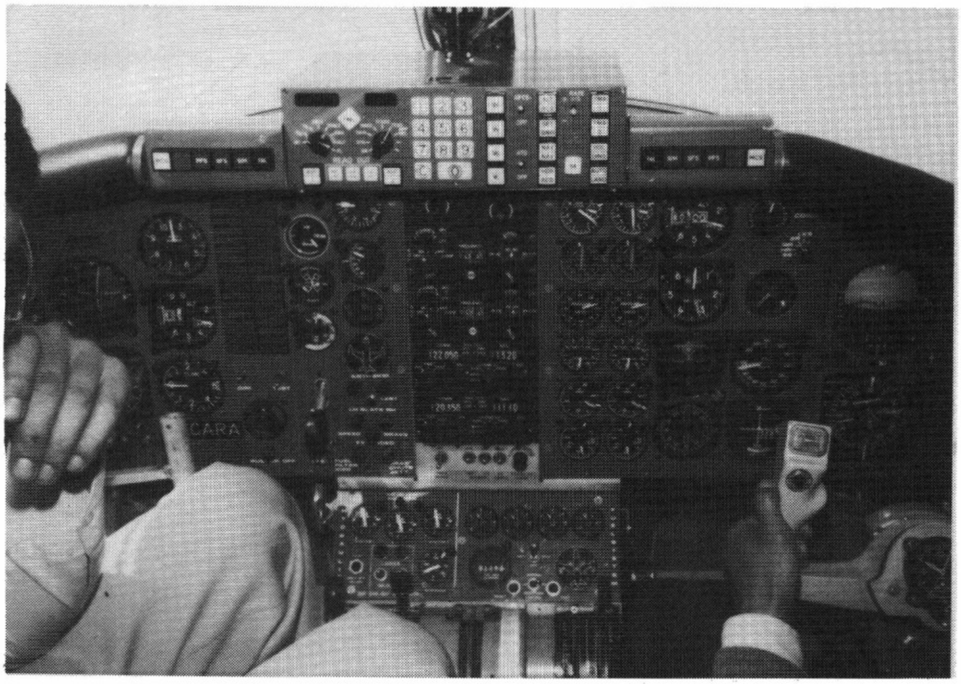
A F C S - CONTROL UNIT FIG. 7



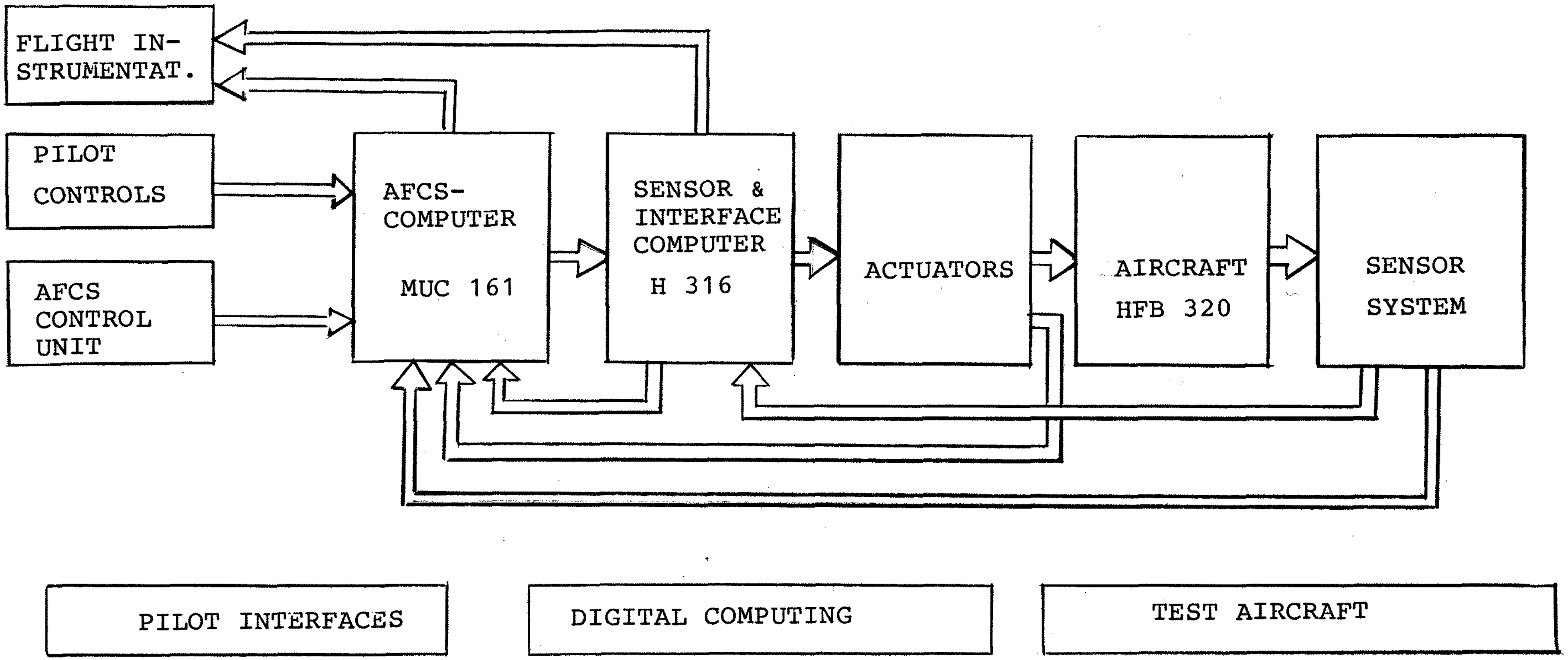
. A F C S - COMPUTER FIG. 8



DIGITAL AFCS HARDWARE FIG. 9

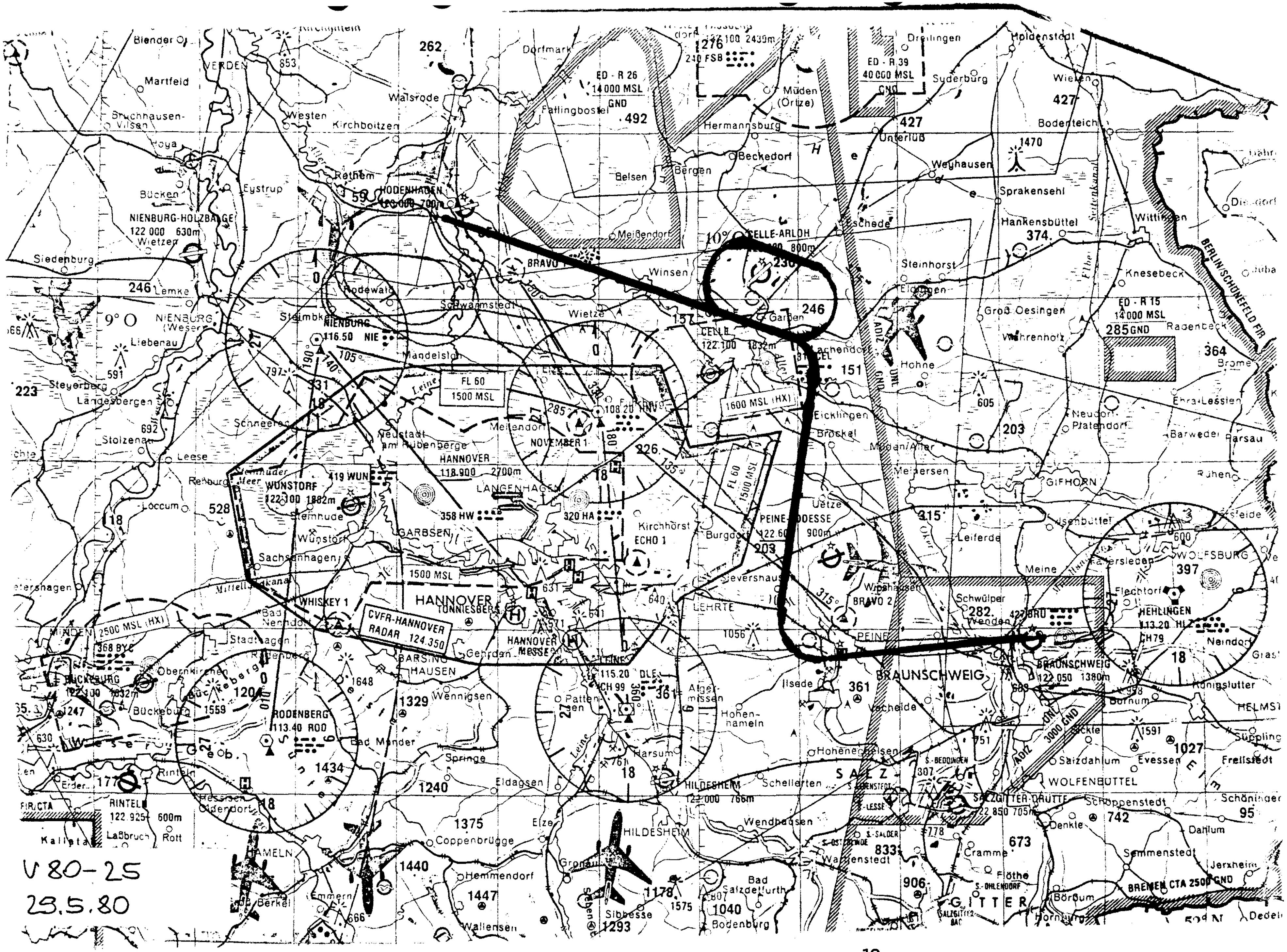


AFCS CONTROL UNIT FIG. 10



FLIGHT TEST SYSTEM

FIG. 11



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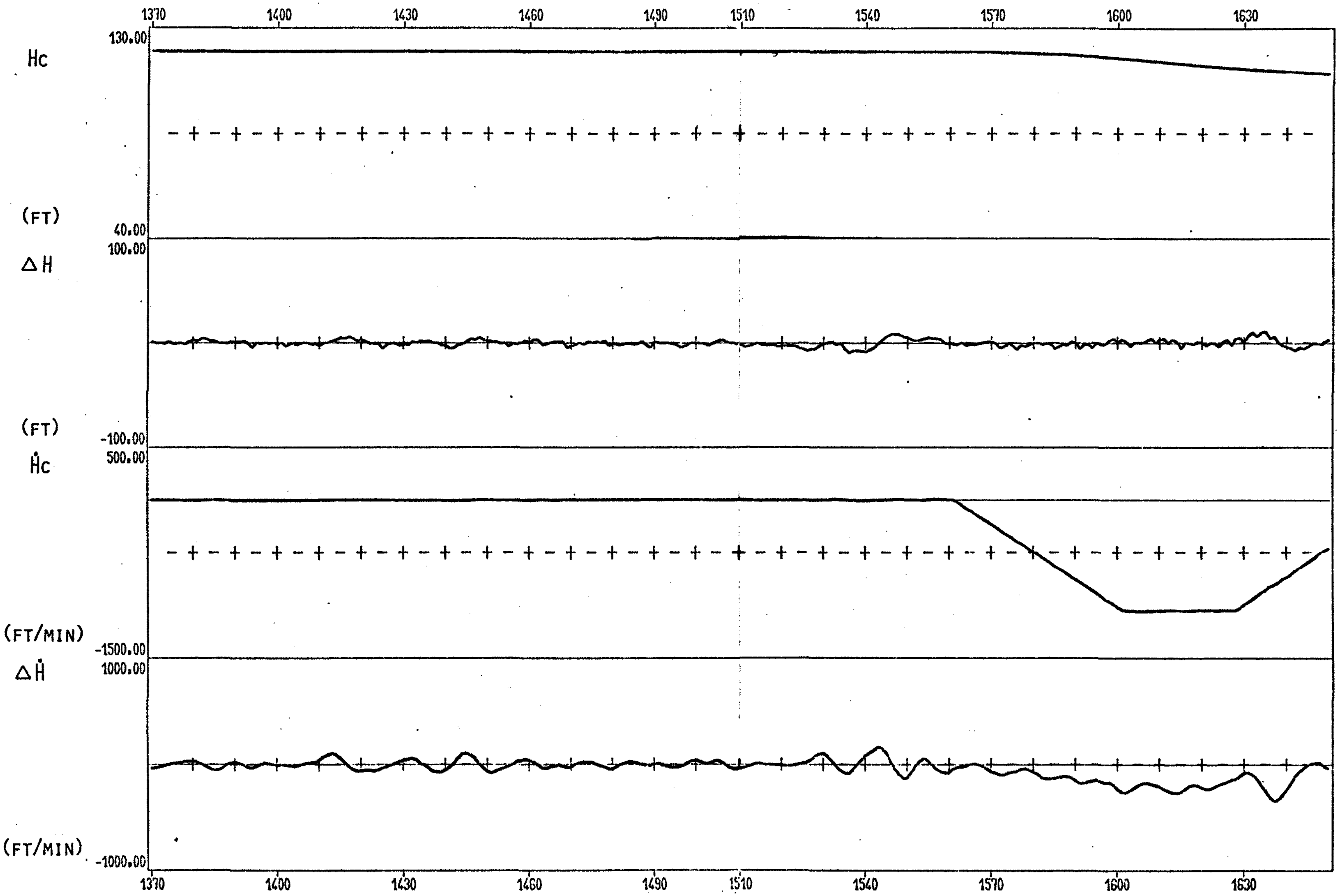
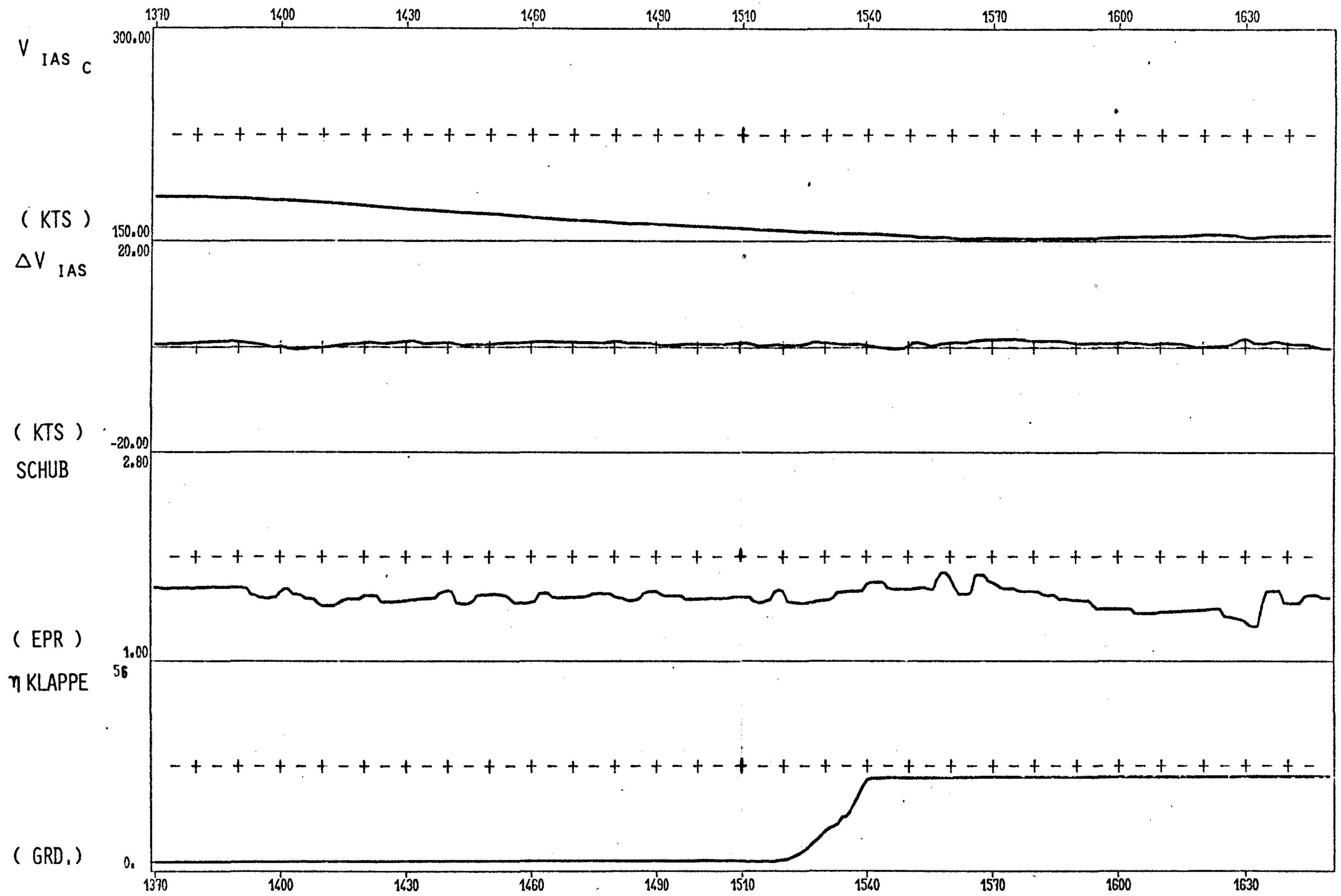
EXEMPLARY FLIGHT PATH

FIG. 12



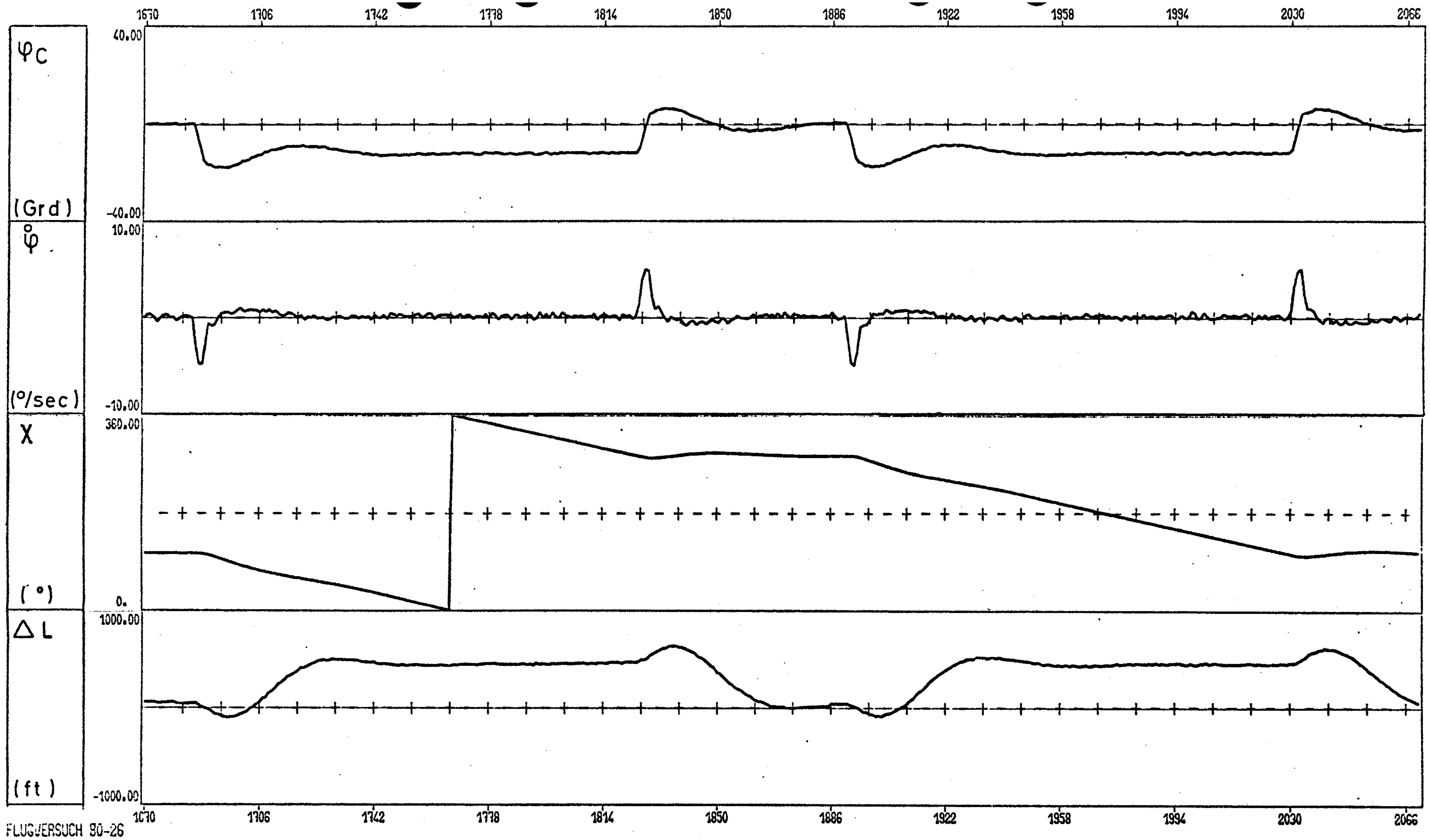
FLIGHT TEST RESULTS "ALTITUDE CONTROL"

ABB. 13



FLIGHT TEST RESULTS "SPEED CONTROL"

ABB. 14



FLIGHT TEST RESULTS "LATERAL CONTROL"

ABB. 15