# APPROACH FLIGHT GUIDANCE OF A REGIONAL AIR TRAFFIC AIRCRAFT USING GPS IN DIFFERENTIAL MODE

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## 1. Introduction

The relative often existing bad weather, especially bad visibility conditions in Europe, influences the regularity of the air traffic.This concerns passenger transport aircraft less than regional air traffic. That is, that part of the air traffic, the feeder service, the business jets as well as twin-engine aircraft of the General Aviation (G.A.) are belonging to. These aircraft are usually conecting regional airfields or regional airfields with international airports.

The present situation at the international airports, however, is that the number of controlled flights is continuously increasing worldwide from year to year. As a result of this development, the number of slots for the G.A. at the airports is continuously reducing. Consequently there will be a dislocation of this part of the air traffic to smaller airfields in the surrounding area. However, most of the regional airfields and most of the airports of the Third World Countries are not equipped with Instrument Landing or Micro Wave Landing Systems. The costs for acquisition, maintenance and operation exceed their respective financial budgets.

A landing in bad weather conditions at the regional airfields is therefore in most cases neither possible nor permissible because of the insufficient equipment on the one hand and because of non existing accuracy requirements on the other hand. Only aircraft for passenger transportation with a mass greater than 5.7t are allowed to proceed on an approach in weather conditions less than CAT I if special conditions are met.

From the technical point of view, it seems to be possible to use the satellite based, worldwide available position finding system (Global Positioning System) as a landing aid without using extensive and expensive ground equipment. That is the reason for a discussion about whether

- the Microwave Landing System (MLS) will be out of date before it is generally used
- the Global Positioning System (GPS) can be used instead of MLS especially for aircraft of the regional flight traffic.

For a realization of an approach flight guidance system using GPS, the following question must be resolved:

is the precision of the determined position, as well as the effect of errors in the flight guidance system tollerable?

## 2. Accuracy Requirements

The tolerated accuracy limits are defined by the International Civil Aviation Organisation (ICAO) for today used Instrument Landing Systems (ILS), and are differentiated from the visibility conditions. They are differentiated in the following operation stages (CAT) (Figure 1):

Non Precision Approach (NPA); CAT I; CAT II
CAT III a,b,c

In order that a passenger service aircraft with a mass greater than 5.7t may carry out a landing with one of these operation stages, the prerequisites must be complied by the ground installations, the aircraft equipment and the air crews. Since a license for an aircraft in the regional air traffic for landing in CAT II requires a considerable improvement of punctuality and reliability, only the following standards of a landing in CAT II (decision altitude 30m) are figured.

According to this the ground installation of the Instrument Landing System must reach the following precision at the runway theshold. (ILS reference point) (Figure 2) /2/.

- the horizontal alignement of the centerline at exactly +/- 4.5m (effective for a new system)
- deviation due to irregularities of the guide beam characteristic must be, with 95% probability, less than 3.45m (2 Sigma= 3.52m).

This results in the following maximum allowable deviations from the centerline:

- horizontal: +/- 5.67m
- vertical: +/- 0.38m

(Prerequisite: distance antenna - threshold: 300m)

Iregularities in the glide path must remain, with 95% probability, less than:

- vertical: +/- 0.5m (2 Sigma= 0.51m)

To these errors add the errors of the airplane receiver. The requirements for the guide beam characteristic are made in a way that the deviation of the entire system, consisting of the ground installation, airplane receiver and aircraft, should be, as a consequence from irregularities, less than:

- horizontal: +/- 5.0m
- vertical: +/- 1.2m

How extreme the requirements for landing systems are, is shown by measurements, which the DFVLR Braunschweig have performed in Frankfurt. As shown in figure 3, the standard deviation of the vertical deviation of the vertical deviation from the glide path is determined from a number of actually carried out approaches. One recognizes, that the actual staggering from the nominal path increases drastically comming up to the middlemarker, and arrives at the value of 8m. This makes the glaring contrast distinct between the value the ICAO has required, and that which actually has been flown.

There is actually no need to ask for an extreme position accuracy, if it cannot be realized with an aircraft flying in turbulence. Therefore, one has to decide:

- which accuracy is necessary for an approach guidance system and
- which accuracy can be realized in real bad weather conditions (wind, turbulence) from a General Aviation Aircraft compared with a large Tranport Aircraft.

These questions are til now not answered. If, however, the approach guidance system should be applied in a commercial airplane with a mass greater than 5.7t for landing approaches in CAT II conditions - without using an ILS - it must accomplish the position finding precision of an ILS. Beyond that it should be cheap, reliable, safe and compatible in relation to the ILS.

A Position Finding System which is able to accomplish these demands is the Global Positioning System (GPS) /4,5/. This system, however, will accomplish these demands just with the use of the differential technique and with extra support.

## 3. Error Characterstic of the Global Positioning System by Aircraft Application

With the use of GPS in aircraft for precision landing approach guidance, the following errors will recognizably disturb:

a) the measured GPS - position has an offset against the real position (figure 4).

b) the offset changes with time even with no aircraft movement because the satellite constellation changes (GDOP, selective availability) (figure 4).

c) the position reacts nearly with a step function if one satellite is setting behind the horizon and a new one is rising (figure 4).

d) the GPS - position measurement is noisy; the amplitude of the noise is receiver dependent; an oscilation is heterodyned (figure 4).

e) according to the receiver type there are dynamic errors during acceleration phases of the aircraft (figure 5, 6).

f) shadow effects will increase position errors, or breakdowns in the GPS - position (figure 7).

How strong the GPS position reacts on acceleration is shown in figure 5. Here are applied the GPS test data during the acceleration phase by take-off of the twin-engine research airplane (DO 128) of the Institute for Flight Guidance and Control of the Technical University of Braunschweig. Here with increasing acceleration, a lateral staggering of the GPS position from up to 7m is established, which is about half of the half-runway width of a regional airport. A further error that likewise appears in dynamic stages of flight is distinctly recognizable by a comparison of the ground speed between GPS and INS (figure 6). Clearly a lag error is registered up to 12 m/s, during the take-off acceleration up to a speed of 43 m/s.

The aforementioned error behaviour differs with the GPS receiver type used. Especially the reactions on acceleration depend on the soft/hardware solution of a specific receiver. One error, however, which every receiver is faced to, occurs especially during turns due to shadowing effects.

The ground track computed from the GPS during three ciruits over the airport is plotted in figure 7. During one circuit a 360 degree circle with a bank angle of up to 60 degree had been flown. In this manoeuver the receiver lossed lock-on on all satellites. Shadow effects during this extreme manoeuver (also during standard rate turns) result that GPS was not able to give any reliable position measurement even for the next 260s after finishing the manoeuver. Just before changing the course to the direction of the centerline the receiver had locked on again. When locking on again the first measurements result to positions which are obviously several hundred meters off from the real position. In the time without a reliable position information a regional commercial aircraft would have flown a horizontal distance of about 9 km and a vertical one of 450m during a landing approach. In those situations during a landing approach under bad weather conditions, the landing approach must be stopped for security reasons, so a go-around manoeuver must be initiated. The error characteristic shows distinctly that the position sensor GPS in "stand alone" operation would be without any use for high precision landing approach guidance up to weather condition CAT II, if the precision of stationary position measurements especially in differential mode wouldn´t be so extremely high. In the differential mode, the offset, the time dependency of the offset and even changing of one satellite used for the calculated position solution can be extensively eliminated by using the differential GPS.

## 4. Differential Global Positioning System

All differential procedures are basically operating with the same principal. The position of a fixed non moving GPS-antenna on the ground is exactly known (Figure 8). While receiving the satellite signals, the position of the satellites in space are known. With these positions the range from the ground to each satellite can be calculated. While comparing the calculated range with the measured range, the actual system error can be estimated. The real measured parameter is the transmission time of a coded signal or the phase of the carrier signal. The fundamental observation equations for the calculation of the position are:

- in case of pseudorange code measurement

$$\Delta R_i = R_i + \delta r_i + c * (\delta T_{si} - \delta T_r) + \delta R_{iTrans} + \chi_i$$

- in case of carrier phase measurement

$$\lambda \Phi_i = R_i + \delta r_i + c * (\delta T_{si} - \delta T_r) + \delta R_{iTrans} + \\ + \lambda \alpha_i + \lambda \chi_{\Phi i}$$

whereby :

$R_i = \sqrt{(x_{si} - x_r)^2 + (y_{si} - y_r)^2 + (z_{si} - z_r)^2}$

$\Delta R_i$ = pseudo range from receiver to satellite i
$\delta r_i$ = range error due to unprecise known satellite position i
$c$ = speed of light
$\delta T_{si}$ = clock error of satellite i
$\delta T_r$ = clock error of receiver
$\delta R_{iTrans}$ = range error due to transition errors from satellite i
$\chi_i$ = pseudo range observation error ( satellite i )
$\lambda$ = wavelength of the carrier signal
$\Phi_i$ = phase difference between received signal from satellite i and reference signal of the receiver
$\alpha_i$ = initial phase ambiguity to satellite i
$\chi_{\Phi i}$ = phase observation error ( satellite i )

Basically there are four unknowns, the receiver position x, y, z and the clock error of the receiver. For a first approximation the parameters like satellite clock error, position of the satellite and transmission errors are known because the satellite message contains correction values for these parameters. Therefore, four independent measurements are necessary to calculate the position and to synchronize the satellite and the receiver clock. As, however, the correction parameters may differ from the true values, a position error still remains. Tests with industrially produced GPS-receivers have shown that with a favourable satellite constellation, the position failed with 15m against known points in a local coordinate system when only the code signals are used to calculate the pseudo range to a satellite.

With the known position of the non-moving ground receiver, the different errors can be estimated. Assuming that the errors on the transmission way from the satellite to the ground-receiver are approximately the same as to the aircraft receiver, the estimated errors can be transmitted from the ground to the aircraft and can be corrected on-board. By this procedure the position error can be reduced to the order of a few meters, depending on the receiver type. If, however, the phase observation is used the position error can be reduced to the order cm or dcm, because of the higher resolution of the phase of the carrier signal. The problem in using the phase observation, however, is the initial phase ambiguity. The phase ambiguity can be estimated by complementary filtering with the pseudo range from the code signal. By doing this a pseudo range is generated consisting of the measured pseudo range in the low frequency range and the phase observation in the high frequency.

By using these correction measures, the dynamic error characteristics, however, are not improved. Only through the use of different supporting measures, and how they would be conveyed into an integrated navigation system, can these bad error characteristics due to dynamic and satellite shadowing be positively influenced.

## 5. Sensor Concept of the Integrated Flight Guidance System

In the Integrated Flight Guidance System for landing approach guidance, the unacceptable error characteristics are clearly diminished. This system is in the base concept composed of two parts; a position finding system and a guidance generator (figure 9). The position finding system computes the aircraft position using a differential GPS position as well as the currently used on-board sensor information. But because the pilot is not able to fly just by a position information, it is necessary to bring the position to a signal the pilot is used to. Also, to show some additional specified commands how to bring the aircraft on an ideal path to the target place. This includes a computation of the specified flight path as well as a glide path computation during the landing approach. To improve the dynamic characteristics of the entire system, and to get enough information about the flight path during a breakdown of satellite information, the Integrated Flight Guidance System is coupled with inertial sensors (acceleration and gyroscope sensors), as well as sensors for barometric and radar height. In this coupling, different gyroscope sensors are working just short of high precision, but over a longer time period they show recognizable drifts, which would lead to intolerable errors in the navigation computation. On the other hand, the GPS has a complementary error characteristic; it has a high long-time precision but is not precise in the short term (dynamic errors, etc.) By use of the Kalman filter technique both signals can be optimally combined. With this Kalman filter technique one is able to estimate the system and sensor errors online; and as it were, to make a permanent calibration of the sensors during the flight. With that, even with a breakdown of the GPS signal, the filter algorithmns give for a certain time highly precise information about the groundspeed vector, the flight path and position angle. A main prerequisite for that is a nearly accurate mathematical model of the error characteristics of the inertial system.

## 6. General Construction of the used Kalman Filter

Figure 10 shows a general construction by using function blocks. The inertial sensors give, aircraft fixed, the measured acceleration as well as the Euler angle (course angle, the pitch angle and the roll angle) of the aircraft, in an aircraft fixed coordinate system. The output of the GPS receiver after differential support with the ground receiver is equal to the position of the aircraft in the earth-fixed coordinate system (WGS 84), as well as, in a tropocentric navigation coordinate system after a transformation. Inside the function block of the navigation equations, one transforms the accelerations by means of the Euler angles of the aircraft in the navigation coordinate system, integrates the acceleration and produces the speed vector over ground. A further integration step gives the covered distance relative to the take-off position.

The difference between GPS and NAV-position results in an error signal which includes only position errors. Out of their dynamic characteristics the sensor- and system errors can be determined. That can just lead to realistic results, when the mathematical error characteristics,with differential equations described, correspond almost exactly with the real error characteristics. To describe the complicated sensor characteristics, (which are dependent on the aircraft movements) more easily - The computation algorithmns should not be too great in order that a computation can be achieved in the limited time frame of the real time process - two error models as well as two Kalman filters have been developed. These two filters will be alternated, depending on the actual dynamic of the aircraft, for example at the beginning of a flight curve. Therefore, it is possible, even with small error models, to estimate extra errors of sensor measures, during a flight curve in relation to the straight flight. As a result, the dynamic of the error characteristics can be described better. Now the navigation equations can be corrected, because the Kalman filters have estimated the errors.

Thus, the further transformation follows respectively. Integration is corrected with the calibration of the sensor signals, which is a decisive prerequisite, for if there were a breakdown of the GPS signals, the system errors would be delimited. Through the correction of the sensor and system errors one has submitted here a closed loop Kalman filter, which is supplementary constructed adaptive for the computations of the performed flight tests. From a mathematical derivation of an adaptive, closed loop Kalman filter, will be specified here under reference /6/ of the literature.

## 7. Flight-test Results

Figure 11 shows the ground track of the same flight as that shown in figure 7. The GPS-position and the position output of the position-finding part of the "Integrated Navigation System for Aircraft" are shown here. Based on the sensor errors which are determined by the system, the position-finding part is able to determine the flight curves at point A faultlessly.

The position output during the remaining phase - the landing approach and landing can be reliably determined by the locations part of the "Integrated Navigation System for Aircraft". Also the physically not possible swinging of the GPS position during the take-off acceleration can be eliminated using the Integrated Navigation System (Fig. 5). Even by a breakdown of the GPS signals, the filter algorithmns still give for a limited time, the position, speed and Euler angle with a high precision. A decisive prerequisite for that is a realistic mathematical model of the dynamic error characteristics of the inertial systems.

The result of the command value generator is plotted in figure 12 and 13 relative to the touch down point. The vertical and horizontal deviation from a nominal glide path are given to the crosspointer indicator. So an indication is generated the pilots are used to from ILS approaches. Of course the vertical deviation growth up to 90 degree, when the pilot leaves the nominal glide path and is passing the nominal touch down point in a minimum height, as it happend during this flight test.

Which overall position accuracy can be achieved using the "Integrated Navigation System for Aircraft"? In figure 14 the ground track of two take-offs, two landings and one back track are plotted in meters relative to the take-off position. During these aircraft movements the pilot tried to fly respectively so as to roll as exact as possible on the centerline. It can be recognized from the plots that the ground tracks deviate from each other less than 1.3 m. This deviation is so small, that one cannot determine - without using a highly precise flight path tracking system - if the 1.3 m is the position accuracy of the Integrated Navigation System or if the aircraft really deviated 1m from the centerline which is possible during landings.

## 8. Summary

The flight tests, which have been made with the "Integrated Navigation System for Aircraft" which has been developed at the Institute for Flight Guidance and Control of the Technical University of Braunschweig until now, have shown good results by combining two sensor systems with different, time dependable, signal qualities: the inertial sensors, with their good short-term characteristics; and the GPS with good long-term characteristics. With the Kalman filter technique it is made possible, even in high dynamic flight phases, to determine a position of high precision and reliability. The horizontal position determined until now is better, than the precision of each system standing alone. A landing approach guidance under bad weather flight conditions up to CAT II seems to be possible with the "Integrated Navigation System for Aircraft".

## 9. Literature

/1/ Avionics Navigation Systems
Kayton, M.; Fried, W.; John Wiley & Sons 1969

/2/ Aeronautical Telecommunications
International Civil Aviation Organisation (ICAO) ANNEX 10

/3/ Richtlinien für den Allwetterflugbetrieb nach Betriebsstufe II
Nachrichten für Luftfahrer NfL I-350/72 Bundesanstalt für Flugsicherung

/4/ Principle of Operation of NAVSTAR and System-characteristics
Milliken, R.J; Zoller, C.J. AGARDograph AG 245

/5/ Differential Operation of NAVSTAR GPS
Kalafus, R.M. Journal of the Institute of Navigation Vol. 30, 1983

/6/ Techniques of the development of Error Models for Aided Strapdown Navigation Systems
Lechner, W. AGARDograph AG 256

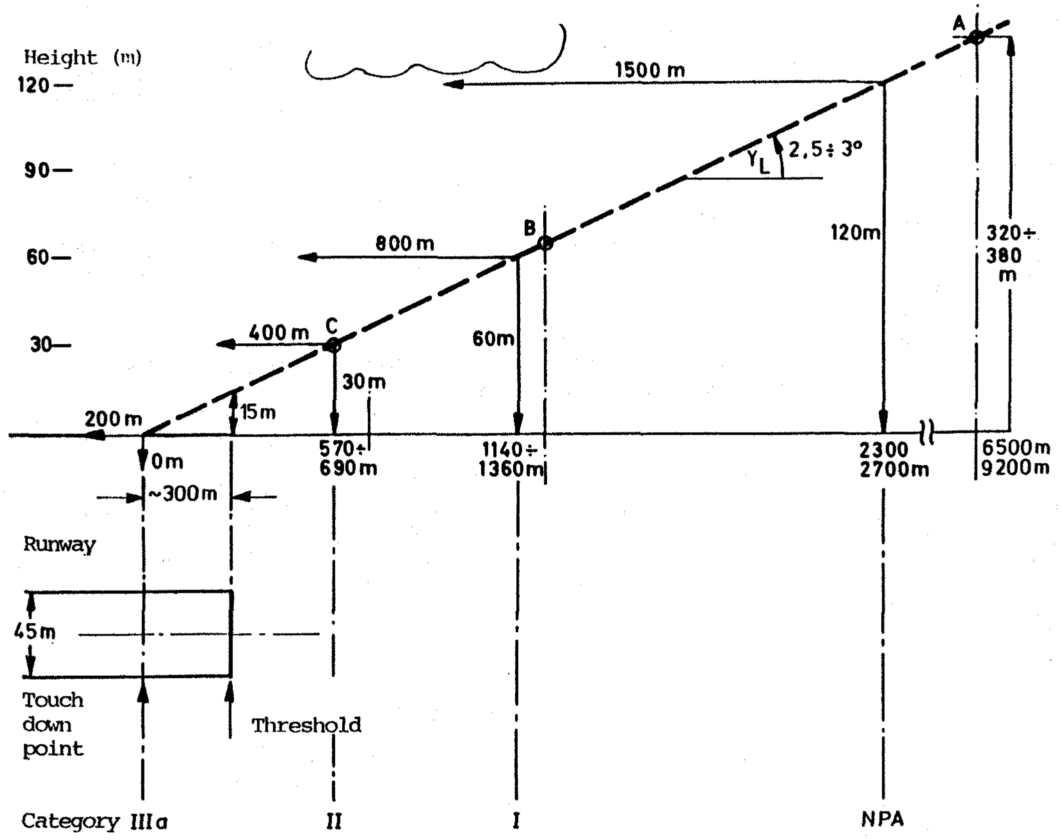

Figure 1: Categories and visual conditions in IFR

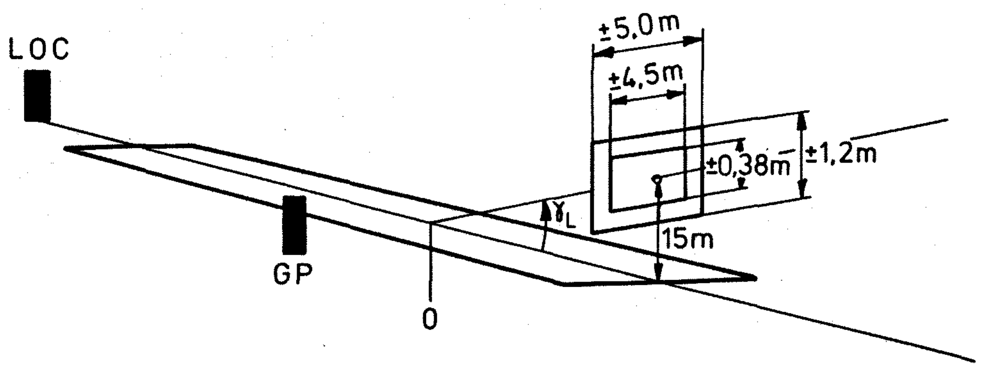

Figure 2: Tolerable errors of the ILS (CAT II)

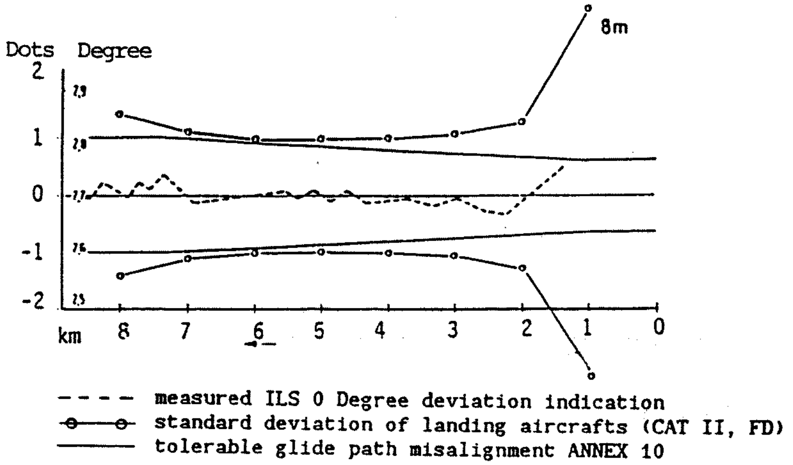

Figure 3: Measured deviation of transport aircrafts from the glide path (ref. DFVLR)

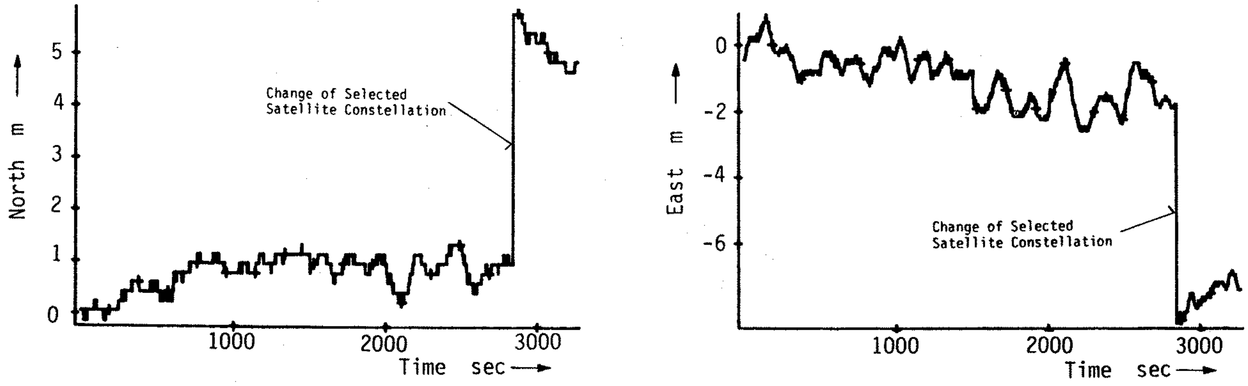

Figure 4: Deviation of the North- and East- Position (non-moving Antenna, C/A Code, 5 Channel Receiver)

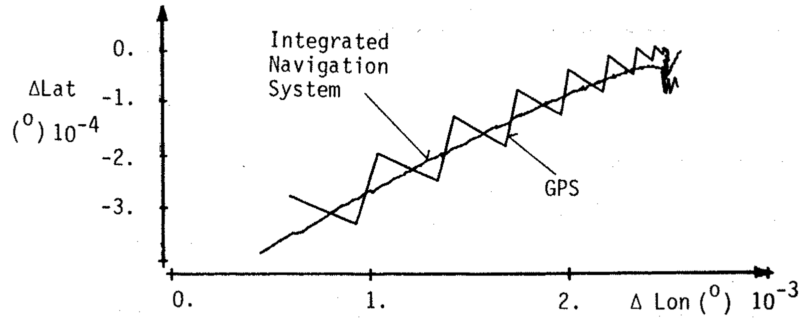

Figure 5: Ground track while accelerating for take-off speed C/A Code Multiplex receiver / Integrated Navigation System

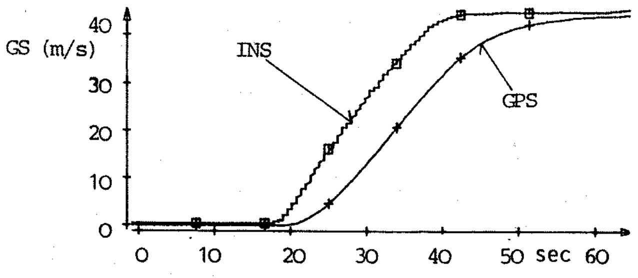

Figure 6: Comparison of ground speed of INS and GPS

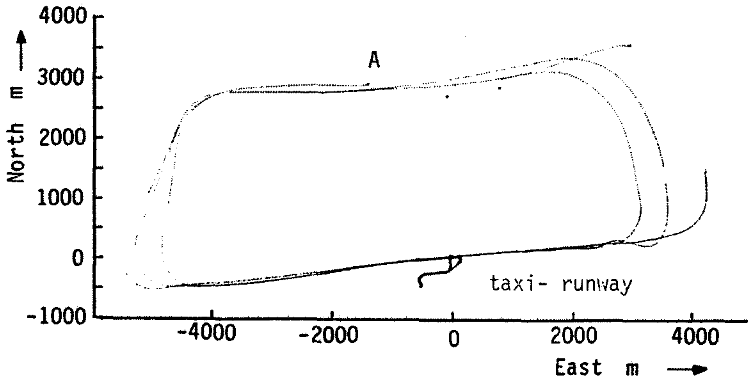

Figure 7: GPS ground track / flight test

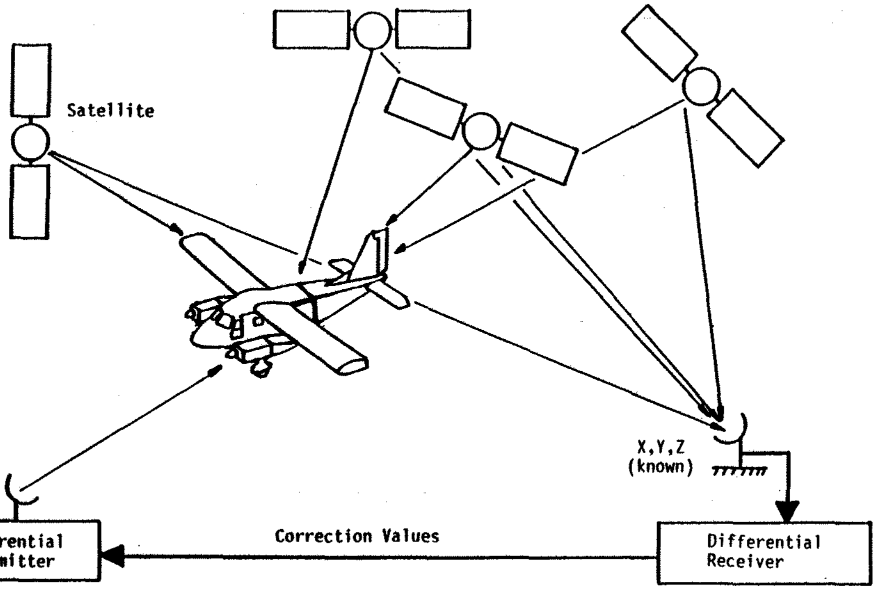

Figure 8: Differential GPS

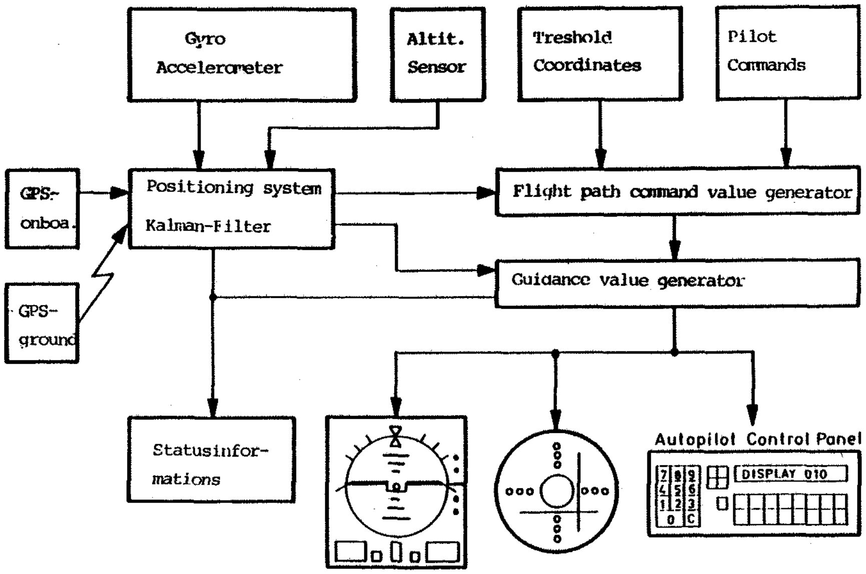

Figure 9: Integrated Navigation System for Aircrafts

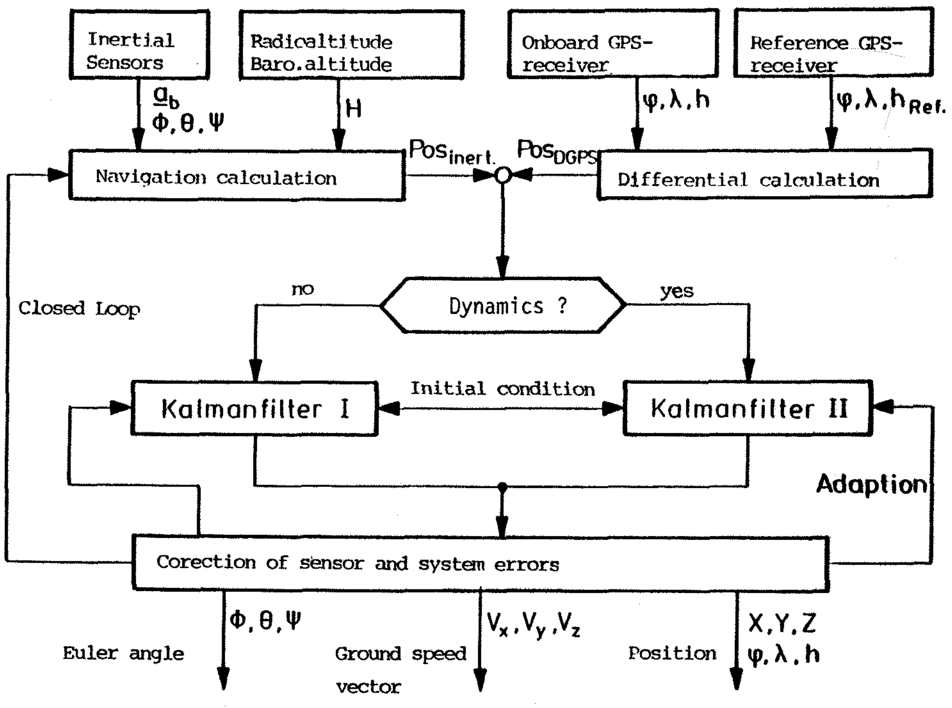

Figure 10: Position Finding Subsystem

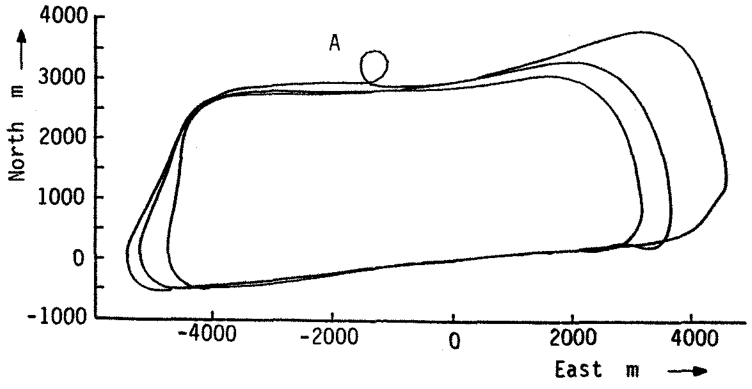

Figure 11: Ground Track comparison of GPS and Integrated Navigation System

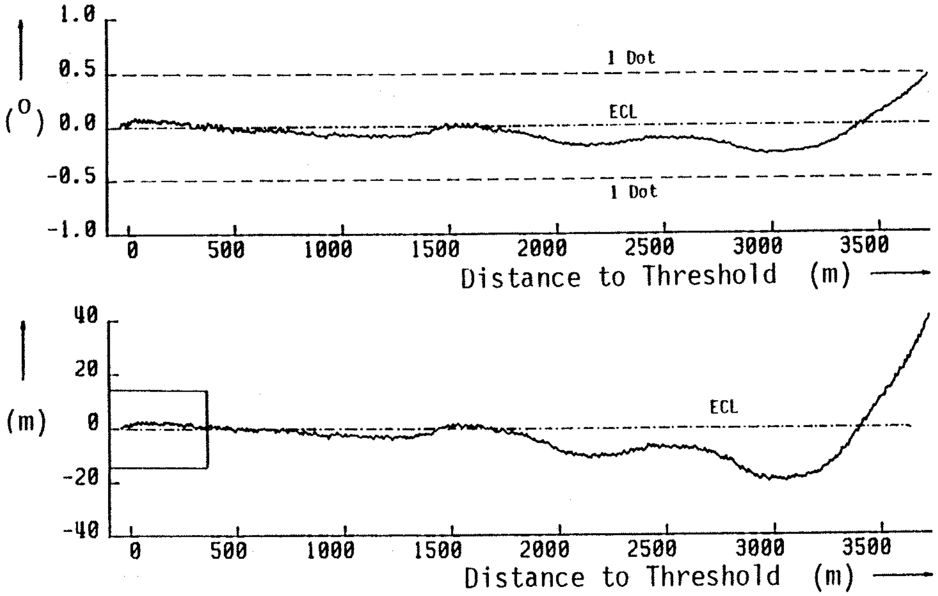

Figure 12: Crosspointer indication: Horizontal deviation calculated by Command Value Generator (Flight Test)

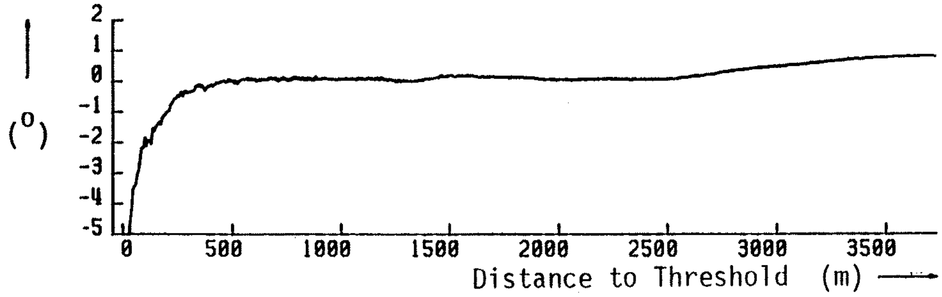

Figure 13: Crosspointer indication: Vertical deviation calculated by Command Value Generator (Flight Test)

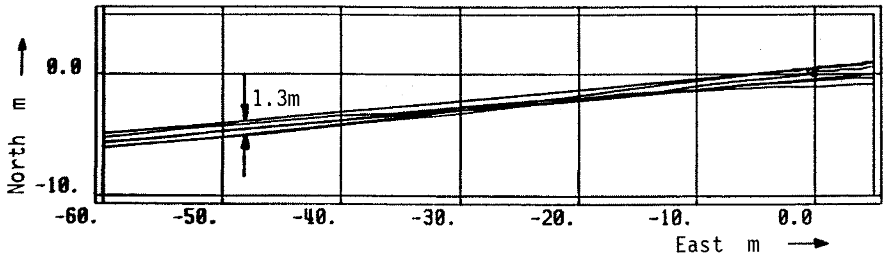

Figure 14: **Ground Track calculated by the Integrated Navigation System for Aircrafts while taxiing, starting and landing (C/A Code Differential)** (Flight Test)