Photogrammetrische Woche 1991
Schriftenreihe, Heft 15, 1991
Institut für Photogrammetrie

SYSTEMINTEGRATION OF INERTIAL NAVIGATION, SATELLITE NAVIGATION AND LASER FOR AIRBORNE POSITONING

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This paper presents a system concept for a high precise position, flight path and attitude information of a moving platform e.g. an aircraft.
The position information is computed by integrating the satellite based Differential - Global Positioning System (GPS) and Inertial Navigation System (INS) into a hybrid system. Using GPS receivers for precision flight guidance, accuracy problems arise due to the influence of dynamic manouvers on GPS receivers. The error behaviour in stationary as well as in dynamic applications is explained. From the error behaviour a system concept of a hybrid Integrated Flight Guidance System is derived. Different concepts of system integration are explained.

By integrating a laser for measuring the range aircraft to ground high precision terrain data can be computed. In a joint flight test program this system has been verified by the Institute of Photogrammetry, University of Stuttgart, the mapping agencies of Lower Saxony and the Institute of Flight Guidance and Control of the Technical University of Braunschweig.

The system fulfills extreme accuracy requirements and can be used in approach and even automatic landings up to CAT III. By using this system, a space based landing aid is given, which allows landings in bad weather conditions. Therefore a landing at any airfield, not equipped with ILS or MLS will be possible be using a very cost effective system. In July 1989 the worldwide first automatic landing, using the presented system, based on GPS has been performed by the Institute of Guidance and Control of the Technical University of Braunschweig. The suitability of this system concept (closed loop mechanization of a Kalman Filter coupling GPS and inertial measurement units (IMU)), for flight path guidance and the accuracy of position finding will be presented by means of flight tests in a commuter aircraft (DORNIER DO 128) and also by simulator results.

2. *Nomenclature*

x, y, z North, East, Vertical Position in a local level coordinate system
ϕ, λ, h Position in Lattitude, Longitude, Height
V_x, V_y, V_z the inertial velocity
Φ, Θ, Ψ (bank, pitch, azimuth) the attitude angles
a_x, a_y, a_z body fixed accelerations
ϵ_N, ϵ_E, ϵ_D coordinate axes misalignment
IMU inertial measurement unit

3. *Introduction*

Satellite Navigation Systems are available as a new position finding aid. It seems feasible, from a technical point of view, to realize even landings under bad weather conditions by using Satellite Navigation as an "Instrument Landing Aid". In flight tests (July 1989) even the worldwide first automatic approach and automatic touch down has been performed by the Institute of Guidance and Control of the Technical University of Braunschweig using an integrated navigation system based on satellite (GPS) and inertial navigation, which is presented in this paper. In addition to the position information the system evaluates a high precise attitude information, which is used in geodetic applications to transform laser heights.

In precision flight guidance applications of GPS receivers accuracy problems arise from the influence of dynamic aircraft manouvers (accelerated flight, turn flight). Additionally, when flying the aircraft in a turn with a bank angle greater than the elevation of a satellite the accuracy of GPS is reduced or even an outage is produced due to satellite masking. To compute aircraft position in turn flight and to compute a positon with higher accuracy in accelerated flight a robust, autonomous sensor information has to be integrated into a hybrid positioning system.

Combining different systems with complementary error behaviour an overall system error can be produced which is better than the error of each system standing alone. A prerequisite for this is a system architecture and an error modelling of the subsystems representing the physical behaviour of the main sensor and system errors.

In establishing digital terrain data from airborne measurements using a laser profiling system we have to measure or estimate (in sense of estimation theory)

- o the position of the laser onboard of the aircraft
- o the position of the aircraft
- o the range measured by the laser from aircraft to ground.

- As, however, the laser is fixed to the structure of the aircraft
- as the aircraft is not aligned horizontally during flight due to turbulence

the laser measures the range but not the vertical distance. To compute terrain heights as difference of

- o the height of the aircraft relative to a reference ellipsoid and
- o the height of the aircraft relative to the ground

the attitude of the aircraft or more precise the attitude of the laser beam has to be known to transform the laser range into the vertical plane.

The question is, which are the accuracy requirements and can they be fulfilled by an airborne system, which has essantially not to calculate the terrain data in real time.

4. *Accuracy Requirements*

Normally in an experimental system for research tasks the accuracy has always to be as high as possible. We have however to ask: which system accuracy is reasonable with respect to system costs?

The accuracy requirements for a laser profiling system to compute digital terrain data have been specified by F. Ackermann at an international workshop of the Sonderforschungsbereich "High Precision Navigation" in 1988. In the paper "Digital terrain models of forest areas by airborne laser profiling"[8] the following accuracy requirements are specified:

	flat terrain	accidented terrain
position: horizontal [m]	few meters	< 0.5
vertical [m]	< 0.3	< 0.5
attitude: roll, pitch [degree]		< 0.05

Figure 1 : Accuracy requirements for aircraft position and attitude

The attitude accuracy requirement is a result of an error analysis of the transformation algorithm. It is a function of aircraft height and vertical accuracy:

$$h_g + \delta h_g = h_{Laser} \cos\Theta \cos\Phi - h_{Laser} \sin\Theta \cos\Phi \delta\Theta - h_{Laser} \cos\Theta \sin\Phi \delta\Phi + \cos\Theta \cos\Phi \delta h \qquad (1)$$

The attitude accuracy has been defined in table 1 for a height of 500 m.

Although GPS in the presented system is just one of many different sensors it is this sensor, that is responsible for stationary accuracy. Therefore, the error characteristic of a high precision 5 channel GPS C/A code receiver in stationary as well as in dynamic flight tests have been analyzed.

5. *Error characteristics of GPS Receivers in Real − Time Differential Mode*

The typical error behaviour of stand-alone GPS[3] Offset and Drift can be extensively eliminated by using Real - Time Differential GPS - Technique (fig. 2) [3],[4],[5], as it has been developed in the Institute of Flight Guidance and Control. Receiving the satellite signals at the ground station, the position of each satellite is known. As the position of the ground antenna is known, the range from the ground to each satellite can be calculated. By comparing the computed range with the measured range the actual system error can by determined. Transmitting these errors to the aircraft via data link, the errors can be corrected in the onboard position finding computation if the distance to the ground station is small enough. Some measurements indicate that distances less than 200 km can be adequate. In optimal conditions (low range between user and reference ground station, no multipath, same propagation path satellite- reference station as satellite-user) this technique can reduce the position error up to the receiver residuals which are in the order of a meter or a few centimeter depending on the receiver type (fig.3). However using this correction measures, the dynamic error characteristic is not improved. In stationary tests, as well as in flight trials, tested GPS receivers have proved to be excellently accurate in the long term, however, a lack of accuracy in dynamic maneuvers has been detected. Depending on the receiver type dynamic errors occure in flight phases with longitudinal accelerations as well as in phases with lateral accelerations. The reasons for the dynamic errors are:

- the influence of acceleration on the receiver clock (crystal oscillator).
- the influence of received signal dynamic to the code tracking loop (delay lock loop) and the costas loop which determines the measured value of the phase of the carrier signal but which are not necessarily the true values.
- receiver integrated software and filtertechnique using low pass filters to reduce noise (fig. 4).
- time lack due to signal processing.
- flying a turn with a bank angle greater than the elevation of a satellite, a masking of the antenna may be produced for two reasons:
    - the hemispherical antenna is focused in such a direction where the locked satellites are undetectable.
    - parts of the aircraft (e.g. wing or body) move into the line of sight satellite - user antenna.
- In the most successful cases this effect produces an error of only several meters or at the worst case a total loss of GPS position information (fig. 5 point A).

6. *Concept of the Integrated Guidance System*

- For improvement of the dynamic behaviour of the system,
- for accuracy in dynamic flight,
- for integrity,
- for safety reasons in a landing approach,

it is a need to generate position information by using sensors (GPS, INS) with a complementary error behaviour including adequate filtering.
In dynamic maneuvers the aircraft position, (ϕ, λ,h), the inertial velocity V, the rate of attitude angles p,q,r (roll rate, pitch rate, yaw rate) and the body fixed accelerations, can be measured and calculated by using an inertial measurement unit (IMU, gyros and accelerometers). IMU's have a good short term accuracy, however, in the long term they have recognizable drifts. The long term accuracy is dependent to the gyro drift which determines the coordinate axes misalignment ϵ_N, ϵ_E, ϵ_D[6]. With today high quality IMUs, a typical drift of 0.5 m/s can be obtained if gyros have an accuracy of $0.01°/h$. Unfortunately the IMUs of this accuracy class are the most expensive ones normally used for long range navigation in passenger aircraft. Considering the costs of such IMUs which uses ring laser gyros it has been investigated at the T.U. Braunschweig, whether it is possible to achieve a high attitude accuracy by using a low cost attitude heading reference system (AHRS) (100 TDM instead of 300-400TDM) and to estimate the errors of the AHRS using the high precise DGPS positions. Obviously a system concept which utilizes the good long term accuracy of the GPS and the good short term accuracy of an IMU would produce a good overall accuracy.

This concept is realized in the "Integrated Flight Guidance System" (fig. 6). It is in the base concept composed of two parts:

- a position finding system and
- a guidance generator.

The position finding system computes the aircraft's position using Differential GPS, as well as, available sensor information currently being used in aircraft.

To improve the dynamic characteristic of the entire system and to get sufficient information concerning the flight path during a breakdown of satellite information, the integrated flight guidance system is coupled by Kalman filter technique with inertial sensors - gyros and accelerometers. Radio or baro altitude sensors are used additionally to GPS for the vertical guidance in aircraft landing. A laser is used for terrain profiling. As all data are recorded online, the data can be computed offline with a higher resolution and accuracy for terrain heights. In realtime calculations flight path guidance data are computed to guide aircraft in special mission flight tests e.g. laser profiling or airborne photogrammetry. Online navigation is computed by the system using D-GPS. Therefore flights can be performed in any area without any ground based navigation infrastructure which is necessary to use VOR or DME navigation. In addition no flight observer is needed, as the flight instruments in the cockpit are used for precise navigation relative to predefined flight path.

Although the best estimation of position is calculated using this technique, no pilot is able to follow a nominal flight path using only a position information in latitude, longitude and height. It was advisible to display the position information to the pilot in a conventional manner. Therefore, one must calculate a nominal flight path consisting of standard rate turns and linear parts using known coordinates of the target place (waypoints of each flight track of the mission profile).

Flight guidance data are calculated from the information of the actual position, the deviation, and the attitude relative to the nominal flight path. With this procedure the pilot receives information on how to follow the nominal flight path, which may be curved horizontally or vertically and how to rereach it if he deviates from it. For the indication during the flight test an ILS cross deviation indicator or a flight director can be used.

7.GPS/IMU System Integration

Combining GPS and IMU, different depths of integration can be realized. The integration and the Kalman filter mechanization is dependent on

- the tasks of the integration,
- the accuracy limits,
- the robustnes,
- the computer time capacity,
- the IMU sensor concept (platform / strapdown / ring laser gyro),
- the stand alone capacity of each subsystem in the emergency case of system failure.

For these tasks the basic concepts for system integration can be devided into the following topics:

- open loop GPS aided IMU (fig. 7
- closed loop GPS aided IMU (fig. 8)

In an open loop or closed loop GPS aided IMU mechanization, both systems are operating autonomously. Whereas both systems compute their own position estimation, this integration concept is relative robust. If one of both systems or the Kalman filter fails, a position is still attainable. The Kalman filter estimates the elements of the state vector by using realistic error modells, from the dynamic of the measurement signal. The position, velocity, attitude and sensor errors must be modelled in this state vector properly.

The open loop implementation can be used in all applications with small system and sensor errors. Otherwise linear error modells will lose their validity. The advantage of the open loop implementation is, that in case of inacurate measurements only the Kalman filter is influenced, however, not the inertial system calculations itself.

As the sensors of the platform system are seperated from the body of the aircraft by gimballs, they are operating normally with a zero reference situation. In this case the sensor errors are kept on a low level. The attitude angles are measured by the angles of the gimballs. In these applications an open loop mechanization may be advantageous. The Kalman filter can run external to the INS.

In contrary to platform systems, sensors of strapdown systems are not uncoupelled from the aircraft body and are operated in a disturbed dynamically environment as there are vibrations, angular accelerations, angular oscilations which result in an additional negativ influence to the system performance. In addition sensors are not operating at a reference point zero [7]. The sensor and system errors may be larger, so that linear error modells will loose validity. Therefore it is advantageous to feed back the estimated sensor errors to the strapdown calculations to compensate for the sensors errors. Consequently, the errors in the inertial computations will be kept low and linear error models can be used.

Depending on the CPU performance the strapdown computations can be performed with a high update rate. The update rate of GPS receivers varies in the range of 1 Hz to 5 Hz, which results to a distance between each position measurement of up to 70 m depending on the speed of the aircraft (typical 70 m/s). As lasers normally operate with update rates of

50 to 100 samples per second no position data are available at each range measurement. An interpolation algorithm, which could be used in a first approach, cannot regard the aircraft motion between the GPS samples. In the integrated system, however, the inertial sensors are sampled with a minimum rate of 50 Hz. Performing the strapdown navigation calculations with 50 Hz it is possible to calculate position and attitude data of the aircraft with 50 Hz, too. Therefore it is possible to compute position data and terrain height by the system in position steps of 1.5 m.

Computing laser heights from laser range measurements the attitude angles are used for transformation. Due to gyro drift the attitude angles have an error in a Schuler tuned INS proportional

$$\epsilon \sim \frac{1}{\omega_s} D_E \sin \omega_s t \tag{2}$$

The velocity error due to gyro drift is

$$\delta v \sim R D_E (1 - \cos \omega_s t) \tag{3}$$

and the position error

$$\delta x \sim R D_E \left(\frac{t-1}{\omega_s \sin \omega_s t} \right) \tag{4}$$

with D_E = gyro drift in east direction, R = earth radii, ω_S = Schuler frequency ($T_S = 84 min$).

These formulas can be reduced to a rough estimation formula that a gyro drift of 0.01 $°/h$ produces a velocity error of 1 km/h which integrates to a positon error. Therefore the gyro drift can be estimated by computing the position error in a Kalman Filter and can be corrected in the INS navigation calculation.

8. *GPS/IMU Simulation System*

To check the accuracy of this integrated system in flight tests a flight path reference system would be necessary with an accuracy which has to be at least by a factor of four better than Differential GPS. As this reference system is not available, a simulation system (fig. 9) for GPS/IMU system integration has been developed in the Institute of Guidance and Control. This system simulates the following components:

- aircraft (real time, based seat simulator equipped with visual and accoustic system)
- satellite motion
- satellite position error
- signal propagation error
- GPS-receiver dynamic
- satellite masking
- receiver position and velocity calculation algorithms
- strap down INS including sensor errors as there are
  - misalignement
  - bias
  - scale factor
  - scale factor asymmetry
  - gyro drifts

After simulating the system aircraft, the sensor systems GPS and IMU which measures the state elements of the system "aircraft", the strap down inertial navigation calculation can be performed. The results of the strap down calculation are compared with the simulated GPS measurements. The computed error signals are given to a Kalman Filter for system integration. By modelling in the Kalman Filter the physical laws of the aircraft motion, the strap down IMU and the GPS, the errors of each system can be estimated. These errors are looped back to the measurement equations of each subsystem to reduce their errors. By this technique an online calibration of the sensor systems is performed. Therefore it is possible to calculate

- the position
- the inertial velocity
- the acceleration
- the attitude angles
- the angular rates

with an better performance than each system standing alone is able to do it.

9. *Simulation and Flight – Test Results*

Fig. 10 presents results of the simulation system. In the simulator the same flight procedure has been flown as in the flight test in fig. 5. The position errors of the subsystem GPS and INS (1 NM/h) as well as the errors of the integrated system are plotted versus time. At t=140 sec a circle with a bank angle of 60 degree has been flown. While flying 60 degree bank angle a masking of 3 satellites has been produced for 100 sec. In this time GPS gives no position information. While the INS has produced a position error of 48 m, beginning at the alignment to the end of the masking, the error of the integrated system is 71% (14 m) lower than the error of the INS. At t=260 sec the aircraft flew a turn returning to the extended centerline (ECL). In this phase of the flight, the satellites have been in a bad constellation (Geometric Delution of Precision GDOP > 10). One satellite has been masked. Here the error of the GPS grows up to 50 meters. The integrated system, however, has produced an error of up to 7m which is 90% lower than the error of the Inertial Navigation System.

These simulations show, that by combining IMU and GPS in the discussed integrated system an overall accuracy can be achieved that is up to 90% better than the accuracy of an INS standing alone, even in phases where no GPS is available. In phases where GPS is available the accuracy of alteration of position is in the dcm - order, using differential GPS phase measurements, however with an performance during high dynamic flight phases which is much better than GPS standing alone.

Fig. 11 shows the ground track of the same flight as that displayed in fig. 5. The GPS-position and the position output of the position-finding part of the "Integrated Flight Guidance System" are presented here. Based on the sensor errors, which are determined by the system, the position-finding part is able to determine the flight path and the attitude angles with a high precision. Even with a breakdown of the GPS signals, the filter algorithmns still give the position, speed and attitude angle with a high precision for a limited time. A decisive prerequisite for that is a realistic mathematical model of the dynamic error characterstics of the inertial systems.

The error estimation of the strapdown INS system and sensor errors have been verified by artificial masking of all satellites in an offline computation. If the system is able to improve the strapdown INS navigation the position errors of the INS should be reduced during the masking. In the flight tests shown in fig. 12 it can be recognized that, during 60 s (T=3940s) of masking the position error grows up to 7m due to the residuals. This results to a velocity error in the order of 0.1 m/s. The sensor errors could be reduced in the integrated system by a factor of 3, resulting also to attitude angles errors which are reduced by a factor of 3.

In figure 13 the estimated attitude data are shown. It can be recognized, that in case of Laser-Strapdown-INS following errors in the attitude data have been estimated:

- $\epsilon_n = 0.05°$
- $\epsilon_e = 0.16°$
- $\epsilon_d = 0.33°$

The result of the commanded flight path generator is plotted in fig. 14 relative to the touch down point in a manual approach. The vertical and horizontal deviation from a nominal glide path are given to the crosspointer indicator, and an indication is generated, which pilots are already accustomed to from ILS approaches. It can be recognized from these plots that the pilot is able to fly the aircraft with high precision in a stable condition to the touchdown point.

Storing waypoint data of the mission profile instead of runway coordinates for the command flight path generator profiles can be flown manually as shown in figure 15. The deviation of the actually flown track relative to the commanded track is in the order of less than 7m cross track error.

10. *Summary*

The flight tests, which have been made with the "Integrated Flight Guidance System", developed at the Institute for Guidance and Control of the Technical University of Braunschweig have demonstrated good results by combining two sensor systems with different, complementary, time dependent, signal qualities: the inertial sensors, with their excellent short-term characteristics; and the GPS with excellent long-term characteristics. With the Kalman filter technique it is possible, even in high dynamic flight phases, to determine a position of high precision and reliability. The position determined in flight tests is better, than the precision of each system standing alone.

It is possible to use the presented system in all high precision navigation applications.

In offline applications of the position finding part of the "Integrated Flight Guidance System" accuracies in the order of 10cm can be achieved, by using special differential techniques (double differential).

The first application of differential GPS/INS guidance will probably be the use as a high precision position reference system and may be in regional air traffic the application as a landing guidance system for such airports which have no ILS or MLS systems installed.

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Die Arbeiten, die die Grundlage für diese Veröffentlichung darstellen, hat der Author während seiner Tätigkeit als wissenschaftl. Mitarbeiter am Institut für Flugführung der Technischen Universität Braunschweig durchgeführt.

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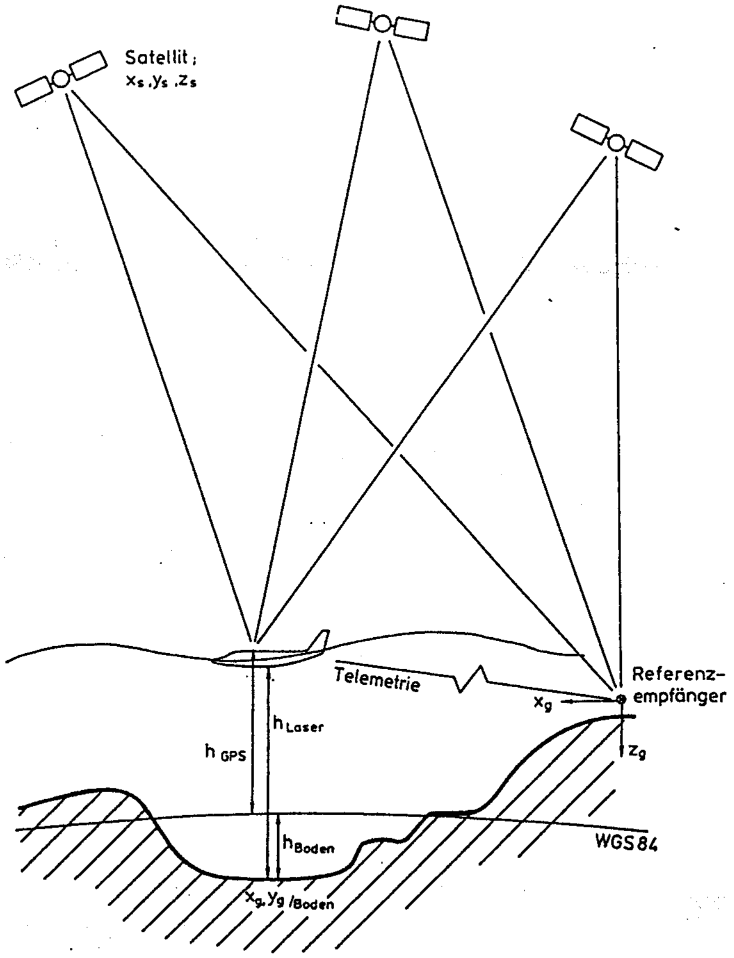

Fig. 2: Differential GPS System Concept

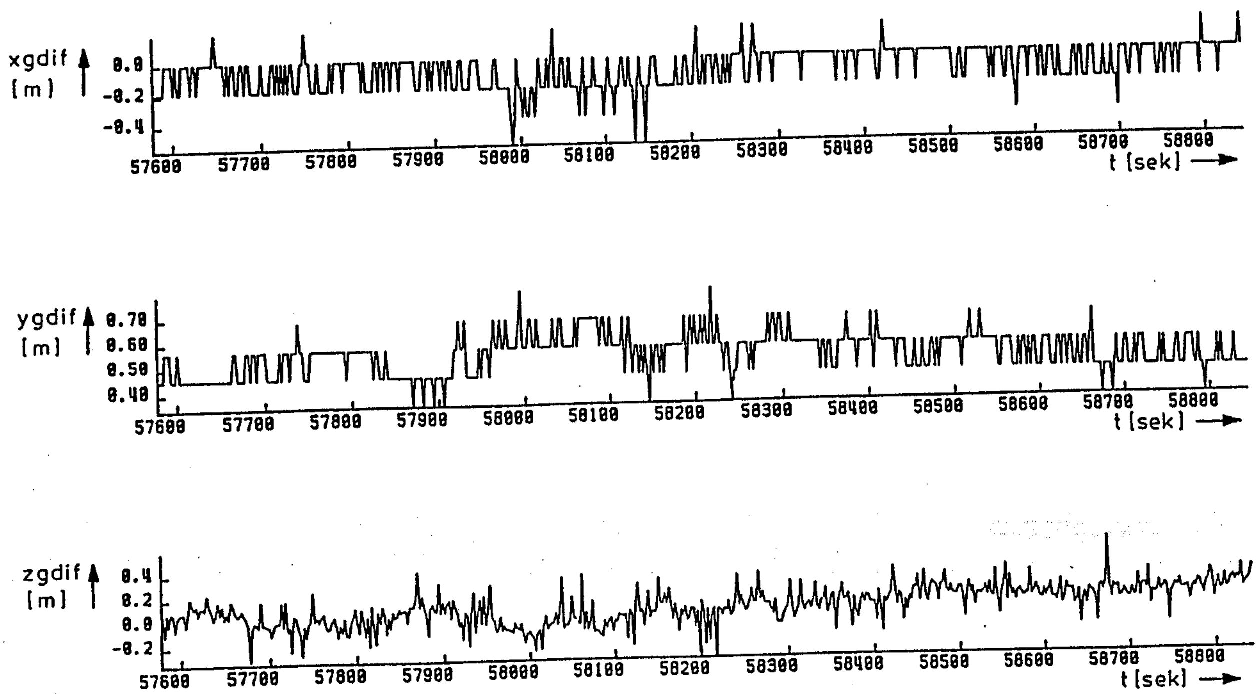

Fig. 3: Real Time Differential GPS Measurement (v=0, 5 channel C/A-Code)

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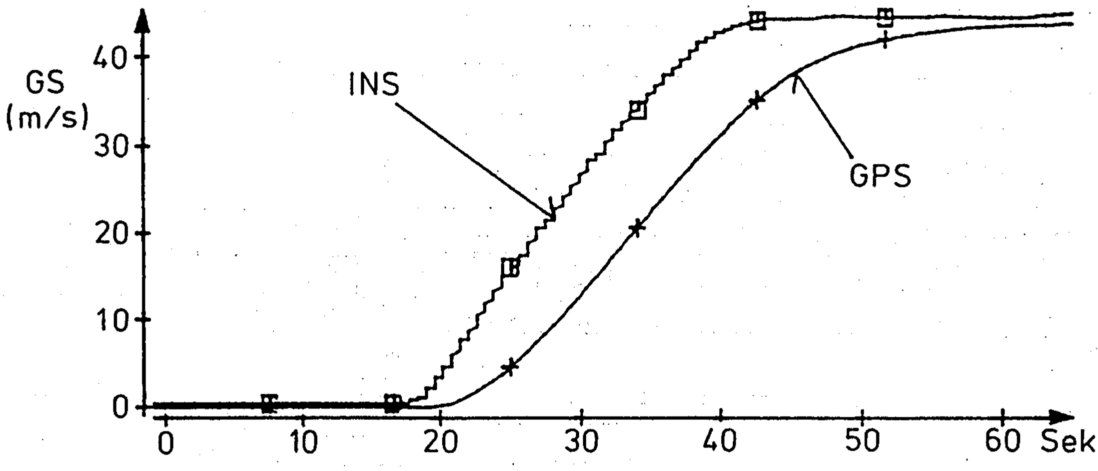

Fig. 4: Groundspeed comparison measured by GPS and INS (take off acceleration)

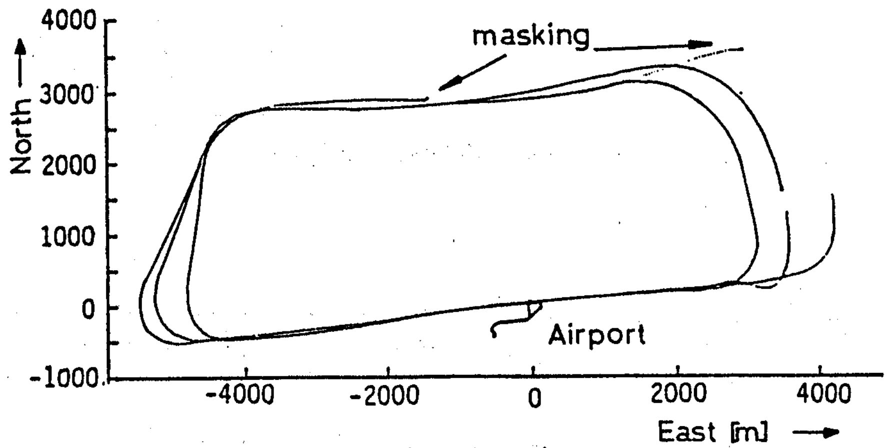

Fig. 5: Flight test of GPS 5 channel C/A-code receiver

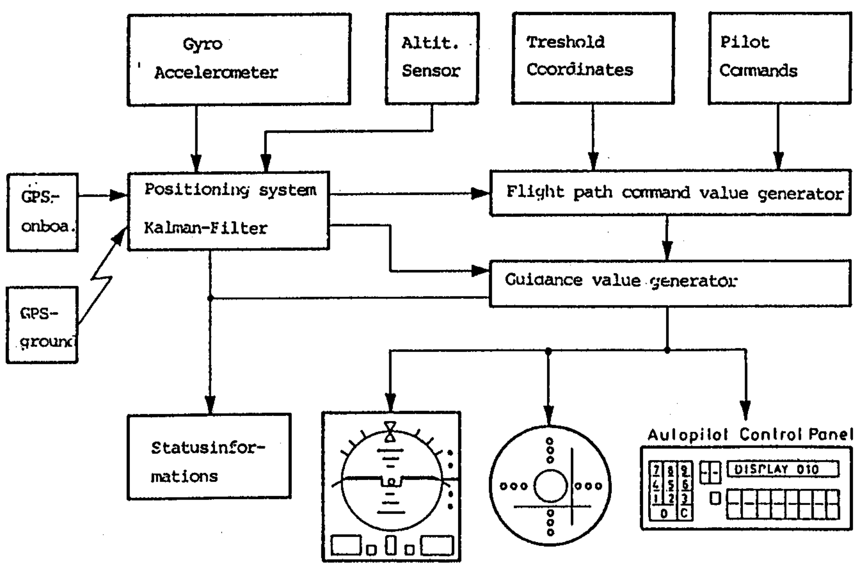

Fig. 6: Integrated Flight Guidance Systems

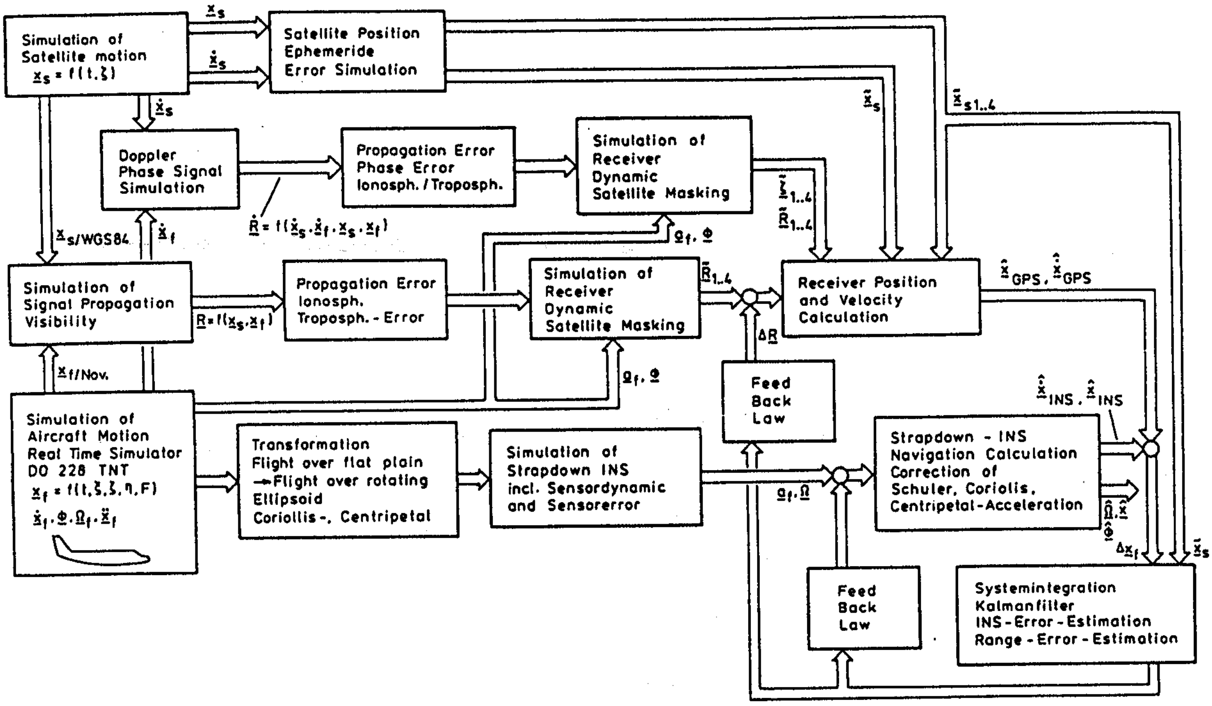

Fig. 7: System to simulate GPS/ Strapdown-INS Integrated System

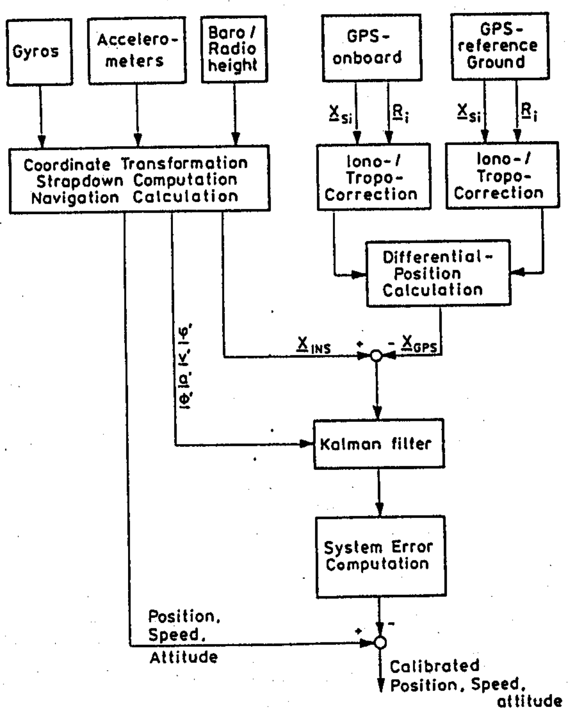

Fig. 8: Open Loop GPS aided INS

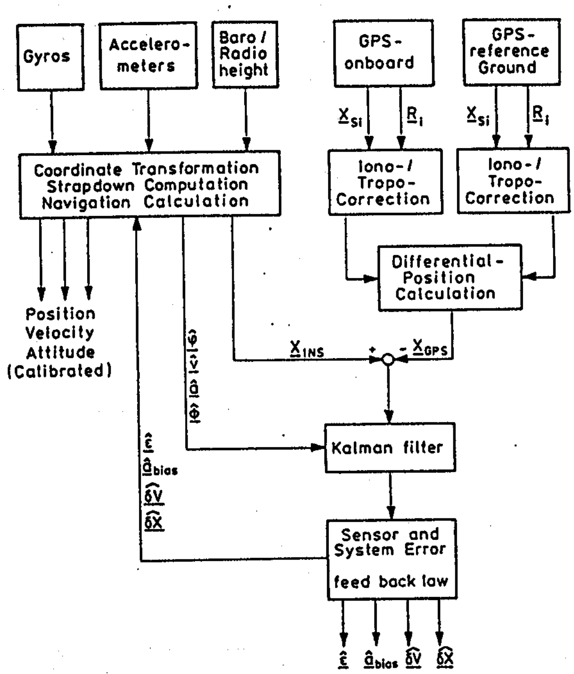

Fig. 9: Closed Loop GPS aided INS

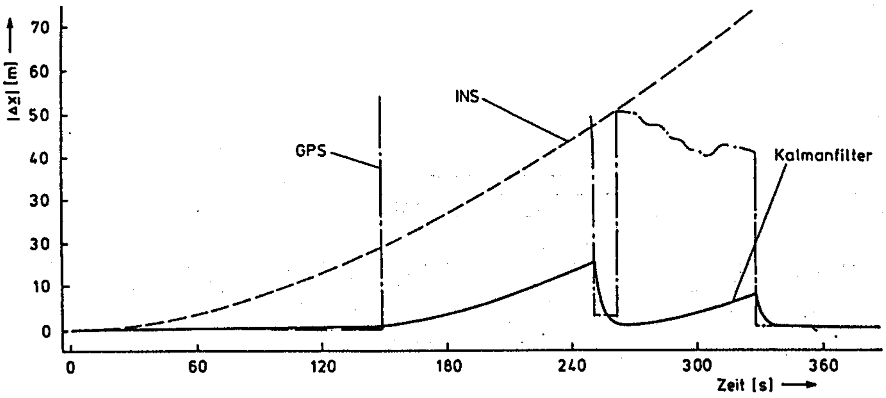

Fig. 10: Position results of Integrated Flight Guidance System in simulation run

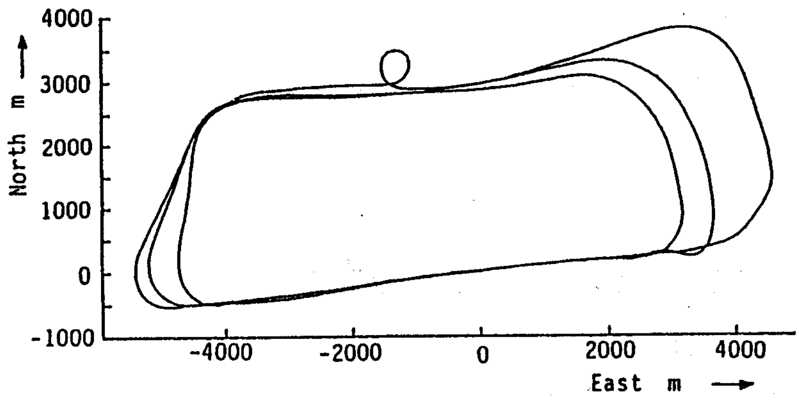

Fig. 11: Flight test position results of Integrated Flight Guidance System

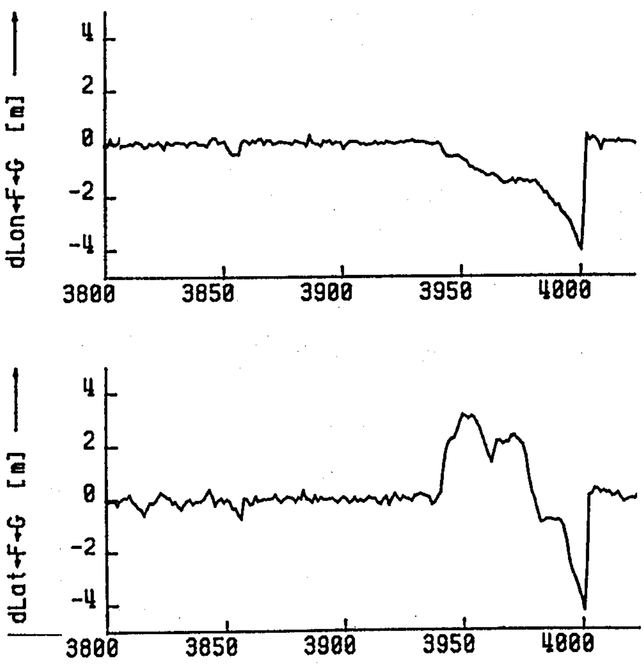

Fig. 12: Position error in flight test while masking 5 Satellites

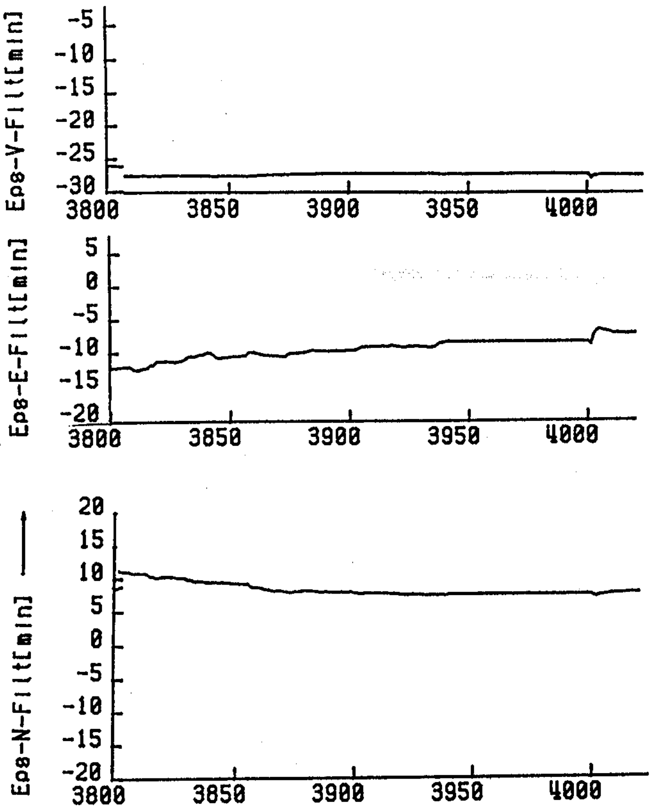

Fig. 13: Estimated attitude errors

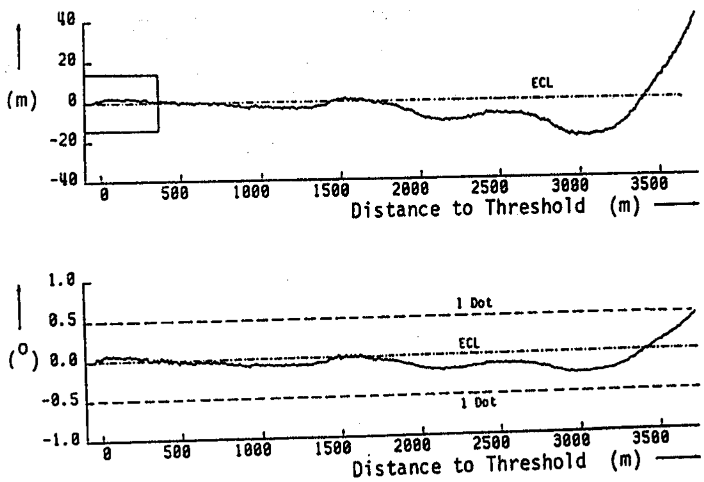

Fig. 14: Manual flown approach and landing using the Integrated Flight Guidance System

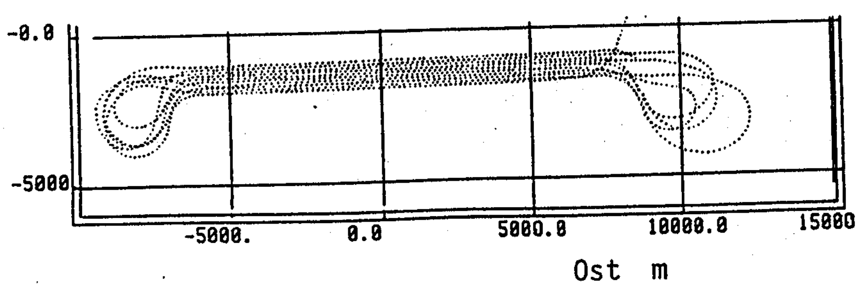

Fig. 15: Airborne photogrammetry flight test results