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Olivera PETROVSKA
St. Kliment Ohridski University of Bitola, Faculty of Technical Sciences,
I.L. Ribar, бб, 7000 Bitola, Republic of Macedonia
Ustijana RECHKOSKA SHIKOSKA
University for Information Science and Technology "St. Paul the Apostle"
6000 Ohrid, Republic of Macedonia
**Corresponding author*. E-mail:petrovskaoli@gmail.com

AIRCRAFT PRECISION LANDING USING INTEGRATED GPS/INS SYSTEM

Summary. The most critical operation for an aircraft to perform is landing. Even in bad weather, more specifically poor visibility, landing becomes virtually impossible of instrument guidance to aid the pilot. The more extreme case occurs when the visibility is near zero and the pilot cannot land the plane manually. This situation requires an automatic landing or precision approach to be performed by the aircraft flight control system in conjunction with a landing/guidance system. This type of guidance has been provided by the integration of the Global Positioning System (GPS) and Inertial Navigation System (INS).

PRECYZYJNE LĄDOWANIE SAMOLOTÓW PRZ UŻYCIU ZINTEGROWANEGO SYSTEMU GPS/INS

Streszczenie. Najbardziej krytyczną operacją do wykonania samolotem jest lądowanie. Podczas złej pogody, zwłaszcza w słabej widoczności, lądowanie staje się prawie niemożliwe. Najbardziej skrajny przypadek występuje, gdy widoczność jest bliska zeru, a pilot nie może wylądować samolotem ręcznie. Ta sytuacja wymaga automatycznego lądowania lub precyzyjnego podejścia do wykonania przez system kontroli lotów samolotowych w połączeniu z systemem wspomagania lądowania. Ten rodzaj wspomagania został zaopatrzony przez integrację z Globalnym Systemem Pozycjonowania (GPS) i Inercyjnym Systemem Nawigacyjnym (INS).

1. INTRODUCTION

For precision approach and landing, the required navigation performance (RNP) includes accuracy (A), continuity (C), integrity (I) and availability (Av).

- Accuracy is the navigation output deviation for correct landing.
- Integrity is the ability of a system to provide timely warnings to users when the system should not be used for navigation.
- Continuity is the likelyhood that the navigation signal-in-space supports accuracy and integrity requirements for the duration of intended operation.
- Availability is the fraction of time the navigation function provides acceptable accuracy, integrity and continuity before the approach is initiated.

In other words, accuracy is how well your navigation system tells you where you are. Integrity is the truthfulness of your navigation system when it gives you a position. Continuity is the ability of your navigation system to constantly provide you an accurate position with integrity. Availability is the ability of your navigation system to provide acceptable continuity, accuracy and integrity. Today's precision approaches and landings based on the minimum weather conditions are classed into 3 categories, Category I, II and III. Decision height (DH) and runway visual range (RVR) are the parameters that characterize these categories. DHs for CAT I, II and III are 200 ft, 100 ft and 50 ft, respectively; and RVRs for CATI, II and III should be greater than 2400 ft, 1200 ft and 700 ft, respectively. When conducting a CAT X (X is either I, II or III) precision approach, at the DH of that category, the pilot has to have the corresponding RVR, otherwise a missed approach will be initiated [AC120-28C].

1.1. The Global Positioning System

The Global Positioning System (GPS), a satellite-based navigation system developed by the U.S. Department of Defense (DoD) in the 1970's, includes the space segment and the ground-based operational control segment (OCS). The minimum space segment has 24 satellites in 6 orbit planes with evenly spaced ascending nodes. Each orbit is nearly circular with a period of 11.97 hours and a 55^o inclination angle. To provide global coverage for the GPS users, satellites in each orbit plane are unevenly spaced to minimize the impact of a single satellite failure. Each space vehicle (SV) has a Cesium atomic clock for precise timing and transmits on frequency on L1 (1575.42MHz) and L2 (1227.60MHz) coded with a unique pseudorandom noise (PRN) to transmit navigation data.

The OCS includes 5 monitoring stations located at Colorado Springs Ascension, Island, Diego Garcia, Kwajalein, and Hawaii to obtain the worldwide monitoring of each satellite in the space constellation. Information gathered by monitor stations is sent to the master control station to generate satellite clock corrections, ephemeris and health condition. This information is then sent to the satellite through three ground antennas distributed worldwide. The user receiver usually is equipped with a less accurate clock such as a quartz oscillator (XO) or a temperature controlled quartz oscillator (TCXO). Therefore, there is a clock bias between the user clock and the SV's clock. For a given SV, range is measured by the user receiver based on the set between the received PRN code phase and a replica generated internally in the receiver. The received navigation data provide the receiver with the necessary information on SV location.

The GPS positioning is to solve for the 3D user's position and the receiver clock bias by measuring ranges from at least 4 SVs with known SV locations. The standard positioning service (SPS) accuracy for the civilian user is limited to 100 meters horizontally and 150 meters vertically considering the major error source known as Selective Availability (SA) [SPS]. SA is the intentional degradation of the signal by dithering the satellite clock to make hostile usage more difficult. With the cancellation of SA in the future, the accuracy for the stand-alone user could be improved to within 10 meters.

1.2. Inertial Navigation System Overview

An Inertial Navigation System (INS) is a combination of sensors able to determine all navigation states of a moving object, i.e. position, velocity and attitude; the ensemble of sensors is an Inertial Measurement Unit (IMU) and consists of three accelerometers and three gyroscopes mounted on an orthogonal triad. The accelerometers measure the specific force, defined in the inertial frame as:

$$f = a - g \tag{1}$$

where: f is the specific force; a is the kinematic acceleration; g is the gravitational acceleration

To obtain the velocity of the moving object, the measured specific force should be corrected of the gravitational term, integrated once and the result added to the initial velocity. Integrating the obtained velocity and adding the initial position, yields the final position. So an INS can be considered a sophisticated Dead Reckoning (DR) system. However the INS is actually more complicated because the measured specific force is expressed in a frame different from the frame in which velocity and position are usually expressed (navigation frame). For this reason the gyro triad is included in the IMU: gyros are able to measure angular rate with respect to the inertial frame, which, when integrated, provides the angular change with respect to the previous, supposed known, initial orientation. So gyros are used to transform the measured specific force in the navigation frame; the transformation can be mechanic.

An uncompensated error in the accelerometer measurement is integrated once introducing a linear error in velocity, which in turn integrated will introduce a quadratic error in position. The presence of an uncompensated gyro error is more critical, introducing linear error in angles and in turn yielding quadratic error in velocity and cubic error in position. Thus the INS performance strongly depends on the quality of the included gyros.

2. GPS/INS INTEGRATION TECHNIQUES

GPS and INS have complementary qualities that make them ideal candidates for sensor fusion. The limitations of GPS include occasional high noise content, outages when satellite signals are blocked, vulnerability to interference, and low bandwidth. The strengths of GPS include its long-term stability and its capacity to function as a stand-alone navigation system. In contrast, inertial navigation systems are not subject to interference or outages, have high bandwidth and good short-term noise characteristics, but have long-term drift errors and require external information for initialization. A combined system of GPS and INS subsystems can exhibit the robustness, higher bandwidth and better noise characteristics of the inertial system with the long-termstability of GPS.

The level and complexity of GPS and INS coupling is dictated by several factors, including desired navigation accuracy, quality of the inertial measurement unit (IMU), and required robustness of the GPS receiver outputs. The levels of integration are usually classified as loose integration (Figure 1), tight integration (Figure 2), and ultra-tight or deep integration (Figure 3).

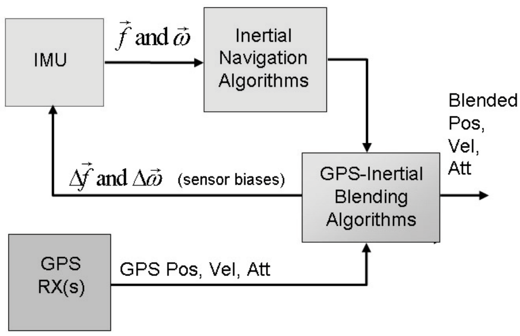

Fig. 1. GPS/INS system with loose integration
Rys. 1. System GPS/INS z luźną integracją

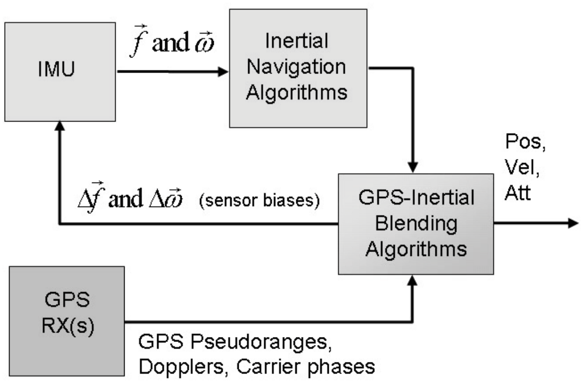

Fig. 2. GPS/INS system with tight integration
Rys. 2. System GPS/INS z ciasną integracją

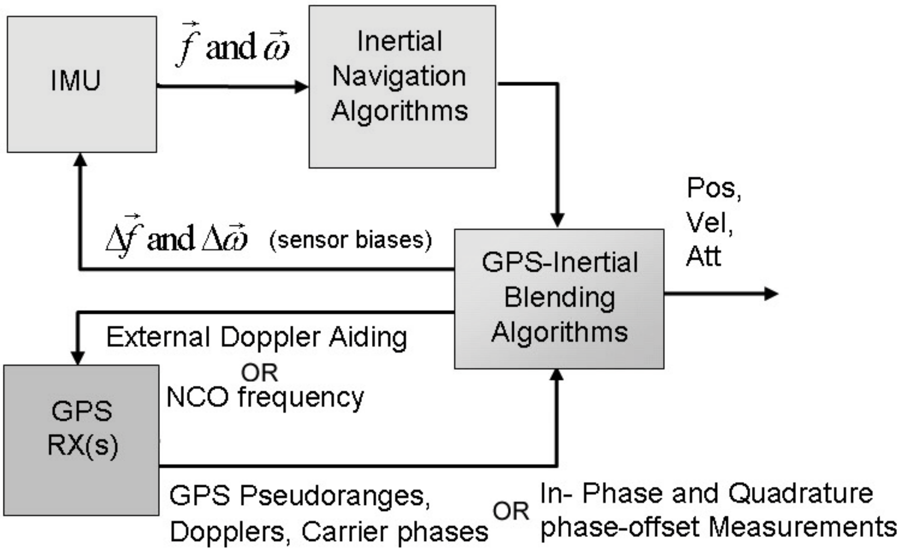

Fig. 3. GPS/INS system with ultra – tight integration
Rys. 3. System GPS/INS z bardzo ciasną integracją

2.1. Integration Modes

The real-time feedback of INS velocities to the GPS receiver enables an accurate prediction of GPS pseudorange and phase at next epoch, thus allowing a smaller bandwidth of the receiver tracking loop in a high-dynamic environment with a subsequent increase in accuracy. Conversely, inertial navigation improves if the GPS solution functions as an update in a Kalman filter estimation of the systematic errors in the inertial sensors. Similarly, GPS positions and velocities may be used to aid the INS solution in a high-dynamic situation by providing a better reference for propagating error states based on the linear approximation.

There are two basic categories of processing algorithms that are centralized and de-centralized. In centralized processing, the raw sensor data is combined optimally using one central processor to obtain a position solution. This kind of processing is usually associated with tight system integration. Decentralized processing is a sequential approach to processing, where processors of individual systems provide solutions that subsequently are combined with various degrees of optimality by a master processor. In principle, if the statistics of the errors are correctly propagated, the optimal decentralized and centralized methods should yield identical solutions. In some cases, such as system fault detection, isolation, and correction capability and the relative computational simplicity makes the decentralized approach more favorable. The centralized approach provides the best performance in navigation solutions that a single robust Kalman filter model.

2.2. Integration limitations

The performance of an integrated INS/DGPS is a complex process depending on a variety of parameters including:

- quality and type of inertial sensors
- the baseline length
- operational aspects
- the validity of error models
- the estimation algorithm

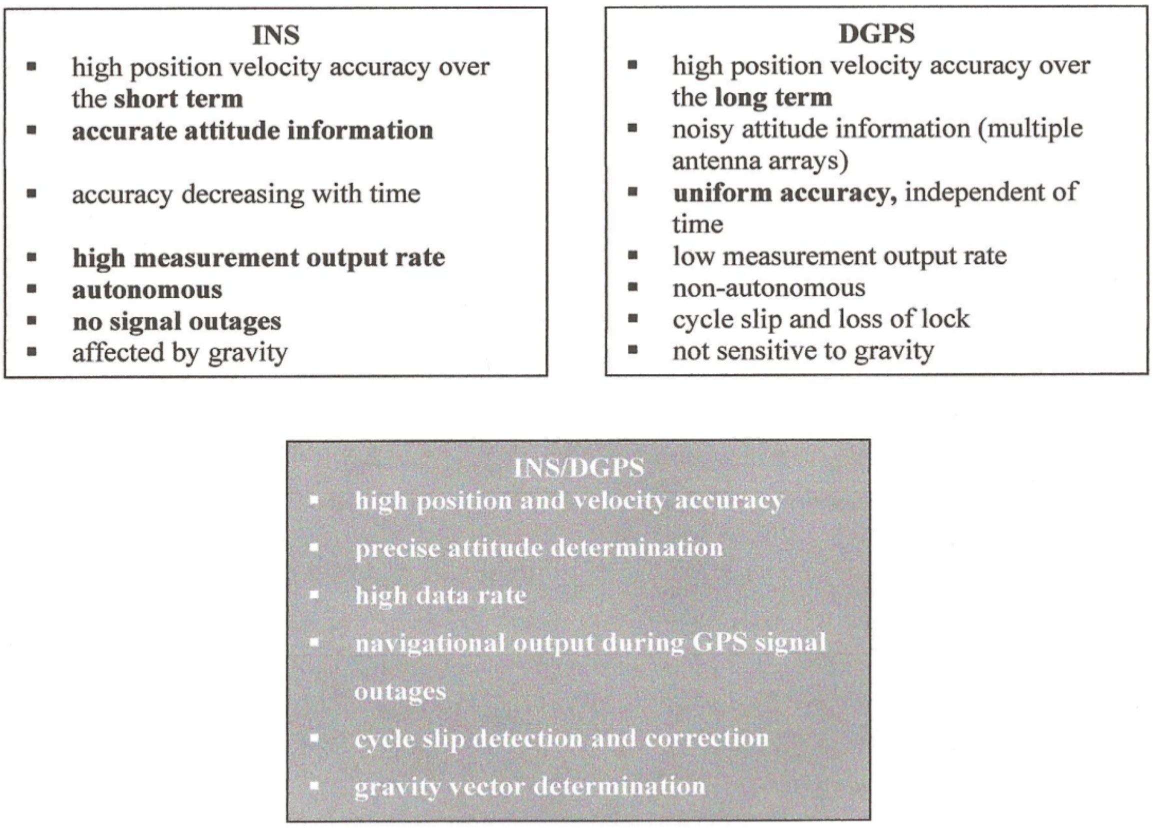

Fig. 4. Benefits of INS/DGPS Integration
Rys. 4. Korzyści z integracji INS/DGPS

In the lower frequencies, the INS/DGPS integration reduces the overall error; and in the high frequencies, the overall error is not reduced.

Integrated systems will provide a system that has superior performance in comparison with either a GPS, an INS, or vision-based stand-alone system. The main strengths and weakness of INS and DGPS are summarized in figure 4.

3. GPS/INS PRECISION APPROACH AND LANDING SYSTEM

Measurement uncertainty of the inertial sensors leads to errors in the computed attitude and position. Measurement uncertainty generally includes bias, temperature effect, noise and scale factor, as well as other factors. Due to the integration process, these error terms will accumulate over time. Therefore, the errors of computed attitude and position increase progressively and smoothly. Figure 5 illustrates the typical position error of an INS. According to this figure, although the long-term error of the INS is poor, the short-term error of the INS is smooth and good.

DGPS is adequate for precision approach and landing applications. The fundamental mathematics of the DGPS uses at least four differential pseudorange measurements and knowledge of the satellite location and the reference station to determine the relative position of the roving user. Error sources include the pseudorange measurement noise, modeling uncertainties, and satellite geometry. Since no integration process is involved in the DGPS algorithm, the position error of the DGPS does not increase with time.

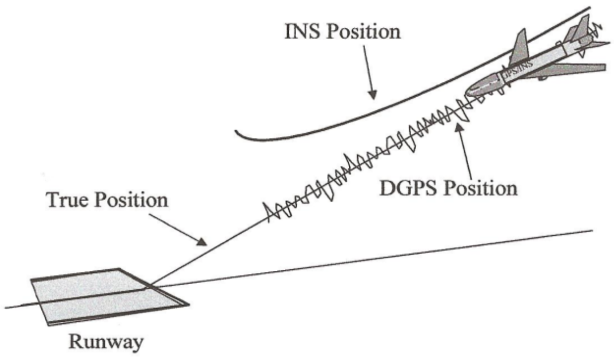

Fig. 5. Position Error Characteristics of the INS and DGPS
Rys. 5. Charakterystyki błędu pozycji dla INS i DGPS

Restated, DGPS is accurate in the long term, despite noisiness in the short term. An illustration is also shown in Figure 6. Besides the above error sources, disturbances such as interference and jamming threats, satellite outages, may also disrupt the availability and continuity of the accuracy of DGPS-based systems.

The above two systems appear to complement each other perfectly. Specifically, the short-term stability of the INS can be employed to smooth the noisy position of the DGPS, while the long-term stability of the DGPS can be used to confine the drifting INS. When the DGPS is available, the error sources of the INS can be calibrated. Meanwhile, when DGPS disturbances occur, the calibrated INS can be used to carry through the disturbed period. Figure 6 illustrates the notion of complementary filtering.

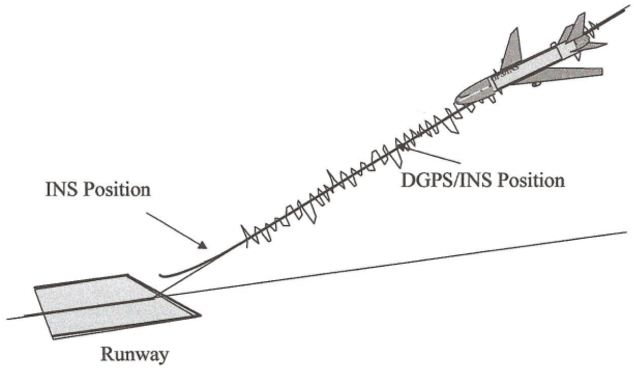

Fig. 6. Position Error Characteristics of the Integrated DGPS/INS
Rys. 6. Charakterystyki błędu pozycji zintegrowanego dla DGPS/INS

To integrate the two navigation systems, the error model of both systems must be developed and calibrated by measurements. The Kalman Filter technique is used to integrate DGPS and INS. The Kalman Filter estimates the major errors of the INS and continuously calibrates the INS in fight. Theoretically, the integrated navigation system should provide a smoother and more accurate position since the DGPS position has been low-pass filtered to eliminate the noise and the INS position has been high-pass filtered to eliminate the long-term error. Consequently, when DGPS disturbances occur, the integrated system navigates based on the corrected INS.

3.1. DGPS/INS – Glidescope integrated approach system

There are four distinct sources of data used in the integrated approach system. The ILS Glideslope, GPS data from the ground reference station, GPS data from the air receiver and attitude data from an AHRS or other attitude determination system. The data from the glideslope receiver is received at a rate of 20Hz. GPS data from the aircraft receiver is at a rate of 4Hz. GPS data from the ground station is uplinked to the aircraft at a rate of 1Hz. Attitude data is available at a rate of 10Hz. The data from these four measurement sources are transferred to the airborne processor and the position of the aircraft is calculated. The data rate typically supplied to the autopilot is 16Hz. This can be achieved through extrapolation via inertial measurement unit data or high rate Integrated Doppler data. A block diagram of the system is shown in Figure 7.

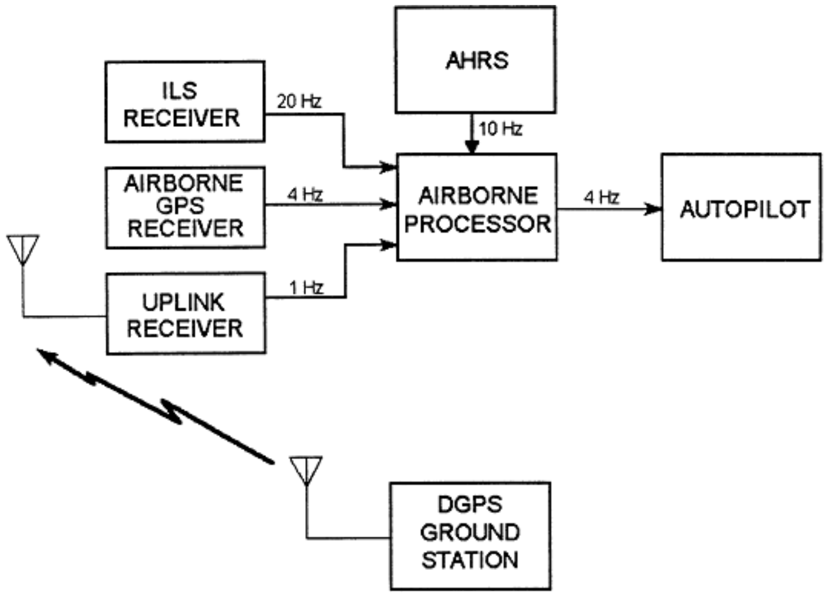

Fig. 7. Block Diagram of DGPS/ILS Glideslope Integrated System
Rys. 7. Diagram blokowy Zintegrowanego Systemu Lotu Ślizgowego dla DGPS/INS

The aircraft's position is calculated in the following manner. At a specific time epoch, a message from the GPS ground reference station is received. The differential corrections are applied to the GPS pseudorange and deltarange measurements from the air receiver. During this time, a glideslope measurement is received from the ILS receiver. The GPS antenna and ILS antenna are at different locations on the aircraft (Fig. 7). To calculate a position, all measurements must be referenced to the same point on the aircraft. The GPS measurements need to be referenced to the ILS antenna point. This is accomplished by translating the pseudorange measurements from the GPS antenna to the ILS antenna using data from the attitude determination system. Once the GPS and ILS measurements are all referenced to the same point, a position solution is calculated.

4. ERROR MODELS USED IN THE KALMAN FILTER

Navigation state equations are non-linear in nature. However, to obtain the error response of an INS, a linearization approach is used. This results in the generation of linear error models. These error models are utilized to provide error information about the systems to be integrated in a traditional Kalman filter. The error models are different from the sensor errors models (for the INS) or the error models used for the GPS code delays. These are in fact differential equations that describe the evolution of errors through time.

A full set of navigation error equations is given by Titterton and Weston (2004), as:

$$\dot{\psi} = -\omega_{in}^{n} x\psi + \delta\omega_{in}^{n} - C_{n}^{b}\delta\omega_{ib}^{b}$$

$$\dot{\delta v} = f^{n} x\psi + C_{n}^{b}\delta f^{b} \tag{2}$$

$$\dot{\delta p} = \delta v$$

where:
ψ is the vector of misalignment
δα and δβ correspond to the attitude errors with respect to the horizontal plane
δγ corresponds to the error about the vertical
$\omega_{in}^{n}$is the angular rate of the navigation frame with respect to the inertial frameexpressed in the navigation frame
$\delta\omega_{ib}^{b}$is the error in the angular rate of the body frame with respect to the inertial frame expressed in the body frame
δ*v* is the velocity error vector of the aircraft
f is the specific force output vector of the accelerometers
δ*p* is the position error vector of the aircraft
$C_{n}^{b}$is the transformation matrix between the navigation frame and the body frame

The matrix form of the error model is given by:

$$\delta\dot{x} = F\delta x + G\delta u \tag{3}$$

where: δ*x* is the vector of error states; δ*u* is the vector of inputs; *F* is the system dynamic matrix
G is the input matrix

The Kalman filter is typically implemented as the measurements from GPS and INS are subtracted to generate the measurement error vector that is the input to the filter (typically latitude and longitude obtained from both systems).

$$z_k = y_{k,INS} - y_{k,GPS} \tag{4}$$

z_k is the error measurement vector at epoch k; $y_{k,INS}$ is the INS measurement vector at epoch *k;* $y_{k,GPS}$ is the GPS measurement vector at epoch *k*

This is the conventional Kalman filter formulation. This is because of the assumption that the dynamic model represents dynamics of the error completely while any random component can be modeled through noise.

5. CONCLUSION

The usage of GPS and INS for the solutions of navigation problems in photogrammetric applications provide a challenging opportunity in the last decade. Basically, there are two different approaches for georeferencing of airborne imagery using GPS and INS data. Direct georeferencing gives the exterior orientation parameters, projection center coordinates and attitude data, as the result of navigation process with GPS and INS observations without using control points in the navigation solution for airborne imagery. The precision of the georeferencing depends on the application parameters such as, image scale, camera specifications, etc.

For precision approach and landing a large investment is made in both systems. The aforementioned GPS augmentations have no dissimilar redundancy which could be provided by two systems being integrated together to strengthen availability, integrity and continuity-of-service. The first consideration for the GPS/ILS integrated system is certification. ILS is a certified system used in automatic aircraft landings where as GPS is not. There are currently GPS receivers certified for en-route navigation and non-precision approach, but none for performing automatic landings in the case of zero visibility. By integrating the two systems, it may be possible for certification of a GPS-only landing system to proceed more swiftly.

An integrated landing system should have a mix of both ground-based and space-based components. This eliminates common-mode failures and thus is a major advantage of the integration. If one part of the system fails, it is still possible to continue the landing operation. The probability of both systems failing is very small due to overall system independence.

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