Analysis of a GNSS/Radar Altimeter integration for improved touch-down performance in automatic landings

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ABSTRACT

In this work the integration of radar altimeter measurements into a GNSS position solution is investigated. The method is intended to be used in low altitudes just before landing of an aircraft in order to reduce a possible vertical bias and improve touchdown performance.

The first section after an introduction and a motivation for the possible benefits introduces the proposed method which follows mainly the idea of barometric altitude aiding. After an initial positioning solution the radar altimeter measurement and digital terrain elevation data are used to create additional ranging information in vertical direction.

The next section discusses the uncertainties in this additional measurement. Apart from the obvious measurement noise, special focus is put on the look-up of terrain elevation data, since this is the most critical step in the process.

Finally this method is tested with flight trial data from late 2009. The results clearly show the potential but also the remaining issues of the proposed method.

INTRODUCTION

Landing in low visibility weather conditions is still one of the remaining challenges for the use of satellite navigation in aviation. Current research is assuming that LPV or even CAT-I requirements can be met with space based augmentation systems (SBAS) and receiver autonomous integrity monitoring (RAIM) techniques in near future [1]. However, for operations beyond CAT-I the situation is different. The tolerable integrity risk of 10^{-9} and the other required performance parameters for automatic landings will most likely only be met with a ground based augmentation system (GBAS) system at the airport [2]. The milestone to get system design approval for CAT-I GBAS has been reached in the US and Australia and is expected to be reached very soon in Europe as well. But research focus is now moving on to CAT-III operations. The corresponding requirements (GAST-D SARPS) have been drafted and frozen.

All evaluations in this paper were based on the use of GBAS since it is the most precise system and all necessary data were available. However, this method is not limited to that and could also be used together with any other kind of augmentation system or other techniques ensuring integrity.

System performance under almost all conditions is excellent and test results show that the average navigation system error (NSE) of an aircraft using GBAS is typically well below one meter. However, under very unfavourable conditions a bias-like error is assumed to be possible. [3] Such an error has an effect on where on the runway an aircraft touches down. A simple geometrical model relates a bias in the vertical position solution (Δh) to an along-track error of the touch-down point on the runway Δx, depending on the glide-path angle (GPA) as

$$\Delta x = \frac{1}{\tan(GPA)} \Delta h$$

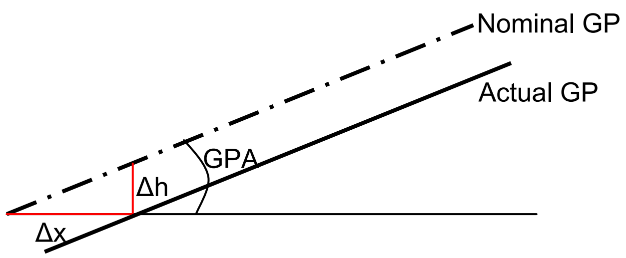

Figure 1: Relation between touch-down point and vertical error

Assuming a maximum vertical error of 10m (corresponding to the vertical alert limit close to the runway) the along-track error of the touch-down point at a typical 3° glide slope would be 190m which is quite significant.

In this work the integration of radar altimeter measurements and terrain elevation data into the GNSS position solution is investigated to address this problem. This solution is intended to be used from (or shortly before) the 200ft decision height on the approach until the flare-out, i.e. for CAT-II and CAT-III operations. It is a very straight forward use of mostly already existing systems and information. In order to keep changes to current systems as small as possible it can be assumed that the radar altimeter in future GNSS-based automatic landing systems will still be used for vertical guidance from several feet above the runway until the actual touch-down. For airports offering CAT-III operation capability, very accurate mapping requirements are already in effect [4]. The only additional information needed onboard the arriving aircraft, compared to today's available information, is the digital elevation map of the area over which the plane is flying. GBAS corrections are used for initial positioning with the calculation of protection levels. A detailed analysis for possible errors in the additional altitude measurement and the elevation data from the map is crucial to evaluate the possible threats.

The studies and simulations are finally verified with flight trial data which were obtained during a GBAS test campaign in late 2009 at DLR's research airport in Braunschweig. First results show that especially in areas with very low terrain roughness (i.e. small variations between neighbouring data points) which is the case in the obstacle clearance area of a runway for CAT-III operations, this method provides a possibly great benefit for improved touch-down performance and a valuable method to crosscheck two independent systems.

ARCHITECTURE

The proposed architecture is a two step-algorithm and uses GBAS corrected GNSS data together with measurements from the radar altimeter onboard the aircraft. The radar altimeter is designed to measure the current aircraft altitude above ground level (AGL), typically at a rate of about 25Hz. In a first step a conventional GBAS position solution, together with the corresponding protection levels is calculated. The second step then combines the altitude measurements, the position solution and digital terrain elevation data (DTED) which contain the altitude above mean sea level (MSL) of the terrain at defined points. The altitude of the aircraft GNSS antenna above MSL consists of the elevation of the terrain, the measured distance from the ground to the aircraft and the difference in altitude of the radar altimeter antenna and the GNSS antenna. In the following a very short recapitulation of the principle of GNSS positioning is given, to be followed by a description of the integration of the new additional measurement.

The well known navigation problem can be formulated as:

$$\rho = S \cdot \hat{x} + \varepsilon \text{ with}$$

$$S \equiv (G^T W G)^{-1} G^T W \text{ and } W^{-1} = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_N^2 \end{bmatrix}$$

where ρ is the measured, corrected and smoothed pseudorange, S the weighted geometry matrix, $\hat{x}$ the position estimate and ε the error term. The σ in the weighting matrix are the expected standard deviations of the range measurement error. The derivation of these values is usually standardized, however for inclusion of the radar altimeter measurement a method for the corresponding standard deviation has to be developed. This will be done in the next chapter.

GNSS positioning has the general problem that the geometry for the vertical estimate is much less favourable than for the horizontal one. This is due to the fact that generally the satellites in view are well distributed across the sky. However, no signals are received from below the user due to the obstruction from the earth. Therefore adding an additional measurement in vertical direction generally improves the condition of the geometry matrix and reduces the overall uncertainty in the calculated position solution.

To increase positioning accuracy and, maybe even more important, to provide integrity information for arriving and departing aircraft, a GBAS at the airport determines corrections and integrity parameters which are broadcast via a VDB transmitter. A ground station typically has four antennas at carefully surveyed positions. From the measurements at these antennas the GBAS parameters for each satellite are derived by comparing the measured signals to the actual range which can be calculated since the satellite position and reference antenna positions are known.

To reduce noise in the measurements the pseudoranges in the airborne system are carrier-smoothed with a 100 second Hatch-filter (and additionally a 30s filter in the case of GAST D (GBAS Approach Service Type intended to support CAT II/III operations) for ionospheric disturbance detection) [5]. These smoothed and corrected measurements are then used in the position solution in the ρ vector.

The main principle of the proposed integration in principle follows the way of barometric aiding to the GNSS solution as described in [6] and is depicted in the following scheme:

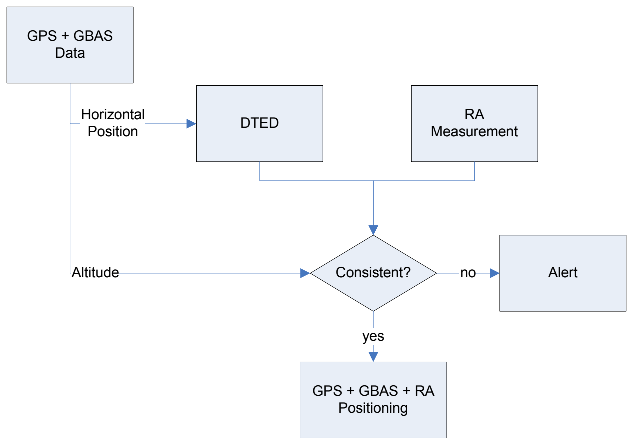

Figure 2: Overview of proposed architecture

A GBAS position solution is calculated first, in order to determine the horizontal position. Together with the position estimate an error bound for the horizontal error is calculated, the so called protection level. Based upon this (horizontal) position and the area of uncertainty the corresponding terrain elevations are taken from a digital terrain elevation map. The average of all terrain data points in this area of the map is used as terrain elevation. Together with the radar altitude measurement a new range is determined to a virtual satellite, which is located vertically under the aircraft's horizontal position on the WGS-84 ellipsoid. If the range computed in this way matches the altitude computed in the GNSS solution with a certain tolerance, the new vertical range information is included in a new position solution, extended by one ranging source. The geometry matrix is extended by one row, respectively. Since the RA measurement does not contribute to the time offset, this additional row just contains the upward facing unit vector and a zero in the fourth column which is a column of ones for the receiver clock bias estimate in a conventional GNSS solution. If there were N satellites in view then the new geometry matrix and the corresponding weighting matrix would be of dimension ($N+1$) x 4 and ($N+1$) x ($N+1$), respectively. With this new information a position solution is computed with the standard least squares method. Determining the standard deviation σ for appropriate weighting of the new measurement is subject of the following section.

Another benefit is that an additional consistency check between the two totally independent sensors GNSS and radar altimeter can be performed and possible undetected failures in satellite navigation as well as malfunctions of the radar altimeter are more likely to be detected.

The overall behaviour of the system and the effects of different disturbances such as vegetation in terrain elevation are studied. With growing uncertainty in the additional range and adequate weighting, the solution converges to the GPS stand alone solution.

THE ADDITIONAL MEASUREMENT AND UNCERTAINTIES

The uncertainty in a GNSS measurement is usually expressed as a standard deviation σ of a Gaussian error distribution. Its derivation is a critical point and has to be evaluated in detail. We assume an additional ranging source right underneath the aircraft. Since the radar altimeter measures height above the (uneven) terrain only, a common worldwide reference is needed. The most natural choices seem to be either the centre of the earth or the vertical projection of the aircraft's position onto the WGS84 ellipsoid. To avoid potential error sources due to the oblatness of the earth and the rectangular projection not going to the centre but the focal point of an ellipsoid we decided to take the position on the ellipsoid as reference. The situation is shown in figure 3.

The actual radar altitude measurement h_{meas} is only one part of the additional range. The other parts to be considered are the height difference h_{WGS84} between the ellipsoid and local mean sea level (MSL) to which the

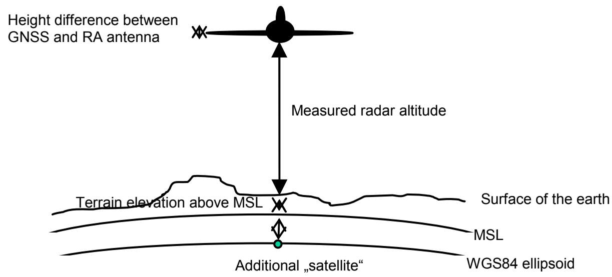

Figure 3. The additional measurement and its components.

terrain elevation map refers, the terrain height h_{DTED} taken from the map at the aircraft's position and the height difference h_{ant_diff} between the GNSS antenna and the reference of the radar altimeter. The new range H is thus expressed as:

$$H = h_{ant\_diff} + h_{meas} + h_{DTED} + h_{WGS84} \quad \textbf{(1)}$$

Each of the parts of H has its own sources of errors which shall be discussed in the following.

h_{ant_diff} : Despite the fact that the antennas are fixed on the aircraft, their height difference cannot be considered as constant. Due to deformations of the fuselage, but mainly due to varying pitch and roll angles of the aircraft this height difference changes. However, with precise knowledge of the aircraft's current attitude (obtained e.g. either through an IMU or a GNSS receiver with several antennas) and the position of the antennas on the fuselage simple geometric calculations can account for this and eliminate most of this error. The residual error originates in unknown deformations of the fuselage and uncertainties in the exact attitude of the aircraft. As usually no better estimate for these error contributions are available we model them as Gaussian distributed with zero mean. The standard deviation depends largely on the quality of the IMU or any other sensor responsible for attitude determination.

h_{meas} : As with all measurements the measured radar altitude is subject to measurement noise. Flight test results showed this very clearly during taxiing of the aircraft where the height above ground should remain constant. Especially during faster taxi periods and the takeoff roll measurements showed variations of up to half a meter. It should be noted, however, that the radar altimeter used in the flight trials was not intended to support autoland operations and. Current altimeters generally show much better performance. By specification [7] the maximum measurement error is defined +-3ft below 100ft indicated altitude and +-3% between 100ft and 500ft indicated altitude at the 95th percentile. The given values are upper bounds and can be modeled accordingly. This altitude dependent behavior was also observed during the flight tests. As in previous works on radar altimeter integration [8],[9] we also observed that the measured altitude was very dependent on the underground. Radar altimeters are designed to measure the altitude above ground and therefore significantly penetrate vegetation and to a big extent also snow. A certain small change in measured altitude depending on the extent of vegetation, amount of snow etc. has to be expected nevertheless. Thus the approach track where the radar altitude is used should be clear of obstacles and disturbances to create repeatable altitude measurement results. This, however, can be expected to be the case under the last few hundreds of meters of the approach track before the runway since this is the intended radar altimeter operation area. Another impact on the data quality originates from the type of sensors used. The available digital terrain elevation data (DTED) from the Braunschweig area were obtained through laser scanning. From the results discussed in the flight test chapter later on it is very obvious that the laser scanning method does not have the same penetration capabilities and thus a significant bias is introduced in the additional measurement if the database and the measurements are not created by the same or a comparable method. Another issue can arise due to the aircraft's attitude and the characteristics of the radar altimeter. It transmits a defined signal and takes the first reflected signal as base for determination of the radar altitude. The antenna is fixed on the bottom of the fuselage and emits signals at a certain fixed beam width. This enables the radar altimeter to measure the shortest distance to the ground even with a bank and pitch angle. However, the area which is seen by the radar signals does change and in uneven terrain a certain point, other than the ground straight underneath the aircraft could reflect the signal and create an error as to what is measured. This situation is depicted in figure 4 where the distance (shown in red) to an obstacle is measured instead of the distance from the ground. Again, under the final approach track no obstacles should be present so that this influence does not create erroneous measurements either.

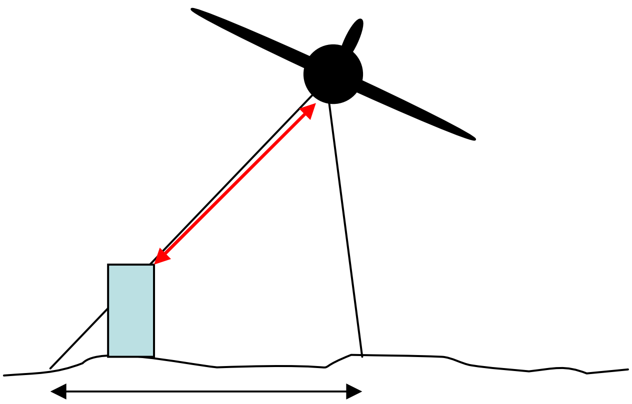

Figure 4. Area covered by the radar altimeter and danger of taking the wrong reference.

To obtain a precise new range, the aircraft's horizontal position has to be known in order to take the correct terrain elevation from the database. This is a critical step since misleading position information automatically translates into a false terrain elevation information and thus directly into an error in the new additional range. To avoid this, a horizontal position with integrity information is needed for the look-up of the terrain elevation. If the position, together with the horizontal protection level (HPL) is available, the area where the plane is located can be considered in the DTED. Depending on the resolution of the map several data points might lie within this region. Together with the beam width characteristics of the radar altimeter signals and the aircraft's attitude a certain area on the ground is defined which could be seen by the aircraft. With increasing altitude this area gets significantly large, nevertheless this method leads to promising results for the final approach for two reasons: (1) the altitude above ground is rather small, thus the visible area for the radar altimeter is limited and (2) the terrain under the final approach path of an airport certified for CAT-II/III operations is reasonably flat. Taking all data points in the area and their first neighbors on the outside of the area to avoid uncertainty due to interpolation methods between data points, thus combines all error sources discussed in this paragraph and results in an uncertainty of the terrain elevation which can be directly derived from the database.

h_{DTED}: The data contained in the DTE database also have to fulfill certain requirements to be suitable for this kind of application. In order to give the additional measurement a certain level of integrity, the elevation data points themselves have to come with assurance that the data are correct. However, mapping requirements for the airport areas and especially the radar altimeter operating areas are already existent so that this factor is not a big concern. ED98-A [4] requires a 95% data integrity and a post spacing (i.e. distance between two adjacent data points) of 10m. Both values are not very stringent for the proposed kind of application and might have to be reconsidered in order to achieve good results. The residual error is hard to model since it depends on the procedures of how the data were obtained in the first place. Thus, only an assumption as to how the errors are distributed can be made in our case. A more precise model can be derived, however, when taking a closer look at the map and its creation. For our purposes it seemed reasonable to assume a Gaussian error distribution.

h_{WGS84}: One other possible source of errors is the common reference to the WGS84 ellipsoid of the earth. Usually the terrain elevation databases are giving terrain elevation above mean sea level (MSL). The sea level reference, however, is not common to all countries. The correct definition of sea level and its reference to the WGS84 ellipsoid has to be known and considered to avoid the introduction of systematic errors due to incorrect or imprecise data conversions. Since the land survey offices until today are often using UTM coordinates or similar, the same holds for conversion of the coordinates to WGS84 coordinates. It usually can be assumed that a correct conversion model is available, and thus a Gaussian model is assumed to bound errors introduced by the approximation through Legendre polynomials [10].

Another issue to be considered is the timing between the radar altimeter and the GNSS measurements. Since the aircraft is moving at speeds typically around 70m/s on the final approach, even small asynchronisms can lead to significant errors in the terrain elevation look-up. If it is not possible to trigger the measurements simultaneously interpolation has to be performed. Course, speed and sink rate are very well known and are a very suitable base for accurate interpolation. However, in this case an error model as to how the timing affects the look-up has to be created. This can be done for example by increasing the position uncertainty and increasing the area considered before in the h_{meas} -section.

With the possibilities of errors evaluated and each individual source of error modeled, it is now possible to obtain a total uncertainty for the additional range. In order to fit to the standard concept in satellite navigation this uncertainty can be defined as a standard deviation of a Gaussian distribution. This practice of Gaussian overbounding is commonly used, however, not without controversy [11]. In order to get a first good insight and comply with the standard methods the cumulative density function (CDF) overbounding as described in [12] can be followed. Other methods have been developed later on and are described e.g. in [13].

The newly derived variance can then be used in a second position solution just like those of the satellite ranges to appropriately weigh the new range in the overall solution.

APPLICATION TO FLIGHT TEST DATA

In November 2009 flight trials with the Vfw-614 research aircraft “ATTAS” for evaluation of DLR’s experimental GBAS station in Braunschweig were carried out. The airport of Braunschweig is rather small and has a CAT-I ILS for runway 26. When approaching from the east to that runway (as done in these flight trials), there is a forest area reaching as close as about 450m to the threshold and about 950m to the touchdown point on the runway. From these flights radar altimeter data together with position information with integrity information were used to evaluate the proposed method. A terrain database of the area around the airport was available from the land survey office. As mentioned in the last section, this terrain model was created by laser scanning and had a post spacing of 10 meters. The big spacing between the points compared with to the relatively small horizontal protection levels lead us to use a linear interpolation of the altitude at a certain point from its four neighboring data points available. The radar altimeter used was a Collins 860F-1. According to the manual it is specified to provide altitude information below 2500ft above ground level (AGL) with an accuracy of +-2ft or +-2% whichever is greater. Thus an output accuracy of +-2ft up to 100ft AGL and for higher altitudes an increasing uncertainty could be expected. Its output rate is 25Hz. The GNSS receiver on board was a Topcon NetG3 of which single frequency recorded pseudorange measurements at a recording rate of 20Hz were used. GBAS corrections and integrity parameters for protection level calculation were processed in the experimental GBAS ground station consisting of three reference receivers and fulfilling the CAT-I criteria. A post processed carrier phase solution of the recorded flight data serves as reference for all evaluations. For illustration an approach to runway 26 with a low pass over the airfield in 100ft AGL and a subsequent go-around is presented here in detail. Unfortunately no reliable attitude information from the flights was available to investigate the influence of attitude. Another drawback in the flight trials was the DTED which were preliminary data from laser-scanning with no integrity information and the already mentioned problem of different reference altitudes compared to the radar altimeter. Since this kind of information was not available, a complete evaluation of the proposed method was not possible. Instead a simplified standard deviation of 1 meter on the additional range was assumed. This value is too optimistic for the areas outside the airport, but rather conservative when flying over the runway at low altitudes.

The following graph shows the results of the determination of the terrain altitude.

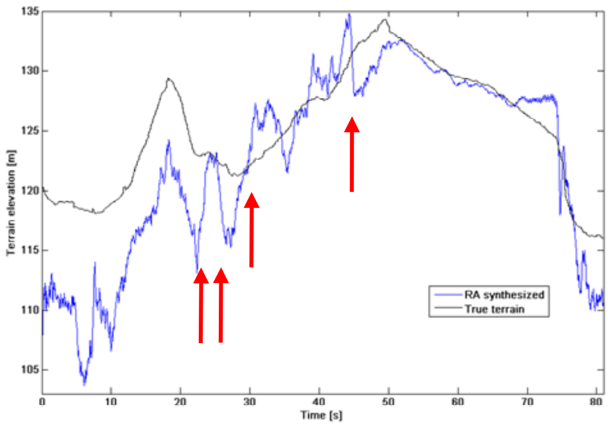

Figure 5. Terrain elevation determined from position and radar altitude (blue) and true terrain elevation from DTED. Red arrows mark overflight of beginning and end of forest

The blue curve shows the estimates of terrain elevation resulting from GBAS augmented GNSS position and the radar altitude measurements with all contributing errors as described in the previous section, while the black curve shows the correct terrain elevation from the DTED at the location. What can be seen very clearly in this plot is the issue of vegetation underneath the flight path. The big jumps in the blue curve marked with the red arrows correspond to the flyover of beginnings or ends of forest areas where the difference in the sensors becomes most obvious. It becomes very clear that sensors with similar characteristics should be used to produce the database and then during the approach to the airport. Another thing which can be observed is a trend of decreasing error when approaching the runway between seconds 0 and 50. This can be explained by the improving accuracy for lower measured altitudes as described before. During the low pass from seconds 50 to 65 the estimated and the true terrain elevation match very well. During this time the runway was a convenient reflecting surface and the terrain was sufficiently flat. Under these conditions which are usually found at an airport and underneath the final approach segment from the 200ft decision height point to touchdown for CAT-III capable airports the database together with the radar altimeter yields good results.

Next we incorporated the additional range into the position solution. The GBAS augmented position solution was only used for determination of the protection level. The blue GNSS curve in the plot are GPS standalone results which have a bigger vertical error and higher noise than the GBAS solution. This was done to show the possible benefits in case of a bias on the GNSS solution. The results for the vertical errors (in reference to the carrier phase solution) are shown in the following plot.

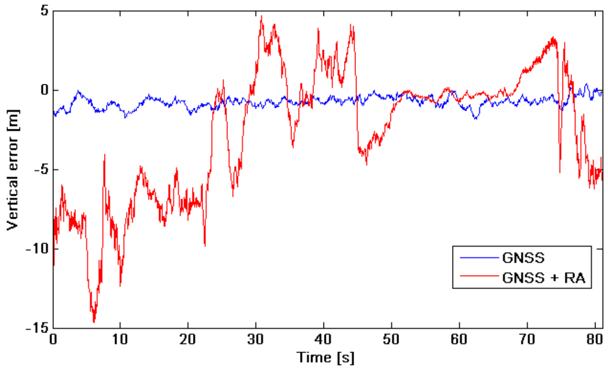

Figure 6. Vertical errors of GNSS with radar altimeter (red) and without (blue)

As we expected the errors in the synthesized terrain elevation show up directly in the vertical position solution with the jumps at the same positions and about the same introduced error. However, when overflying the airport where the radar altitude measurements were sufficiently good, the overall position results are fitting the true position extremely well and were generally slightly better than the GNSS solution.

CONCLUSION AND FUTURE WORKS

We investigated the integration of radar altimeter information into a GNSS position solution. First flight tests showed that the method gives good results over flat terrain but is not suitable over uneven areas with vegetation. In order to achieve integrity for the new position the error sources have to be understood and modeled. After appropriate overbounding a variance for the new range can be determined and used for appropriate weighting in the position solution and in a next step also for integrity considerations.

If sufficient trust can be put into the new measurement and its derived variance it might also be used for protection level calculations or other integrity assurance techniques in the future.

The method also provides a valuable means of crosschecking two systems. Radar altimeter measurements and GNSS data are completely independent but are very important systems on which the autopilot heavily relies during landing. Even with a bias in one of the systems the combination of both and the complementary geometrical characteristics result in an improved overall position solution. Incorporation of the radar altitude in the GNSS solution and possibly increased weighting of the new range with decreasing altitude produces more reliable and smoother results than when both systems are used independently.

Hence, the touch-down dispersion on the runway due to navigation system error (NSE) can be significantly reduced and results in safer operations under low visibility weather conditions.

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