Abstract - Standalone on-board GNSS systems used in general aviation are sufficiently accurate and precise to be used as part of instrument approach procedure. The number of standalone on-board GNSS systems on general aviation aircraft is increasing at high rate. Many of general aviation pilots use standalone on-board GNSS systems as a supplementary means of situational awareness when flying. Accuracy and precision of positioning of those systems are two critical elements for flight safety in final approach phase. Unlike the conventional ground based navigation systems such as ILS, VORs and NDBs, standalone GNSS receivers which are not integrated in aircraft avionics still need testing in order to prove their applicability for general aviation under IFR conditions. Aircraft trajectory was analyzed during final approach phase of flight in terms of accuracy and precision in order to determine the horizontal and vertical deviations from ideal approach path. Trajectory analysis proved that standalone on-board GNSS systems used in general aviation are accurate and precise enough to be safely used as part of instrument approach procedure.

Index Terms - general aviation, trajectory analysis, satellite navigation

INTRODUCTION

With predicted annual growth of air traffic by 2% [1] and rapid growth of general business aviation (68% more Worldwide Business Aircraft Operators in period from 2000 to 2015 [2]) sky is getting highly congested. To ensure safe conduct of air traffic European Aviation Safety Agency has issued Notice of Proposed Amendment which states conditions regarding implementation of Performance Based Navigation with December 2018 as final deadline for implementation [3]. There are many advantages of implementing such procedures. Final approach segments can be curved paths, there is no need for installing costly ground equipment and approach paths can be shortened, therefore reducing costs and fuel consumption.

This paper is based on the assumption that standalone on-board GNSS systems used in general aviation are sufficiently accurate and precise to be used as part of instrument approach procedure. To test this, a series of data collection have been conducted, both on ground and on-board aircraft flying approach procedure.

With the cancelation of GNSS Selective Availability in 2000 GNSS systems became suitable for civilian applications, such as air navigation. Also, implementation of augmentation systems improved already high accuracy as well as reliability and integrity monitoring. Three augmentation systems are in use today; space based (SBAS), ground based (GBAS) and air based (ABAS) systems [4]. During data collection, European space based augmentation system EGNOS was in active use.

It is important to highlight the difference between precision and accuracy regarding GNSS systems. Figure 1 shows the relationship between precision and accuracy. Dashed vertical line indicates the mean of the dataset (the inflection point at which the histogram balances). Red arrows bracket the spread of the dataset at one standard deviation from the mean (precision), while the black arrows bracket the offset of the mean from truth (accuracy). Accuracy is the difference between the true and expected value.
Accuracy can be evaluated in two ways: by using information internal to the data, and by using information external to the data. External accuracy is when a standard, another instrument, or some other reference system is brought to bear to gauge accuracy.

For the purpose of the testing, an Instrument Landing System (ILS) was used as external reference, with the assumption that the flight was conducted perfectly following the ILS path.

**STATIC DATA COLLECTION**

Data collection was done in two stages: static data collection and inflight data collection. First part of analysis was based on static data gathered by GPS receivers mounted on the car roof while the car was parked on an open area to minimize interference. Static data collection phase lasted for 30 minutes, and the GPS data was recorded on a laptop in the form of NMEA 0183 sentences. Program used for recording data was VisualGPS. Objective of static data collection was to establish the initial system state of the GPS receiver, define possible differences and errors and acquire information of system in static conditions.

Average altitude recorded was 384 [ft] with standard deviation 9.552 [ft]. Figure 3 shows the characteristics of the GPS altitude signal which will form normal distribution after enough recorded samples (as stated by Langley around 12 hours [4]). Mean altitude is shown with a green line, while the blue line represents actual measurement. Note that during data collection vehicle was stationary, and altitude did not change. In contrast the GPS altitude is significantly wandering from the mean altitude. As showed by figure 3 deviations from mean can be separated in two sets of oscillations – high frequency oscillations and low frequency oscillations. High frequency oscillations are errors caused by thermal noise within the receiver while low frequency oscillations are errors caused by satellite position and the quasi-random effect of multipath [4].

**INFLIGHT DATA COLLECTION**

Inflight data collection was conducted on Cessna 172N aircraft which is equipped with minimum equipment needed for conducting flight under Instrument Flight Rules (IFR) conditions. The data collection was carried out on segment of approach path for runway 05, Zagreb International Airport which starts from the starting point of approach (8.3 [NM] IZA DME) to a decision height (DH) distance 0.7 [NM] according to IZA DME. As seen from Figure 2 starting point of approach (point of ILS signal interception) is at altitude 3000 [ft] and decision altitude is 553 [ft]. Altitude at outer marker is 1550 [ft], and the final approach course is 044 degrees.

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**Figure 1 – Relationship between precision and accuracy. [4].**

**Figure 2 – Altitude measurement in static conditions**

**Figure 3 – Approach segment studied for GNSS accuracy [5].**
The data collection was carried out following ILS approach path, i.e. the ILS path was used as a fixed reference in space. Data was recorded using Garmin GPSmap 76CS connected to VisualGPS, Garmin GPSmap 196 and Apple iPad.

Dashboard was filmed via video camera for later comparison between recorded track and ILS indicator deviation. According to course deviation indicator trajectory didn't deviate from ILS path and is to be assumed perfect (without off-track deviation) ruling out pilot error.

To comply with Required Navigation Performance requirements GPS RNAV approach trajectory must be within required minimums for RNP 0.1. Which means that off-track deviation in lateral plain is within 0.1 [NM] from projected track in 95% of time. Vertical guidance must be conducted with barometric altimeter, which makes GNSS approach a non-precision approach.

DATA ANALYSIS

During both data collection stages EGNOS function was enabled on all devices, data was recorded on a laptop in a form of NMEA sentences using VisualGPS program. Figure 4 shows one print-out of the approach track (horizontal and vertical).

![Figure 4 – Recorded final approach trajectory](image)

Collected data was analyzed by comparing recorded trajectory with projected one. Projected trajectory was created by generating an overlaying on already known ILS locator path. Initial approach fix was used for the initial point of projected trajectory while the end point was OM (as shown on Figure 3). These two points form a straight line and represent an ideal approach path which was assumed to be flown. Second set of points was extracted from collected GPS data. Distance between points generated during data collection and ones created in ideal approach trajectory represent horizontal deviation from ideal flight path. Distance between two points was calculated using simplified formula (1):

\[
d = \cos(\sin \varphi_1 \cdot \sin \varphi_2 + \cos \varphi_1 \cdot \cos \varphi_2 \cdot \cos \Delta \lambda) \cdot R \quad (1)
\]

This method was earlier described as external accuracy evaluation, since the external reference was used to calculate accuracy.

As mentioned earlier, for non-precision approach, vertical guidance is provided by barometric altimeter. Since flight was conducted on ILS approach path ILS glide slope will be used as reference for creating projected trajectory. Projected trajectory in vertical plain will be compared to GPS data applying same principles as it was done for horizontal plain. Reference flight path was calculated using known published points. In this case, the initial altitude 3000 [ft], and final altitude at OM is 1550 [ft].

RESULTS

<table>
<thead>
<tr>
<th>Table 1 – Results analysis for GPS accuracy - horizontal</th>
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<tbody>
<tr>
<td>Result</td>
</tr>
<tr>
<td>Average deviation</td>
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<tr>
<td>Standard deviation</td>
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<tr>
<td>RNP.01 probability (% of results within 0.1 NM)</td>
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<tr>
<td>Deviation width for 95% probability</td>
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From the Table 1, it is clear that the accuracy of recorded trajectory well exceed the requirement from RNP 0.1 (100% of all points are within 0.1 [NM] off-track). For this set of data, 95% of all measured positions are within 0.0222NM from projected track, which is significantly better than required.

<table>
<thead>
<tr>
<th>Table 2 – Results analysis for GPS accuracy - vertical</th>
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<tbody>
<tr>
<td>Result</td>
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<tr>
<td>Average deviation</td>
</tr>
<tr>
<td>Marginal deviation</td>
</tr>
<tr>
<td>100 ft probability (% of results within 100 ft)</td>
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<tr>
<td>Deviation width for 95% probability</td>
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Table 2 provides information on marginal deviation and average deviation. Currently there is no defined standard for minimum vertical deviation from desired altitude for GNSS devices because these devices cannot be used for vertical guidance. For the purpose of this paper a marginal deviation width of 100 [ft] was used at maximum acceptable deviation. For all performed approaches almost all recorded points were within those margins (maximum measured deviation is
109 [ft] in the first measurement). In two approach trajectories with highest vertical deviations first trajectory had 95% of all recorded points within ±57 [ft] from the ideal approach path while in the second approach, 95% of all results are within ±38 [ft].

Figure 5 – Vertical approach profile

CONCLUSION

This paper is proves that standalone on-board GNSS systems used in general aviation are sufficiently accurate and precise to be used as part of instrument approach procedure for horizontal guidance. A selection of available off-the-shelf devices was used and tested in flight. Conventional instrument approach systems were used for computation of reference trajectory and inflight guidance. Recorded GPS data was than compared to generated reference trajectory for determining precision and accuracy of standalone on-board GNSS systems.

Analysis of collected data proved that horizontal accuracy is sufficient for inflight application and even exceeds the expectation. This confirms that available standalone on-board GNSS systems are accurate enough to be used as part of instrument approach procedure.

Analysis of vertical accuracy shows that current standalone on-board GNSS systems are not accurate enough to be used in vertical guidance. Next stage in research is to calculate vertical accuracy based on 2-dot glide slope deflection (margins becoming smaller as aircraft approaches to threshold) and repeating data collecting with addition of standalone barometric altimeter.

Based on the carried analysis and data available it can be confirmed that standalone on-board GNSS systems used in general aviation are sufficiently accurate and precise to be used as part of instrument approach procedure in horizontal plane, and that it is plausible to be used for vertical guidance, but further research is required.

REFERENCES


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