A Combined GPS Satellite/Pseudolite System for Category III Precision Landing

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Abstract—This paper presents the results of a computer simulation, which models a combined GPS, satellite/pseudolite navigation system for precision landing. The goal of this system is to meet the CAT III requirements exploiting a combined system of satellites/pseudolites under severe geometry, weather, and jamming conditions. The simulation includes the aircraft position/velocity estimation and probability of false alarm and misdetection utilizing the satellite and/or the pseudolite navigation system.

Aircraft trajectory, GPS satellite constellation, pseudolite location, and the system noise input parameters form the system inputs. The system output is given in terms of the position/velocity estimation error vs. simulation time. Performance measure of the system integrity are also computed and presented. The overall system performance is the combination of the system navigation accuracy and integrity.

It is well known that the GPS satellite navigation system lacks vertical information, which results in poor vertical accuracy. On the other hand a pseudolite navigation system provides very good vertical information thus improving the vertical accuracy which is crucial for CAT III precision landing. Both satellite and pseudolite systems are all weather navigation systems, which guarantees optimal performance under any weather conditions. The pseudolite system can perform navigation in the S band or bands different from the L band; therefore, enabling the aircraft landing under severe jamming conditions of the L band.

Index Terms—GPS, satellite, airport pseudolite, aircraft, category III, precision landing.

I. INTRODUCTION

Previously [1], we have explored the need of having an autonomous system of 6 APLs to perform Category III precision landing, under the assumptions that all the APL clocks are perfectly synchronized with a reference time (this reference time might as well be the GPS time). The synchronization of a system of 6 APLs may be performed in using (at least) two approaches: (1) the first approach may require equipping each APL with a GPS receiver. (2) the second approach may require a master/reference APL and synchronizing all APLs with the clock of the master APL. The system cost for either approach appears to be high; therefore, in order to reduce the cost we seek an alternative approach to synchronization. We anticipate that an autonomous system with uncalibrated APLs is inadequate to meet CAT III requirements [2]. This implies that a calibration period for the APL clocks is required. This calibration can be performed by introducing a dual receiver: one that tracks GPS satellites at L1 and the other that tracks APLs at a frequency less vulnerable to jamming/interference (i.e., S band). Both the navigation and the integrity performance measures are evaluated for the SAT, uncalibrated APL, calibrated APL, and combined SAT/(calibrated) APL system. We anticipate either one of the following:

1. The combined SAT/APL system gives the best navigation and integrity performance measure; i.e., it meets and exceeds the CAT III requirements
2. The autonomous APLs with uncalibrated clocks provides the worst navigation and integrity performance measure; this system is unable to meet the CAT III requirements.

Although the SAT only and the autonomous APLs with calibrated APLs provides a performance measure worst than the combined SAT/APLs it would be sufficient to meet CAT III requirements.

This paper is organized as follows: The general system description is given in Section II. The proposed navigation and integrity filter is given in Section III. The simulation, which includes the simulation inputs, software, and results, is given in Section IV. Finally, summary and conclusions are shown in Section V.

II. GENERAL DESCRIPTION

The general description of the system is given in terms of the graphical description of the system and the system inputs.

A. Graphical Description of the System

The APL architecture and the aircraft glide-slope geometry approaching the runway for landing are given in Fig. 1 (a) and (b) respectively.
B. System Inputs

The system inputs consists of:

1. GPS Satellite constellation
2. Location of five pseudolites or ground-based GPS transmitters which transmit at a single frequency $S=2575.42 \text{ MHz}$
3. Permitted glide-slope tolerances both vertically and horizontally, which are specified in Table 1 [1] and Table 2 [1].

Moreover, the aircraft is equipped with a dual antenna GPS receiver to track both SAT and PSL. The aircraft is also equipped with integrity system, which measures the probability of false alarm and misdetection with time to alarm less than 2 sec.
A detailed description of the analytical description of the integrity measure can be found in [1,3-5]. Although the integrity measure provided in [1] attempts to quantify the probability of false alarm, $Pr(FA)$, and misdetection, $Pr(MD)$, under normal conditions for ideally calibrated APLs, the same integrity measure can be used for SATs only, calibrated APLs only, and their combination. Fig. 2 (b) outlines the general description of the SAT/APL system integrity.

IV. SIMULATION

In this section we describe the simulation inputs, software, and results.

A. Simulation Inputs

Here briefly we describe the simulation modes, which are:

1. The state vector $\mathbf{u}_k = \{x^k, y^k, z^k, v_x^k, v_y^k, v_z^k\}$ in the local coordinate system characterizes the aircraft trajectory, which is stored in the data file named “traj.dat”.

2. The GPS satellite constellation

3. The locations of APLs, their PRN number, and their frequency is stored in the data file named “pseudo.dat”

4. The measurements, which are stored in the file named “measu.dat” For each epoch the system noise measurement model consists of the week, time of week, pseudorange PRN number, pseudorange, the accumulated phase, and Doppler measurement corresponding to the APL PRN number.

B. Simulation Software

Simulation software is named “Simulator.exe” and is developed in C++. It processes the simulation inputs based on the proposed navigation and integrity filter (see Section III).
C. Simulation Scenarios and Results

The simulated performance measure is assessed for four scenarios: SATs, 5-uncalibrated APLs, 5-calibrated APLs, SAT and 5 calibrated APLs.

The APL latitude in degrees versus APL longitude in degrees is pictured in Fig. 3 (a), which corresponds to a 5-APL layout.

The aircraft trajectory is presented as the aircraft altitude versus time (see Fig. 3 (b)).

The navigation performance when processing satellite data only is illustrated by the lateral and vertical position navigation error, Fig. 4 (a) and (b). The absolute lateral and vertical position error (m) is computed as the difference of the filter position estimate with the true simulated position in the North East Down local frame.

It appears that for this scenario the lateral and vertical position error is smaller than the required lateral and vertical position error most of the time.

Similarly, the absolute lateral and vertical position error (m) for a 5-uncalibrated APL layout is presented in Fig. 5 (a) and (b).

We observe that the ambiguities were estimated as float during this simulation. Note that the lateral and vertical position error is larger than the required one; thus, this approach is not acceptable and some kind of synchronization mechanism is required.

The navigation performance measure of the system with 5 calibrated APLs is pictured in Fig. 6 (a) and (b), for the absolute lateral and vertical position error (m). Although the lateral and vertical position error falls within the required CAT III lateral and vertical position error, the filter appears to diverge near the end of the simulation. This implies that the calibration of the APL is useful only for short range approaches. If we were interested for longer range approaches that we need to seek an alternative solution to this problem. The last scenario gives a positive answer to this issue.
Similarly, we present the navigation performance of the combined system of GPS satellites/calibrated APLs in terms of the absolute lateral and vertical position error (m), Fig. 7 (a) and (b). It can be concluded that for this scenario not only is the lateral and vertical position error an order of magnitude smaller that the required CAT III one but also the stability of the filter is very good.

While the approach with calibrated APLs can be employed for APL clocks with good short-term stability the system with combined APLs and SATs can be employed for clocks with either good long term or short-term stability. Therefore, the remaining error during the calibration phase for APLs can be overcome by processing SAT data.

The overall navigation performance measure of this system is summarized in Table I, where for every system/error both the sample mean and the standard deviation of the sample mean are presented.
Fig. 8. $Pr(MD)$ and $Pr(FA)$ with (a) Sat data, (b) 5 un-calibrated APLs, (c) 5 calibrated APLs, and (d) 5 calibrated APLs and Sat data.

According to the navigation performance measure results summarized in Table I the following can be concluded:

1. The system with 5 uncalibrated APLs is inadequate to perform the navigation requirements of CAT III landing.
2. The system of the combined APLs and GPS satellites achieves the best the navigation accuracy performance measure. Hence, this is the desired system to be employed under normal conditions.

For four combinations of the GPS satellite and/or calibrated/uncalibrated APLs, the average probability of misdetection and the average probability of false alarm are computed using different values of the residual threshold (see Fig. 8 (a), (b), (c), and (d)). The 95% confidence interval of the mean of the probability of misdetection and probability of false alarm are constructed and pictured in Fig. 8 (a), (b), (c), and (d) for any of the scenarios described in the beginning of this section.

### Table II

**Summary of the Integrity Performance Measure**

<table>
<thead>
<tr>
<th>System</th>
<th>$P_{FA}$</th>
<th>$P_{MD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAT</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Un-cal. APLs</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Cal. APLs</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>SAT &amp; Cal. APLs</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The overall integrity performance measure of this system is summarized in Table II, where for every system only the sample mean of the probability of false alarm and misdetection is presented.

Based on the integrity data shown in Table II we conclude that:

1. Any of the SAT, uncalibrated APL, and calibrated APL systems cannot achieve a probability of misdetection of 0.001.
2. Only the combined system of SATs and calibrated APLs can achieve a probability of misdetection of 0.001.

### V. Summary and Conclusion

In order to fulfill the CAT III navigation and in integrity requirements under severe geometry, weather and interference/jamming conditions a combined system of 5-APLs and satellites can be used. This system provides superior navigation and integrity performance compared to any of the SAT, uncalibrated APL, and calibrated APL systems.

Note that once the APL clocks are calibrated, then a great deal of improvement on the navigation/integrity performance measure is obtained (see Fig. 8(b)). Calibration period enables the APL system to meet the CAT III requirements on navigation accuracy and a probability of misdetection of 0.001. The S band frequency of APLs enables safe operation of the navigation/integrity system under severe interference and/or jamming conditions.

A higher trajectory resolution will enable better estimation of the probability of misdetection and false alarm.

### ACKNOWLEDGMENT

The support of the Department of Electrical and Computer Engineering at Worcester Polytechnic Institute is greatly acknowledged.
REFERENCES


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