Opportunistic Integrity Monitoring for Enhanced UAV Safety

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An opportunistic advanced receiver autonomous integrity monitoring (OARAIM) framework for unmanned aerial vehicle (UAV) navigation is developed. This framework aims at fusing ambient terrestrial signals of opportunity (SOPs) with global navigation satellite system (GNSS) signals to provide tight protection level (PL) bounds. A receiver is assumed to make pseudorange measurements on multiple GNSS satellites and terrestrial SOPs. The PLs of the proposed framework are analyzed, and the reduction in the PLs of a SOP-GNSS solution over that of a GNSS-only solution is studied. It is demonstrated that adding SOP measurements, which inherently come from low elevation angles, is more effective in reducing the PLs than adding measurements from new satellites. Experimental results are presented demonstrating the performance of the proposed system. The results show that OARAIM reduces the vertical and horizontal PLs by 46.7% and 50.9%, respectively, compared to the ARAIM method.

Introduction and Motivation

Autonomous unmanned aerial vehicles (UAVs) are predicted to revolutionize a wide range of sectors, such as surveying, farming, filming, construction, transportation, emergency response, infrastructure inspection, and package delivery. As these vehicles approach full-autonomy, the accuracy and integrity of their navigation system become ever more stringent [1]. While the notion of accuracy is self-explanatory, the notion of integrity is less obvious, but it is of utmost importance in the safety critical application of aviation. Integrity is a criterion to evaluate the reliability and to measure the level of trust in the information produced by a navigation system. A high-integrity navigation system must be able to detect and reject faulty measurements and provide an integrity measure of the confidence in the system performance at any time. Several methods have been developed to monitor a navigation system's integrity, among which the receiver autonomous integrity monitoring (RAIM) method inherently possesses desirable characteristics due to its design flexibility and adaptability [2]. RAIM is a technique primarily based on checking the consistency of redundant measurements. RAIM calculates the protection level (PL) on-the-fly, which is the radius of a circular area centered at the user's true position, containing the estimated position with a probability less than or equal to an acceptable integrity risk. By comparing the PL with a pre-defined alert limit (AL), the availability of the navigation system could be determined; specifically, if the PL is less than the AL, the navigation solution is deemed reliable for the pre-defined integrity risk, and unreliable otherwise.

RAIM was initially proposed for GPS-based navigation. Recently, advanced RAIM (ARAIM) algorithms have been developed for multi-constellation navigation systems, which use measurements from different global navigation satellite systems (GNSS) [3], e.g., Galileo-GPS, GLONASS-GPS, etc. Nevertheless, relying on GNSS signals alone poses an alarming vulnerability for UAV navigation due to line-of-sight (LOS) blockage by high-rise structures, unintentional interference, intentional jamming, and spoofing. Besides, due to the geometric configuration of GNSS satellites, the GNSS navigation solution suffers from large vertical error and uncertainty [4]. To account for GNSS limitations, alternative sensors have been integrated into UAV’s navigation system, and the integrity of these sensors has been the subject of recent studies [5].

In addition to sensors, ambient radio signals in the environment, which are not intended for navigation, have been recently considered as a supplement or an alternative to GNSS signals. These signals, termed signals of opportunity (SOPs), can be terrestrial (e.g., cellular and digital television) [4] or space-based (e.g., low Earth orbit (LEO) satellites) [6]. SOPs possess desirable characteristics for navigation purposes: (i) ubiquity, (ii) high received power, (iii) large transmission bandwidth, (iv) wide range of transmission frequencies, and (v) geometric diversity. Recent research has demonstrated centimeter-level-accurate UAV navigation with cellular SOPs [7] and meter-level-accurate UAV navigation with LEO satellite signals [8]. Moreover, it has been demonstrated that fusing GNSS and cellular SOPs results in significant reduction in the UAV’s position uncertainty [4].

Despite the promise of SOPs, their integrity has been barely studied in the existing literature. This article presents a new paradigm, termed opportunistic ARAIM (OARAIM), which reduces the PLs of UAVs by fusing GNSS and terrestrial SOP pseudorange measurements. It is shown that by incorporating SOPs, the PLs can be made smaller than the ones from any combination of current GNSS constellations, as shown in Figure 1. This reduction is essential in order to meet stringent integrity standard needed for safe UAV operations, especially in (i) GNSS-challenged environments and (ii) environments with poor satellite-to-user geometry. Also, this reduction alleviates the need for additional sensors onboard the UAV, which could be prohibitive due to payload constraints.
A preliminary study to assess the PL reduction due to using SOPs has been considered in [9]. This article extends [9] and makes four contributions. First, the characteristics of cellular SOP measurements for integrity monitoring purposes (namely, accuracy and failure rate) are studied. Second, an SOP-GNSS OARAIM framework is developed and the corresponding vertical PL (VPL) and horizontal PL (HPL) are calculated. Third, Monte Carlo simulations are performed to study the reduction of the SOP-GNSS PLs as a function of the existing satellite-to-user geometry and SOP transmitter-to-user geometry. Fourth, experimental results with cellular SOPs are presented evaluating the efficacy of the proposed OARAIM framework on a UAV. The results show that the proposed GNSS-SOP framework can reduce the VPL and HPL by 46.7% and 50.9%, respectively.

**Terrestrial SOPs Error Characterization**

In order to incorporate SOP measurements into an ARAIM-type framework and determine the integrity of the combined SOP-GNSS system, one must statistically characterize SOP pseudorange measurements, namely determine their accuracy and failure rates. While recent research have studied fault and error sources in SOP-based navigation [10], this article is interested in the statistical properties of these resulting errors.

Two important characteristics of SOP measurements must be evaluated: accuracy and availability. Accuracy refers to the degree of conformance of the measurements with the true ranges, while availability refers to the percentage of time that the measurements are usable by the navigator. In contrast to GNSS signals, SOPs do not have publicly available records for their ranging characteristics. Therefore, the definition of a “fault” in these measurements is still open to interpretation. A study analyzing the statistics of cellular SOP pseudoranges for ground vehicle navigation was conducted in [10]. This article extends [10] to characterize cellular SOP pseudoranges for UAV navigation. The methodology adopted in [10] and in this article can be applied to other types of terrestrial SOPs.

In this article, the data collected by the Autonomous Systems Perception Intelligent and Navigation (ASPIN) Laboratory over several years of experimental campaigns was used to characterize the statistics of cellular SOP pseudorange measurements. Cellular SOP pseudoranges were recorded for an aggregate of tens of hours from UAVs and ground vehicles (GVs). These pseudoranges were obtained using the Multichannel Adaptive TRansceiver Information eXtractor (MATRIX) [4] software-defined receiver (SDR) in (i) different environments; (ii) at different carrier frequencies; and (iii) for different signal types, including long-term evolution (LTE) and code-division multiple access (CDMA) signals. Note that the data collected by GVs was used to characterize cellular SOP measurements, mimicking UAVs flying at low altitudes (e.g., during takeoff and landing phases and performing missions such as goods delivery). Table 1 summarizes the characteristics of the recorded cellular SOPs.

Next, the error component of the SOP measurements (an error equivalent to the GPS user range error (URE)) was characterized using the empirical data and the method discussed in [10]. Figure 2 illustrates the different environments in California, USA, in which the measurements were collected and the empirical probability density functions (pdfs) calculated from the collected measurements. Overlaid on the empirical pdfs are their corresponding Gaussian approximations. The Gaussian parameters, namely measurement error means and standard deviations, were obtained through a maximum likelihood (ML) estimator, and they are summarized in Table 2 for the different environments and flight altitudes. Here, open sky refers to an environment where the receiver has clear LOS to the transmitter, while low (high) altitude refers to altitudes less (greater) than 5 meters above the ground. As can be seen from Table 2, cellular SOP pseudorange error’s standard deviations range from around 10 centimeters to nearly 5 meters.

Calculating the SOP measurements’ availability is a more challenging problem, since no official SOP measurement integrity standard has been established so far. According to the Air Force GPS Standard Positioning Service Performance Standard [11], a fault is identified by a measurement error greater than 4.42 times the broadcast User Range Accuracy (URA) standard deviation. Since cellular SOP measurements have a comparable accuracy to the GPS URE, which is around 4 meters, the same fault identification criterion could be used to determine the availability of cellular SOP measurements. However, URA information pertaining to SOP measurements is generally non-existent. To address this issue, an empirical method similar to the one discussed in [12] was used to approximate the URA standard deviation from collected SOP measurements. To this end, the URE standard deviation was first calculated empirically from the data, as discussed above. Note that the URA standard deviation is a safety critical parameter; hence, it must be more conservative than the URE standard deviation. It is common to inflate the URE standard deviation by 1.5 to obtain the URA standard deviation [2]. For cellular SOP measurements, the URE standard deviation was taken to be the mean of the last column in Table 2, which
Table 1 Characteristics of recorded cellular SOPs.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Platform</th>
<th>Number of transmitters</th>
<th>Signal type</th>
<th>Frequency [MHz]</th>
<th>Bandwidth [MHz]</th>
<th>Traversed path [m]</th>
<th>Test date [DD/MM/YYYY]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open sky</td>
<td>Stationary</td>
<td>2</td>
<td>LTE</td>
<td>2125 and 1955</td>
<td>20</td>
<td>-</td>
<td>13/5/2019</td>
</tr>
<tr>
<td>Semi-urban and urban</td>
<td>GV</td>
<td>2</td>
<td>LTE</td>
<td>2145 and 1955</td>
<td>20</td>
<td>1500</td>
<td>15/11/2016</td>
</tr>
<tr>
<td></td>
<td>GV</td>
<td>3</td>
<td>LTE</td>
<td>2145 and 1955</td>
<td>20</td>
<td>2000</td>
<td>20/1/2017</td>
</tr>
<tr>
<td></td>
<td>GV</td>
<td>4</td>
<td>LTE</td>
<td>2145 and 739</td>
<td>20 and 10</td>
<td>1600</td>
<td>22/6/2018</td>
</tr>
<tr>
<td></td>
<td>GV</td>
<td>5</td>
<td>LTE</td>
<td>1955 and 739</td>
<td>20 and 10</td>
<td>580</td>
<td>27/6/2016</td>
</tr>
<tr>
<td></td>
<td>GV</td>
<td>3</td>
<td>LTE</td>
<td>739</td>
<td>10</td>
<td>825</td>
<td>5/11/2017</td>
</tr>
<tr>
<td></td>
<td>GV</td>
<td>5</td>
<td>LTE</td>
<td>1955 and 739</td>
<td>20 and 10</td>
<td>1800</td>
<td>22/8/2018</td>
</tr>
<tr>
<td>Deep Urban</td>
<td>GV</td>
<td>2</td>
<td>LTE</td>
<td>2145 and 1955</td>
<td>20</td>
<td>345</td>
<td>12/10/2018</td>
</tr>
<tr>
<td></td>
<td>UAV</td>
<td>2</td>
<td>CDMA</td>
<td>882.75</td>
<td>1.23</td>
<td>3300</td>
<td>13/5/2017</td>
</tr>
<tr>
<td></td>
<td>UAV</td>
<td>7</td>
<td>CDMA</td>
<td>882.75</td>
<td>1.23</td>
<td>2900</td>
<td>22/2/2017</td>
</tr>
<tr>
<td></td>
<td>UAV</td>
<td>8</td>
<td>CDMA</td>
<td>882.75</td>
<td>1.23</td>
<td>2200</td>
<td>1/10/2017</td>
</tr>
<tr>
<td></td>
<td>UAV</td>
<td>8</td>
<td>CDMA</td>
<td>882.75</td>
<td>1.23</td>
<td>2600</td>
<td>1/10/2017</td>
</tr>
<tr>
<td></td>
<td>UAV</td>
<td>2</td>
<td>CDMA</td>
<td>882.75</td>
<td>1.23</td>
<td>3500</td>
<td>15/11/2017</td>
</tr>
<tr>
<td>Urban</td>
<td>UAV</td>
<td>11</td>
<td>LTE</td>
<td>739, 1955, 2125, and 2145</td>
<td>10</td>
<td>605</td>
<td>16/6/2019</td>
</tr>
</tbody>
</table>

Figure 2 Characterization of cellular SOP pseudoranges: SOPs environments and corresponding pdfs.
PLs, OARAIM performs fault detection and exclusion to combining navigation signals from different navigation sources. ARAIM, for simplicity. ARAIM is a robust framework for with GNSS signals to form OARAIM. In addition to providing with different signal properties, e.g., different URA values and As such, ARAIM is well-suited for combining SOP signals with the PLs, i.e., horizontal and vertical regions centered at the UAV’s estimated position with a certain level of confidence. In this section, an ORAIM framework is developed to perform integrity monitoring for SOP-GNSS-based navigation. A well-designed integrity monitoring framework provides the UAV with the PLs, i.e., horizontal and vertical regions centered at the UAV’s true position, which are guaranteed to contain the UAV’s estimated position with a certain level of confidence. In this article, a baseline multiple hypothesis solution separation (MHSS) ARAIM, which was introduced in [13], is used to calculate the PLs. In the sequel, ARAIM will refer to MHSS ARAIM, for simplicity. ARAIM is a robust framework for combining navigation signals from different navigation sources with different signal properties, e.g., different URA values and different probabilities of single or multiple simultaneous faults. As such, ARAIM is well-suited for combining SOP signals with GNSS signals to form OARAIM. In addition to providing PLs, OARAIM performs fault detection and exclusion to mitigate the effect of SOP and/or GNSS system faults on the navigation solution. Figure 3 summarizes the OARAIM SOP-GNSS framework for UAV navigation.

OARAIM first constructs a fault tree, whose branches are the different possible fault modes with corresponding a priori probabilities of occurrence. The tree also includes the fault-free mode. The system is assumed to be in one of these possible modes. OARAIM performs multiple statistical tests to detect faults, and then it attempts to exclude the detected faults. The HPL and VPL are subsequently calculated. In the following, the SOP-GNSS fault tree is constructed and the OARAIM algorithm is briefly described.

Fault tree and fault modes
OARAIM considers a list of faults that need to be monitored and determines the corresponding prior probabilities that must be assigned to each mode. For simplicity, a combined SOP-GPS fault tree will be discussed. Extension to other GNSS constellations is expected to be straightforward. In this article, a maximum of three simultaneous faults are considered; therefore, the probability of four or more simultaneous faults is negligible. Also, the probability of a constellation fault (i.e., a fault that affects all transmitters) for both GPS and SOP transmitters are assumed to be sufficiently improbable. This assumption relies on the historical record of these signals. GPS records show that there is no evidence of a constellation fault since the first GPS satellites were launched [14]. Moreover, no SOP “constellation” faults were experienced in any of the tests listed in Table 1. The resulting SOP-GPS fault tree is depicted in Figure 4.

To calculate the mode probabilities, the probability of GPS satellite and SOP transmitter failures must be known, namely \( \{ P_{GPS,i} \}_{i=1}^{N_{GPS}} \) and \( \{ P_{SOP,i} \}_{i=1}^{N_{SOP}} \), respectively; where \( N_{GPS} \) and \( N_{SOP} \) are the numbers of visible GPS satellites and SOP transmitters, respectively. In this article, all SOP transmitter failure probabilities were set to \( P_{SOP,1}^{N_{SOP}} = 10^{-4} \), as calculated earlier, and all GPS satellite failure probabilities were set to \( P_{GPS,1}^{N_{GPS}} = 10^{-5} \), according to the historical records detailed in [14]. Therefore, the SOP-GPS fault tree and the corresponding prior probability of the fault modes can be expressed as shown in Figure 4, where mode 0 corresponds to the fault-free mode, which is the most likely event. Modes 1 to 9 correspond to the faulty operations, including one, two, and three simultaneous faults, while mode 10 is assumed to never occur.

**OARAIM Framework**

In this section, an ORAIM framework is developed to perform integrity monitoring for SOP-GNSS-based navigation. A well-designed integrity monitoring framework provides the UAV with the PLs, i.e., horizontal and vertical regions centered at the UAV’s true position, which are guaranteed to contain the UAV’s estimated position with a certain level of confidence. In this article, a baseline multiple hypothesis solution separation (MHSS) ARAIM, which was introduced in [13], is used to calculate the PLs. In the sequel, ARAIM will refer to MHSS ARAIM, for simplicity. ARAIM is a robust framework for combining navigation signals from different navigation sources with different signal properties, e.g., different URA values and different probabilities of single or multiple simultaneous faults. As such, ARAIM is well-suited for combining SOP signals with GNSS signals to form OARAIM.

### Table 2: ML parameters of Gaussian fits for cellular SOP pseudoranges in different environments.

<table>
<thead>
<tr>
<th>Altitude</th>
<th>Environment</th>
<th>Measurement error mean [m]</th>
<th>Measurement error standard deviation [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low altitude</td>
<td>Open sky</td>
<td>(1.14 \times 10^{-13})</td>
<td>(0.11)</td>
</tr>
<tr>
<td>Low altitude</td>
<td>Urban &amp; semi-urban</td>
<td>(-1.24 \times 10^{-13})</td>
<td>(2.74)</td>
</tr>
<tr>
<td>High altitude</td>
<td>Semi-urban</td>
<td>(-1.65 \times 10^{-13})</td>
<td>(5.42)</td>
</tr>
<tr>
<td>High altitude</td>
<td>Urban</td>
<td>(-3.66 \times 10^{-14})</td>
<td>(0.75)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(7.10 \times 10^{-19})</td>
<td>(1.23)</td>
</tr>
</tbody>
</table>

**Table 2** ML parameters of Gaussian fits for cellular SOP pseudoranges in different environments.

amounts to about 2 meters. For high altitude UAVs, which are the interest of this article, 2 meters is a conservative value for the URE standard deviation, as can be seen from Table 2. Accordingly, a bias larger than \(2 \times 1.5 \times 4.42 = 13.2\) m in the SOP pseudorange measurement is considered a fault. Subsequently, the probability of a cellular SOP transmitter being in a faulty state was calculated empirically by counting the number of times the measurement error in the data exceeded 13.2 m. This probability was found to be \(10^{-4}\).
frameworks, where pseudorange measurement errors are assumed to have zero-mean, ARAIM accounts for unknown but bounded pseudorange biases denoted by $\mathbf{b}_{\text{GPS}}$, $\mathbf{b}_{\text{SOP}}$, $\mathbf{b}_{\text{GGLS}}$, and $\mathbf{b}_{\text{GPS}}$, $\mathbf{b}_{\text{SOP}}$, $\mathbf{b}_{\text{GGLS}}$. For GPS measurements, these biases bound nominal errors, mainly due to the code correlation peak deformation [15]. The values of the biases are extracted from the integrity support message (ISM) and can be limited to 0.75 m [2]. A similar value can be conservatively used for biases in SOP measurements, denoted by $\mathbf{b}_{\text{SOP}}$, $\mathbf{b}_{\text{GGLS}}$, $\mathbf{b}_{\text{SOP}}$, and $\mathbf{b}_{\text{GGLS}}$, as SOP signals are unaffected by atmospheric errors.

A summary of the OARAIM algorithm is given below. The steps shared between OARAIM and ARAIM are not presented here for brevity, but they can be found in [13].

**Step 1:** Evaluate each fault mode: This step derives the following parameters for each fault mode:

- The variance of the fault-tolerant position
- The difference between the fault-tolerant position and the all-in-view position and the variance of this difference
- The worst-case impact of $\mathbf{b}_{\text{GPS}}$, $\mathbf{b}_{\text{SOP}}$, $\mathbf{b}_{\text{GGLS}}$, and $\mathbf{b}_{\text{SOP}}$, $\mathbf{b}_{\text{GGLS}}$ on the position estimate

1 The estimated position using all measurements, except the measurements in the fault mode being evaluated.

2 The estimated position using all measurements.

- Solution separation tests and solution separation thresholds
- A chi-squared sanity test and its threshold

**Step 2:** Calculate PLs: If all of the solution separation tests pass, OARAIM calculates the VPL and HPL using the methodology described in [13]

**Step 3:** Exclude the faults: If any of the solution separation tests fails, ARAIM attempts the exclusion using the methodology described in [2]

**Step 4:** Formulate the vertical positioning performance criteria:

- Criteria 1: 95% accuracy parameter
- Criteria 2: 10^{-7} fault-free position error bound
- Criteria 3: Effective monitor threshold (EMT)

Figure 5 summarizes the OARAIM algorithm.

The achievable positioning accuracy in the vertical domain 99.99999% of the time. According to the LPV-200 standard, the 95% accuracy must be limited to 4 m.

The achievable positioning accuracy in the vertical domain 99.99999% of the fault-free time. According to the LPV-200 standard, the $10^{-7}$ fault-free position error bound must be limited to 10 m.

A parameter that takes into account the faults with a prior $\geq 10^{-6}$. According to the LPV-200 standard, EMT must be limited to 15 m.
degraded due to the ionosphere, troposphere, and multipath. In satellites’ elevation angles theoretically range between 0 and 90 degrees. GNSS receivers typically restrict the lowest elevation angle to a predefined elevation mask (typically around 10 degrees), to discard GNSS signals that are heavily degraded due to the ionosphere, troposphere, and multipath. In contrast, the proposed OARAIM framework sweeps twice the GNSS-only elevation angle range, i.e., -90 to 90 degrees, due to the fact that UAVs can fly directly above terrestrial SOPs.

To illustrate the expected reduction in the PLs as a function of the elevation angle of a newly added transmitter, 10,000 Monte Carlo realizations were generated. In each realization, the azimuth and elevation angles of $N_{GPS}$ GPS satellites were drawn from uniform distributions over the interval [-180, +180] degrees for the azimuth angles and the interval [-90, +90] degrees for the elevation angles. Then, an additional measurement from a new transmitter was introduced. The new transmitter’s azimuth angle was also drawn from a uniform distribution over the interval [-180, +180] degrees, while its elevation angle was swept between -90 to 90 degrees. Figure 6 shows the reduction in the VPL and HPL as a function of the new transmitter’s elevation angle, for different $N_{GPS}$ values and different GPS elevation angle mask.

The following may be concluded from Figure 6. First, while adding measurements from additional satellites decreases PLs, measurements from transmitters at low elevation angles (shaded green region) are on average more effective at minimizing PLs than transmitters at elevation angles between 0 and 90 degrees. Therefore, adding terrestrial SOP measurements, which are coming from transmitters at practically -90 to 0 degree elevation angles, are on average more effective at minimizing the PLs than adding GNSS satellite measurements. Second, the reduction is almost constant at negative elevation angles. This conveys an important conclusion that regardless of the UAV’s flight height (whether above the SOPs or at the same height with respect to SOPs), OARAIM can provide the same PL reduction. Third, in practice, GNSS receivers impose an elevation mask of about 15 degrees, which increases the PLs due to limited satellite-to-user geometry. In such cases, adding SOPs compensate for this limitation and tightens the PLs.

**Table 3 Inputs to the SOP-GPS OARAIM algorithm.**

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
<th>Obtained from</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_{GPS,i}^{N_{GPS}}$</td>
<td>GPS pseudorange measurements</td>
<td>GPS front-end and tracking loop</td>
</tr>
<tr>
<td>$z_{SOP,i}^{N_{SOP}}$</td>
<td>SOP pseudorange measurements</td>
<td>SOP front-end and tracking loop</td>
</tr>
<tr>
<td>$\sigma_{UBA,GPS,i}^{N_{GPS}}$</td>
<td>Standard deviation of GPS user range accuracy</td>
<td>ISM</td>
</tr>
<tr>
<td>$\sigma_{UBA,SOP,i}^{N_{SOP}}$</td>
<td>Standard deviation of SOP user range accuracy</td>
<td>The value of URE multiplied by 1.5</td>
</tr>
<tr>
<td>$\sigma_{URE,GPS,i}^{N_{GPS}}$</td>
<td>Standard deviation of the GPS user range error</td>
<td>ISM</td>
</tr>
<tr>
<td>$\sigma_{URE,SOP,i}^{N_{SOP}}$</td>
<td>Standard deviation of the SOP user range error</td>
<td>Table 2</td>
</tr>
<tr>
<td>$b_{nom,GPS,i}^{N_{GPS}}$</td>
<td>Maximum bias for a GPS measurement</td>
<td>Similar to the GPS maximum bias</td>
</tr>
<tr>
<td>$b_{nom,SOP,i}^{N_{SOP}}$</td>
<td>Maximum bias for a SOP measurement</td>
<td>Similar to the GPS maximum bias</td>
</tr>
<tr>
<td>$p_{GPS,i}^{N_{GPS}}$</td>
<td>Probability of a single GPS fault</td>
<td>Historical records. Currently used value is $10^{-3}$</td>
</tr>
<tr>
<td>$p_{SOP,i}^{N_{SOP}}$</td>
<td>Probability of a single SOP fault</td>
<td>Proposed value is $10^{-4}$</td>
</tr>
<tr>
<td>$P_{Const,GPS}$</td>
<td>Probability of GPS constellation fault</td>
<td>Historical records. Currently used value is 0</td>
</tr>
<tr>
<td>$P_{Const,SOP}$</td>
<td>Probability of SOP constellation fault</td>
<td>Proposed value is $10^{-4}$</td>
</tr>
</tbody>
</table>

**Figure 5 OARAIM algorithm.**

**Performance Evaluation**

This section evaluates the performance of the OARAIM framework numerically and experimentally.

**Simulation Results**

A numerical simulation study was conducted to evaluate the reduction in HPL and VPL by incorporating an additional SOP measurement versus an additional GNSS measurement. Since all GNSS satellites are typically above the UAV, the satellites’ elevation angles theoretically range between 0 and 90 degrees. GNSS receivers typically restrict the lowest elevation angle to a predefined elevation mask (typically around 10 degrees), to discard GNSS signals that are heavily degraded due to the ionosphere, troposphere, and multipath. In contrast, the proposed OARAIM framework sweeps twice the...
In order to study the performance of the OARAIM algorithm under faulty conditions, a simulation was performed with \( N_{SOP} = 6 \) and \( N_{GPS} = 8 \). A fault of a magnitude of 30 m was injected into the sixth SOP measurement. To illustrate the accuracy and integrity performances simultaneously, a so-called Stanford diagram was plotted in Figure 7, where the position error (PE), PL, and AL are shown for three scenarios: GPS-only (brown dots), GPS-SOP without OARAIM fault exclusion (red dots), and GPS-SOP with OARAIM fault exclusion (blue dots). The following may be concluded from this diagram. First, by comparing the blue and brown dots, it can be seen that adding SOPs eliminates system unavailability. Second, injecting the fault into an SOP measurement caused a misleading operation (red dots); however, the OARAIM algorithm rejected the faulty measurement to achieve nominal operation (blue dots).

The UAV flew for 4 minutes, while collecting LTE signals from 11 LTE transmitters in the environment. The stored LTE signals were then processed by the LTE module of the MATRIX SDR to produce LTE SOP pseudoranges, which were then fused with raw GPS pseudorange measurements obtained from the Septentrio receiver to produce the navigation solution along with the corresponding OARAIM integrity measures.

Two sets of results were produced to evaluate the impact of SOP measurements on navigation and safety: (i) a navigation solution and ARAIM integrity measures using GPS measurements only and (ii) a navigation solution and OARAIM integrity measures using GPS and cellular SOP measurements. The two-dimensional (2-D) and three-dimensional (3-D) position root-mean squared errors (RMSEs) and maximum position errors are tabulated in Table 4 for both navigation solutions: GPS-only and SOP-GPS. Figure 9 also shows (i) UAV’s traversed trajectory, (ii) GPS-only and SOP-GPS skyplots showing satellite-to-user and SOP transmitter-to-user geometry, and (ii) GPS-only and SOP-GPS PLs.

<table>
<thead>
<tr>
<th>Solution</th>
<th>2-D RMSE [m]</th>
<th>3-D RMSE [m]</th>
<th>2-D Max. error [m]</th>
<th>3-D Max. error [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS-only</td>
<td>2.34</td>
<td>4.37</td>
<td>9.11</td>
<td>18.08</td>
</tr>
<tr>
<td>SOP-GPS</td>
<td>1.13</td>
<td>3.63</td>
<td>8.28</td>
<td>15.86</td>
</tr>
<tr>
<td>Reduction</td>
<td>51.4%</td>
<td>16.98%</td>
<td>9.14%</td>
<td>12.25%</td>
</tr>
</tbody>
</table>

Table 4 Navigation solution performance comparison

**Conclusion**

In order to meet stringent integrity standards, the PLs of an integrity monitoring system must remain small. This article shows that by incorporating SOPs, the PLs can be made smaller than the ones from any combination of current GNSS constellations. To this end, the article presented an OARAIM framework for enhanced UAV safety. OARAIM enables safe UAV navigation with GNSS and SOPs, producing tight PLs, while identifying and excluding faults, if present. The article characterized the statistical properties of cellular SOP pseudorange measurements for integrity monitoring purposes by studying data collected over extensive experimental campaigns. It was concluded that cellular SOPs have similar characteristics to GPS pseudorange measurements. A fault tree was constructed for SOP-GPS-based navigation and the OARAIM algorithm was presented. Simulation were presented demonstrating that SOPs are more effective than GNSS at decreasing the UAV’s PLs. Experimental results were presented showing that the OARAIM reduces the vertical and horizontal PLs by 46.7% and 50.9%, respectively, compared to the ARAIM method. The PL reduction in OARAIM translates to higher availability of the integrity monitoring system, allowing the UAV navigation system to meet more stringent integrity standards than ARAIM with GNSS only. Subsequently, UAVs can navigate safer and for longer periods of time with OARAIM.

![Figure 7 The Stanford diagram demonstrating the accuracy and integrity performances simultaneously. Although the PL is not calculated after the fault, it is calculated for a longer duration for subsequent analysis.](image-url)
Figure 8: Experimental environment, experimental setup, and experimental results showing the traversed trajectory, the GPS-only and SOP-GPS skyplots, and the PLs. The results show that OARAIM reduces the vertical and horizontal PLs by 46.66% and 50.87%, respectively, compared to the ARAIM method.
Acknowledgements

This work was supported in part by the National Science Foundation (NSF) under Grant 1751205 and in part by the Office of Naval Research (ONR) under Grants N00014-16-1-2809 and N00014-16-1-2305. The authors would like to thank Kimia Shamaei for her help in data collection.

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