Wide Area Multilateration Demonstration System

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Abstract—The Radar Research Group of the Budapest University of Technology and Economics has been developing a distributed passive radar system. Multilateration principle is used to locate aircraft in the zone defined by the location of the receivers. This position estimation method is based on accurate time measurement. The current system uses the signaling of the secondary surveillance radar, specifically the signals emitted by the onboard transponders. As the receivers are far from each other, GPS based synchronization method was developed to maintain the accurate timing at each site. The developed radar system is now capable of simultaneously tracking multiple civilian aircrafts.

Keywords—passive radar; multilateration; GPS based synchronization

I. INTRODUCTION

The need to improve security and reliability of air transport has been a quest since man began to fly. These lead to develop various air traffic control and monitoring systems, including primary and secondary radars. Our system proposes a semi-independent monitoring service, which is based on the signaling of the secondary surveillance radar system, but it can operate independently of that, if it is relying on the transponders so-called squitter mode. The developed system was designed to be a tertiary radar system, to improve availability of air traffic control. As this system is based on multiple receiver stations, it can easily achieve redundant operation. The stations are passive ones, this makes it easier to install at variety of locations.

II. MULTILATERATION PRINCIPLE

The multilateration technique can be used to estimate the location of a signal source, by measuring the emitted signal’s time of arrival at multiple – spatially distributed – sites. As the moment of the emission is unknown, only the differences between the measured values can be used. The presented system uses a method to estimate the location of the source by solving system of linear equations, as described in [1].

Performed simulations indicate that the position estimation error increases away from the zone defined by the receivers. In Fig. 1 is shown a simulation of the location dependent position estimation error phenomenon.

Fig. 1. Location dependent position estimation error with 5 receivers

According to the simulation results, the detection zone is limited by the arrangement of the receivers.

III. WAMLAT SYSTEM

In Fig. 2 is shown the block scheme of the presented system. The system consists of the receivers (light gray boxes) and the central processing server.

Fig. 2. System block scheme
The receivers are connected to the processing server via Internet, which simplifies the installation, since various connection methods can be used.

The main parts of a receiver station are the GPS disciplined oscillator (GPSDO), which provides the accurate timing, and the secondary surveillance radar receiver, which captures the microwave signals, and interprets them. Valid received datagrams are time stamped and sent to the processing server.

IV. GPSDO

The role of the GPS disciplined oscillator is to maintain the system wide synchronism. This component basically is a phase-locked loop, which controls the clock generator to maintain the phase relationship with the GPS receiver’s PPS signal. The PPS is a pulse emitted by the GPS receiver every second. It is accurate to the UTC on average.

Test result in Fig. 3 is shown a long term comparison between two GPSDOs, measuring timing error between them every second.

Fig. 3. Time difference between two GPSDOs

Using this type of synchronization method, the distributed sensor system can be kept in synchronism within tens of nanoseconds.

V. RESULTS

Demonstration measurements were carried out with five receivers, installed across and around the city of Budapest. In Fig. 4 is shown the approximate arrangement of the receivers.

Fig. 4. Approximate arrangement of the receivers

The installation potential was limited; therefore the arrangement pattern is not optimal. Even so it allowed the testing of the system. In Fig. 5 is shown a simulation about the applied arrangement of the receivers. In this case all five receivers were taken into consideration.

Fig. 5. Location dependent position estimation error simulation for the applied arrangement

In the measurements it was allowed, to estimate position from only four received datagrams. In Fig. 6 is shown a worst case simulation of location dependent position estimation errors, where arbitrary four receivers were used in the simulation.

Fig. 6. Worst case location dependent position estimation error

Parallel with the measurements, a comparison was made using real-time data from http://www.flightradar24.com to justify the results.

Legend of the following figures is shown in Table 1.
TABLE I. LEGEND OF THE FIGURES

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>•</td>
<td>position of a receiver</td>
</tr>
<tr>
<td>••</td>
<td>ADS-B datagrams; position estimation</td>
</tr>
<tr>
<td>•••</td>
<td>Mode S datagrams, excluding ADS-B; position estimation</td>
</tr>
<tr>
<td>••••</td>
<td>Mode A and Mode C datagrams; position estimation</td>
</tr>
<tr>
<td>White polygon</td>
<td>the border of Budapest</td>
</tr>
<tr>
<td>Dark blue line</td>
<td>Danube</td>
</tr>
<tr>
<td>Yellow polygon</td>
<td>Budapest Ferenc Liszt International Airport</td>
</tr>
</tbody>
</table>

The red lines and white texts were added later as an image after processing. The information about the flights was gained from [http://www.flightradar24.com](http://www.flightradar24.com).

The position estimations are shown with persistence of couple of minutes. This technique enables to show the trace of the moving aircraft. There may be holes in the traces, caused by the fact, that multiple receiver stations are needed to "see" the aircraft, and current installation sites are not perfect in this manner.

Results are shown in Fig. 7 and Fig. 8 was captured at August 27, 2013. In Fig. 7 and Fig. 8 is shown, that the Mode A and Mode C based multilateration (marked as light blue crosses) produces unreliable results, as the false detection rate is very high. Nevertheless the Mode S based multilateration seems to be good.

As in Fig. 7 and Fig. 8 is shown, the Mode A and Mode C based multilateration produces high false detection rate. A decision was made to use only Mode S based multilateration.

In Fig. 9 only Mode S based multilateration is shown. The measurement results provide good coverage of the traces. At some locations there are "splashes" of the position estimations. This is because of the poor pattern of the receivers. This causes singularity zones, where the accuracy is highly reduced, ergo the position estimation differs from the actual location. This effect could be reduced with a better pattern of the receivers.

It was mentioned earlier, that the flight information was gained from [http://www.flightradar24.com](http://www.flightradar24.com). In Fig. 10 is shown a situation, where a take off flight is unknown, because there was no ADS-B datagrams transmitted. (According to the legend of the figures, the ADS-B datagrams are marked with purple diamonds. It can be noted, that the take off path is exempt from those. The other traces otherwise have ADS-B counts.) Therefore this aircraft was invisible for [http://www.flightradar24.com](http://www.flightradar24.com), while our system could follow it.
VI. QUANTIFYING

It is shown, that the presented system is able to locate aircrafts. Now it must be quantified, how accurate our system is. Our choice for the determination of the accuracy was to decode positions embedded in ADS-B messages, while simultaneously estimate the position of these datagrams by multilateration. The main disadvantage of this method is, that there is unknown delay between the aircraft's GPS receivers, but it means that the accuracy estimation will be upper bounded.

Fig. 11. Long term dataset

In Fig. 11 is shown a long term overlapped measurement result. The purple crosses mark position calculated from ADS-B messages, while green squares mark multilateration estimated position. The shown dataset is clipped, limited to the zone around the receivers.

Accuracy quantifying is based on the distances between the corresponding ADS-B - multilateration positions, which were calculated by the haversine formula. In every case the altitudes were 0 meter above mean sea level, because multilateration cannot resolve it from the available measurements.

Based on the long term dataset:
- the standard error (distance) deviation is 768 meters,
- the average error is 330 meters,
- the median is 128 meters.

The ratio is 6:2.6:1 (relative to the median, respectively). It should be mentioned, that an ideal 2D Gauss distribution has 1.2:1.06:1 ratio.

The probable cause of the significant difference between the ratios is the mentioned delay in the encoded position values of the ADS-B messages. This delay unknown and variable, there was a case for example, where a nearly constant offset (valued approximately 1500 meters) was between the position results of the two method. These outliers distort the parameter estimations.

Assuming the nearly ideal 2D Gauss distribution in the position estimation, the accuracy of the multilateration system is approximately 150 meters, based on the median value.

VII. LIMITATIONS

In Fig. 1 is shown that the position estimation error increases away from the zone defined by the receivers. Measurement in Fig. 12 demonstrates this effect.

Fig. 12. Location dependent accuracy

VIII. SUMMARY

The results provided by our system show a good correlation with data from independent source. Ongoing works include map based displaying, improving the multilateration's accuracy and improving the method of the accuracy estimation.

Our solution can be used as an auxiliary system for improve air traffic safety, especially during unexpected events in air traffic control.
ACKNOWLEDGMENT

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REFERENCES

