Combined ADS-B and GNSS Indoor Localization

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***Abstract*—Satellite-based localization systems do not work well indoors. Signals sent by aircraft in the ADS-B protocol however can be used for indoor localization. We propose improvements to the multilateration using ADS-B messages and then combine ADS-B multilateration with satellite-based localization. Even in situations where not enough satellites are available to estimate a position, the addition of ADS-B signals allows for high localization accuracy. We evaluate our improvements to the ADS-B multilateration and our combined method using a smartphone and an affordable RTL-SDR.**

***Index Terms*—ADS-B, aircraft, GNSS, multilateration, software-defined radio**

I. INTRODUCTION

Knowing your own position has become a need in many situations. People would like to know their positions even in extreme situations, far away from civilization as well as inside a building or urban canyon. Currently no single localization system is reliable in all situations. For outdoor localization, GPS and other satellite-based positioning systems give an accurate location. Inside buildings or in urban canyons, however, satellite signals are often too weak to be received.

Previously, a localization method based on signals transmitted by aircraft has been proposed [1]. Aircraft regularly broadcast information such as their location and velocity for air traffic surveillance in small messages in the ADS-B protocol. Using a software-defined radio (SDR), these messages can be received with much higher signal strength than signals from satellites. With these signals, an approximate location can be computed even inside a building, and in urban situations. Aircraft-based signals are an ideal complement to GPS, as they cover exactly the situations where GPS has disadvantages. However, the localization accuracy of aircraft-based localization is not as good as GPS. In difficult reception conditions messages have to be collected over a long time period.

In this work we present a novel localization system that combines the advantages of satellite-based and aircraft-based localization. First, we introduce novel improvements to ADS-B localization to increase the amount of messages that can be used for the positioning, especially in difficult reception conditions. Especially indoors, interference and low signal strength will reduce the amount of correctly decoded messages.

Messages from aircraft do not include a transmit timestamp. For any multilateration using these messages, we therefore need a system of distributed reference stations in known locations that also receive the messages from aircraft. Using these receivers, we can calculate the send timestamps at the aircraft.

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We propose to use information from this system of reference stations to help the mobile receiver find messages. The mobile receiver can check whether the received signal is similar to an expected message and then calculate the exact arrival time. Correct decoding of the message is not necessary for the estimation of the arrival time.

We then show a method to combine the measurements from ADS-B and satellites to calculate a single position estimate. The few satellites that can be received indoors can be combined with the measurements from ADS-B to help improve the position information, even if there are not enough satellites to compute a position.

We evaluate the performance of the system in different conditions with a smartphone used as mobile receiver. The smartphone can by itself already receive the satellite signals. With an attached cheap RTL-SDR receiver connected over USB, it is also able to decode the ADS-B messages from aircraft.

II. RELATED WORK

Many different methods have been proposed for indoor localization. Especially signals of opportunity are often researched for localization. These signals that are already present for a different purpose can be used for localization as well.

In indoor localization using signals of opportunity, a position is often estimated using a fingerprint of the received signal. For example the received signal strength indicator (RSSI) or the channel state information (CSI) can be calculated for every location in a building to build a database for lookup. When a mobile device estimates the fingerprint, it can look for the closest fingerprint in the database. Fingerprinting methods been proposed for many signals of opportunity, such as Wi-Fi [2], Bluetooth [3] or even FM-radio [4].

Signals transmitted by aircraft in the ADS-B protocol for air traffic control have previously been proposed for localization [1]. However, for accurate localization in difficult reception conditions, messages have to be collected over a long time. By proposing improvements to ADS-B multilateration and combining it with GNSS signals, we can achieve better localization accuracy with only three seconds of recorded data.

ADS-B signals are also interesting for many other applications. As they are not encrypted, they can easily be received using software-defined radios (SDRs). Websites such as Flightradar24 and FlightAware show on a map an overview of the air traffic and can also be used to see delays of flights. The OpenSky Network collects data from aircraft using many receivers for research purposes.

A collaboration with one of these networks would allow us in the future to extend the coverage of our localization system. As aircraft do not transmit at predictable times and do not include a transmit timestamp in the ADS-B messages, we need a system of receivers at known locations that observes the ADS-B messages and calculates the send times. This is necessary for the multilateration using ADS-B messages and also for our improvement where we propose possible messages seen by other receivers to the mobile receiver.

Collected messages from aircraft have also been used for many other purposes than localization. In [5] it has been shown that they can also be used to estimate meteorological parameters such as temperature, wind speed and air pressure. Data about global air traffic can also be used to track movements of government and military aircraft and infer information about relationships and secret meetings between countries [6].

III. SATELLITE-BASED LOCALIZATION

Developed in the 1970s in the USA, GPS was the first accurate satellite based localization method. The basic design principles have not changed since then and many other satellite based localization system have been developed such as GLONASS (Russia), Galileo (Europe) and BeiDou (China). Such systems are collectively called *global navigation satellite system* (GNSS). Generally, a receiver measures the arrival times of signals from satellites on known orbits enabling it to estimate its position.

Usually, a GNSS consist of three components. The *space segment* consists of a satellite constellation with usually more than 20 satellites that orbit the earth. In case of GPS and GLONASS, the altitude of the satellites is approximately $20\,000\,\mathrm{km}$. The satellites continuously send timing and orbiting information to earth. The *user segment* consists of receivers that decode the signals from the satellites and use them in order to calculate their position. The last component is called the *control segment* and consists of infrastructure on the ground. Because satellite clocks might drift and their orbits change slightly, the control segment on the ground is used to periodically check and update the satellite information.

A. Communication

For communication, the satellites use electromagnetic waves between $1\,\mathrm{GHz}$ and $2\,\mathrm{GHz}$, the so-called L-band. These waves are able to pass through the atmosphere, clouds, rain and fog and are therefore ideal for the purpose of transmitting signals from space to earth. Because all satellites broadcast their messages at the same time, *code division multiple access* (CDMA) or *frequency division multiple access* (FDMA) is used to encode their messages. In CDMA, each satellite is assigned a so called *pseudorandom noise* (PRN), which have a cross-correlation function of almost zero. For communication, the PRN is repeated at a high rate and modulated with the actual message bits at a lower rate.

B. Navigation messages

Before the receiver can decode the navigation messages, it first needs to determine which satellites are in view. This process is called *acquisition* and works by correlating the incoming signal with all PRN sequences and all possible frequency offsets. The latter is necessary due to the fact that satellites travel at fast speeds of up to $800\,\mathrm{m\,s^{-1}}$ relative to a stationary receiver on earth resulting in a large Doppler shift. After acquisition, the receiver can decode the navigation messages. The structure of the navigation messages is individual for each GNSS, but it contains at least the following pieces of information:

- The *time of transmission* of the navigation message. This is the core of the GNSS and is used for the range measurement.
- The *clock information* of the satellite.
- The *ephemeris* data, which gives the precise trajectory of the satellite. This enables the receiver to precisely calculate its position. Ephemeris data is usually only valid for a few hours.
- The *almanac* information of the constellation. This information contains details about the trajectories of all satellites and is valid for a long time.

C. Range measurement

The receiver can precisely measure the time of arrival t_j^r of a navigation message from satellite j. Using the time of transmission t_j^t which is contained in that message, the receiver is able to calculate the so called *pseudorange*:

$$\rho_j = c(t_j^r - t_j^t) \tag{1}$$

The clocks are not synchronized and the signal will not travel at exactly the speed of light due to atmospheric properties. To take this into account, we introduce the following error variables:

- T_j represents the delay caused by the troposphere. Depending on the azimuth and the elevation of the satellite with respect to the receiver, this delay can introduce errors in the pseudorange of about $0.2\,\mathrm{m}$.
- I_j models the delay caused by the ionosphere. The effect of the ionosphere also depends on the azimuth and elevation of the satellite and can introduce errors of up to $5\,\mathrm{m}$.
- Δt_j^{SV} is the clock error of the satellite to the GNSS system time. This value is transmitted in the navigation message and is precisely known.
- Δt_G is the unknown clock error between the receiver time and the GNSS system time.

Given an approximate position of the receiver and using atmospheric models, we are able to calculate the approximate values of the first two error variables for every satellite.

Therefore, we can derive the estimate of the range from the receiver to satellite j with the only unknown being Δt_G:

$$d_j = c(t_j^r - t_j^t + \Delta t_j^{SV} + \Delta t_G - T_j - I_j) \tag{2}$$

D. Localization

We are interested in calculating the unknown position of the receiver P_H. The distance between the position of the receiver and the position of the satellite P_j^{SV} needs to be equal to the measured range d_j. We can determine the precise position P_j^{SV} using the time of transmission t_j^t and the ephemeris data. However, the coordinates of P_H and P_j^{SV} are both expressed in a so-called *earth-centered, earth-fixed* (ECEF) coordinate system. Because of the rotation of the earth, the coordinate system also rotates between the time of transmission and the time of arrival [7]. Therefore, we calculate a rotation matrix R_{θ_j} that transforms the position of the satellite represented in the coordinate system at the time of transmission to the corresponding position in the coordinate system at the time of arrival.

Using this rotation matrix, we can now set the geometric distance equal to the measured range:

$$\underbrace{||P_H - R_{\theta_j} P_j^{\mathrm{SV}}||_2}_{\text{geometric distance}} \overset{!}{=} \underbrace{c(\overbrace{t_j^r - t_j^t}^{\text{time of flight}} + \overbrace{\Delta t_j^{SV} + \Delta t_G}^{\text{clock offsets}} - \overbrace{T_j - I_j}^{\text{delays}})}_{\text{range measurement}} \tag{3}$$

With multiple range measurements, this gives us a system of non-linear equations with unknowns P_H and Δt_G. As the system of equations is usually over-determined, we are interested in finding the best approximation in a least squares sense. This leads to an estimate of the desired receiver position P_H.

IV. ADS-B LOCALIZATION

Instead of signals sent by satellites, also other signals can be used for localization. Signals sent by aircraft in the ADS-B standard are interesting for this application as in most populated areas many aircraft are visible at the same time. The signals are received over shorter distances and with higher power than satellite signals.

A. ADS-B

ADS-B stands for Automatic Dependent Surveillance–Broadcast and is a protocol used for air traffic control. Equipped aircraft regularly send short messages containing information such as their position and velocity. Different message types are transmitted at different rates, e.g. position messages are sent about twice per second. The transmission times are not coordinated with other aircraft. To avoid repeated collisions of messages with other aircraft, the transmission times are chosen slightly randomly.

An ADS-B message has a length of 112 bits. The bits are modulated using pulse position modulation (PPM) with a symbol length of $1\,\mu\mathrm{s}$. The position of the pulse of $0.5\,\mu\mathrm{s}$ depends on the bit value. Each message starts with a fixed preamble pattern of $8\,\mu\mathrm{s}$.

B. Synchronization

ADS-B messages do not contain a transmit timestamp. As the transmit times are chosen randomly, we can also not precisely predict when the next message will be sent. To be able to use them for a localization system, this time first has to be calculated. With a receiver at a known location, and the location of the aircraft included in the position messages, the send timestamp can be calculated.

A receiver can decode ADS-B messages up to several hundred kilometers depending on obstacles. Messages from aircraft at low altitudes cannot be received very far. To increase the coverage and to improve the robustness, multiple fixed receivers can be used. Messages that have not been received by any of these reference stations cannot be used for the localization of a mobile receiver in a later step as the transmit timestamp will not be known. This network of reference stations continuously decodes ADS-B messages and forwards them to a central server. The receivers include a precise arrival timestamp for each message. These times are however not synchronized between the different reference stations. The clocks have an offset and additionally also suffer from a drift. The server therefore not only has to compute the transmission timestamps of the ADS-B messages, but additionally also synchronize the reference stations based on messages that have been seen by multiple stations.

C. Localization

A mobile receiver that wants to calculate its position also needs to receive ADS-B messages for a short time period. After decoding the messages, it can look up these messages on the central server to get their transmission timestamps at the aircraft. The time of the mobile receiver, however, is not synchronized to the system of reference stations.

With the unknown time offset Δt_H and drift D_H of the mobile receiver, we can express the distance between the mobile receiver and the airplane for message j which was sent at time t_j^t and received at time $t_{H,j}^r$:

$$d_j = c(t_{H,j}^r - t_j^t + \Delta t_H + D_H(t_{H,j}^r - t_{H,1}^r)) \tag{4}$$

Similar to the satellite based localization, we can set the geometric distance equal to the measured range with the location P_j of the aircraft and the unknown receiver location P_H:

$$\underbrace{||P_H - P_j||_2}_{\text{geometric distance}} \overset{!}{=} \underbrace{c(\overbrace{t_{H,j}^r - t_j^t}^{\text{time of flight}} + \overbrace{\Delta t_H + D_H(t_{H,j}^r - t_{H,1}^r)}^{\text{clock offset and drift}})}_{\text{range measurement}} \tag{5}$$

With multiple received messages, a system of non-linear equations can be formed from Equation 5 with the unknowns P_H, Δt_H and D_H. By solving this with a least-squares solver, the position of the mobile receiver can be determined.

V. METHOD

We propose a localization method that combines satellite-based localization with messages sent by aircraft in the ADS-B protocol. By combining the two signals, we have the advantages of both. ADS-B signals are received much stronger and can even penetrate walls. Satellite-based systems allow for a higher localization accuracy but in many cases too few satellite signals can be received inside buildings. By combining the two, we have the availability of the aircraft-based system as well as the accuracy of a satellite-based localization.

Before we combine the ADS-B and satellite-based localization, we propose improvements to the multilateration using ADS-B messages.

A. *Improved ADS-B localization*

Let us look at how ADS-B messages are received and decoded in more detail. The software framework that we use, `dump1090-hptoa` [8], searches for the message preamble in the stream of incoming samples and then tries to decode the message bits. Very weak messages can therefore be missed. Also, the messages can only be used for localization if they contain less than two bit errors. Messages with more than two bit errors have to be discarded as their payload cannot be reconstructed with the checksum included in the ADS-B message. We want to leverage the network of reference stations that continuously receives all ADS-B messages. This enables us to explicitly search for messages in our received signal and therefore increase the number of messages that can be used for localization.

For this improvement to be applied, we make some small assumptions. We assume that the position of the mobile receiver is approximately known and that we successfully decoded any other ADS-B message that has also been seen by our reference stations. This enables us to calculate the offset between the system time of the receiver to the system time of the reference stations. We can assume a clock drift of zero and can calculate the offset by reformulating Equation 5:

$$\Delta\tilde{t}_H = \frac{||\tilde{P}_H - P_j||_2}{c} - (t^r_{H,j} - t^t_j) \tag{6}$$

Given this offset and again assuming a clock drift of zero, we can calculate the approximate time of arrival for any other message j as:

$$t^r_{H,j} = t^t_j - \Delta\tilde{t}_H + \frac{||P_H - P_j||_2}{c} \tag{7}$$

Despite the uncertainty of our reference position and the error introduced by the clock drift, this leaves us with a maximum of a few hundred microseconds (light travels around 30 km in 100 µs) that could contain the message. Once we have identified the samples in our received signal where the message should be present, we correlate them with the ADS-B message from the server. The highest correlation value identifies the start of the message, if it is present.

To determine whether the message is actually present in our received signal we try to decode the message. This is done by looking at all 1 µs intervals of the 112 µs long message signal. We compare the sample mean of the two halves of every interval and decode it to either 1 or 0 according to pulse position modulation. While this gives the correct information bit for an actual message symbol, an interval containing only noise will decode to either 1 or 0 with the same probability.

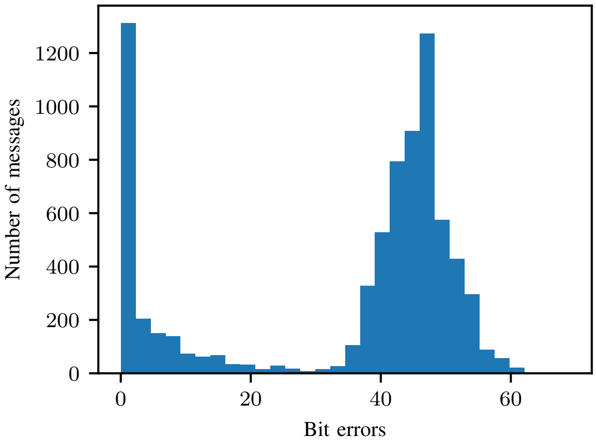

Fig. 1: Distribution of bit errors of a total of 7597 ADS-B messages that were decoded in our received signal. We see a separation of the distribution between 20 and 30 bit errors. This separation splits the messages that are visible with some errors from the messages that are not present at all.

After decoding all intervals, we compare the bits to the actual message payload. If the message is not present in the samples, we expect about half of the bits to be erroneous, which means 56 bit errors in expectation. Figure 1 shows the resulting distribution of the bit errors for 7597 messages that were received by our network of reference stations. The distribution seems to clearly separate messages that are present in the received signal from messages that are not. We therefore assume that messages with less than 20 bit errors are present in the received signal with a high probability and can be used for localization.

The normal ADS-B multilateration solves the system of equations presented in Equation 5. No weighting of the individual equations takes place. However, using our message hinting approach we are able to also use messages with very low signal strength for localization. This also leads to larger uncertainty in the arrival times. We trust the information contained in some equations more than others and want to apply proper weighting. We choose the weights as the reciprocal of the number of bit errors: a message with no bit errors should have a much higher weight than a message that contains a large number of bit errors. For a message with e_j bit errors, we set the weight of the corresponding equation to

$$w_j = \frac{1}{e_j + 1}. \tag{8}$$

B. *Combined localization*

The improvements presented in the last section enable us to use more messages for localization. We now show how to we can combine the ADS-B localization system with a set of range measurements from GNSS. Let us recall the systems of equations for satellite and airplane-based localization presented in Equations 3 and 5. Both set the geometric distance equal to the range measurements. As both systems of equations share the unknown P_H, we can combine them and jointly find the best approximations for the union of the unknowns using a non-linear least squares solver.

As we are interested in improving the accuracy in an indoor setting, we need as many satellites as possible. Therefore combining several GNSS is beneficial. If we combine multiple GNSS, we need to take the time bias between the different GNSS into account [9]. We introduce $\Delta\tau_2, \dots, \Delta\tau_l$ as unknown time biases for l different GNSS and use the first GNSS as reference. For GNSS i and satellite j, the equations of the satellite range measurements now have the following form:

$$||P_H - R_\theta P^{SV}_{i,j}||_2 \overset{!}{=} c(t^r_{i,j} - t^t_{i,j} + \Delta t^{SV}_{i,j} + \Delta t_G + \Delta\tau_i - T_{i,j} - I_{i,j}) \tag{9}$$

This equation can also be combined with the airplane-based system. As the system of equations now contains equations resulting from ADS-B measurements and others from GNSS signals, we weight the equations of the satellite range measurements relative to each other and relative to the equations of the ADS-B messages. For the ADS-B messages in the previous section we chose a weight between 0 and 1 depending on the number of bit errors. In general, we expect the ranges from satellites to be more precise than the ranges calculated from the ADS-B messages. Therefore, we set the weights of satellites to a number larger than 1. However, using weights that are too large, the system of equations can become ill-posed as we expect the indoor satellite range measurements to come from similar directions (for example through the same window). We therefore choose to set the weights for the satellite equations between 1 and 2. The concrete weight is derived by adding 1 to the uncertainty estimate $\sigma_{i,j} \in (0, 1]$ of the time of arrival.

We therefore have the following system of equations for a localization approach using both aircraft signals and satellite range measurements of multiple GNSS. For every satellite range measurement of satellite j of GNSS i, we add the extended equation

$$||P_H - R_\theta P^{SV}_{i,j}||_2 \overset{!}{=} c(t^r_{i,j} - t^t_{i,j} + \Delta t^{SV}_{i,j} + \Delta t_G + \Delta\tau_i - T_{i,j} - I_{i,j})$$

using the weights

$$w_{i,j} = \sigma_{i,j} + 1.$$

Additionally, for every ADS-B message k we add the equation

$$||P_H - P_k||_2 \overset{!}{=} c(\hat{t}^r_{H,k} - t^t_k + \Delta t_H + D_H(\hat{t}^r_{H,k} - \hat{t}^r_{H,1}))$$

using the weights

$$w_k = \frac{1}{e_k + 1}.$$

With n satellite measurements from l different GNSS and m ADS-B messages, this results in $n + m$ equations and the unknowns P_H, Δt_H, D_H, Δt_G, $\Delta\tau_2$, $\dots$, $\Delta\tau_l$ that can be solved using a least-squares solver.

VI. EVALUATION

We have proposed improvements to multilateration using ADS-B signals and combined it with GNSS signals. We evaluate the performance of the system indoors and outdoors and show the performance improvements compared to ADS-B multilateration and localization using GNSS signals.

A. Setup

A Sony Xperia 10 smartphone is used with an attached RTL-SDR receiver to record data for the evaluation. A ported version of dump1090-hptoa runs on the smartphone to receive the raw samples from the SDR and decode ADS-B messages. An additional app is used to save the ADS-B data to JSON files for offline evaluation. The same app also records the raw GNSS measurements of the GNSS subsystem for both GPS and GLONASS.

The recorded JSON files are evaluated offline on a computer to calculate all position estimates. However, it would also be possible to calculate the positions directly on the smartphone. Communication between the smartphone and the central server collecting the ADS-B messages would be necessary to have access to the ADS-B messages seen by the reference stations and the calculated transmit timestamps of the messages at the aircraft.

With a sampling rate of $2.4\,\mathrm{MHz}$ for the RTL-SDR, each recording of raw ADS-B samples of three seconds duration requires $14.4\,\mathrm{MB}$ of storage. The decoded ADS-B messages and the satellite range measurements range measurements only need a few kilobytes. However by computing the positions directly on the smartphone, this storage would not be necessary.

For satellite range measurements we used an Android framework that provides access to raw GNSS measurements on supported Android devices [10]. The GNSS subsystem handles the acquisition and tracking of the satellites and provides the app with the raw measurements of all supported GNSS in a unified way.

The GNSS sub-system provides a full set of raw measurements for all satellites once per second. During three seconds of recording, which is necessary to receive a sufficient number of ADS-B messages, we therefore have multiple sets of raw GNSS measurements. We combine all range measurements in a single system of equations and compute a single position out of them. Range measurements of the same satellite are treated as two different satellites with slightly different timestamps.

To compare the improvement of our proposed localization methods, we calculate the following four position estimates:

a) ADS-B: This estimate computes the position using multilateration with only the directly decoded ADS-B messages of each recording.

b) Improved ADS-B: This estimate computes the position with ADS-B messages with the improvements described in Section V-A. The position estimate is obtained by using the raw ADS-B signal and applying the proposed improvements.

c) GNSS: With the satellite range measurements of the GNSS subsystem, we compute this estimate using the open-source framework `laika` [11].

TABLE I: Collected data sets with median position error for all position estimates. The seven data sets recorded in buildings and the two data sets recorded outdoors are evaluated for four different position estimation methods. Data set 3 was recorded in a room without any windows and localization was possible for less than half of the recordings. Its performance is discussed in Section VI-B.

#	Date	recordings	ADS-B [m] [1]	Improved ADS-B [m] (our work)	GNSS [m]	Combined [m] (our work)
1	2020-03-14	89	51.7	26.4	13.5	**12.9**
2	2020-03-15	90	81.9	72.3	173.1	**54.1**
3	2020-02-24	50	-	-	-	-
4	2020-03-15	80	40.5	35.1	**21.6**	24.5
5	2020-02-21	164	20.0	18.2	90.5	**17.6**
6	2020-02-24	93	30.8	25.2	33.2	**16.1**
7	2020-03-10	90	55.1	33.7	192.1	**24.1**
all indoor sets		656	38.0	30.4	54.2	**21.5**
8	2020-03-14	90	46.6	33.3	**8.7**	18.3
9	2020-03-15	90	23.0	20.2	**9.7**	14.5
all outdoor sets		180	31.6	26.2	**9.0**	16.7

d) Combined: This estimate combines the ADS-B and GNSS measurements as described in Section V-B. It uses all satellite range measurements and includes the improvements to the ADS-B localization.

All position estimates only use the data included in a recording of three seconds duration. The position estimates are independent of each other. A Kalman filter could be used while tracking to filter the results and achieve even higher accuracy.

As GNSS localization by itself already gives very accurate positions in outdoor settings, we are mostly interested in the performance in buildings. Indoors the reception conditions are much more difficult and also not all ADS-B messages are visible anymore. Therefore, we have collected recordings in nine data sets, seven of them inside and two outdoors. The performance of the different localization methods for the individual data sets can be seen in Table I. Most of the indoor settings were in rooms with windows on one side. One data set, set 3, however was recorded in the middle of a building in a bathroom with no windows.

B. Localization accuracy

We evaluated the four position estimates for all data sets. The results can also be seen in Table I. The given error is the horizontal distance between the estimated position and the actual position of the mobile receiver.

In this difficult condition of data set 3 most localization estimates were unsuccessful, therefore the median accuracy does not exist in the table. The results on this data set will be discussed later in this section.

The 656 recordings indoors have a median localization error of 21.5 m with our proposed *Combined* localization method. Also the *Improved ADS-B* method based only on ADS-B messages with a median error of 30.4 m performs better than the *ADS-B* and *GNSS* methods that achieve median errors of 38.0 m and 54.2 m. Figure 2 shows the cumulative distribution function of the localization error for all indoor data sets together. As we can see in this figure, not only the median accuracy differs between the methods, but also the ratio of successful localization estimates. We see that the *Combined* method outperforms all others, with the *Improved* method following. The *GNSS* method has the fewest successful localization estimates indoors. These results show us that by combining the ADS-B and GNSS measurements, the few available GNSS range measurements still improve the performance over only using the ADS-B measurements also in an indoor setting.

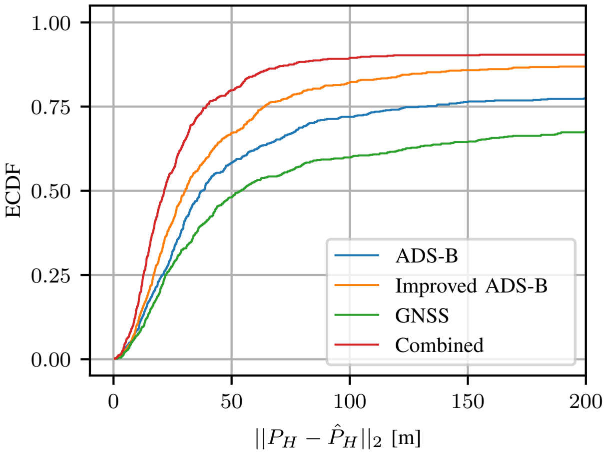

Fig. 2: Distribution of the position error for the 656 indoor recordings. The *Improved ADS-B* and especially the *Combined* estimates are more often successful and more accurate than the *ADS-B* and *GNSS* estimates.

In the outdoor settings with 180 recordings, the *Combined* method achieves a median accuracy of 16.7 m. The two methods using only ADS-B signals, *ADS-B* and *Improved ADS-B*, achieve an accuracy of 31.6 m and 26.2 m. The best results are achieved with the *GNSS* method with a median error of 9.0 m. This shows that for localization outdoors using

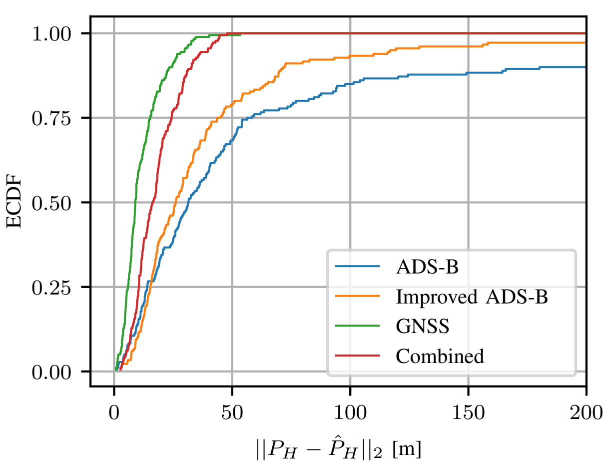

Fig. 3: Distribution of the position error for the 180 outdoor recordings. The *GNSS* estimate has the highest accuracy, but also the *Combined* estimate achieves a median accuracy of 16.7 m. The estimates only based on ADS-B messages are less accurate.

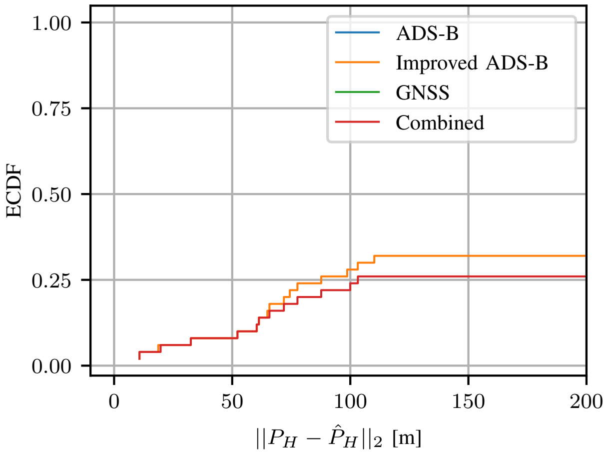

Fig. 4: Distribution of the position error for data set *3*. In this setting in a room with no windows, only the *Improved ADS-B* and the *Combined* method could sometimes successfully estimate a position.

ADS-B messages does not give as accurate results as only GNSS measurements. It would therefore also be possible to decide based on the number of GNSS measurements to either use the *GNSS* or the *Combined* method. Figure 3 shows the cumulative distribution function of the localization error for all outdoor recordings.

Figure 4 shows the position accuracy for data set 3. We can see that in this extreme setting in a room with no windows only the *Improved ADS-B* and *Combined* methods are successful sometimes. Only very few ADS-B messages could directly be decoded and therefore the *ADS-B* estimate was not successful.

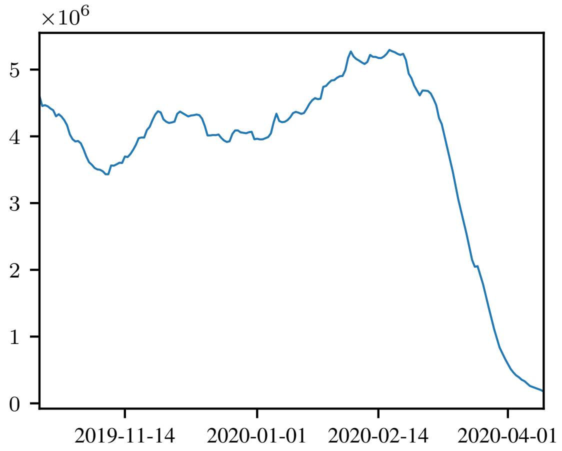

Fig. 5: Moving average of ADS-B messages collected per day by the network of reference stations. The number of received messages drastically decreased in March of 2020.

In the indoor setting the number of aircraft from which messages can be decoded has a large impact on the localization performance. The left plot of Figure 6 shows for these data sets from how many aircraft there were decodable messages. The plot on the right shows the localization performance for the *ADS-B* and the *Improved ADS-B* methods in relation to the number of aircraft. For both methods the accuracy improves with a higher number of aircraft. The *Improved ADS-B* method is able to estimate an accurate position with fewer visible aircraft as the messages do not need to be perfectly decodable. Multiple messages from the same aircraft are possible in a recording. For the accuracy, the number of distinct aircraft is more important than the number of messages as the aircraft are in different locations and help reduce the dilution of precision. ADS-B messages can be received over several hundred kilometers. A quick glance at flight tracking website such as Flightradar24 shows us that in populated areas, the density of aircraft is high, even without an airport nearby. The indoor localization should therefore work in most places.

As we have shown, the improvements to the ADS-B multilateration allow us to use more messages from aircraft, even if they cannot be perfectly decoded at the mobile receiver. This results in a better localization accuracy. However, we still need sufficiently many aircraft that send messages and also the combination with GNSS signals only works well if messages from many aircraft are available. In March of 2020 the number of aircraft over Europe reduced drastically. Due to the coronavirus pandemic the air traffic was severely restricted. In Figure 5 the number of ADS-B messages collected by our system of receivers can be seen. The decline in air traffic might already have affected some of our data sets that were collected around this time. Because the air traffic is still quite limited, we have to rely on the data sets recorded before this decline in air traffic.

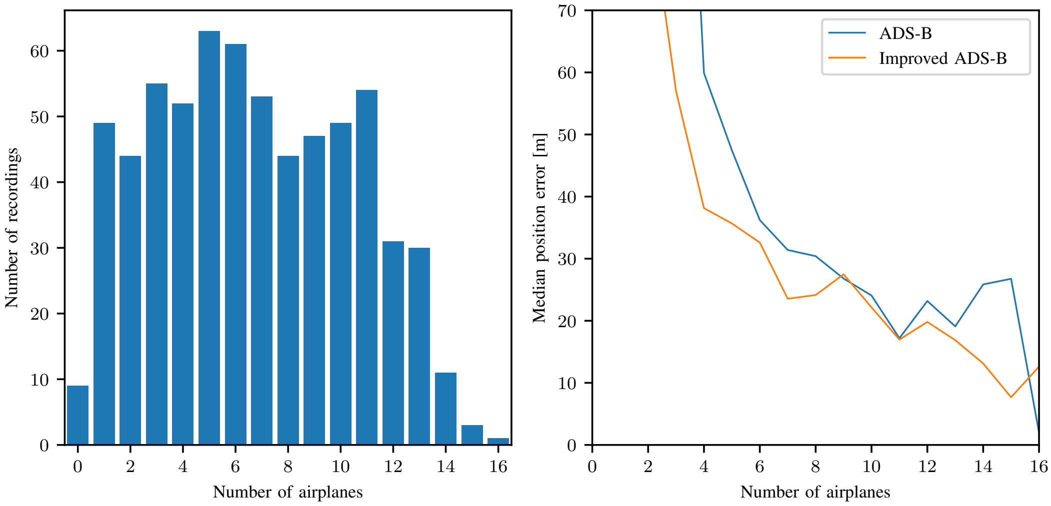

Fig. 6: Median localization error for the indoor data sets depending on the number of airplanes decodable at the mobile receiver. On the left the distribution of the number of aircraft directly decodable using the standard ADS-B decoding, on the right achieved localization accuracy. The *Improved ADS-B* method is more accurate than the *ADS-B* method, especially for low numbers of aircraft from which messages could be decoded. It also is able to estimate a location when messages from too few aircraft can be decoded for the *ADS-B* method.

VII. CONCLUSION

We have proposed improvements to the multilateration with ADS-B signals. With the knowledge about the sent messages, we can help the receiver find messages and use more ADS-B messages for localization. This allows a median localization accuracy of $30.4\,\mathrm{m}$ indoors. Additionally, we have shown a combined localization method using GNSS and ADS-B signals. This method exceeds the results of both GNSS and ADS-B localization in buildings. The localization accuracy is higher with a median error of $21.5\,\mathrm{m}$ and the system is more often successful in estimating a location. Even if not enough aircraft or satellites are visible, by combining the two signal sources, a successful localization is often still possible. Therefore, GNSS signals also help in indoor localization as long as signals from some satellites are visible. As we have shown, this works well in rooms that have at least windows on one side. Outdoors, GNSS localization still allow for the most accurate position estimates.

We have evaluated the localization methods using a smartphone with an attached SDR receiver. In a production system, the ADS-B receiver could be integrated in the smartphone as well.

In the future it would be interesting to combine the proposed method with even more diverse signal sources, such as LTE signals or digital radio in the DAB standard. Especially DAB signals could be interesting for localization as they are sent in a lower frequency band and therefore reception inside buildings should be better than for ADS-B and GNSS.

REFERENCES

[1] M. Eichelberger, K. Luchsinger, S. Tanner, and R. Wattenhofer, “Indoor localization with aircraft signals,” in *Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems, SenSys 2017, Delft, Netherlands, November 06-08, 2017*, M. R. Eskicioglu, Ed. ACM, 2017, pp. 12:1–12:14.

[2] P. Bahl and V. N. Padmanabhan, “RADAR: an in-building rf-based user location and tracking system,” in *Proceedings IEEE INFOCOM 2000, The Conference on Computer Communications, Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies, Reaching the Promised Land of Communications, Tel Aviv, Israel, March 26-30, 2000*. IEEE Computer Society, 2000, pp. 775–784.

[3] R. Faragher and R. Harle, “Location fingerprinting with bluetooth low energy beacons,” *IEEE J. Sel. Areas Commun.*, vol. 33, no. 11, pp. 2418–2428, 2015.

[4] Y. Chen, D. Lymberopoulos, J. Liu, and B. Priyantha, “Fm-based indoor localization,” in *The 10th International Conference on Mobile Systems, Applications, and Services, MobiSys’12, Ambleside, United Kingdom - June 25 - 29, 2012*, N. Davies, S. Seshan, and L. Zhong, Eds. ACM, 2012, pp. 169–182.

[5] R. Trüb, D. Moser, M. Schäfer, R. Pinheiro, and V. Lenders, “Monitoring meteorological parameters with crowdsourced air traffic control data,” in *Proceedings of the 17th ACM/IEEE International Conference on Information Processing in Sensor Networks, IPSN 2018, Porto, Portugal, April 11-13, 2018*, L. Mottola, J. Gao, and P. Zhang, Eds. IEEE / ACM, 2018, pp. 25–36.

[6] M. Strohmeier, M. Smith, D. Moser, M. Schäfer, V. Lenders, and I. Martinovic, “Utilizing air traffic communications for OSINT on state and government aircraft,” in *10th International Conference on Cyber Conflict, CyCon 2018, Tallinn, Estonia, May 29 - June 1, 2018*, T. Minárik, R. Jakschis, and L. Lindström, Eds. IEEE, 2018, pp. 299–320.

[7] M. Petovello. How does earth’s rotation affect gnss orbit computations? Accessed 2021-05-30. [Online]. Available: https://insidegnss.com/how-does-earths-rotation-affect-gnss-orbit-computations/

[8] dump1090-hptoa. Accessed 2021-05-30. [Online]. Available: https://github.com/openskynetwork/dump1090-hptoa

[9] I. G. Petrovski, *GPS, GLONASS, Galileo, and BeiDou for Mobile Devices: From Instant to Precise Positioning*. Cambridge University Press, 2014.

[10] Raw gnss measurements. Accessed 2021-05-30. [Online]. Available: https://developer.android.com/guide/topics/sensors/gnss

[11] Laika. Accessed 2021-05-30. [Online]. Available: https://github.com/commaai/laika