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Indoor Localization with Aircraft Signals

Sensys 2017

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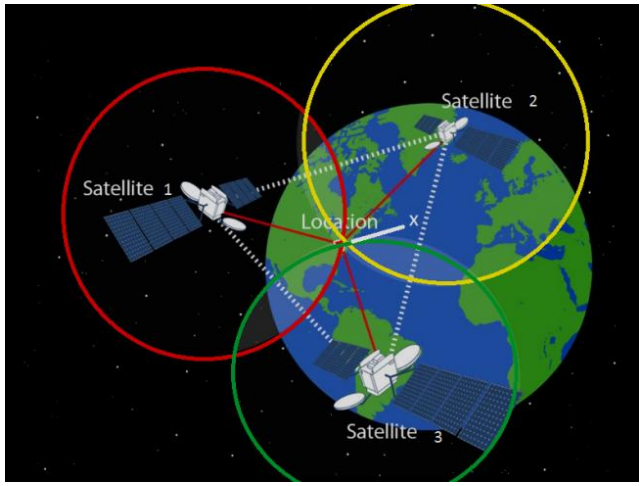
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1. INTRODUCTION

• The British Science Association has recently called GPS technology the #1 invention "that changed the world".

• Originally developed by the US military, GPS is now used in a majority of mobile devices.

• However, GPS also has a major drawback — Its satellite signals cannot be received indoors.





• A GPS satellite gets its energy from a dual solar array, which (depending on the generation of the satellite) generates about 400-2900 W of power.

• With an altitude of about 20,000 km, this relatively weak signal barely makes it to earth, already the free space path loss is in the order of 180 dB.

• In contrast, airplanes and other aircraft are flying at an altitude below 13.7 km.

• For safety reasons, airplanes and helicopters repeatedly transmit their location, pretty much like GPS satellites.

• These so-called ADS-B signals are strong enough to be received indoors, even with cheap hardware.

✓ three challenges

• Aircraft do not fly on an orbit;

• aircraft do not have accurate predetermined flight paths and unexpected changes to their route are always possible, for instance due to a holding pattern when approaching a crowded airport.

• Aircraft are not uniformly distributed in the sky.

• This is in stark contrast to GPS satellites, which cover the sky in a regular pattern in order to maximize user localization performance.

• Aircraft position signals are not precise:

• an aircraft has an unpredictable delay between learning its position from the GPS satellites and retransmitting this position;
• unlike GPS satellites with their atomic clocks, aircraft transmissions do not include time information;
• some aircraft in fact do not even include position information.

✓ three challenges

• Aircraft do not fly on an orbit;
=> passengers and crew certainly do not appreciate abrupt flight path changes.

• Aircraft are not uniformly distributed in the sky.
=> at least in urban areas there are more aircraft available than satellites.

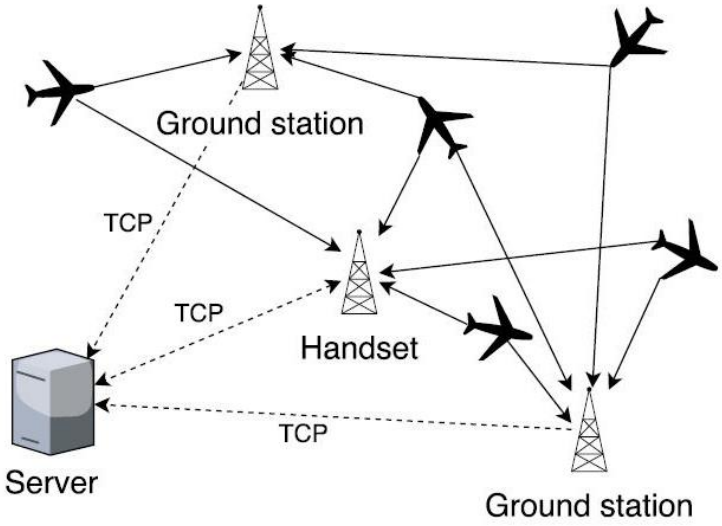
• Aircraft position signals are not precise:
=> A large number of received signals hopefully reduces the statistical uncertainty of the position estimation from noisy measurements.

✓ Consists of

• a network of receivers with known positions, which we call ground stations
=> receive aircraft signals, decode messages, precisely time their arrival times and send the messages together with the time stamps to the server.

• a receiver whose position should be determined – we refer to this receiver as the handset

• a server, which connects the ground stations and the handset
=> determine the message's transmit position and time.



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✓ Results

• The GPS Performance Standard [13] by the US government currently lists a worst-case horizontal GPS accuracy better than 17 meters in 95% of all cases.

• Depending on the quality of the receiver and whether different advanced correction methods are available, the horizontal accuracy can be substantially better, in the order of 3-7 meters.

• In terms of accuracy, our method cannot compete with these indoor localization techniques, and does not even achieve the typical GPS outdoor accuracy.

• Our prototype implementation has a median error of about 25 meters.

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✓ Application

• On the plus side, it works both indoors and outdoors!

• our method may tell you in which building you took some photograph.

• our method can help you catch the next bus from your current location.

• one can automatically log the working time of employees by just knowing an approximate indoor position.

• Due to the higher signal strength of the aircraft signals, our system also works in urban canyons.

• Generally, our system works well when the application needs both indoor and outdoor locations, or when dedicated indoor localization infrastructure is too costly to deploy.

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✓ Contribution

• Generally, our system works well when the application needs both indoor and outdoor locations, or when dedicated indoor localization infrastructure is too costly to deploy.

• Finally, and probably most importantly, our method may serve as a more accurate initial guess for Assisted GPS (A-GPS) than currently provided by cellular networks.

• Another upside of our method is that it is pretty much independent from additional infrastructure, as for real-time tracking only an Internet connection

• Since our method and implementation presented in this paper are a proof of concept, future improvements might yield more accurate positioning.

•To the best of our knowledge, there is no closely related prior work to our approach.

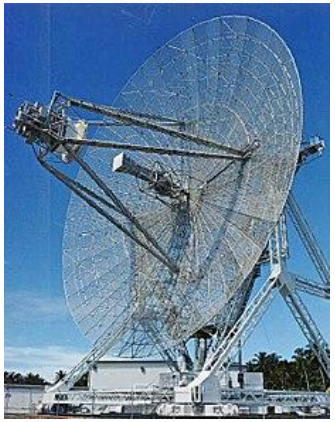
2. BACKGROUND

✓ Air Traffic Surveillance - Primary Radar



• Air traffic surveillance has emerged as a fundamental requirement for air traffic control.

• Radar systems send out powerful pulses of electromagnetic signals. When these pulses are reflected at an object, the back-scattered energy can be detected.



•Given the angle of arrival and the round trip time, the position of that object can be determined.

• Due to the resulting high energy consumption(소비), radar antennas are tied to the ground as fixed facilities.

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✓ Air Traffic Surveillance - Secondary Surveillance

• The messages we employ for our method are part of the secondary surveillance system for air traffic control.

• Two types of secondary surveillance techniques exists:

• Aircraft can be “interrogated(응답하는)” by ground stations and respond appropriately, or they simply transmit messages periodically.

• The former is denominated Secondary Surveillance Radar and the latter is called ADS-B.

• In contrast to the primary radar, the received power of the secondary surveillance signals is higher, because the signals are actively sent by the aircraft.

✓ Air Traffic Surveillance - Secondary Surveillance Radar(SSR)

• Detects and identifies aircraft and receives barometric pressure measurement data, from which the flight level of aircraft can be determined.

• The SSR has multiple interrogation modes with different message formats.

• Mode A : aircraft reply with their identity.

• Mode C : gather aircraft altitude(고도) calculated from the barometric pressure

• Mode S : supports different message formats, including ADS-B messages

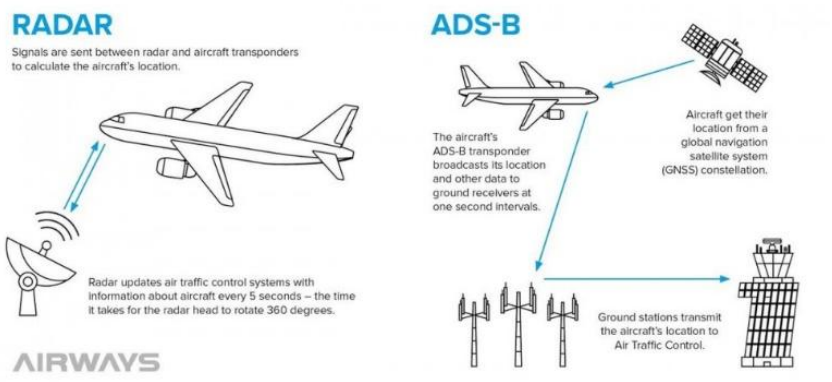
✓ Air Traffic Surveillance - ADS-B(Automatic Dependent Surveillance – Broadcast)

• aircraft with ADS-B transponders send out messages periodically, that is without interrogation.

• ADS-B messages can contain a variety of information.

• For our system, mainly the position and the velocity of the aircraft are of interest.

• the most commonly used is the 1090 MHz channel, because many aircraft already have a transponder for Mode C installed, which operates at this frequency.

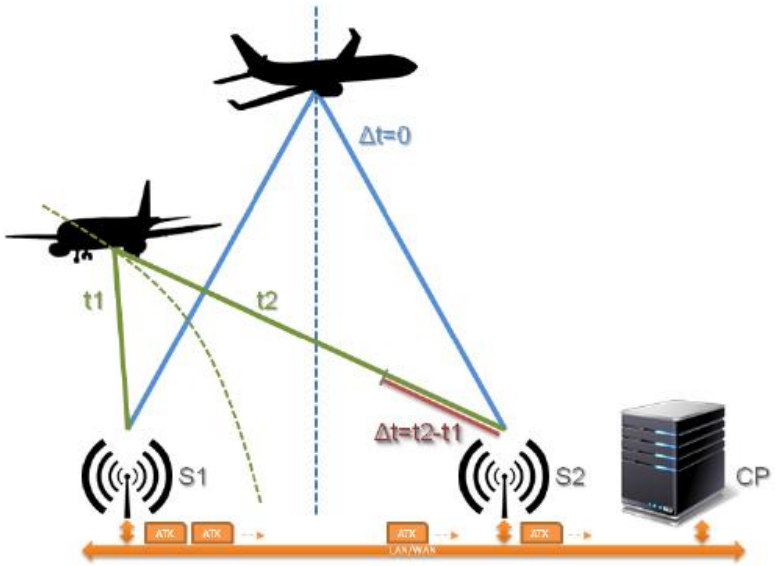


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✓ Multilateration

• Multilateration is an established technique and used in many radio navigation systems such as GPS and LORAN-C.

• It is also called time difference of arrival (TDOA) which stems from its usage of measurements of signal arrival time differences from multiple transmitters.



3. METHOD

• The main idea of our method is to replace GPS satellites with aircraft in order to receive stronger signals, which are more suited for indoor reception than GPS signals.

(1) The ground stations and the handset send the recorded ADS-B messages with the corresponding time stamps to a server.

(2) The server collects the messages and matches the messages from the handset to those from the ground stations.

(3) The server computes send times of the messages and the position of the handset

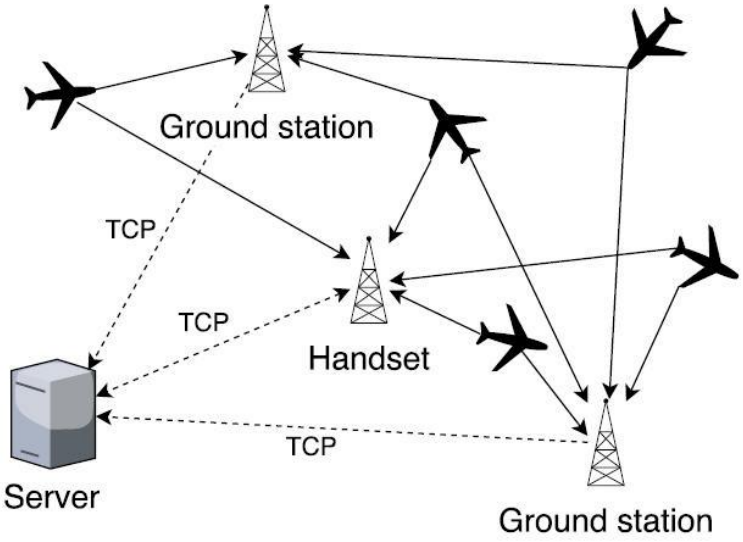


Figure 1: System consisting of a server, ground stations at known locations, a handset at unknown location and aircraft. The ground stations and handsets determine the receive time of messages from aircraft to then calculate the send time of the messages and the location of the handset.

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✓ **two steps**

(1) Calculation of message send times and aircraft positions (if not given in messages)

(2) User localization: Multilateration using messages with now known send times.

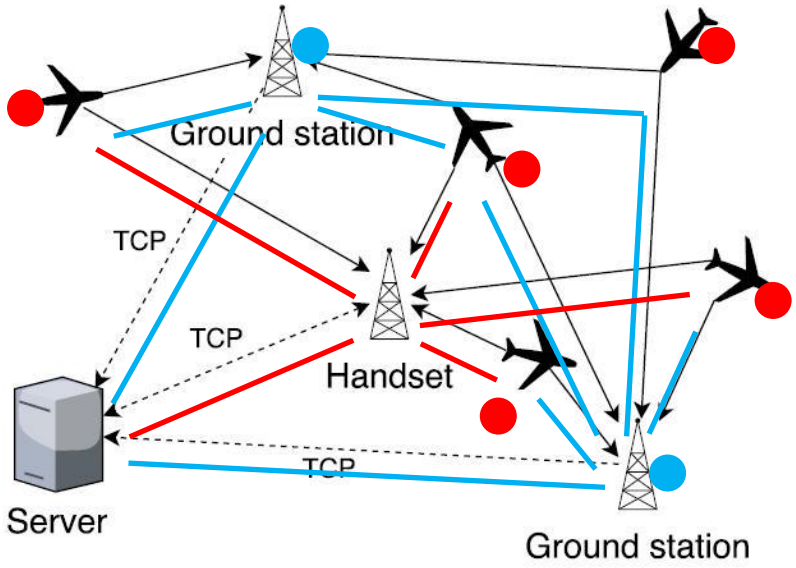
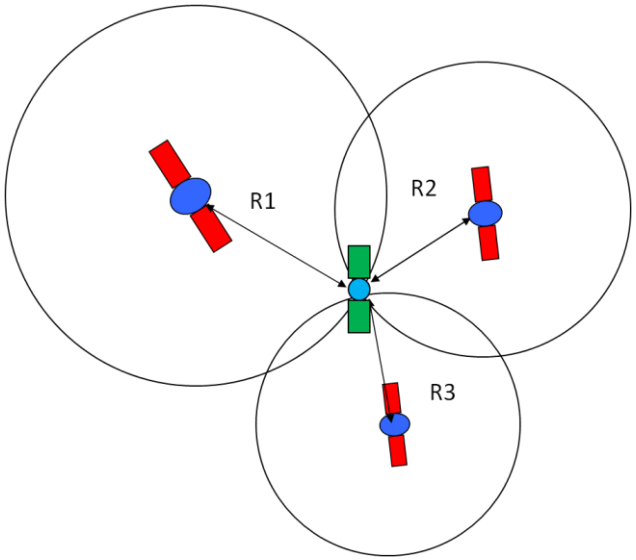


Figure 1: System consisting of a server, ground stations at known locations, a handset at unknown location and aircraft. The ground stations and handsets determine the receive time of messages from aircraft to then calculate the send time of the messages and the location of the handset.

✓ User Localization

• Instead of satellites with known position and time of signal transmission, we use aircraft and ADS-B messages transmitted by them.

•At least four points Pj are needed to estimate the handset position and time offset.



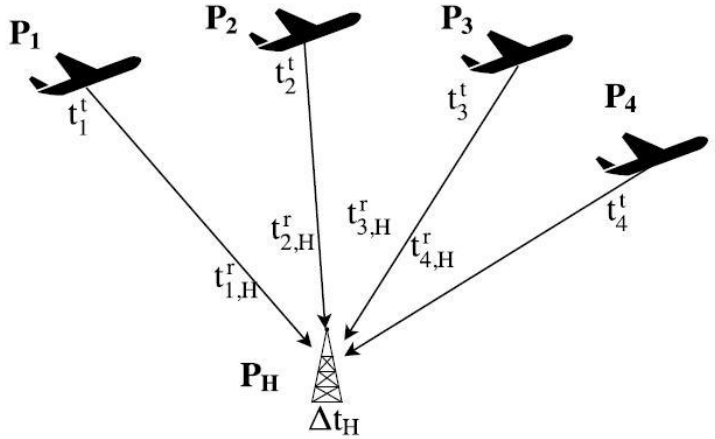


Figure 2: Handset multilateration: The handset receives messages from different aircraft that are then used for multilateration.

✓ User Localization

• The handset position and clock offset can be found by solving a non-linear least squares problem.

- $\mathrm{P_j}$: the position from where the message was sent
- t_j^t : the send time
- $\mathrm{P_H}$: the handset position
- Δt_H : the clock offset of the handset to the ground stations
- $t_{j,H}^r$: the receive time of the message at the handset
- $w_{j,H}$: the noise

$$\left\|\mathrm{P_H} - \mathrm{P_j}\right\|_2 + c\Delta t_H \stackrel{!}{=} c(t_{j,H}^r - w_{j,H} - t_j^t)$$

$$e_j(\mathrm{P_H}, \Delta t_H) = \frac{1}{c}\left\|\mathrm{P_H} - \mathrm{P_j}\right\|_2 + \Delta t_H + t_j^t - t_{j,H}^r + w_{j,H}$$

$$(\widehat{\mathrm{P_H}}, \widehat{\Delta t_H}) = \underset{(\mathrm{P_H}, \Delta t_H)}{\arg\min} \sum_j e_j(\mathrm{P_H}, \Delta t_H)^2$$

✓ User Localization

• The position estimation error is the product of the signal arrival time measurement error and the DOP(Dilution of Precision) value.

• A rule of thumb is that the larger the volume spanned by the aircraft, the better the localization precision [22].

• And the receiver should be close to the aircraft.

• Due to the aircraft geometry, the vertical positioning uncertainty is often larger than the horizontal uncertainty, because most aircraft are at a low elevation angle.

• Therefore, it is useful to determine the handset height using a different method, for instance with a barometric pressure sensor.

✓ Transmission Time and Location

• To calculate the position of the user, the transmission time of the message at the aircraft has to be known.

• By using a ground station with a fixed location, the time-of-flight from the aircraft to the ground station can be calculated to then compute the transmission time.

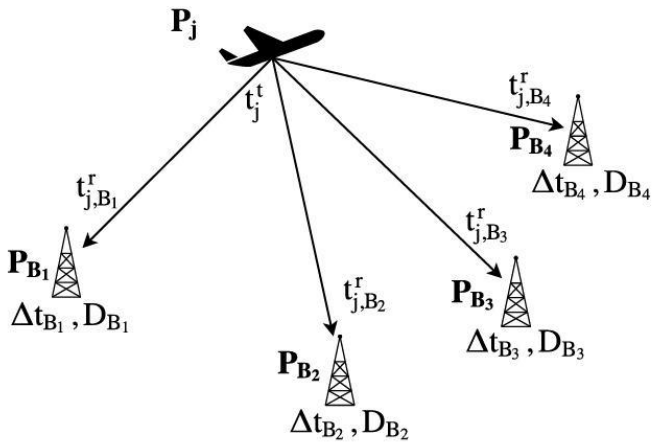


Figure 3: Calculation of message send time and aircraft position: Multiple ground stations receive the messages from the aircraft and can calculate the send time of the messages and optionally the position of the aircraft.

✓ Transmission Time and Location

• This system of equations can be solved using a linear least squares solver to compute the transmission times of the messages in the synchronized time.

• As the clock drift rate and offset may change over time, the synchronization has to be repeated regularly.

•To calculate Pj, we therefore use a nonlinear least squares solver.

- t^r_{j,B_i} : the receive time stamp
- t^t_j : the send time at the aircraft
- Δt_{B_i} : the clock offset
- D_{B_i} : the clock drift

$$t^r_{j,B_i} - w_{j,B_i} - \frac{1}{c}\left\|\mathbf{P}_{\mathbf{B_i}} - \mathbf{P_j}\right\|_2 = t^t_j + \Delta t_{B_i} + D_{B_i}(t^t_j - t^t_1) \qquad (1)$$

✓ Ground Station Requirement

• Since signals can be received several hundred kilometers from an aircraft, in principle one ground station is enough to cover a large urban area or a small country.

• Using multiple ground stations has several benefits:

• Measurement errors can be reduced.

• Note that the different parts need to have some overlap in order to be able to synchronize the ground stations' times.

• Less messages are lost and therefore a larger number of the messages of a handset can be matched by the server with a message from a ground station.

•Lastly, note that handsets do not need to be in line-of-sight of any ground station since the time synchronization of aircraft messages and the position computation of a handset are decoupled.

4. IMPLEMENTATION

✓ Receiver

• receivers which consist of a 7 cm long antenna, a USB software-defined radio receiver dongle and a Raspberry Pi 3 board.

•To receive the messages from the aircraft, we use software-defined radios (SDRs).

• For this project USB dongles based on the RTL2832U chipset are used, which were originally designed to be DVB-T TV tuners.

• The total cost of such a receiver is less than $100.

• Our signal reception and decoding software is a modified version of the open source project dump1090.

• With these cheap receivers, messages sent from aircraft as far as 250 km away can be received.

• Currently the ground stations and the handset are based on identical hardware configurations.

• equip the handset with a barometric pressure sensor.



Figure 4: Hardware of ground station: Raspberry Pi 3 with FlightAware Pro Stick Plus and antenna. The Raspberry Pi decodes the messages and sends them to the server via LAN or WLAN.

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✓ **Server**

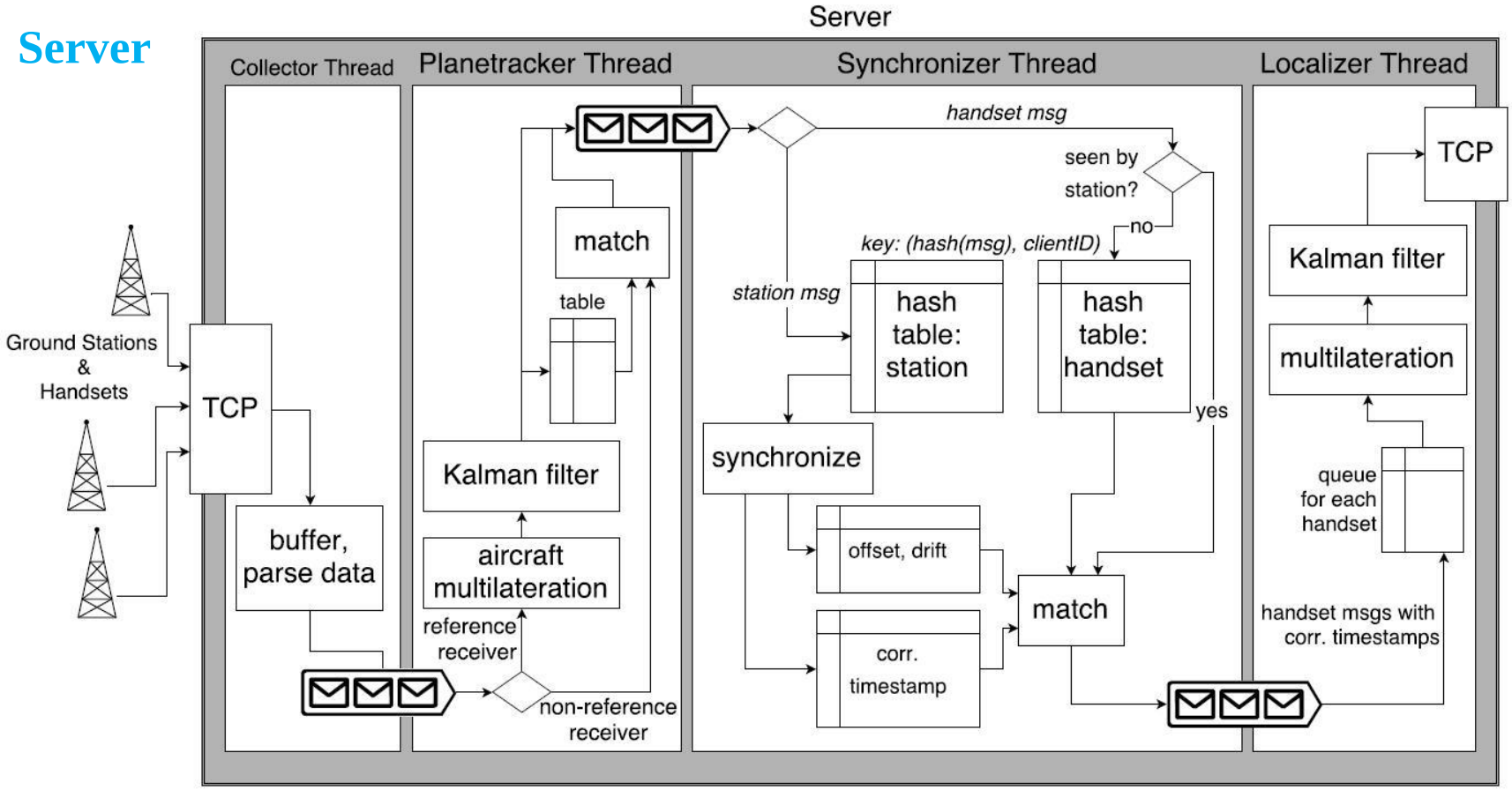


Figure 5: Server application: The server receives the messages from the ground stations and handsets, matches the messages from the different receivers. Then the clock offset and drift between the ground stations is computed with messages from different receivers. In the last stage, the multilateration of the handsets is performed.

5. RESULTS

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• To evaluate our method, we deployed six ground stations in a region approximately 110 km in diameter.

• building weatherproof cases was outside of the scope of this work. Therefore, the ground stations for our evaluation are placed inside buildings.

• Our evaluation should be considered as a mostly qualitative analysis, since we could not yet test our system performance extensively.

• Not only is there a daily cycle of flight patterns and air traffic density, but for instance different wind directions influence the routing of aircraft on different days and there are even seasonal differences, as during holidays, the number of passenger flights increases significantly.

• Furthermore, the landscape around the receiver also influences the reception of aircraft signals, for instance by blocking the line of sight between a handset and some aircraft.

• Finally, note that all these parameters are not independent, which makes it even more challenging to evaluate our system thoroughly.

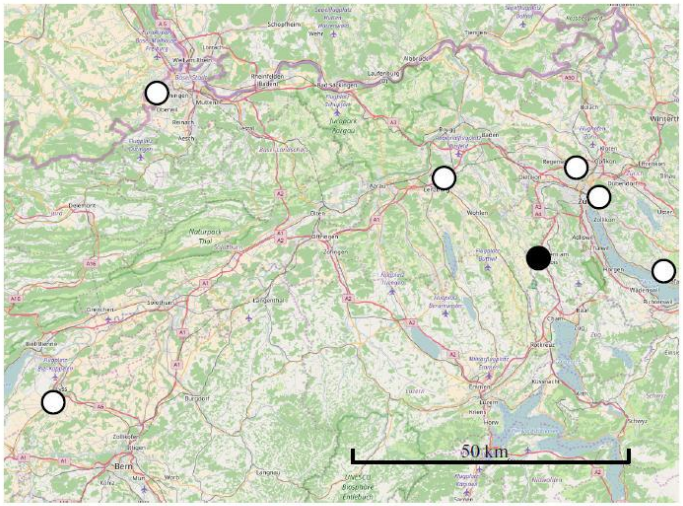


Figure 6: Location of the ground stations (white circles) and a handset (black circle) for the evaluation. The ground stations span over a region approximately 110 km in diameter.

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✓ Reception Quality

• The maximum range within which aircraft signals can be received heavily depends on the antenna characteristics and placement.

• With our ground stations, which were all located indoors, messages from approximately 190 km away can be received.

• When placing the antenna on a roof, the range increases to about 250 km.

• Indoors the number of unique aircraft from which signals are received decreases by a quarter.

✓ Localization Accuracy

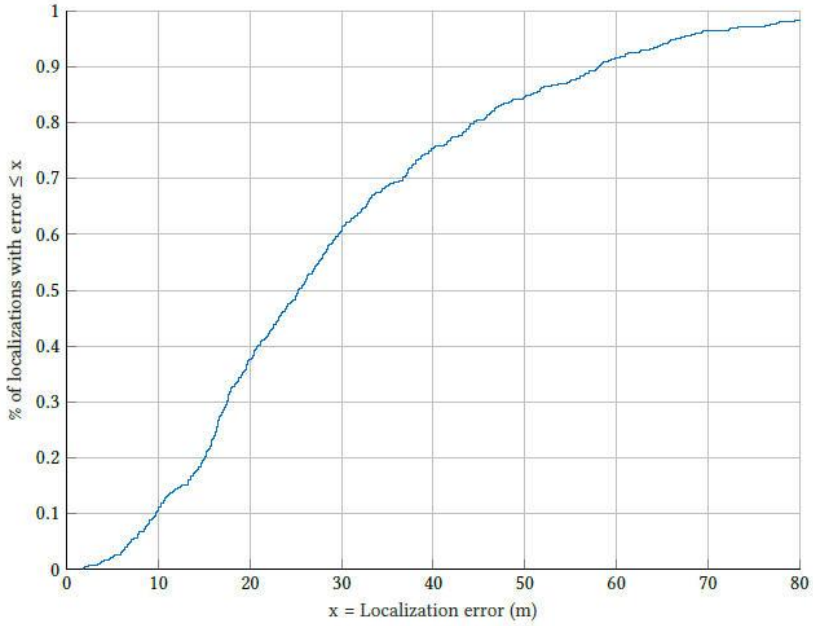


Figure 7: Cumulative distribution function of the positioning errors of an outdoor handset using data from six ground stations. The handset altitude is known and the horizontal coordinates are determined using the aircraft signal measurements from the ground stations.

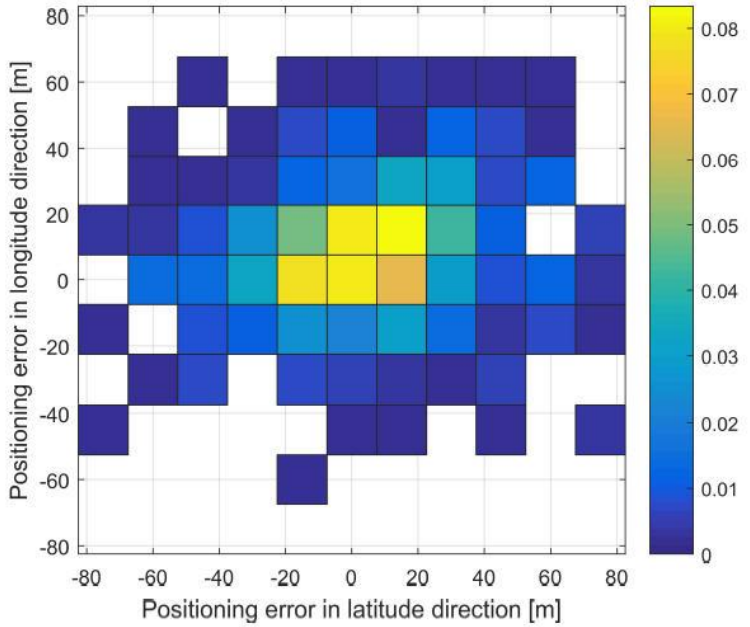


Figure 8: Distribution of positioning errors in latitude and longitude direction. The handset altitude was known. These results were obtained using six ground stations and a handset outdoors. The plot shows that the positioning solutions are approximately normally distributed.

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✓ Number of Ground Stations

• This is what we expected, since one ground station is sufficient to calculate the send time of a message from an aircraft.

• One reason for the slightly better results with 5 and 6 ground stations might be that errors in the calculated clock offsets and drifts of the ground stations are averaged out.

• The median error is only 5.6 % larger indoors, and the standard deviation increases by 14.7 % compared to the outdoor case.

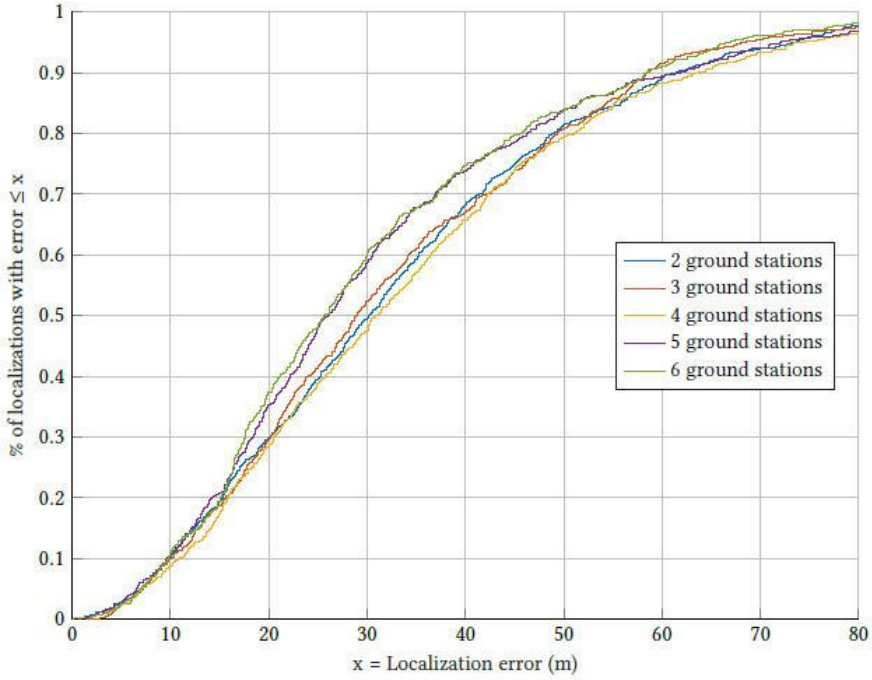


Figure 9: Absolute positioning error outdoors for different numbers of ground stations. As expected we do not see large differences of the localization error since one ground station is sufficient to calculate the send time of an aircraft message.

✓ Number of Observed Aircraft

• when not many aircraft are within range of the handset and the receivers, messages from a longer time period might have to be combined.

• This can lead to a larger synchronization error between the ground stations.

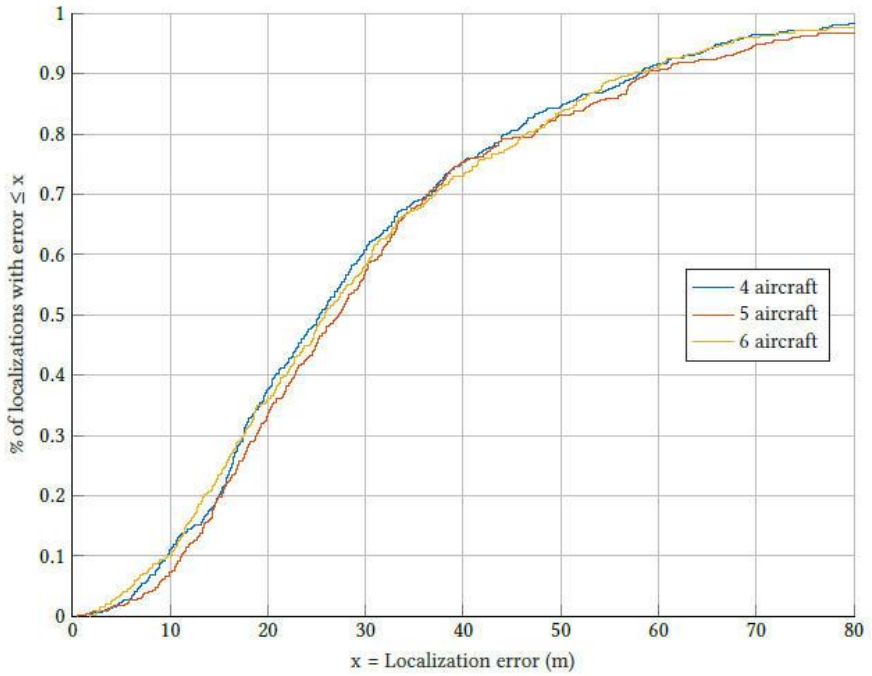


Figure 10: Absolute positioning error for different numbers of aircraft used for multilateration. The localization error does not decrease with more aircraft used in the multilateration. We assume that the sychronization error increases because messages have to be combined over longer periods of time.

✓ Known vs. Unknown Altitude

• Adding the barometer reduces the median error by 52 %.

• The conclusion of this experiment is that a barometer is a crucial feature of a handset multilateration method based on aircraft signals.

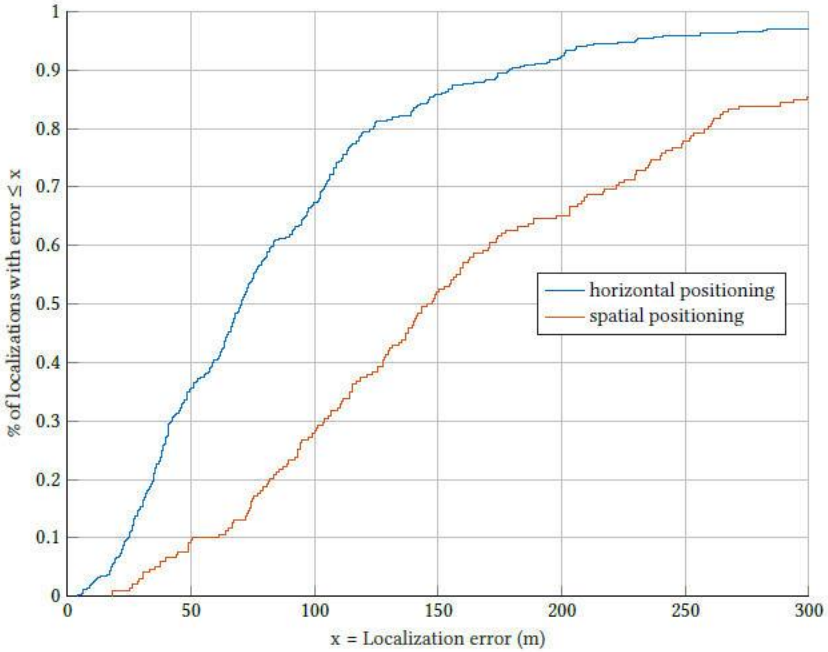


Figure 11: Positioning error with known handset altitude (horizontal positioning) compared to unknown handset altitude (spatial positioning). These results are from a preliminary experiment with a version of our implementation, which did not include all the improvements present in the final version.

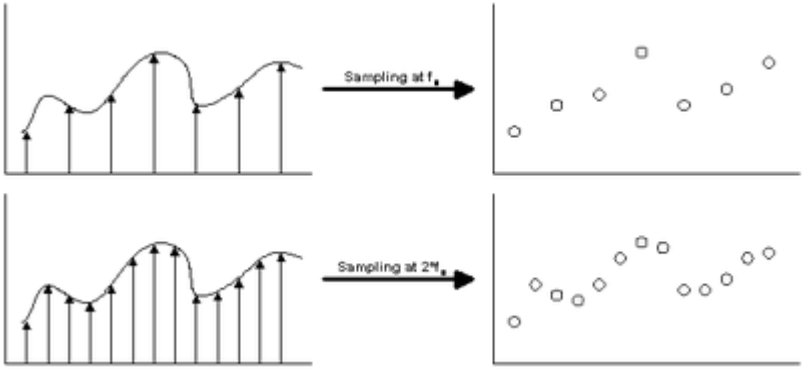
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✓ Upsampling

• Figure 12 demonstrates that the positioning error decreases when upsampling of the received signal is performed.

• However, the necessary computation power increases substantially.

• This problem could probably be resolved by installing a heat sink on the processor.



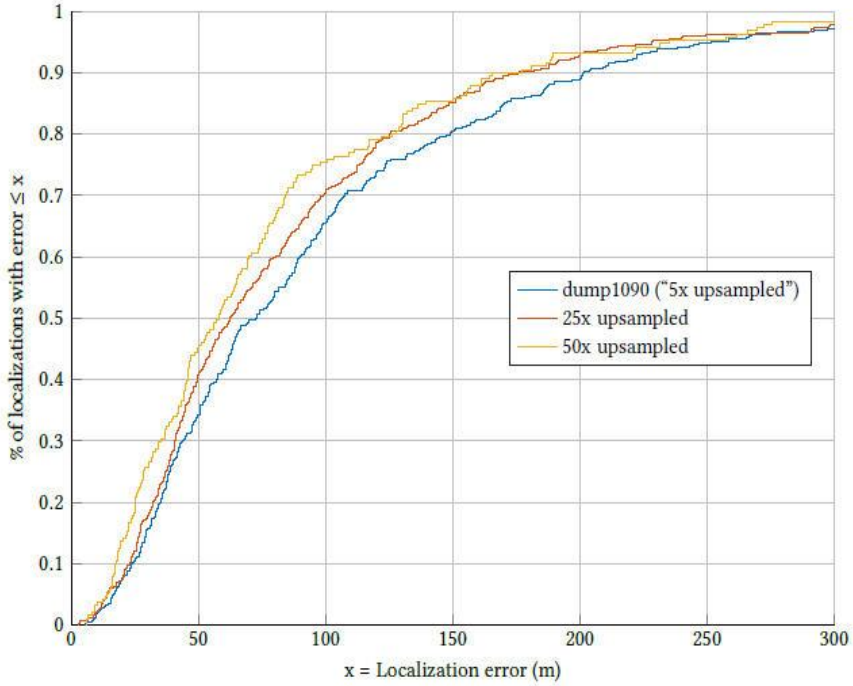


Figure 12: Positioning error based on 25-fold and 50-fold upsampled time stamps, as well as the default time stamps output by *dump1090*. These results were obtained using two ground stations and also an old version of our implementation, like the results from the barometer experiment.

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✓ Error Source

• Multiple possible error sources of the localization exist.

• The multipath effect caused by signal reflections from buildings and ground has a big impact.

• Accurate time stamps are essential for the multilateration. As shown in Section 5.7, the time stamps can be improved using upsampling.

• Since the ground stations do not have synchronized clocks, the estimation of the clock offset and drift has to be repeated regularly.

• In practice, up to 50 % message loss is possible.

• Small errors are also introduced by the ground station positions.

• Additional errors are introduced by the uncompensated latency in the aircraft between the reception of the GPS position and the transmission of the ADS-B message.

• Also the GPS receiver and the transponder have a position offset depending on the aircraft model.

✓ Using Messages from Multilaterated Aircraft

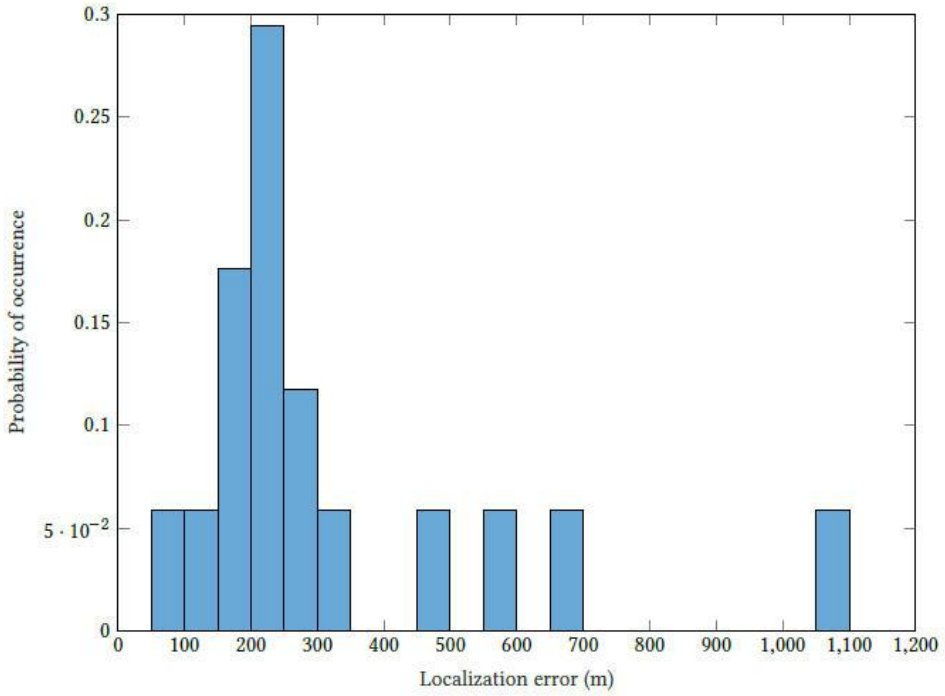
• the system can also compute the position of the aircraft that do not transmit their position.

• According to the OpenSky Report 2016 [31], about 70% of transponders support ADS-B messages.

• For the evaluation of the position accuracy, the multilateration has been performed on messages from aircraft that also transmit their position.

• The calculated positions have a median error of approximately 300m.

• We did not reach a conclusion yet, why these errors are much larger than the handset multilateration errors.



6. RELATED WORK

✓ Indoor Localization

• The cost factors to get so accurate are

(1) the installation of dedicated Infrastructure, like for instance one beacon in each building up to several in each room;

(2) a Training or initialization phase to gather data which is necessary for the subsequent localization;

(3) the usage of Expensive user equipment.

• our method fills the void between cheap, global and easy to use outdoor localization such as GPS and precise, but local or expensive, indoor localization.

•A plethora of indoor localization methods exist and different classifications are possible.

(1) For instance, Seco et al. [32] classify the methods into four categories: geometry-based, minimization of a cost function, fingerprinting and Bayesian.

(2) Another classification can be made based on the type of employed signals(the whole range of the electromagnetic spectrum up to light have been used).

(3) the methods by their kind of fundamental measurements, which include received signal strength (RSS), time of arrival (TOA), time difference of arrival (TDOA) or angle of arrival (AOA).

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✓ Indoor Localization

신호	인프라	정확도	제약사항	가격	방법
WiFi(done)	WiFi hotspots필요없음	수미터	학습단계필요, DB Update	-	RSS
Ultrasound	전용하드웨어	수센치	거리한계, 소음, 동물건강해로움	저렴	TDOA
Light	레이저, 카메라,LED	수센치~수십센치	거리한계, 학습단계필요, 벽투과안됨	고비용	RSS, AOA
Bluetooth	WiFi유사, 빠른응답	수미터	거리한계	-	RSS
RFID(done)	활성태그, 수동태그(태그 설치)	수미터	거리한계	-	RSS, TOA, TDOA
Sensor Fusion(done)	IMU(가속도계, 자이로스코프, 나침반)	오류누적	오류누적,재조정필요	-	상대적위치
GSM(Global System for Mobile Telecommunication)	셀룰러 네트워크 안테나	전역좌표, 50~150m	35km이내수신, 학습단계필요	-	TDOA

7. CONCLUSION

7.CONCLUSION

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• This paper have shown that using aircraft signals to localize users is a viable approach, even when the receiver is indoors.

• This method fills a gap between globally available outdoor localization and accurate but expensive or cumbersome indoor localization.

• A few ground stations are enough to serve a region several hundred kilometers in diameter, which makes our method basically infrastructure free.

• Plenty of accuracy improvements to our prototype system are possible:

(1) Using more advanced signal processing to more precisely detect signal arrival times and detect more signals per time.

(2) Improvements to the RF chain, such as employing antennas designed for ADS-B.

(3) Applying enhancements to the position estimation, such as selecting only "good" measurements for the least squares computation, computing a weighted least-squares solution, applying multipath mitigation techniques or using a different localization algorithm such as a maximum likelihood approach.

(4) Precisely localizing ground station positions.

(5) Choosing an optimal placement of the ground stations, to reduce error sources such as multipath and to maximize received signal strength, number of received messages and observed unique aircraft.

8.CRITIQUE

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- 논문에서 강조한 것처럼 이전에는 고안되지 않은 새로운 시도로 판단됨.
- ground station의 위치나 aircraft의 분포상태에 따라 정확도의 상당한 차이가 예상됨
- aircraft의 위치정보 유무에 따른 정확도 차이의 표현이 없음.
- 사실상 50%이하에서 25M 의 큰 오차는 실내에서 유용하게 사용되기는 힘듦
- 단일한 기술이 아닌, 다양한 기술의 보완된 사용으로 활용의 가치가 있을 것으로 판단됨.

Q & A
감사합니다