Accepted for presentation in: IEEE Global Communications Conference Workshops (GLOBECOM Workshops), The 9th International Workshop on Wireless Networking and Control of Unmanned Autonomous Vehicles (Wi-UAV), Abu Dhabi, United Arab Emirates, December 2018.

Supporting Maritime Search and Rescue Missions through UAS-based Wireless Localization

Janis Tiemann, Ole Feldmeier and Christian Wietfeld
TU Dortmund University, Communication Networks Institute (CNI)
Otto-Hahn-Str. 6, 44227 Dortmund, Germany
{janis.tiemann, ole.feldmeier, christian.wietfeld}@tu-dortmund.de

***Abstract*—The use of unmanned aircraft systems to support maritime search and rescue missions holds great potential. Applications range from the fast and efficient search of vessels and persons in distress to the provision of rescue and communication resources. In this paper, we address a received signal strength based localization method of persons without dedicated search and rescue equipment. The specific challenge addressed in this work is to analyze the proposed localization method under realistic conditions. Thus, a maritime channel model is implemented and by means of field tests experimentally validated. Furthermore, the proposed approach is evaluated in a two step concept: In the first step the capability of different search patterns and localization algorithms is analyzed and evaluated in a hardware in the loop simulation environment. In the second step, a scaled experimental setup, which uses a technology comparable to cellular communications, is evaluated to prove the viability of the overall system. Besides the overall accuracy, the required localization time is a key performance indicator. The resulting outcome of the simulations using active trajectory generation underlines the potential of the discussed approach by achieving localization errors of lower than 200 m in under 10 mins. The experimental results obtained in the outdoor field test of under 30 m absolute euclidean error confirm the simulative results and verify that the proposed concept can significantly improve search and rescue operations.**

Keywords*—*Search and Rescue (SAR), Unmanned Aircraft System (UAS), Received Signal Strength, Wireless Localization.

I. Introduction and Related Work

When an emergency call comes in at a maritime rescue station, every minute counts for ships in distress and persons in the water [1]. A rescue mission's success depends strongly on the information available to rescuers. Today, water based search and rescue strategies are developed to a high degree. However, boats are comparably slow and can not enter some coastal areas due to vegetation or shallow water. Aerial search is carried out using helicopters which involves high costs and is difficult to carry out during high winds, strong precipitation or limited visibility. Our goal is to provide quick mission support through deployment of an unmanned aircraft system (UAS). The challenge is to localize users without specific search and rescue (SAR) devices solely based on their mobile user equipment (UE). Using alternative approaches is required due to the limited use of dedicated SAR equipment in water sports and recreational activities. Large vessels at high-sea are required to be equipped with SAR equipment such as the satellite-based [2] emergency position indicating radio beacons (EPIRB) [3]. Commercial vessels operate the automatic identification system (AIS) enabling them to receive emergency signals transmitted by the corresponding search and rescue transmitter (AIS-SART) [4]. While radar transponders (radar-SART) where the standard for a long time, global navigation satellite system (GNSS) [5] enabled transponders find wider attention as they are also small enough to be integrated in life vests or smaller sport boats. The majority of water sports equipment though, does not carry dedicated SAR devices as defined in the global maritime distress and safety system (GMDSS) [6]–[8]. Due to this, locating user equipment to support SAR missions is a viable option in situations where people are missed at sea.

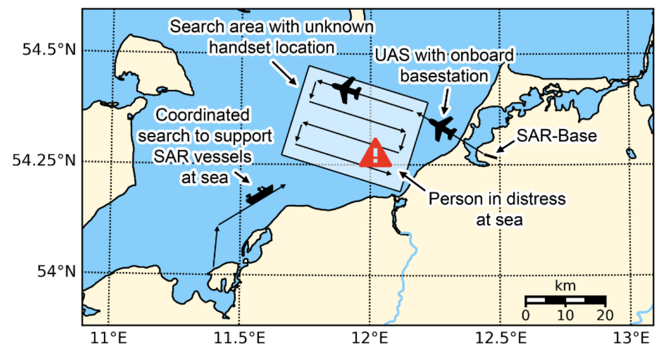


Fig. 1. Illustration of the proposed scenario. A fast unmanned aerial system supports maritime SAR missions. Wireless localization of user equipment is used to gain significant time and coverage advantages and improve survival rates of persons in distress at sea without dedicated SAR equipment.

A basic illustration of the proposed approach is depicted in Fig. 1. The location of the UE is approximated using successive signal strength measurements. A detailed description of the approach is given in section II. Due to recent developments in UAS systems [9], a wide range of opportunities emerged. Related work illustrates the feasibility of the proposed approach. The work in [10] presents a UAS for SAR in forest environments using WLAN. In [11] a local base station is used to localize user equipment in collapsed buildings using dedicated jammers to suppress reception from local mobile networks. Approaches for signal strength optimized path planning are presented in [12], while in [13] RF based localization approaches for microUAVs are evaluated. In contrast to many other works that use simulation-only approaches, this work evaluates the use over maritime surfaces and shows both, simulatively and experimentally that UAS-based wireless localization is a viable option to support maritime SAR missions. A video illustrating the simulations and experiments is provided alongside this work [14].

II. Proposed Concept

In order to localize the person in distress, a set of parameters has to be known a priori. There has to be an emergency call issued either by the person in distress itself or a related person issuing the following information:

- Mobile phone registration (*Identification*)
- Current, last or target location (*Initial search area*)
- Last contact (*Search area radius*)

Based on this information, and additional water current data a search area is defined and a UAS is launched and targeted at the search area. The UAS carries a device that can either listen to mobile network communication, when the UE is still within range of shore-based networks, or span a mobile base-station that enables the UE to associate to the airborne network. The basic concept of the second option would be implemented as such that it carries similar functionality to international mobile subscriber identity (IMSI) catchers used in law-enforcement [15]. Here, 2G and 4G-based solutions [16] or other technologies are imaginable. Through this, the UAS is enabled to measure the received signal strength (RSS) of messages from the UE. Due to the different dynamics of the UAS and the localization target, the UAS positions and the corresponding RSS can be used as virtual anchor nodes to successively approximate the position of the UE, see Fig. 2. In typical networks, location updates are infrequent and therefore, not capable of providing sufficient samples to localize the UE in distress. In this work we propose either issuing a call to the person in distress and using the measurement reports to obtain frequent RSS updates or using silent SMS [17] and leveraging the corresponding ACK messages. Other technologies might have different mechanisms to achieve frequent signal strength measurements. In order to localize the mobile target, a wide range of methods is available. In this work we will focus on non-linear least squares (NLLS) estimators to obtain the position from the UE through the previously mentioned virtual anchor nodes. Using a free-space channel model, virtual distances $\tilde{d}^k$ are estimated from the RSS, see [18]–[20]. However, due to the special characteristics and distribution of the true distance d^k estimation error ε using RSS-based signals, other filter approaches such as the weighted least squares (WLS) can provide increased performance, see [21].

$$\varepsilon = \sum_{k}^{K} \frac{1}{Var(\tilde{d}^k)} \left(d^k - \tilde{d}^k \right)^2 \tag{1}$$

The error ϵ that is to be minimized is defined in (1).

$$x_i = \left(A_i^T W_i A_i \right)^{-1} A_i^T W_i b_i \tag{2}$$

$$W_i = \begin{bmatrix} w_i^1 & 0 & \dots & 0 \\ 0 & w_i^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & w_i^K \end{bmatrix} \tag{3}$$

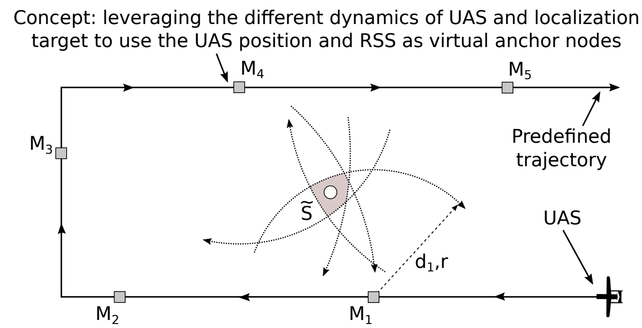


Fig. 2. Schematic illustration of the underlying localization concept. The UAS successively approximates the UEs position by taking RSS samples at different points along a predefined or actively generated trajectory.

Using this, the solution for the state vector x_i of a typical NLLS changes to (2) with the Jacobian A_i and the measurement vector b_i. While W_i is a diagonal matrix with the elements $w_i^k = 1/Var(\tilde{d}_i^k)$ as defined in (3). Due to this, we can leverage the error distribution of the RSS-based distance estimation and improve the accuracy of the localization results significantly.

III. Simulative Analysis

In order to evaluate the the proposed approach, first a test scenario with a $20 \times 20\,\mathrm{km}^2$ search area was simulated using a hardware-in-the-loop (HiL)-simulation, see Fig. 1. The general structure of the HiL setup using a hardware autopilot is depicted in Fig. 3. The system is based on three key components:

- *Physics Simulation* Autopilot coupled with realistic flight physics simulator
- *Communication Simulation* Based on a context-aware maritime channel model
- *Localization and Path Planing* Conventional and novel active trajectory generation

The *Robot Operating System* (ROS) is used as the central component, interfacing all individual parts comprising the setup in a flexible and modular way. A *Pixhawk* autopilot

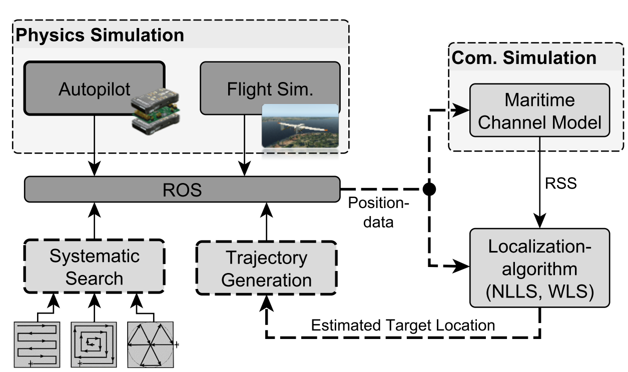


Fig. 3. Setup of the simulative environment. A hardware in the loop simulation using either systematic search or active trajectory generation is conducted. Note that the simulations use a maritime channel model.

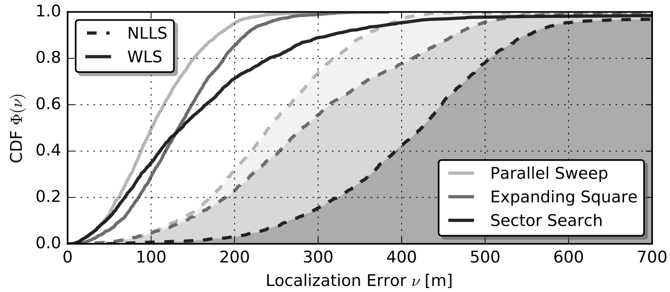


Fig. 4. Cumulative distribution function of the localization error θ for different search-patterns. Note the difference in accuracy between typical NLLS-based and the proposed weighted localization.

and a commercial flight physics simulator were used for the HiL simulation. To enable the autopilot for autonomous search missions, a suitable waypoint list is needed. This can be done either in a static way in form of a predefined search pattern, or in a dynamic approach, where the trajectory is calculated in real-time based on the estimated target position. In order to send waypoints to the autopilot and to tunnel the information between the autopilot and the flight physics simulation the *MAVLink* protocol was used. In context of this work, the search and rescue scenario is defined in a maritime environment. Therefore a convenient channel model is developed based on [22]. Here, the diffraction aspects are modeled as stochastic components using a Douglas-scale [23] depended Rician distribution, see [24].

To achieve representative results, three different predefined search patterns were selected. The parallel sweep, which creates a meander pattern along the search area, the expanding square, which starts in the centre of the search area and expands in a rectangular spiral using the same spacing as the parallel sweep and the sector search which creates a trajectory in defined angles through the center of the search area. A top-down view of the patterns is depicted in Fig. 3. A quadratic search area with 400 km^2 is defined as the search area, while the localization target is placed at a random spot in this area using a uniform random distribution for the position. The channel parameters used to feed the maritime channel model are listed in Tab. I. A set of 2000 simulated runs was conducted to obtain statistically relevant results. The resulting

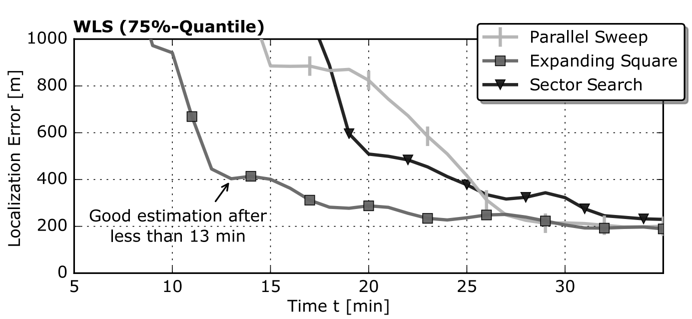


Fig. 5. Localization error over mission duration for different localization search-patterns. Note that the expanding square already reaches sufficient accuracy after 13 min. Note that corresponding to Fig. 4 the localization error for the other patterns decreases further over the full mission duration.

cumulative distribution functions for the NLLS and WLS-based localization is depicted in Fig. 4. It is clearly visible that the accuracy of the WLS is a significant improvement above the NLLS localization. Furthermore, the parallel sweep performs better than the expanding square and the sector search using both localization schemes.

Although overall localization accuracy is an important performance indicator, the time after which a certain location accuracy can be achieved is even more important in SAR scenarios. Therefore, the 3rd quartile localization accuracy of the different schemes was analyzed over the mission duration, see Fig. 5. It is clearly visible that the expanding square is capable of achieving a higher localization accuracy in a shorter timespan. To evaluate the confidence in the accuracy, Fig. 6 depicts the statistic behavior of the error distribution over mission time for the best-performing approach in Fig. 5. Here, it can be seen, that even in the 95 % quantile, an accuracy of below 400 m can be achieved after a mission duration of 30 min. The non-monotonous behavior is induced by the static flight pattern.

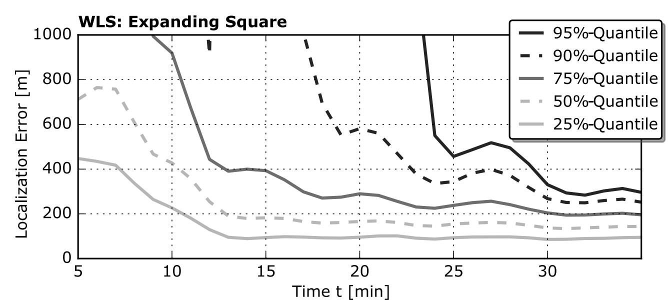
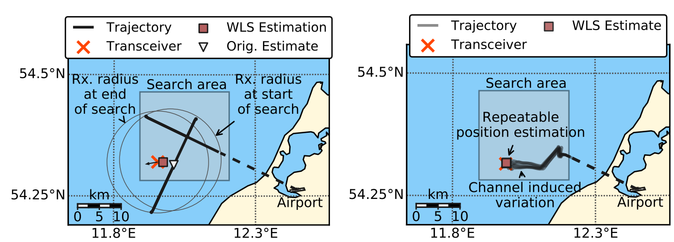


Fig. 6. Localization error quantiles over mission duration for the expanding square pattern. Note that a certain localization accuracy can not be guaranteed, but even the 95 % quantile reaches an accuracy below 400 m after 30 min.

Although the predefined search pattern already show promising results, two approaches using active trajectory generation were also analyzed. In this case an approach from the IAMSAR reference manual [25] was implemented. The



(a) IAMSAR Pattern (b) Active Search

Fig. 7. Top-down trajectory plots of the simulated active search procedures. The standardized IAMSAR pattern (a) operates using reception range, while the active search (b) flies towards the current position estimate.

TABLE I. CHANNEL PARAMETERS OF THE SIMULATIONS.

Carrier Freq. f $[MHz]$	**Tx. Power** P_s $[dBm]$	**Antenna Gain** G $[dBi]$	**Rx. Height** h_e $[m]$	**Tx. Height** h_s $[m]$	**Douglas-Scale**
900	14	0	150	1	3

resulting trajectory is depicted in Fig. 7(a). This approach follows a very robust and often used pattern to localize objects based on wireless signals. Once the UAS receives a signal it keeps the current orientation and continues until the signal is out of reception. After it lost the signal, it will fly back to the center of reception. Once there, it will turn 90°, keeps orientation until out of reception, turns 180° and searches for the localization target in the center of that line. The result of a simulated flight is depicted in Fig. 7(a). Another approach is to generate the trajectory dynamically based on the currently estimated position of the localization target as depicted in Fig. 7(b). Here, six individual flights were performed using the same target position as in the IAMSAR-Pattern flight. After initial meandering, the UAS is capable of reproducibly find the location of the missed UE using the WLS algorithm.

In both simulations the device that is to be localized is moving with a simplified typical drift current of 1 m/s to evaluate the performance under more realistic conditions. Therefore, the proposed WLS filter is only using a recent subset of the obtained samples.

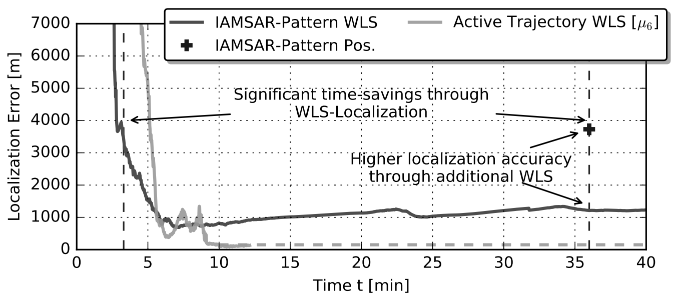


Fig. 8. Localization error over mission duration for the simulated dynamic patterns. Note the difference in long-term behavior between the IAMSAR pattern and the active trajectory generation.

The localization error over the mission duration for both procedures is depicted in Fig. 8. It can be clearly seen that both procedures are capable of achieving high localization accuracy in under 10 min using WLS in the evaluated scenario. However, strictly following the IAMSAR pattern and not using WLS in parallel, a location is only available after 35 min

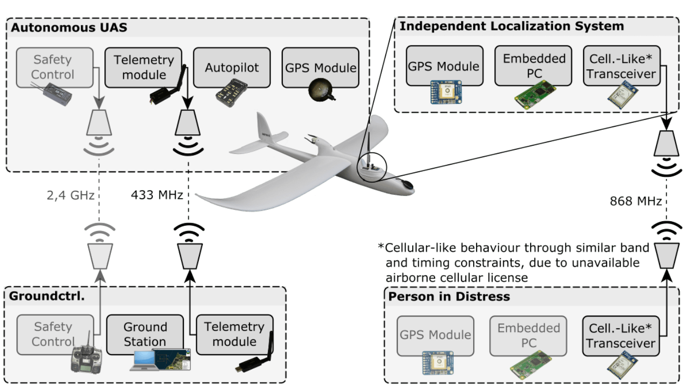


Fig. 9. Schematic illustration of the experimental setup. The scaled UAS system is controlled by a commercial autopilot. Note that the localization unit is carried as a payload on the UAS.

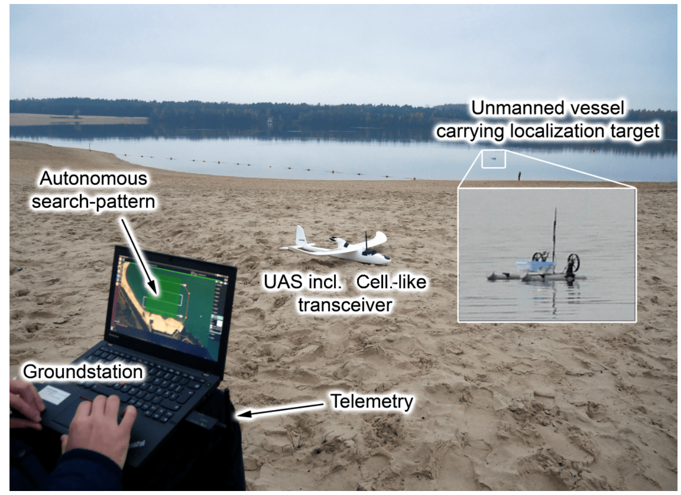


Fig. 10. Picture of the experimental setup. Depicted is the groundstation, the UAS carrying the GSM-like transceiver and the unmanned vessel that holds the target which is to be localized.

with an error of above 3 km due to the long-term drift. In comparison, the WLS addition to the IAMSAR pattern can more than half this error. The slow increase of the error is due to the current-induced drift of the mobile target. When looking at the error of the active trajectory generation, the upsides become directly visible. Depicted is the mean of all six simulated flights μ_6. Due to the close tracking of the mobile target, an error of below 200 m can be achieved consistently.

IV. Experimental Results

In order to validate the assumptions and feasibility of the approaches presented in the previous sections, a scaled experiment is conducted. The experimental setup is based on a lightweight UAS and a typical autopilot configuration using a pixhawk controller, a telemetry link on 433 MHz and a remote control for manual safety override. Due to regulatory circumstances the wireless technology used for the localization system was chosen to be within the 868 MHz ISM band. Here we assume similar behavior to cellular systems, which operate in the 900 MHz range. A schematic illustration of the experimental testbed is depicted in Fig. 9. An unmanned movable experimental vessel is placed on the water surface

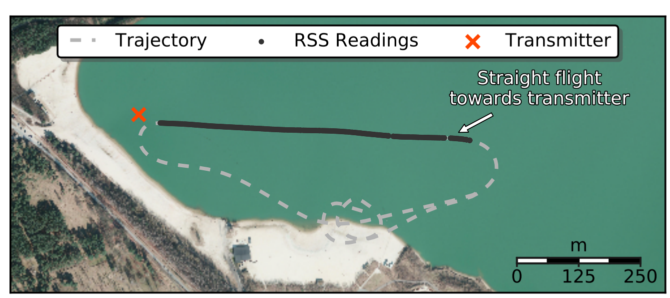


Fig. 11. Top-down plot of the experiment to evaluate the channel model used carry out the simulations. The UAS flies towards the localization target in a straight line at different heights.

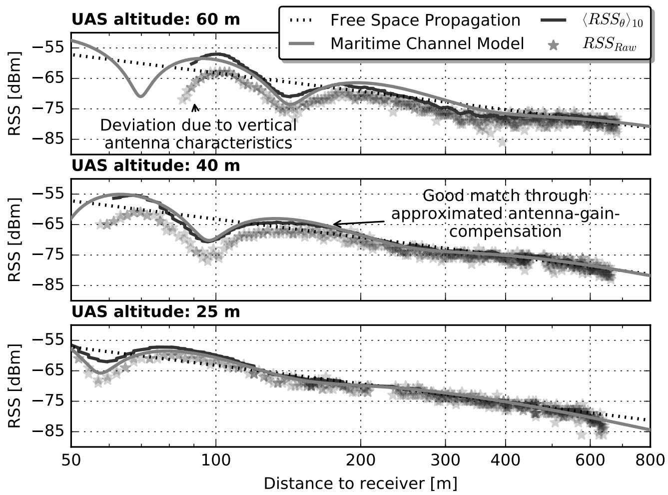


Fig. 12. Distance to received signal strength plot for the channel model evaluation experiments. Note the close match between analytical, experimental and antenna angle-compensated values.

to carry the localization target and a precise GNSS receiver for ground-truth. Here, the transmitter is placed at 0.65 m height. A picture of the setup at location is shown in Fig. 10. The resulting distance versus received signal strength plots are depicted in Fig. 12. It can be clearly seen, that the raw measurements RSS_{Raw} follow the analytical model for the maritime channel used in the simulations at all three heights. However, at increased heights the deviation due to the vertical antenna characteristics of receiver and transmitter antenna becomes noticeable. This effect originates to the monopole antenna used in the experiments. When taking the angle-depended antenna characteristic into account and using the angle of incidence θ calculated through the height and position difference of the nodes, the resulting compensated values averaged over ten samples $(RSS_\theta)_{10}$ match the analytical model closely.

In a first step an experiment is conducted to validate the assumptions on the channel used for the simulative analysis. The UAS is flying in a straight line towards the transmitter that is to be localized in a later step, see Fig. 11. In order to obtain a better understanding of the behavior, the UAS was flown in three heights of 25 m, 40 m and 60 m above the water surface respectively.

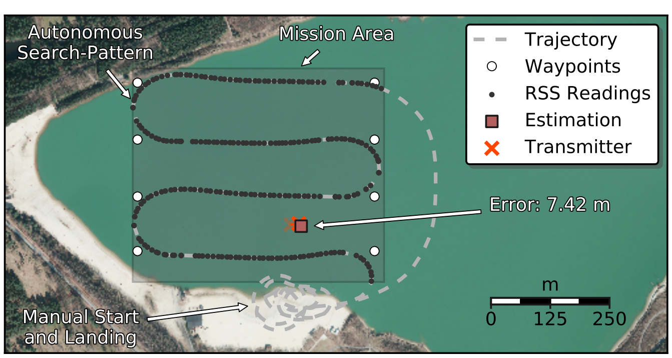


Fig. 13. Top-down plot of the scaled localization experiment. The UAS follows a predefined trajectory and uses its position and the signal strength to determine the position of the target.

In a second step an experiment evaluating the localization capabilities of the proposed approach in a scaled scenario is conducted. Here, the temporal behavior of the mobile network are projected on the wireless localization system by assuming measurements at a rate of 2 Hz through frequent silent SMS. The UAS is set up to follow a predefined parallel sweep along a quadratic search area of approximately 500 m width. The unmanned vessel carrying the transmitter system is placed at a semi-static position in the search area, drifting with wind and current, while the ground truth is obtained using an on-board GNSS receiver as depicted in Fig. 13. Using the WLS localization algorithm, the position of the transmitter could be obtained with an absolute euclidean error below 8 m. To gain basic statistical relevance, a set of four trajectories was flown at the experiment site, the error did not exceed 30 m.

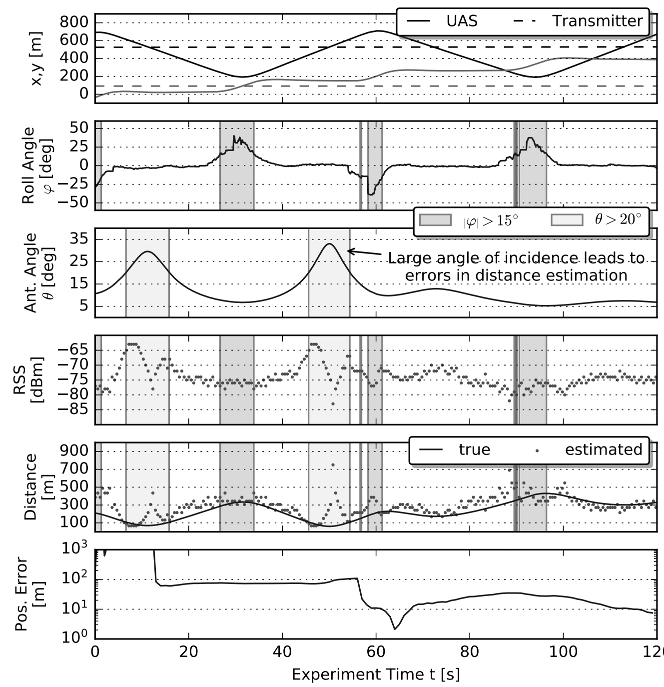


Fig. 14. Time-series of the scaled localization experiment. Note the influence of the angle of incidence for both, transmitter and receiver on the RSS-based distance estimation.

A time-series of the experiment is depicted in Fig. 14. The positional coordinates in a local reference frame are depicted next to the roll angle of the UAS and the position difference induced angle of incidence at the antennas. The time-spans where either the absolute roll angle, or the angle of incidence is higher than a certain threshold is highlighted to illustrate the influence on the resulting RSS and hence, distance estimation. Especially when the angle of incidence is high, large corresponding errors can be seen in the distance estimation. Due to the scaled nature of the experiment and the relatively high UAS speed of around 70 km/h the search duration is only around 120 s while collecting around 240 RSS samples. Although the ground-truth measurements for the current position of the UAS and the transmitter rely on GNSS receivers, the provided accuracy is sufficient to evaluate the given scenarios. Due to the flat water surface and surroundings a wide range of satellites is received, allowing for precise GNSS measurements. It is clearly visible that after half of the overall trajectory, the UAS is capable of obtaining a localization error sufficient to support a SAR mission by the means of significantly reducing the area of search. In real SAR missions with a larger search area this reduction can lead to significant time-savings or even enable a space-constrained visual search in bad visibility conditions. A video detailing the conducted simulations and experiments is provided alongside this work, see [14].

V. Conclusion and Future Work

This paper proposed a novel method to support maritime search and rescue missions through wireless localization using unmanned aircraft systems. A concept on how to integrate was given alongside with simulations that prove the applicability of the proposed approach by the means of predefined search patterns and active trajectory generation using either established methods or direct active search. Furthermore, the channel models used in the simulations were validated in a scaled experimental setup above a water surface. It could be shown that in a scaled experimental proof of concept search a localization accuracy below 30 m is achieved, illustrating the potentail of the proposed approach. A video [14] illustrating the hardware in the loop simulations and experiments is provided alongside this work.

Acknowledgement

The work on this paper has been partially funded by the German Federal Ministry of Education and Research (BMBF) in the course of the LARUS project under grant number 13N14133. It was also supported by the federal state of Northrhine-Westphalia and the "European Regional Development Fund" (EFRE) 2014-2020 in the course of the "CPS.HUB/NRW" project under grant number EFRE-0400008. Furthermore, the work on this paper received partial funding by Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Center SFB 876 "Providing Information by Resource-Constrained Analysis", project A4/B4. We would like to thank the "Betreibergesellschaft Silbersee II Haltern am See mbH" and especially Dr. Eberhard Geisler for his kind support. We also thank Philipp Gorczak for his support with the simulations and Lucas Koring for his support with the experiments.

References

[1] M. Howorth and F. Howorth. *The Sea Survival Manual*. Sheridan House, Inc., 2005.

[2] R. J. H. Barnes and J. Clapp. COSPAS-SARSAT: A quiet success story. *Space Policy*, 11(4):261–268, 1995.

[3] International COSPAS-SARSAT Program. Detailed COSPAS-SARSAT System Description. https://www.cospas-sarsat.int/en/system-overview/detailed-cospas-sarsat-system-description, [Online: Dec 2017].

[4] J. Arroyo. The Automatic Identification System: Then, Now, and in the Future. Technical report, Coast Guard Washington DC Office of Navigation, 2011.

[5] T. Cinar and F. Ince. Contribution of GALILEO to Search and Rescue. In *Proceedings of 2nd International Conference on Recent Advances in Space Technologies*, pages 254–259, Jun 2005.

[6] K. Korcz. Concepts of the GMDSS Modernization. In *Information, Communication and Environment, 11th International Symposium on Marine Navigation and Safety of Sea Transportation*, pages 75–82, 2015.

[7] D. Bréhaut. *GMDSS: A User's Handbook*. Adlard Coles Nautical, 2013.

[8] IMO International Maritime Organization. Guidelines for the harmonization of GMDSS requirements for radio installations on board SOLAS ships (COMSAR/Circ.32), Aug 2004.

[9] A. C. Watts, V. G. Ambrosia, and E. A. Hinkley. Unmanned Aircraft Systems in Remote Sensing and Scientific Research: Classification and Considerations of Use. *Remote Sensing*, 4(6):1671–1692, 2012.

[10] J. Sundqvist, J. Ekskog, B. J. Dil, F. Gustafsson, J. Tordenlid, and M. Petterstedt. Feasibility Study on Smartphone Localization using Mobile Anchors in Search and Rescue Operations. In *19th International Conference on Information Fusion*, pages 1448–1453, Jul 2016.

[11] S. Zorn, R. Rose, A. Goetz, and R. Weigel. A Novel Technique for Mobile Phone Localization for Search and Rescue Applications. In *International Conference on Indoor Positioning and Indoor Navigation*, pages 1–4, Sept 2010.

[12] K. Dogancay. UAV Path Planning for Passive Emitter Localization. *IEEE Transactions on Aerospace and Electronic Systems*, 48(2):1150–1166, 2012.

[13] J. Wang, J. Hinton, and J. C. L. Liu. RF Based Target Search and Localization with microUAV. In *IEEE International Conference on Computational Science and Computational Intelligence (CSCI)*, pages 1077–1082, Dec 2016.

[14] O. Feldmeier, J. Tiemann, and L. Koring. Supporting maritime search and rescue missions through UAS-based wireless localization, video: https://vimeo.com/278152015. Jul 2018.

[15] M. Hadžialić, M. Škrbić, K. Huseinović, I. Kočan, J. Mušović, A. Hebibović, and L. Kasumagić. An approach to analyze security of GSM network. In *2014 22nd Telecommunications Forum Telfor (TELFOR)*, pages 99–102, Nov 2014.

[16] S. Fr. Mjølsnes and R. F. Olimid. Easy 4G/LTE IMSI Catchers for Non-Programmers. *CoRR*, abs/1702.04434, 2017.

[17] N. J. Croft and M. S. Olivier. A silent SMS denial of service (DoS) attack. *Information and Computer Security Architectures (ICSA) Research Group South Africa*, 29, 2007.

[18] H. P. Mistry and N. H. Mistry. RSSI Based Localization Scheme in Wireless Sensor Networks: A Survey. In *5th International Conference on Advanced Computing Communication Technologies*, pages 647–652, Feb 2015.

[19] Q. Luo, Y. Peng, J. Li, and X. Peng. RSSI-Based Localization Through Uncertain Data Mapping for Wireless Sensor Networks. *IEEE Sensors Journal*, 16(9):3155–3162, May 2016.

[20] Y. He and A. Bilgic. Iterative Least Squares Method for Global Positioning System. *Advances in Radio Science (ARS)*, 9:203, 2011.

[21] P. Tarrío, A. M. Bernardos, and J. R. Casar. Weighted Least Squares Techniques for Improved Received Signal Strength Based Localization. *Sensors*, 11(9):8569–8592, 2011.

[22] F. Huang, X. Liao, and Y. Bai. Multipath Channel Model for Radio Propagation over Sea Surface. *Wireless Personal Communications*, 90(1):245–257, 2016.

[23] World Meteorological Organization. *Guide to Meteorological Instruments and Methods of Observation*, volume 8. Jan 2008.

[24] J. An. Empirical Analyses on Maritime Radio Propagation. In *IEEE Vehicular Technology Conference (VTC)*, volume 1, pages 176–180. IEEE, 2004.

[25] International Civil Aviation Organization and International Maritime Organization. *IAMSAR Manual, Volume II: Mission Co-ordination*. IMO Publishing, 2007.