Self-Localization: A proposal to equip first responders with a robust and accurate GNSS device

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ABSTRACT

In this paper we explore the GNSS positioning capabilities in the context of search and rescue operations. Our contribution is a tool that robustly receives and precisely evaluates GNSS signals. The final positioning information is then transmitted to an orchestrator where other tools like augmented reality utilities or the command and control have access to. During the time from the project start in September 2021 to December 2022 the components have been chosen, and the design and software of the tool have been developed. Furthermore, some of the tool's capabilities have been tested and compared during field trials with first responders and measurement campaigns. The developed tool outperforms the commonly used smartphone localization in terms of accuracy, operation time and time to get a GNSS fix. This reliability improvement helps to identify someones position in adverse conditions.

Keywords

Self-Localization, GNSS, first responder localization, multi frequency GNSS, multi constellation GNSS

INTRODUCTION

The RESCUER project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 101021836. It is focusing on the design and development of a First-Responder-centered technology toolkit. The toolkit will be based on several components which will enhance the operational capacity and safety of First Responders (FR) acting in the field and of those participating from the operation centers. A glance at the toolkit and its interactions is given in Figure 1.

The International Forum to Advance First Responder Innovation (IFAFRI) has identified ten common global capability gaps. Among them "the ability to know the location of responders and their proximity to risks and hazards in real time" (IFARI 2022) is the number one gap. This underlines the importance of self-localization and accurate positioning, since an error in the provided location might cause disorientation and may lead to new dangerous situations. Therefore, a reliable and accurate positioning is a strong requirement for self-localization techniques. For FRs, a fast access to the position information is required and navigation techniques based on infrastructure might not be applicable because infrastructure may be disturbed or disabled due to the loss of power. In this context, infrastructure-less approaches are considered in RESCUER.

A very important problem to be solved within RESCUER is the localization of FRs at the unstable and high-risk environments they operate in. A set of complementary, multi-modal solutions will be developed in RESCUER, being one of them the Global Navigation Satellite System (GNSS) localization (Petrovski 2014) for highly accurate outdoor localization. GNSS localization is mainly available outdoors. The other localization solutions, namely visual and inertial based solutions, can be improved if GNSS signals are available and, moreover, a spatio-temporal

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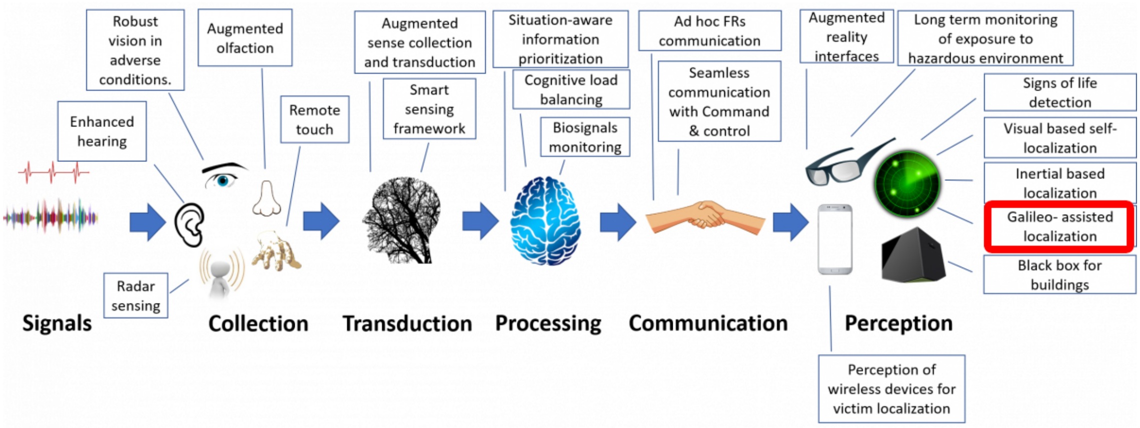


Figure 1. Complete RESCUER toolkit at a glance with the Galileo assisted localization (marked in red), from RESCUER web page 2023.

reference can be provided. This combined, complementary solution is more robust and accurate, furthermore the position of the FRs can be presented in a global navigation frame. Both visual and inertial navigation in combination with GNSS signals approaches will provide seamless accurate indoor/outdoor navigation solutions, where no additional infrastructure has to be installed and no assumptions on pre-installed infrastructure is made.

For this purpose, first a robust and light weight prototype of the Galileo localization tool is developed, that can be quickly used and tested by the end-users during the field tests and pilots. After that, coupling of the GNSS-signals with the inertial and visual based localization techniques will be investigated during the next phase of the project. Inside RESCUER, the positions of the FRs are transmitted to a data sharing orchestration service, which provides an ad-hoc network for intra-team and command and control (C2) communication. At the C2 the positions of all FRs in action will be visualized. Furthermore each FR's own position and the positions of FRs in the vicinity will be visualized in a so called mini-map in an augmented reality utility like a Hololens. Seamless communication, orchestration, and visualization are also developed in the RESCUER project by respective RESCUER partners.

The structure of this paper is as follows: First the background and the state of the art is presented followed by the end-user requirements. After that the development of the Galileo localization tool with respect to the end-user requirements is explained. Then, the results of the first experiments in an internal measurement campaign, a field test and a pilot are described. Finally, we give some conclusions and outlook.

BACKGROUND

Investigations on the use of Galileo signals alone (Linty et al. 2020) or in combination with GPS for navigation purposes were widely pursued since the start of Galileo (Margaria et al. 2012) and the development and availability of Galileo receivers (Simsky and Sleewaegen 2015). Since 2016, GNSS receivers became available in almost every smartphone (Zangenehnejad and Gao 2021). Additionally, a GNSS analysis tool accessing raw GNSS data is offered for instance by Google (Diggelen 2017). The use of Galileo signals in combination with inertial navigation is investigated in a project called SARHA – "Sensor-Augmented EGNOS/Galileo Receiver for Handheld Applications in Urban and Indoor Environments" (Weimann et al. 2007) assisted by a transponder system to be installed inside the building. In the ESA project DingPos (Niedermeier et al. 2010) a system is introduced, where GPS and Galileo receivers are used in an indoor localization system assisted by map matching, UWB, and WiFi. In the European H2020 project PROTECT (The European Commission 2022), a GPS-aided inertial navigation system, called Arianna, is especially designed for professional use cases and tested with fire fighters.

In contrast to the above-mentioned approaches, the RESCUER project seeks to enhance existing infrastructure-less visual and inertial based indoor-localization techniques with quickly and easily applicable GNSS signals, to provide more accurate positioning wherever possible. The inertial and visual localization tools are to be developed by the project partners CERTH and University of Greenwich. In addition to their approaches, DLR already has researched on visual aided inertial and standalone inertial navigation techniques, supplemented and advanced by reference localization sources like GPS (Börner et al. 2017; Diaz et al. 2018). Besides the fusion of GPS data in inertial and visual localization, the GNSS raw data of the first smartphone enabling the reception of multi frequency signals – namely the Xiaomi 8 - is deeply investigated in (Kaiser et al. 2021) and compared to the data of high precision devices. Smartphone positioning suffers mainly from duty cycling (Riley et al. 2017; Paziewski et al. 2019). Because the phase is not continuously available, a precise point positioning (PPP) is not always possible.

END-USER REQUIREMENTS

In addition to the development of a highly accurate localization system, the FR specific requirements to the localization system are worked out with the end-users in RESCUER. The end-user requirements are specified all FR teams of the project and discussed and evaluated in collaboration with them.

The most relevant requirements are depicted in Table 1. We included the requirements that are weighted with a "should". One of the relevant performance criteria for the GLT tool is a time to operation of 1-2 minutes. The time to operation is not equal to the time when locations can be retrieved. Since the first one is dependent on the time to start the mini-CPU and to start receiving data of the GNSS tool, the second time is dependent on the chip-set used, the satellites in view, the signal to noise ratio (SNR) of the received signals, and with it the possibility to calculate a position out of it. Therefore, this time to operation cannot be influenced by the design of the tool itself. If it is impossible to receive enough satellite signals at a specific location, the tool is not able to calculate a position out of it and it will provide no position. This means, that in that case a position fix can only be obtained after the FR moved to a location with better reception conditions. Beside time to operation, also range and accuracy are performance criteria. Since the accuracy is strongly dependant on the environment, it was not specified. But during discussions with the FRs, it was mentioned that it is preferable to obtain an accuracy of 1-3m with the localization tool in an outdoor area.

The second "should" requirement of Table 1 is the compatibility with the personal protective equipment (PPE). Compatibility with the PPE is given when the tool fits under the PPE or inside a pocket of the PPE. More specifically, if the tool is integrated in the helmet or worn under the PPE, the tool is protected in adverse conditions such as fire, dust, or rain.

Another group of requirements are the endurance criteria: the operation should be guaranteed for 8h in the max power mode and 12h in the eco mode. The power bank used and the power consumption of the device has to be designed so that this requirement is fulfilled.

The robustness performance criteria are the thermal resistance, shock resistance and IP class. The thermal resistance can be achieved if the device is worn under the PPE, especially in the case of PPE of firefighters. The drop on the floor will be tested during the field measurements. The IP class IP66 includes that the device is fully protected against dust and splash-proof. If the device is worn under the PPE and the PPE is within that class, this is ensured. Furthermore, the box of the device can be designed such that IP66 is fulfilled. The chosen GNSS antenna is of protection class IP67, which includes protection against complete temporary water submersion which is stronger than that of IP66.

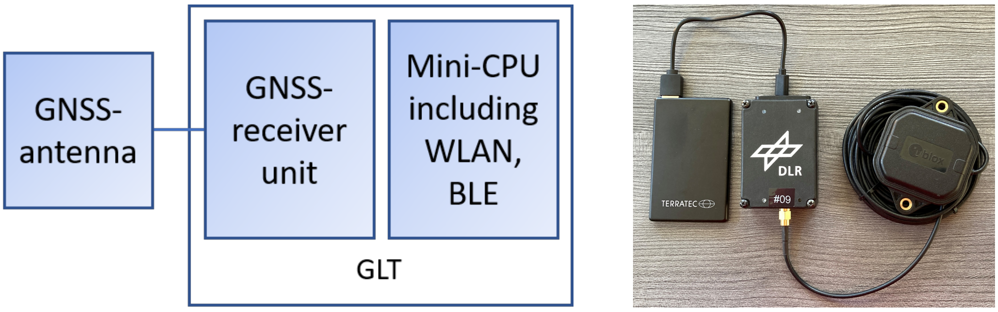
Since the tool is designed to run properly when powered on, the reconditioning is only applicable when the power bank or power source has to be changed. If a fully loaded power bank is available, the 3 minutes for reconditioning the tool can be hold. Otherwise, the time of reloading has to be considered. The device is only unavailable if it is out of order and can be repaired in that case. Furthermore, there will be no costs of maintenance since no calibration of the tool is needed.

Table 1. Most relevant requirements.

Requirement	Value
Time to operation	1-2min
Compatibility (PPE, others)	PPE
On-site maximal autonomy (eco mode)	12h
On-site maximal autonomy (max power mode)	8h
Thermal resistance	[-25°C; +150°C]
Shock resistance	1m drop on concrete floor
IP class	IP66
Time required for reconditioning	3min = Change of component
Unavailability yearly acceptable time/period	1 week

DEVELOPMENT OF A GALILEO LOCALIZATION TOOL

In RESCUER, we developed a Galileo assisted Localization Tool (GLT) for high precision outdoor positioning. The results of the GLT will be also compared to the pure use of smartphone GNSS localization. In this work, we use a Google Pixel 6 Pro for comparison.



(a) (b)

Figure 2. The architecture of the Galileo Localization Tool (a) and the GLT (b)

For receiving multi-frequency, and multi-constellation GNSS signals, a small and light weight GNSS receiver board of high accuracy was chosen that is able to receive also raw data. The GLT has to be adapted to the RESCUER needs in terms of size, weight, accuracy and robustness, and in addition to the RESCUER communication tools including their specific requirements like sending the data to the orchestrator in a specific format. There are several GNSS chipsets on the market from different manufactures, for instance from STMicroelectronics, U-Blox, Sony Semi-Conductor Solutions, Furuno electric, NVS Technologies AG, NovAtel, Trimble, and Broadcom. Small GNSS receiver breakout boards can be found from U-Blox, NVS Technologies AG, NovAtel, and Trimble. Since the boards from NVS Technologies AG and Trimble do not provide raw data, and the Trimble UAS1 (Trimble 2022) module is designed for UAVs (Cozzens 2019), they were not selected. One of the smallest breakout board that could be found and acquired for the prototype was the Spark-Fun GNSS receiver board, with a U-Blox ZED-F9P (U-Blox 2022) receiver chip on it.

The developed GLT is a small unit containing a GNSS receiver and a mini-CPU for further communication (see Figure 2(a)). We selected a Raspberry Pi Zero 2W as CPU. The CPU is chosen to be as small as possible while selecting a good processor unit that is capable to receive the GNSS data, apply an algorithm and send the data wirelessly to the orchestrator. The Raspberry Pi Zero 2W contains a 64-bit Arm Cortex-A53 CPU, clocked at 1GHz, where the processor is a Broadcom BCM2710A1 die with 512MB RAM. It offers additionally 2.4GHz 802.11 b/g/n wireless LAN and Bluetooth 4.2, which is necessary for sending the data to the orchestrator. The GNSS Sparc-Fun U-Blox GNSS ZED-F9P receiver board is connected to it via UART.

In the current version, the GLT box is sized $75 \times 50 \times 23$ mm with an additional active GNSS multi-frequency antenna connected to it (see Figure 2(b)). The box is of light weight and can easily be carried in the backpack or inside the PPE. In the actual version, for obtaining a better accuracy the antenna is a U-Blox ANN-MB-00 Multi-band (L1, L2/E5b/B2I) active GNSS antenna. The size of the antenna is $82.0 \times 60.0 \times 22.5$ mm and the weight is 173 g. Compared to the GLT tool the weight of the antenna is much larger. The antenna can either be placed on a helmet, or close to the small box, if worn in the backpack or inside a pocket. If the antenna is placed on the helmet (or alternatively incorporated in the helmet, for being secured against fire), it is preferable to integrate the device also in the helmet to avoid a cabled connection that might be disturbing for the FRs. Alternatively, the antenna can either be located at the GLT box (but outside the GLT-box), or it can be replaced by a small and light weight active multi frequency antenna inside the GLT-box in order the prevent disturbing cables. With this, the results will be slightly worse. Therefore, we will investigate in the future the use of different antennas worn at different locations of the body.

The GLT box is powered via a mini-USB connector connected to a small and light weight power bank. It should be noted, that the prototype weight and size can surely be reduced when designing a final product.

For comparison, the GNSS receiver of the smartphone is used. Recent smartphones include a multi constellation and multi frequency receiver, like the Broadcom BCM47755 (Moore 2017) chip. It can track BeiDou B1 and GLONASS L1 and QZSS L1/L5 signals besides L1/E1 and L5/E5a frequency bands of Galileo and GPS. The chosen Google Pixel 6 Pro smartphone is one of the new smartphones that offers the BCM47755 chip. With the support of two frequencies per constellation a higher resistance to multipath and reflected signals in urban scenarios is achieved (Wang et al. 2012). Since 20 smartphones based on Android operating systems provide the possibility to access the raw data using for instance the GNSS-Logger-App. With this, the data can be analysed and used for obtaining better accuracy in smartphone positioning.

(a) (b) (c)

Figure 3. Tool usage and performance in Mosbach: two rescue dog squads (a), Tool positions (b) and GNSS accuracy changes when entering or leaving the woods (c).

FIRST RESULTS

Field Trial in Mosbach

The Field Trial in Mosbach (Germany) in June 2022 has two goals: tracking positions of multiple GLT in the field and tracking the GNSS accuracies for different environments. These goals are defined with International Search and Rescue (ISAR) as an end-user in preparation for the first RESCUER Pilot in November 2022. Within the trial the update frequency is tested at the following rates: 30s, 1min, 2min, 5min. A useful interval is investigated in collaboration with the incident commander. An assumption is, that high frequent position updates for all FRs at the C2 are useless or even an information overload for the incident commander. For the field trial, two groups of a rescue dog squad (see Figure 3(a)) are equipped with the GLT. Four members of each group are hereby tracked during a 4h training exercise. Tool and antenna positions vary between the members (see Figure 3(b)): one device is placed inside a breast pocket, another device on a helmet and the remaining devices in bag packs. All GNSS receiver tools are powered via small powerbanks at the starting point and immediately start gathering GNSS signals including raw data at a rate of 1Hz. In this field trial our tool is used as a stand-alone-device and no live signal broadcast is tested. Thus all data is locally stored on the SD card of the tools. In a geographic information system an animated time series simulates the aforementioned different update frequencies, ranging from 30sec to 5min. As one result from the discussion with the incident commander, we can state that an update interval of 2min seems to be sufficient. This is well in line with requirements found by IFARI. They state that the location of responders on the incident scene should be determined at least every 3min (IFARI 2018). Another aspect of the data is the positioning accuracy. During the exercise, no buildings are entered but different forests are crossed. As expected, the accuracy decreases when entering forests (see Figure 3(c)). Two tracks show walks from north to south and one track shows a walk from south to north. Further campaigns will investigate the placement of the GLT and its influence on the accuracy.

Measurement campaign at DLR

In beginning of August 2022, a measurement campaign was performed at DLR-KN, Oberpfaffenhofen (Germany). In this area, different outdoor Ground Truth Points (GTPs) are already provided outdoors that are measured with a Leica tachymeter (Bousdar Ahmed et al. 2017). In addition to that, indoor GTPs are given for the Institute for Communications and Navigation (short KN-building) that are measured with the Leica tachymeter and a laser/tape measurer. The indoor points can be used when investigating the indoor/outdoor behaviour of GNSS signals.

During the measurement campaign we walked different routes with a GLT at different locations and with its respective antenna on the helmet, on the arm or in the backpack. We passed different GTPs indoors and outdoors. The smartphone was either in the backpack or placed on the upper left arm. For a fair comparison, we placed also the GNSS-antenna on the arm when the smartphone was placed on the arm. We measured the GNSS positioning solutions as well as raw data. The raw data is stored for future research purposes.

The environment allows for walking close to high buildings (up to 4 levels) - like in urban areas - and in quasi rural areas where no building is hiding satellite signals.

The results are given in this document for two walks with different routes. For the first walk, the smartphone and GLT were in the backpack, and the GLT antenna was placed on top of the helmet. During this route 19 GTPs were passed by stopping 3-10s at the GTP and the distance at the GTP was measured. Figure 4 shows the walk tracked with the GLT (red) and the Google Pixel (blue). The 19 GTPs are given as yellow markers. One can see that the path of the GLT is more stable, whereas the of the Google Pixel varies much more. From Table 2 one can see that this is also reflected in the error values calculated at the GTPs. In this table, the error values are given for each of the 19 GTPs, and additionally the mean value is given. The best values are marked in bold style. The mean error is 1.63m for the external GLT and 3.09m for the Google Pixel. This leads us to the conclusion that the GLT provides localization very close to the ground truth (1-3m) in urban areas with high buildings in the vicinity of the pedestrian causing multipath effects.

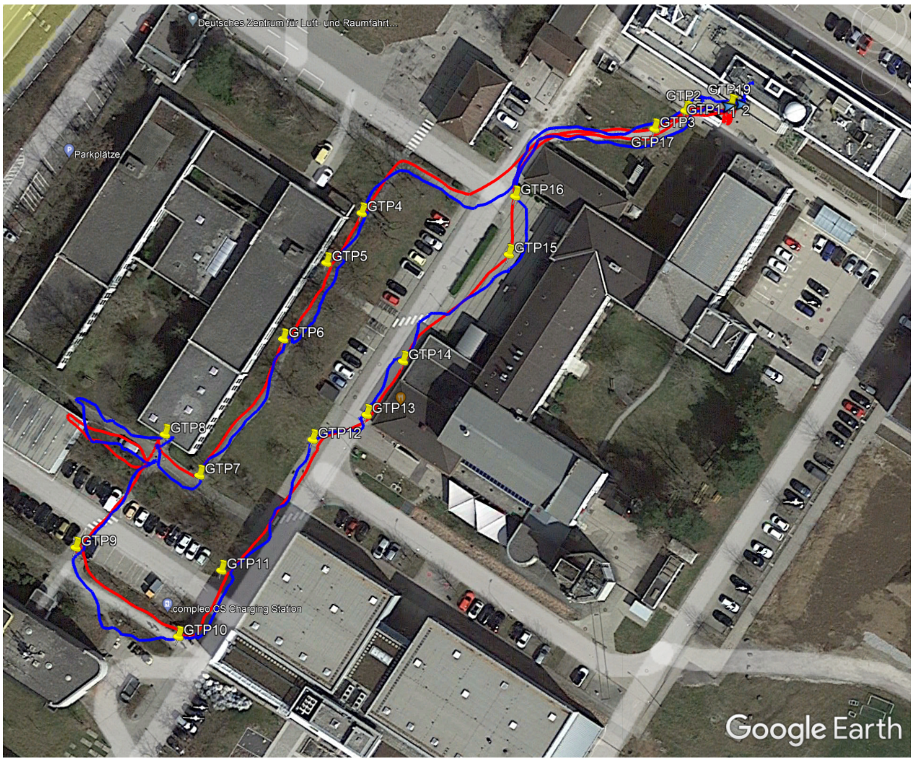


Figure 4. The route of the example walk: The results for the GLT are shown in red and the results for the Google Pixel smartphone are shown in blue. The positions of the GTPs are shown as yellow markers. The figure is created with Google Earth.

Table 2. Errors in meters at GTPs for the example walk when using the external GLT and Google Pixel positioning. The mean error is 1.63m for the external GLT and 3.09 for the Google Pixel.

GTP	GTP1	GTP2	GTP3	GTP4	GTP5	GTP6	GTP7	GTP8	GTP9	GTP10
GLT	**2.2**	**0.7**	**0.8**	**1.6**	**1.3**	**1.8**	1.9	**1.3**	**1.2**	2.3
Google Pixel	6.2	6.1	4.8	2.4	4.2	3.2	**1.8**	2.7	2.4	**1.8**
GTP	GTP11	GTP12	GTP13	GTP14	GTP15	GTP16	GTP17	GTP18	GTP19	Mean
GLT	**2.0**	**1.4**	1.8	**0.7**	1.4	**3.6**	2.1	**1.6**	**1.2**	**1.63**
Google Pixel	2.5	1.6	**1.2**	2.5	**1.3**	8.6	**0.8**	1.8	2.9	3.09

In a second walk, we wanted to compare the results for the smartphone with the results for the GLT with similar antenna position for both devices (see Figure 5). In this walk, the antenna of one GLT was placed at the upper arm and the smartphone was placed at the same arm. For comparison, the results for another GLT with antenna on the helmet are given in that figure, too. The results for the GLT with antenna at the helmet are given in red, for the GLT with antenna at the upper arm in green, and the smartphone results with smartphone position at the upper arm in blue. The positions of the 17 passed GTPs are shown as yellow markers. From the results one can see that the results for the GLT with antenna on the helmet are very close to the GTPs. The GLT with antenna at the arm provides worse results compared to this and the worst results are given for the smartphone localization. It should be noted that the antenna at the arm was applied with no ground plane which could worthen the results (U-Blox 2016). From this figure, it is obvious that the smartphone solution is worst and, therefore, for precise positioning we prefer to use the GLT. In addition, the antenna position plays an important role for getting better accuracy. The best position is on the helmet with a ground plane under it. If the building is close to the arm or another person is hiding the satellite signals the results degrade which can be seen for instance at GTP15 for Google Pixel when walking close to a 4-floor building and between GTP4-GTP6 for Google Pixel and GLT with antenna at the upper arm. This is also reflected in the error values that are given in Table 3. Due to the fact that the antenna is only roughly at the GTP, because we were maybe not exactly standing on the GTP and the antennas are located at different parts of the body, the error values are rather a rough estimate of the error. In addition, during standing on a GTP, the error varies, which is not taken into account in the error calculations, since the errors are calculated at a certain time that we calculated for standing still on the GTP. From the mean error we can see, that it is advantageous to wear the antenna at the helmet (2.8m instead of 2.02m for the GLT). Due to the fact that the antenna is directed to the ceiling, the signals are better received and will not be additionally blocked by persons or buildings close by. In addition, it is more probable to receive the direct path from the satellites instead of reflections from buildings.

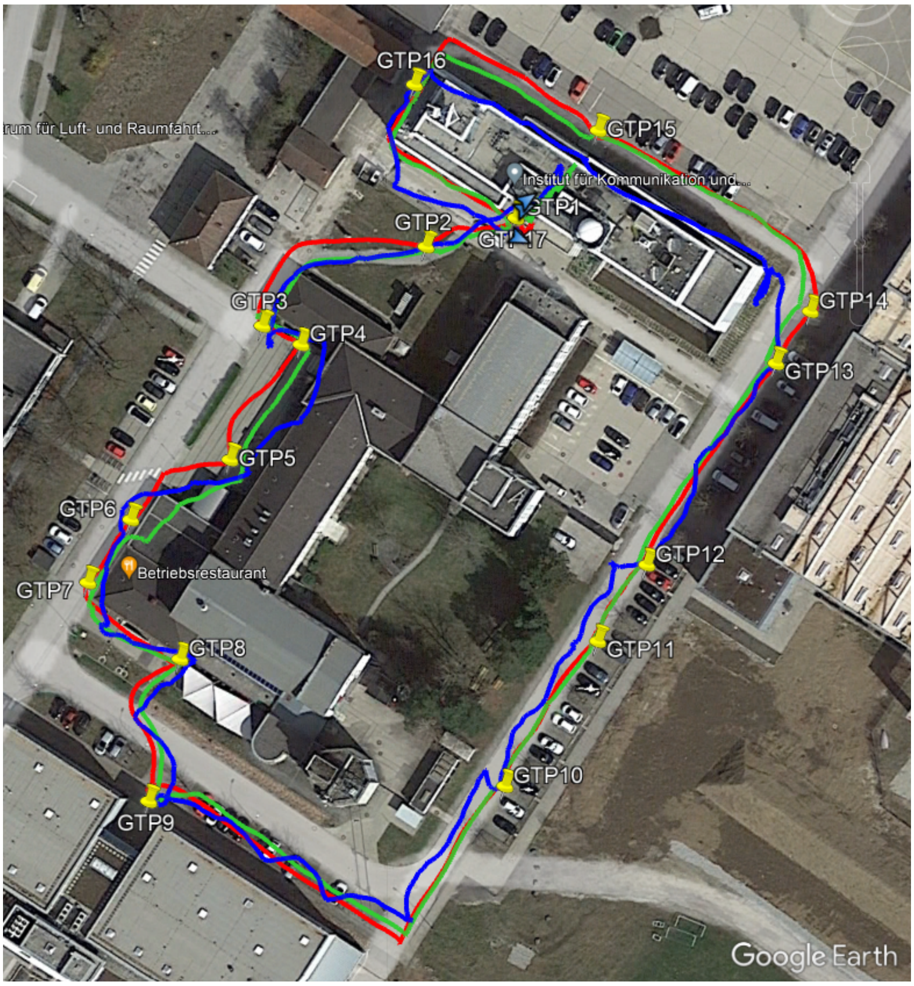


Figure 5. The route of the second walk: The results for the GLT with antenna at the helmet are given in red, for the GLT with antenna at the upper arm in green, and the smartphone results with smartphone position at the upper arm in blue. The positions of the GTPs are shown as yellow markers. The figure is created with Google Earth.

Table 3. Errors in meters at GTPs for the second example walk when using the external GLT with antenna at the helmet, antenna at the arm, and Google Pixel at the arm. The best results are obtained for the external GLT with antenna at the helmet.

GTP	GTP1	GTP2	GTP3	GTP4	GTP5	GTP6	GTP7	GTP8	GTP9
GLT, helmet	**0.87**	**2.49**	2.79	**2.2**	**2.0**	1.85	**1.07**	**1.52**	4.0
GLT, arm	7.3	3.15	3.5	2.67	2.49	2.23	2.66	2.47	**2.41**
Google Pixel, arm	5.86	4.65	**1.49**	4.97	3.4	**0.84**	5.73	4.1	3.01
GTP	GTP10	GTP11	GTP12	GTP13	GTP14	GTP15	GTP16	GTP17	Mean
GLT, helmet	**2.56**	2.33	2.52	1.63	**2.46**	**1.44**	**0.72**	1.91	**2.02**
GLT, arm	3.24	**1.6**	**2.51**	2.82	4.1	**1.44**	0.76	2.26	2.80
Google Pixel, arm	2.85	3.72	5.69	**1.44**	10.48	3.3	0.77	**0.2**	3.68

First Pilot in Weeze

During the project pilot in Weeze (Germany) in November 2022, an assessment exercise is used to verify the accuracy of the GNSS localization and to broadcast the position information to the C2. The test scenario is an earthquake with collapsed buildings where several victims have to be rescued (see Figure 7(a)). In order to track the accuracy for the 3hr lasting building assessment one FR is equipped with three GNSS receivers. One receiver is online and receives permanent differential GPS (DGPS) correction data. This tool is used as reference setup, since it provides localization accuracies of 3cm and better for most of the time. Only for periods when the FR is inside a building, the DGPS accuracy decreases. These indoor periods are omitted for the accuracy comparison. The second receiver is the GLT with its antenna placed in the backpack. A Google Pixel 6 Pro serves as third GNSS receiver and is placed next to the GLT antenna in the same backpack. In Figure 6 the horizontal error of the GLT and the smartphone compared to the DGPS reference are plotted over time.

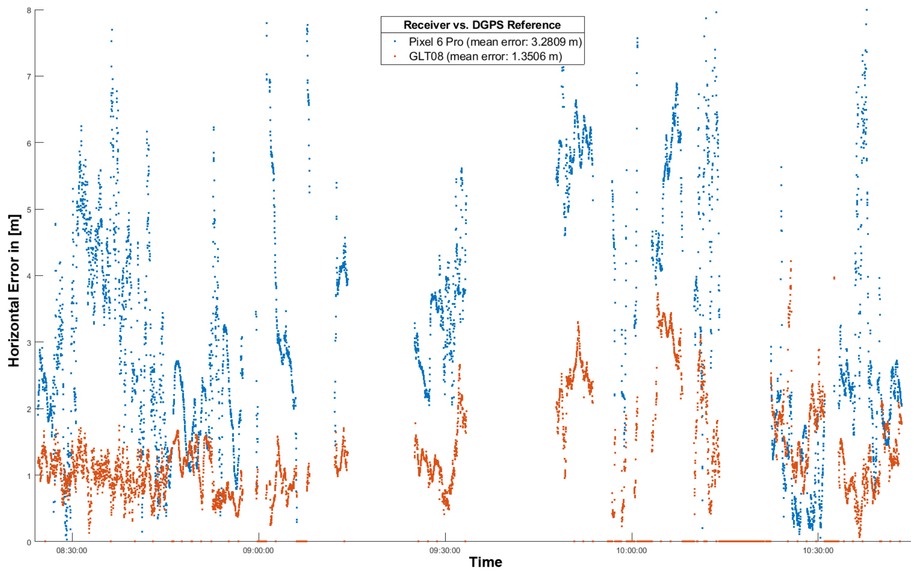


Figure 6. Horizontal error in meter of the GLT (reddish) and the smartphone (blueish) compared to the DGPS reference plotted over time

The blank spaces represent the periods where no DGPS fix was available. Besides the continuous reference measurements and the real test scenario, this setup is comparable to the measurement campaigns at DLR. The accuracies of the GLT are in the range of 3 to 4m, while the smartphones' error often becomes twice as large with 7-8m. In addition the mean errors, with 1.4m for the GLT and 3.3m for the smartphone, confirm the observations which were described in the previous section.

In this pilot it is the first time that all tools of the RESCUER project are used in parallel. Therefore, initial integration tests are performed. Among them the GLT is tested with the live broadcast via the orchestrator. The aforementioned GLT in the backpack transmits the localization information via LTE to the orchestrator. Live position and corresponding FR ID are shown on a map (see Figure 7(c)) at the provisional C2 (see Figure 7(b)), which is located several kilometers apart. ID 0 in 7(c) refers to the postion of the C2, while ID 1 represents a first responder during the 3h building assessment exercise.

(a) (b) (c)

Figure 7. Earthquake scenario: Training base in Weeze (a), provisional C2 setup at the site (b) and live localization of FR during building assessment (c).

OUTLOOK AND CONCLUSIONS

In the very early stages of the project we focused on an external GNSS receiver tool including an external antenna. Mainly this decision was driven by the inappropriate design of GNSS antennas inside smartphones. The first results including the accuracy verifications confirm this assumption. Furthermore extended GNSS localization tests with the Google Pixel 6 Pro lead to blackouts due to overheating.

Especially in difficult environments like under trees and in close proximity to man made infrastructure, the time to get a first GNSS fix is considerably shorter when using a dedicated GNSS antenna like we did with the presented GLT. Another aspect for using an external device is that we are able to adapt more easily to new technological improvements like the Galileo High Accuracy Service (HAS). The HAS aims at providing a Precise Point Positioning service worldwide, transmits precise orbits, clocks and biases, for both Galileo and GPS, in the signal-in-space and through a ground channel (Fernandez-Hernandez et al. 2022). If HAS capable receivers become available during the project time, we are going to exchange the current u-blox F9P unit, since it is an infrastructure-less service that provides accuracies of an order of magnitude better. Furthermore we want to improve the ability to buffer localization information in case of low bandwidth or connection loss (Hanssen 2021).

Our main focus will be on the integration with the other two localization tools in the project, namely visual localization and inertial based localization, since the synergy is of high importance when dealing with indoor-outdoor transitions.

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