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RESEARCH ARTICLE

Standalone Solutions for Clean and Sustainable Water Access in Africa Through Smart UV/LED Disinfection, Solar Energy Utilization, and Wireless Positioning Support

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This work involved human subjects or animals in its research. The authors confirm that all human/animal subject research procedures and protocols are exempt from review board approval.

ABSTRACT This paper provides a unique multi-disciplinary survey of standalone solutions for clean and sustainable water access in Africa and proposes a three-segment architecture, comprised of an UV-LED-based water disinfection unit, a solar-powered battery, and a wireless positioning system. In addition, our paper also provides initial snapshot results from all the three segments of the proposed architecture, as well as two examples of the water analysis and user-survey-based results collected from Togo, Africa. We believe that the features of our envisaged system such as long battery life, low maintenance cost, ability to significantly increase the quality and disinfect at least 1.5 l/min of water and ability to offer wireless positioning without the need to access a cellular or WiFi network, for accurate annotation of water sources, localization of misplaced or lost disinfection systems, and user standalone positioning capabilities, are attractive features towards improving the quality of life of people with limited access to potable water or to water that fulfills international quality criteria.

INDEX TERMS African continent, backpack/head-held solution, Global Navigation Satellite Systems (GNSS), pseudoranges, solar energy, ultra violet light-emitting diodes (UV-LED), user surveys, water disinfection, water management.

I. INTRODUCTION AND MOTIVATION

According to a recent UN survey [1], the access to clean and safe drinking water in Africa was still below 30% in 2020 and

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an universal access to safely managed drinking water is of timely and significant interest, as emphasized also in the worldwide sustainable development goal (SDG6) on clean water and sanitation [2], [3], [4].

Also, according to a recent study in [5], more than 50 billion EUR per year would be required to cover the needed infrastructure costs that would ensure clean and safe water availability for all population in Africa. Thus, it is important to find out more cost-effective solutions for water purification/disinfection, water monitoring and management, as well as robust solutions for safe access to water sources. Moreover, it has been recently shown in [6] that investments in improving the water access and infrastructure in sub-Saharan Africa can also lead to significant economic growth and the need for finding novel low-cost water treatment solutions was emphasized among the future drivers towards efficient solutions.

Recent literature has addressed various aspects regarding clean water solutions, such as water monitoring [5], water waste treatment planning [7], water recycling [8], and water disinfection [9], [10], [11]. Yet, there is still a lack of comprehensive multi-disciplinary surveys, addressing the various building blocks towards efficient, sustainable, and possibly game-changer solutions for universal water access.

In terms of water monitoring solutions, the work in [5] focused on machine-learning approaches for water monitoring, and one of the conclusions in that work was that countries without a water monitoring system in place are those in the highest need of better solutions and enabling systems for water access. One of such countries without a water monitoring system in place is Togo, where we have conducted several one-to-one interviews and one focus-group interview.

Besides the challenge of access to clean water worldwide, also the access to energy is an important key to economic development. However, according to the 2022 report of the international Energy Agency (IEA) approximately 775 million people worldwide live without electricity access, with the majority living in remote areas of Sub-Saharan Africa [12]. The links between energy and water are recognized and the scarcity of safe drinking water is paired to the lack of energy access. Hence, people who live in rural and isolated places would benefit greatly from the development of autonomous devices for providing clean water independently from conventional energy sources. Therefore, renewable energy sources such as solar, wind, and hydroelectric power, which have the ability to provide sustainable and clean energy, are the most suitable for such systems.

Wireless localization aspects have not been yet addressed, to the best of the Authors' knowledge, in the content of access-to-clean- water solutions so far; yet, they could provide significant added value when mobile systems such as backpacks or head baskets are envisaged to be used, not only for localizing and tracking misplaced, forgotten, lost of stolen systems, but also for geo-tagging new water sources, studying migration patterns for water access, and providing low-cost and standalone navigation possibilities to people traveling to access the water sources.

Our overarching goal is to develop an innovative solution for water disinfection based on UV/LED, powered by solar energy, and having a wireless location engine as an added value. In conjunction with this overarching goal, we are presenting in this work the following novel aspects:

- Offering a unique and multi-disciplinary survey of standalone solutions for clean and sustainable water access in Africa;
- Identifying the challenges and possible solutions for efficient, low-cost/affordable, and real-time water disinfection solutions through the use of available sensor technologies;
- Proposing a three-segment cross-field architecture, relying on water filtration and UV-LED disinfection, solar energy use for a battery-powered standalone system, and satellite-based wireless positioning support;
- Detailing the components and requirements of such a cross-field architecture, based also on a use-case analysis of water in two locations in Togo;
- Providing initial snapshot results, both based on the technical aspects of the envisaged solutions as well as on the user surveys and focused-group discussions conducted in Togo during fall 2022 (from 27th October till 7th of November 2022).

The present paper is structured as follows: We address the adopted methodology in Section II. The three segments of the proposed architecture, together with snapshot examples and results are addressed in Section III (water disinfection solutions), Section IV (solar-powered solutions), and Section V (wireless positioning support). Section VI describes the results of our analysis of the water quality in Togo in two places and Section VII describes the results of our surveys and interviews with Togo inhabitants during a research visit during fall 2022. Section VIII presents a discussion of the findings, study limitations, and open challenges and it summarizes our work.

II. METHODOLOGY

As mentioned in Section I, our enveloping and long-term goal is to develop affordable technologies to provide off-the-grid clean water by using a smart portable unit based on UV/LED disinfection augmented with classical decontamination, powered by renewable energy sources, and equipped with a low-cost wireless positioning engine. Our envisaged solution is illustrated in Fig. 1, comprising three main components: a water disinfection unit (in our examples based on UV/LED disinfection), a solar energy module to power the other components, and a standalone positioning engine relying on satellite navigation data (i.e., no wireless access required) and aiming at low-cost low-power processing. The whole system can be fit into a backpack or a head basket and

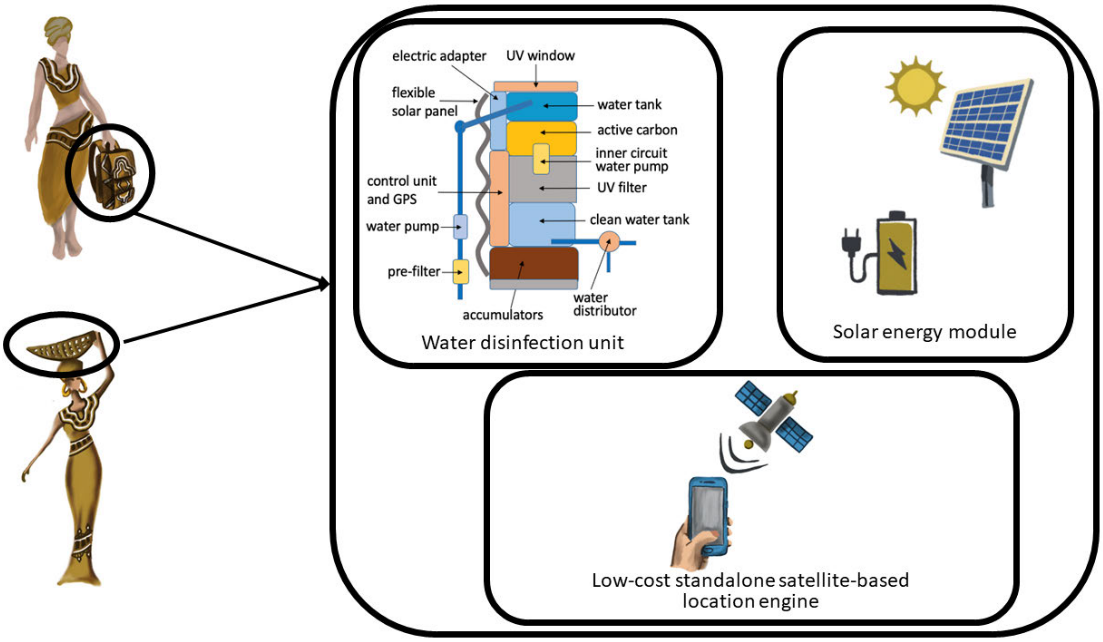


FIGURE 1. **Main building blocks of our envisaged standalone solution for clean and sustainable water access: i) smart UV-LED disinfection, ii) solar energy utilization, and iii) standalone wireless positioning support.**

carried back and forth to and from the water sources, which can be contaminated and need disinfection.

The adopted methodology in the rest of this paper is to offer a comprehensive survey on existing and potential solutions of self-powered wearable devices (e.g., a backpack or a head-carried container as illustrated in in Fig. 1) and to focus on its three components illustrated in Fig. 1: i) UV-LED-based disinfection solutions, ii) solar-energy based power source and iii) wireless and standalone satellite-based positioning engine which does not require access to cellular or WiFi data, and which can offer an easy-to-use and affordable technology to local population who is off the grid or suffers from limited access to drinking and clean water. Our methodology has been dictated by the following identified needs of the sustainable water solutions of the future (as explained later in Section VII, based on the conducted user surveys):

- Stand-alone solutions, i.e., not requiring access to mains electricity or to wireless connectivity (WiFi/cellular) as such wireless connectivity may be available only in a discontinuous manner in the regions of interest in Africa;
- Self-powered carry-on solutions (e.g., backpack or head-carried basket, equipped with solar-powered batteries); for reasons detailed later, in Section VII, a head-carried basket seems preferable to a backpack;
- Real-time and efficient water purification techniques, which do not require long processing times or heavy-to-carry external sources. Sources of water pollution, such as (endo)parasites originated from animals sharing the same water sources must also be considered, as described later in Section VI;
- Easy-to-use, easy-to-be-learnt solutions;
- Affordable, low-cost, and preferably low-power solutions.

The last part of this paper (Sections VI and VII) includes water measurement results from two places in Togo, as well as results from our user surveys conducted in Latakopé, Togo and a discussion about the limitations and challenges to overcome based on the findings from the interviews.

The following three sections detail each segment of the three-segment architecture from Fig. 1, emphasize the open challenges and show illustrative snapshot results, when available.

III. WATER DISINFECTION SOLUTIONS

Water purification is, in general, based on several methods and technologies targeting different types of impurities including germs which threaten human health. Here we will discuss the methods and the technologies that are or can be deployed in a portable water purification equipment to be used off-grid, in emergency situations, or when the resources are scarce. Special attention will be paid to disinfection, i.e. germ removal or inactivation.

Water heating or boiling is a simple method to inactivate most micro-organisms. The result depends on the temperature and duration, but usually, while heating the water up to the boiling point, a proper disinfection is already achieved irrespective of the presence of other contaminants or suspended particles [12]. However, heating will not improve the quality of water in any other way – e.g. with respect to its smell, taste, or aspect – and may need to be combined with other methods of purification, such as filtration. Besides these considerations, water heating/boiling is relatively a time-consuming method and needs a comparatively strong source of (thermal) energy.

Filtration is a purification method which can be used to eliminate suspended particles, micro-organisms, and dissolved chemicals. Commercially available ceramic-filter cartridges can even remove a very large fraction of impurities with sizes of 200 to 300 nm and, thus, efficiently retain most bacteria and other pathogens, but not viruses [13], [14]. Activated carbon filters are efficient in removing certain organic and inorganic chemicals from water [12]. This kind of filters are usually deployed after ceramic filters. Such a filter combination will thus improve water quality both by disinfection and removal of suspended particles and chemicals. However, since the filters retain the impurities, periodical cleaning or exchange is needed. Moreover, to improve disinfection subsequent chemical or ultra-violet (UV) treatment [15] has usually to be employed.

Two other types of filtration are to be mentioned here, too: the ultra-filtration and the reverse osmosis [16], [17]. Both use special membranes with very small pores, which, in the case of reverse osmosis, are not of the piercing kind.

Recently, a Portable Aqua Unit for Lifesaving (PAUL), a device based on the so-called ultra-low pressure ultra-filtration, has been developed for usage in emergency situations [18]. It is relatively cheap and it can also be used to provide small communities with clean water, if this is not contaminated by solutes – the developers specifically recommend rainwater ponds as the optimal water source [18].

Reverse osmosis can, in principle, eliminate any kind of impurities or solutes, including salt, but it needs pressures of at least 2.8 bar to overcome the so-called osmotic pressure. Thus, adequate pumps are needed. Moreover, the special membrane which has to be deployed needs to be protected from certain impurities, thus water is to get filtered in advance. For optimal results, one may add a final chemical or UV based disinfection step to account for leaks and membrane imperfections.

As it can be deduced from the overview above, chemical or UV-based disinfection is needed or at least desirable as a last step after filtration. Conversely, applying these disinfection methods without filtration may lead to poor results since both are affected by certain impurities present in water [19].

Chemical disinfection is mainly based on substances containing chlorine or iodine. While being a widely used and effective method of disinfection, a chemical disinfection requires precautions with respect to handling, storage, and usage, see for example the instructions given for Sodium Dichloroisocyanurate Dihydrate (NaDCC) granules [20] and also [19]. Besides, it usually affects the taste of water. This is why the UV-based disinfection, which can achieve comparable levels of pathogen inactivation, has become a widely spread alternative to chemical disinfection. With the advent of Light-emitting Diodes (LEDs) with peak intensities at wavelengths between 260 and 280 nm, thus emitting in the UV-C and UV-B ranges [21], which extend from 100 to 280 nm and 280 to 315 nm, respectively, this method can be applied also in portable water purification equipment. An illustration of an UV-LED disinfection module is shown in Fig. 2.

FIGURE 2. An example of an UV-LED disinfection module; in-lab tests.

To sum up, the best results are usually achieved by combining a water treatment step with a filtration step, in order to remove at least the macro- and larger microscopic impurities. After an initial filtration, a second step can be boiling/heating, chemical treatment, or UV disinfection. Based on our analysis, UV-LED and solar-energy-based disinfection have a lower cost on the long run since there is no need to replenish stocks and issues related to handling, storage and usage are avoided. Moreover, it also is highly portable and relatively fast (less than 1 min/l is presently achievable).

IV. SOLAR-POWERED SOLUTIONS

The second segment of the proposed architecture from Fig. 1 is a solar battery to power up the whole system.

In regions with high solar potential, such as in Togo and Algeria (2.1 MWh/m^2/year and 2.7 MWh/m^2/year, respectively) [22], [23], [24], photovoltaic (PV) devices can offer an attractive alternative in terms of cost, efficiency, and reliability to other sources of electricity. However, designing an effective PV system depends on a variety of factors, including the weather, geographical location, energy load required, panel characteristics, and technical components. When it comes to a portable system, the complexity is even greater, since the developed system must comply with the requirement of the onsite user, while the location is variable (energy production is variable) and the total weight and dimensions

TABLE 1. Estimated energy needs for our envisaged water-purification solar-powered system equipped with a standalone positioning engine.

Appliances	Power of appliances [W]	Average operation Hours [h]	Average daily energy consumption [Wh]
Pump 5L/min	5	0.58	2.91
Pump 1.5L/min	6	1.25	7.5
Electronic control boards 1	3	0.58	1.74
Electronic control boards 2	3	1.25	3.75
Solenoid valve	5	1.25	6.25
GNSS chipset	5	0.58	2.91
UV-LED unit	20	1.25	25
Standby system	0.22	24	5.28
Estimated total	43.42	10.16	57.24

of the PV system components (battery and PV module) are important.

Most commercially available self-powered backpacks are low voltage (up to 11V in the best case) and low-power output (up to 20W) because they are designed to power portable devices for personal use or applications that require some degree of freedom, such as mobile phones/smartphones, tablets, GNSS systems, Bluetooth speakers, power banks, cameras, and robots. A possible architecture of the electrical components in an envisaged standalone system that would work with a minimum voltage of 12V and would need a high power output to meet the daily user needs ($\approx$ 60 Wh/day) as specified in Table 1 is illustrated in Fig. 3.

As discussed so far, such a system would require the design of its specific solar powered backpack (or a head-held basket), to meet certain criteria including energy requirements, electric components, energy management and user's comfort (backpack weight). In order to achieve this goal, flexible or foldable solar panels are the most suitable as they are lightweight and can easily be integrated into the backpack (or a basket) design. Moreover, the selected components have to have low energy consumption characteristics, and work in direct current (DC) mode to avoid energy losses due to the conversion from DC to alternative current (AC) (estimated at least at 5%). Control boards are incorporated to manage the operation of the device's components, for optimum energy savings. In addition, to meet the energy demand, a lithium-ion battery is added to store excess produced energy and provide power when electrical load is higher than the PV production. Lithium-ion batteries are commonly chosen over other battery types in remote applications, due to their superior energy density and lifetime. This, in addition to the ease of repairing them using individual replacement cells, and their low self-discharging rate [25], [26]. The Li-ion battery charge is controlled using a Maximum Power Point Tracking (MPPT) charge controller, to adjust the load characteristic as the conditions change. The most difficult part of designing an efficient PV system is adapting the same setup for different regions (e.g., Togo, Algeria, etc.) characterized by diverse weather patterns and different solar potentials (the solar activity is also related to the ionospheric delays that can be measured based on the GNSS signals, as discussed in section V. Herein, simulation can play an important role in predicting the performance of the designed system under diverse conditions. To meet the stated objective, the PVsyst software can be used. This is a modelling tool that allows to determine how much solar energy can be harnessed from different specific locations, analyse PV losses and predict the efficiency of the system.

V. WIRELESS POSITIONING SUPPORT

The third and last segment of the envisaged architecture from Fig. 1 is a standalone wireless positioning engine. A standalone positioning means that no access to WiFi or cellular network is necessary and the user device (e.g., smartphone) computes the position solely based on the signals received from the visible satellites on sky.

Currently, outdoor positioning relies heavily on Global Navigation Satellite Systems (GNSS), usually via low-cost single-system single frequency receivers. Sub-meter positioning accuracy can be achieved in outdoors with multi-system multi-frequency receivers, provided that there are no obstructions in the path of GNSS signals or there are additional Inertial Measurement Unit (IMU) sensors integrated with the GNSS pseudoranges [27]. However, when walking or driving through dense vegetation, in crowded urban areas, or in hilly or mountain areas, the GNSS signals can be temporarily lost and the accuracy can degrade, becoming several meters or tens of meters. In addition, the presence of interferences in GNSS bands (e.g., jammers, spoofers) and the higher ionospheric scintillations towards Equatorial regions may further and significantly reduce the positioning accuracy [28]. Last-but-not least, low-cost GNSS receivers, such as those available on low-end smart phones, may

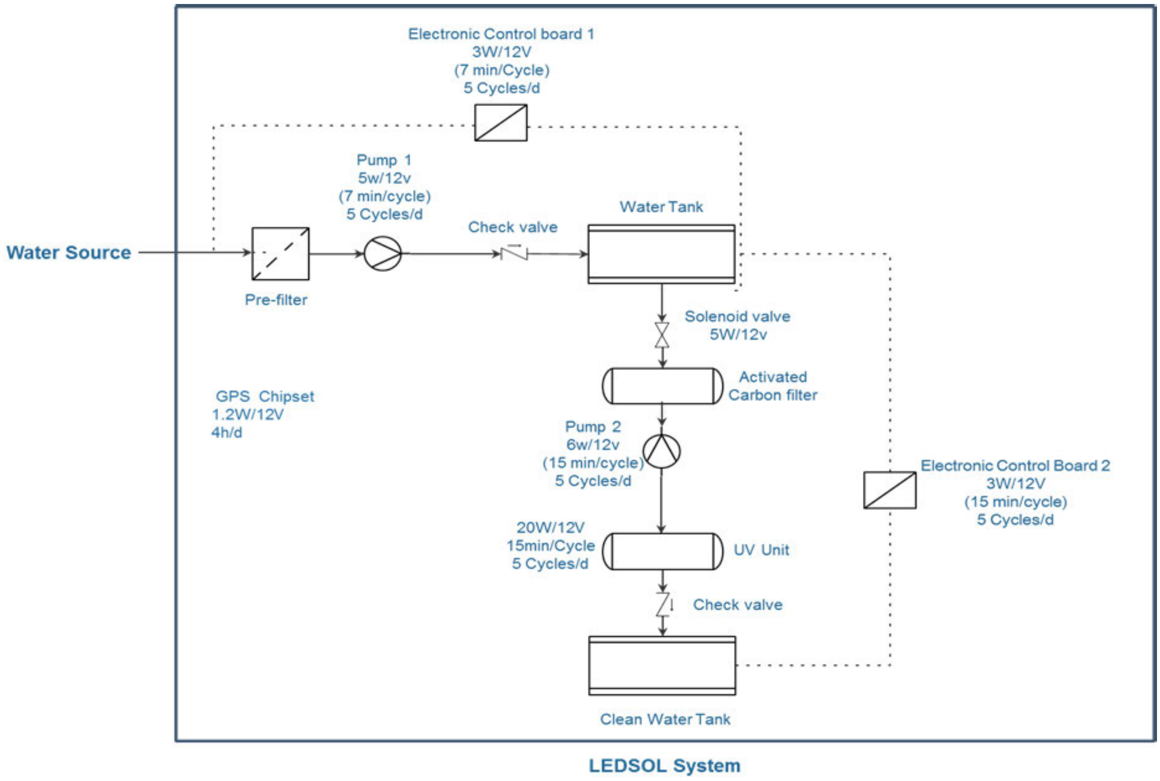


FIGURE 3. **A block diagram of the components and electrical requirements of the proposed solar energy operated system, called LEDSOL according to the funded-project name.**

provide noisy and discontinuous pseudorange measurements that need to be processed in novel and cost-efficient manner in order to reach satisfactory positioning accuracy. Achieving moderate-to-high positioning accuracy and robust localization with low-cost receivers is challenging and important in the context of water-source and backpack localization/geo-tagging, work-force tracking, vehicle localization and tracking for water carrying vehicles, or route optimization [29], [30].

Our envisaged solution (see Fig. 1) relies on the assumption that users will have access to battery-operated devices with GNSS chipsets, such as low-cost smartphones, and that standalone positioning (without the need to access the WiFi or cellular networks) will be provided based on the GNSS raw pseudorange data (and, when available, on raw carrier-phase data as well). Since 2016, when the Android smartphones opened the access to GNSS raw data, the use of GNSS pseudoranges has become very easy for a variety of location applications and services [31], [32].

However, as emphasized, for example in [30], the raw observations coming from low-cost chipsets, as those typically available on low-end Android smartphones, are affected by a substantial number of errors and outliers and developing robust positioning schemes with such data is a challenge not yet fully solved, according to existing literature. The authors in [33] have also identified the following challenges on the path of reaching low-cost GNSS computing: wireless environments characterized by the presence of multipath and interferences and increased signal complexity in modernized GNSS, due, for example, to the use of Binary Offset Carrier (BOC) modulations instead of the traditional Binary Phase Shift Keying (BPSK) used in legacy GPS signals. Examples of the power consumption of commercially available GNSS receivers ranged between 4 mW (in low-precision receivers) to 1200 mW (in high-precision receivers), as shown in [33], proving a huge variability of chipsets and the possibility to find optimal tradeoffs between positioning accuracy and power consumption at the receiver based on the target user requirements and use-case scenarios.

A wide measurement campaign has been conducted in the first quarter of 2023 at various locations in Africa and Europe based on various Android phones, in order to investigate the quality of GNSS measurements, the achievable positioning accuracies in standalone mode (using only GNSS signals) and to compare the various satellite-positioning errors, such as ionospheric (iono) and tropospheric (tropo) models.

The data was collected by volunteers at different locations, based on informed consent; in addition, data was stored in anonymized manner and no personal identifier was used in our data analysis.

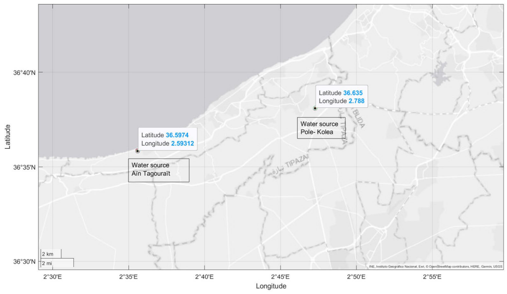


FIGURE 4. **Example of the locations of the GNSS measurements conducted in Algeria (in Pole Kolea and Aïn Tagouraït), during 21.03.2023.**

The raw GNSS data was collected via the GNSSlogger app [34] from Android Google Play store; raw pseudoranges as well as National Marine Electronics Association (NMEA)-formatted position estimates are stored every second; data acquisition duration varied at each analyzed location between 17.5 minutes (i.e., 1050 measurements) and 76.1 minutes (i.e., 4564 measurements). The data was collected at walking speeds for all cases except for Bucharest scenario where the data was collected in a moving vehicle in traffic, at an average speed of 40 km/h. The purpose of such heterogeneous data has been to understand the achievable accuracies and error models with the well-known Single Point Positioning (SPP) algorithm. The two main classes of positioning algorithms based on GNSS data collected from Android devices are the SPP and the Precise Point Positioning (PPP). SPP is only using the code pseudoranges, available from all the Android smartphones with an Android version newer than version 10, while PPP requires both the carrier-phase measurements and the code pseudoranges; carrier-phase measurements are typically supported only by higher-end Android smartphones, such as Google Pixel 7.

In our examples, for a fair comparison between the measurements with different devices we used SPP estimates with a Weighted Least Squares (WLS) positioning algorithm, described, for example, in [35] and [36]. The WLS estimates (i.e., standalone GNSS mode) were compared with the NMEA estimates (i.e., solution based on GNSS combined with cellular-network aiding and sensor aiding, based on available sensors on each phone). The iono and trop error models have been derived following the well-known Klobuchar ionospheric error correction model [37], [38] as well as the dry/hydrostatic Saastamoinen tropospheric error correction model [38], [39]. As all the various phones used in the measurements support GPS measurements, the results we show in here for the positioning and error models are based on GPS only. Some of the measurement phones, such as Google Pixel 7, supported also the other three GNSS systems in addition to GPS, namely Galileo, Beidou, and Glonass. However, no significant improvement in the positioning estimates was observed when combining all four GNSS systems compared to GPS only, no doubt due to noisy measurements and the fact that WLS estimates are not able to properly remove noise.

Fig. 4 illustrates the two locations of measurements in Algeria, taken near two water sources (Pole Kolea and Aïn Tagouraït), while Fig. 5 shows the locations in Lomé, Togo where the measurements were taken. In both cases, several measurements of 5’-10’ were taken during several days; we have analyzed them jointly, within one country, for the error analysis. In both Figures 4 and 5, the NMEA-based position estimates (relying also on additional sensors in the phone and on the cellular network) are shown together with the WLS-based estimates (relying only on single-frequency GPS pseudoranges); however, due to the larger distances between the measurement locations in Algeria than in Togo, these are distinctly visible only on the Togo map (Fig. 5).

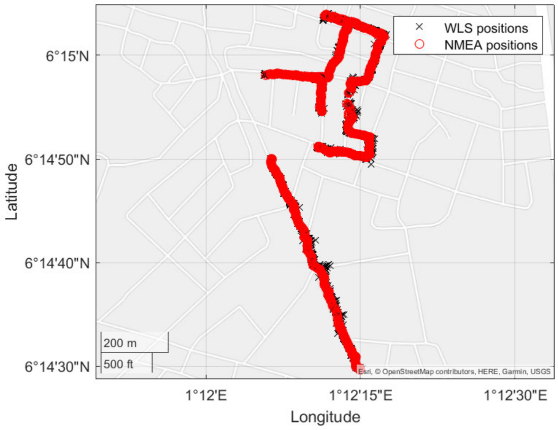
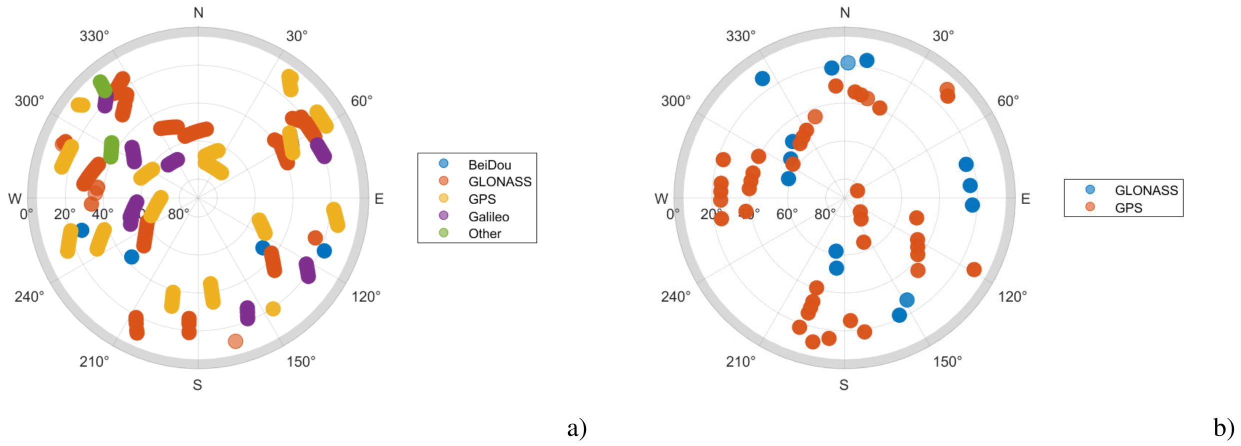


FIGURE 5. **Example of the position estimates based on Togo measurements on 10.3.2023 via two approaches: the NMEA-based estimate using additional sensors in the mobile as well as the cellular network and the standalone WLS estimates using only GPS signals coming from the visible satellites on the sky.**

Fig. 6 illustrates the skyplot of the data collected in Algeria and Togo with Oppo F19 and Itel P36 phones, respectively. A skyplot shows the azimuth and elevation of the visible satellites on sky, as captured by the mobile phone at the time of the measurement. The Oppo F19 phone used in Algeria supports all four GNSS systems (GPS, Galileo, Beidou, Glonass), as well as few other regional systems, shown as ‘Other’ in the skyplot, such as European Geostationary Navigation Overlay Service (EGNOS) and Quasi-Zenith Satellite System (QZSS). The Itel P36 phone used in Togo was only able to capture GPS and GLONASS data. As the cumulative measurement duration in Algeria was longer (36’) than in Togo (30’), the skyplot lines are slightly more spread in the left-hand plot than in the right-hand plot in Fig. 6.

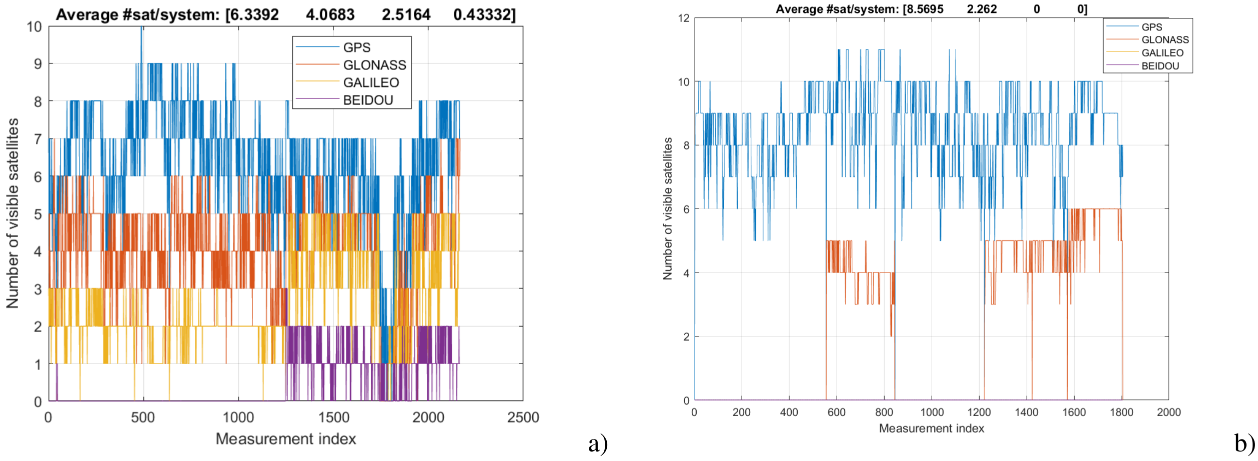
Fig. 7 shows examples of the number of visible satellites per GNSS system (GPS, Glonass, Galileo, and Beidou) based on the measurements in Algeria and Togo. As noticed also from the sky plots in Fig. 6, in Togo data only the GPS and Glonass satellites were available. The figure’s titles in Fig. 7 also shows that we have on average minimum 4 satellites (as needed for a positioning solution) only from GPS and Glonass systems in the case of Algeria and only for GPS in the case of Togo. That is why, the results shown later in this article are based on GPS-only estimates, which were available in all the studied scenarios. Fig. 7 also shows that, even when a mobile device supports a certain GNSS system



a)

b)

FIGURE 6. Example of the sky plots with the visible satellites on sky as captured by the measurement devices in a) Algeria (Oppo F19 phone) and b) Togo (Itel P36 phone).



a)

b)

FIGURE 7. Example of the number of visible satellites per GNSS system, as captured by the measurement devices in a) Algeria (Oppo F19 phone) and b) Togo (Itel P36 phone).

such as Beidou, the quality of measurements is not always guaranteed, most likely due to various hardware specifics on the phone and initialization issues; for example zero Beidou satellites are observed in the first set of 1200 measurements in Algeria, while few Beidou satellites were observed starting around measurement index 1200. Therefore, a challenge in dealing with raw data collected from Android devices is to obtain enough measurements of high quality, especially from Beidou, Glonass, and Galileo systems.

Table 2 shows the positioning errors for the five sets of measurements taken in five different countries, when one compares the standalone WLS estimates with the NMEA estimates. In general, 2D estimation errors are 10-20 m more accurate than 3D errors, due to the additional altitude dimension that affects the 3D errors; one exception is for Togo data, where 2D and 3D errors are very similar, showing thus very little differences between the altitude level estimation in standalone (WLS) mode and in sensor-aided NMEA mode; this does not necessarily mean a more accurate altitude estimation in Togo than in the other scenarios, but it rather pinpoints to less additional information from cellular network and additional sensors than in the other scenarios; in addition, the mobile device used in Togo (Itel P36) was only supporting GPS and Glonass systems, as shown previously, which makes the NMEA-based estimates to rely only on two out of the four GNSS systems on sky.

Our results in Table 2 are comparable with other results reported in the literature when SPP is used. For example, the authors in [40] reported SPP-based 3D errors with standalone GNSS between 29 m and 107 m based on raw pseudoranges collected with an Oppo Reno5pro phone in a dynamic scenario; the authors in [40] also mentioned that the SPP results reported in the literature under static scenarios are typically much better (of the order of 7–10 m), but that standalone GNSS with basic SPP positioning has quite poor performance in complex environments, as it can be seen also from our Table 2. The solution proposed in [40] to enhance the accuracy up to 25 times was to rely on an additional reference

TABLE 2. Positioning errors (mean and standard deviation in x, y, and z directions) of a standalone SPP-WLS estimate with GPS L1 signals versus the network-aided NMEA estimate using all available GNSS signals and all available positioning sensors on the device.

Location and mobile phone type	Mean 2D error [m]	Std of 2D error [m]	Mean 3D error [m]	Std of 3D error [m]	Number of measurements
Bucharest, Romania (Samsung Galaxy S10+)	35.4	19.8	50.2	21.2	1097
Pole Kolea and Aïn Tagouraït, Algeria (Oppo F19)	41.4	62.2	53.2	135.9	2167
Hannover, Germany (OnePlus Nord 5G)	39.5	32.2	61.4	43.7	1050
Lomé, Togo (Itel P36)	20.0	19.4	21.5	19.5	1800
Tampere, Finland (Google Pixel 7)	19.14	16.94	32.09	21.58	4564
Tampere, Finland (OneNord Plus 2)	11.66	7.39	23.65	11.58	2383

base station sending accurate carrier-phase observations and to perform Real Time Kinematic (RTK) positioning. Yet, under the low-cost and no network-access constraints, RTK is not a viable solution and novel standalone approaches must be derived. The authors in [41] showed that, if two nearby smartphones can exchange pseudorange information, accuracy increases of up to five times can be achieved with additional filtering; this idea is worth investigating further, as the nearby smartphones could exchange information via Bluetooth Low Energy (BLE), for example.

Fig. 8 shows the distribution of various GNSS errors in each of the five studied scenarios; each scenario plot (a) to e)) has four subplots: the upper subplot shows the histogram of the ionospheric errors, the upper-middle subplot shows the histogram of the tropospheric errors, the lower-middle subplot shows the histogram of the receiver clock errors (namely the estimated drift between the receiver inaccurate clock and the accurate satellite clock) and the lower subplot shows the histogram of residual errors after clock corrections and ionospheric and tropospheric delay error corrections; these residual errors comprise for example multipath errors, noise and interferences encountered in the wireless signal propagation from the satellite to the user's mobile device, as well as additional estimation errors and hardware errors that are not modeled separately. All x axes are expressed in meters for a fair comparison, while the y axes show the error histograms (i.e., the probability distribution function). It is interesting to see that the ionospheric errors are, on average, smaller in the measurements in Europe than in the measurements in Africa, as ionospheric delays increase when one goes closer to the Equatorial regions, while the tropospheric errors are comparable in all five environments (means ranging between 4.2 and 5.3 m), and, also as expected, they are at least half smaller than the ionospheric errors in all studied environments (the mean and standard deviations of each of these errors are visible in the figures' captions in each scenario of Fig. 8). In terms of the residual errors, the mean residual errors are comparatively high in all scenarios (typically around 12– 15 m in absolute value), while the standard deviation of the residual errors is higher in the scenarios with more heterogeneous data such as Algeria (where measurements where done at two geographically distant places, see Fig. 4) or in dense urban areas such as Bucharest and Hannover, where more multipaths are expected than in rural areas. Another observation is that the receiver clock errors are significantly higher in the measurements conducted in Tampere both with Google Pixel 7 and OnePlus Nord 2 devices compared to all the other scenarios and this basically means that the measurement devices used in Tampere had a more drifting receiver clock than the other devices as well as they span over a longer measurement duration. As long as such receiver-clock drift is correctly estimated, it does not deteriorates the positioning accuracy, as it can be removed; the clock jitter (i.e., the random fluctuations) which are not estimated correctly affect more the location accuracy than a correctly estimated large drift, therefore it is not obvious – based only on the receiver clock estimated errors– which measurement device had a better receiver clock, as this is typically measured based on the stability of the local oscillator at the receiver (i.e., the clock jitter).

The main conclusions we can draw from these error distributions is that SPP-WLS estimates relying on single-frequency (L1) and single-system (GPS) pseudoranges are not sufficient to reach high accuracy positioning, as seen from the comparison with the more accurate NMEA estimates relying on multi-frequency, multi-system, and multi-sensor estimates and most likely more advanced (but proprietary and undisclosed) estimation algorithms compared to SPP-WLS.

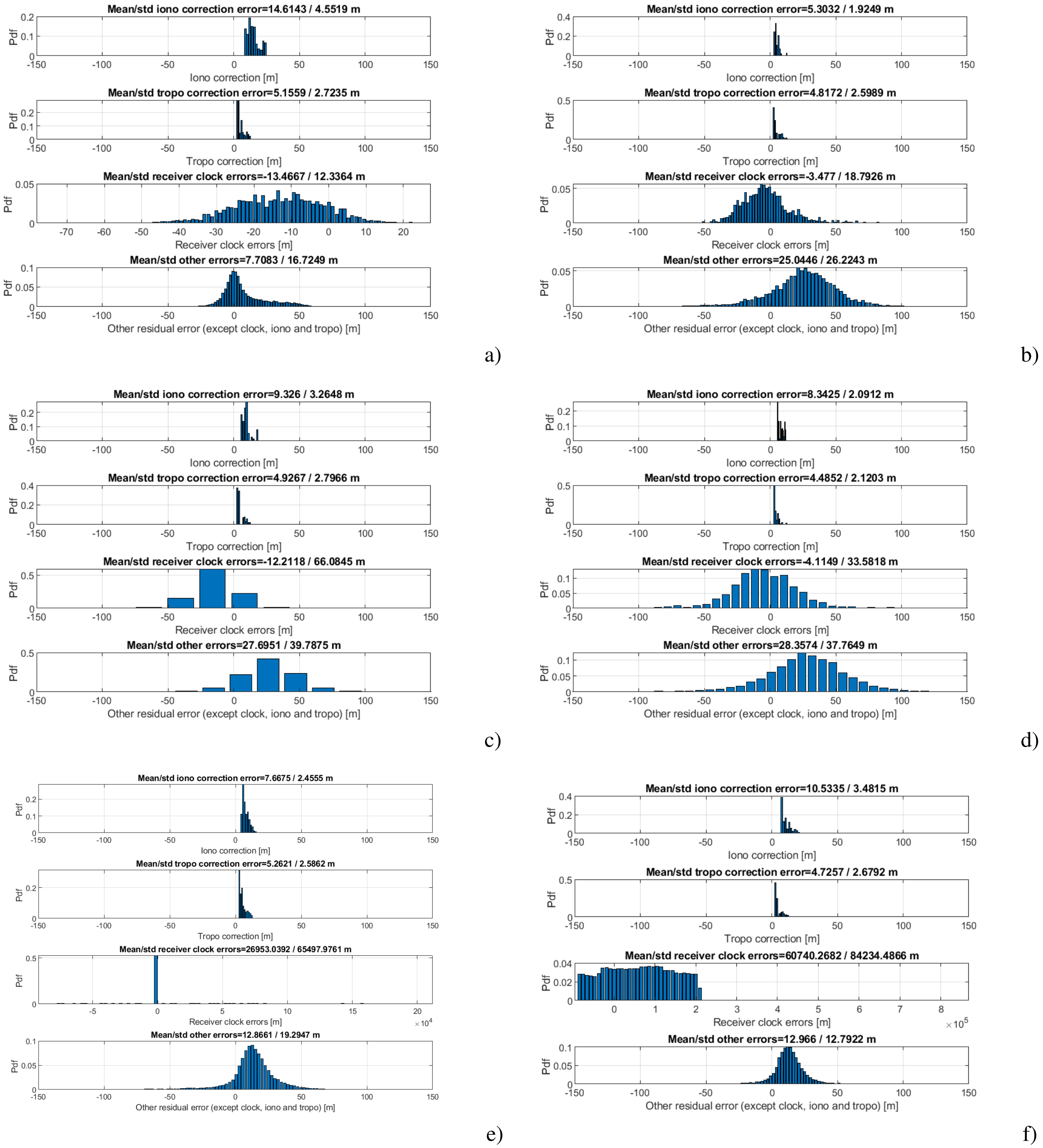


FIGURE 8. GPS error distributions based on Android measurements: a) Lomé, Togo (Itel P36 phone); b) Bucharest, Romania (Samsung Galaxy S10+); c) Djellouli, Algeria (Oppo F19 phone); d) Hannover, Germany OnePlus Nord 5G phone); e) Tampere, Finland (Google Pixel 7 phone); f) Tampere, Finland (OnePlus Nord 2 phone).

While more advanced methods do exist, as summarized in Table 3, the main tradeoff is between complexity and need of external data, on one hand, and the accuracy of the position estimate, on the other hand.

Table 3 groups various position estimators from the literature into two main categories, SPP and PPP, and presents different variants of both, by specifying whether carrier phase data is needed in addition to the code pseudoranges, if dual or multi-frequency receivers are needed, and if additional reference stations or additional sensors (e.g., accelerometers, gyroscopes, barometers) and connectivity (e.g., cellular, WiFi) are needed. The typical SPP approaches are based

TABLE 3. Overview of GNSS positioning algorithms from the literature taking as inputs raw pseudorange, and, possibly, carrier-phase data.

Algorithm	Need for carrier phase	Need for dual frequency	Need for reference station	Need for additional sensors
SPP-WLS [32], [36]	No	No	No	No
SPP-KF [42]	No	No	No	No
RTK [30], [43]	Yes	No	Yes	No
DGNSS [44]	No	No	Yes	No
INS-GNSS [45]	No	No	No	Yes
Classical PPP [46], [47]	Yes	No	No	No
GAMP [48]	Yes	Yes	No	No
PPP-AR [49]	Yes	Yes	No	No
PPP-RTK [43]	Yes	No	Yes	No

either on the straightforward WLS solution or they also apply a Kalman Filter (KF) to smooth the WLs estimates. The methods requiring additional reference stations with high antennas and network connectivity from the mobile to these reference stations are RTK and differential GNSS (GNSS). The methods requiring inertial sensor (INS) data from additional sensors in the mobile phone are grouped under the INS-GNSS category. Finally, the PPP methods have currently various implementations in the literature, such as PPP with undifferenced and uncombined observations or GNSS Analysis software for Multi-constellation and multi-frequency Precise positioning (GAMP) method, the Precise Point Positioning with Ambiguity Resolution (PPP-AR) or the combined PPP-RTK method. A remaining challenge, as derived from Table 3 is to use as little information as possible (e.g., single frequency, no carrier phases, no external aids or reference stations) and yet to achieve good enough accuracy for geo-tagging water sources, helping users to navigate to/from the water sources, and possibly enabling GNSS-based route optimization and mobility tracking. The main reason for which the available input information needs to be kept to a minimum is because the vast majority of low-cost mobile devices/smartphones nowadays are still not supporting dual/multiple frequencies or carrier-phase measurements, and the access to a cellular or WiFi network may be difficult, especially in rural areas in most need of access to good-quality drinking water.

The next section shows a detailed water analysis from two water sources in Togo, so that the Reader can get a better understanding of the challenges regarding the access to potable and uncontaminated water.

VI. USE CASE: WATER QUALITY - AN ANALYSIS FROM TOGO

Raw surface water and groundwater are readily available in Togo. However, due to very weak drinking water supply, more than 39% of Togolese do not use potable water each day for domestic purpose. Two places were selected for our preliminary studies: water from the Haho river in Latacopé, as a rural area characterized with surface water consumption, and Agoé Zongo characterized by several artesian wells. The water samples were collected from river Haho boarding Latacopé and from a traditional well at Agoé Zongo a suburb of Lomé. AFNOR[1] standard methods were used for physical-chemical and microbiological characterization. The surface water shows a high turbidity and organic matter loading, while the well water is characterized by high potassium and sodium concentration compared to World Health Organization (WHO) standard. Snapshot illustrative results from the Agoé Zongo well are shown in Table 4; the ones in red are outside the WHO limits. In general, this well water is characterized by a high mineralisation; it has acceptable chemical characteristics, however high levels of sodium and potassium as well as high levels of germs and bacteria.

Similarly, Table 5 shows the water quality measured from the Haho river, Latakopé rural area from Togo. This water is characterized by a high turbidity, beyond WHO standard. It has acceptable chemical characteristics, however it has high levels of organic mater and a total iron beyond the maximum WHO Standard. In addition, we noted an unsatisfactory hygienic quality according to the bacteriological analysis.

As shown in Tables 4 and 5, our results have revealed that there is a significant degree of microbiological pollution of the water used for drinking at the two locations. The faecal streptococi and the total germs exceeded the levels approved by the World Health Organization, therefore the bacteriological quality of the samples were found unsatisfactory. The water pollution resulted, in the two places, primarily from domestic waste water, agricultural runoff, and natural hydrologic processes.

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[1] AFNOR stands for Association Française de Normalisation, namely the French association for standardization.

TABLE 4. Measured water quality in the Agoé Zongo well, Togo.

Parameter	Methods	Results	Maximum concentrations (WHO standard) [50]
Platine/cobalt	Platine/cobalt	< 5	15
Turbidity	Nephelometry	1.5	5
Odour	Qualitative	Odourless	–
Flavor	Qualitative	Tasteless	–
pH	Electrometry	7.9	$6.5 - 8.5$
Temperature	Thermometer	27.5 C	–
Electrical conductivity at 20^o C [µs/cm]	Conductivity	1626 [µs/cm]	400 [µs/cm]
Total alcalinity	Acidimetry	39 [$^o f$]	–
Sodium (Na$^+$) [mg/L]	Atomic absorption	163 [mg/L]	150 [mg/L]
Potassium (K$^+$) [mg/L]	Atomic absorption	75 [mg/L]	12 [mg/L]
Magnesium (Mg^2+) [mg/L]	Complexometry	27.2 [mg/L]	50 [mg/L]
Total Iron (Fe^2+ and Fe^3+) [mg/L]	Spectrophotometry	0.5 [mg/L]	0.3 [mg/L]
Nitrates (NO$_3^-$) [mg/L]	Spectrophotometry	11.2 [mg/L]	50 [mg/L]
Chlorides (Cl$^-$) [mg/L]	Argentimetry	178 [mg/L]	250 [mg/L]
Total germs at 30^o C [UFC/ml]	NF EN ISO 4833-1	7000 [UFC/ml]	100 [UFC/ml]
Total coliformes at 30^o C [UFC/250 ml]	NF EN ISO 4832	1200 [UFC/250 ml]	1 [UFC/250 ml]
Escherichia coli at 44^o C [UFC/250 ml]	NF EN ISO 16649-2	< 1 [UFC/250 ml]	< 1 [UFC/250 ml]
Faecal Streptococi at 37^o C [UFC/250 ml]	NF EN ISO 7899-2	9 [UFC/250 ml]	< 1 [UFC/250 ml]

In order to significantly reduce the risks associated with contaminated drinking water used for domestic purposes, it is essential that interventions are implemented in the communities by providing a strong, portable system to achieve at least proper disinfection.

VII. USER SURVEYS FROM TOGO

The development of a portable stand-alone water decontamination system which is supposed to provide clean drinking water for people in remote areas must be customized to the user's needs in their every-day routines. Since socio-cultural and climatic differences across countries do not imply a one-size-fits-all solution, a more in-depth analysis of the user needs must be carried out to fit the system to the individual needs of the local people. This increases the applicability and acceptance of the system [51]. Therefore, we conducted a field study based on a mixed-methods design in Togo, West Africa, where a suburban community in the capital of Lomé (see example pictures in Fig. 9) and a rural community towards the northern part of the country (see example pictures in Fig. 10) were inspected using a combination of social research methods such as individual and expert interviews as well as focus groups and visual footage of the sites.

Informed consent was obtained from all the participants in the interviews and focus groups and data was anonymized, thus no personal identifier was used in our data analysis.

In the suburban areas of Lomé, people mostly live closely together with their family and relatives in a housing community with a shared patio including a common drilled-well (see an example in the right-hand picture of Fig. 11; the left-hand picture shows an example of water storage habits both in sub-urban and rural areas). A few families have access to the municipal water supply. Most of the houses are connected to the municipal electricity network. The well water's taste is salty due to the sea-water intrusion and the water quality is not reliable because of the contamination caused by rain. The consumption of this well water can cause indisposition and diseases of the digestive system and people mostly use the well water for cleaning activities and their personal hygiene and not for cooking or drinking. But this depends on the economic situation of the families and some families simply cannot afford to buy purified drinking water and must use the well water. Some families buy water from neighbors with a connection to the water system.

On the countryside, outside of the agglomeration area of the big city Lomé, living conditions are more backward and simpler. People live in stonewalled or clay cabins in small

TABLE 5. Measured water quality in the Haho river, Togo.

Parameter	**Methods**	**Results**	**Maximum concentrations (WHO standard) [50]**
Platine/cobalt	Platine/cobalt	< 5	15
Turbidity	Nephelometry	6.9	5
Odour	Qualitative	Odourless	–
Flavor	Qualitative	Tasteless	–
pH	Electrometry	8.4	$6.5 - 8.5$
Temperature	Thermometer	27.4 C	–
Electrical conductivity at 20^o C [µs/cm]	Conductivity	391 [µs/cm]	400 [µs/cm]
Total alcalinity	Acidimetry	19 $[^o f]$	–
Sodium (Na$^+$) [mg/L]	Atomic absorption	33 [mg/L]	150 [mg/L]
Potassium (K$^+$) [mg/L]	Atomic absorption	3 [mg/L]	12 [mg/L]
Magnesium (Mg$^2+$) [mg/L]	Complexometry	24.5 [mg/L]	50 [mg/L]
Total Iron (Fe$^2+$ and Fe$^3+$) [mg/L]	Spectrophotometry	0.5 [mg/L]	0.3 [mg/L]
Nitrates (NO$_3^-$) [mg/L]	Spectrophotometry	1.2 [mg/L]	50 [mg/L]
Chlorides (Cl$^-$) [mg/L]	Argentimetry	22 [mg/L]	250 [mg/L]
Total germs at 30^o C [UFC/ml]	NF EN ISO 4833-1	28000 [UFC/ml]	100 [UFC/ml]
Total coliformes at 30^o C [UFC/250 ml]	NF EN ISO 4832	1100 [UFC/250 ml]	1 [UFC/250 ml]
Escherichia coli at 44^o C [UFC/250 ml]	NF EN ISO 16649-2	< 1 [UFC/250 ml]	< 1 [UFC/250 ml]
Faecal Streptococi at 37^o C [UFC/250 ml]	NF EN ISO 7899-2	6 [UFC/250 ml]	< 1 [UFC/250 ml]

FIGURE 9. Sub-urban area in Togo: Lomé university (left picture) and sub-urban community (right picture).

communities. The rural villages do not have electricity, nor are they connected to a water supply system. The people of this remote research site must fetch water from the adjoining river Hahó and are therefore highly dependent on the seasons. In rainy season, the water of the river is polluted, the water level is very high and the footpath to the river is muddy and can be even flooded; in dry season the riverbed is dried up and water must be dug for in the riverbed. Interviewees reported water-related health issues for children and adults, aggravated in rainy season. The way from the village to the river takes about fifteen minutes and mostly women are responsible for water fetching because of socio-cultural traditions. The women carry the water on their heads in big aluminum bowls that can take up to 25 liters. They must go to the river to fetch water around six times per day which takes them about two hours in complete. The transportation of goods and water on

FIGURE 10. Rural area in Togo: village view (left picture) and distant well source (right picture).

FIGURE 11. Example of the water storage habit (left-hand picture) and drilled well in a Togo housing community (right-hand picture).

the head has a very long tradition and is very common in Africa and other less developed countries around the globe especially among women.

Female interviewees reported to prefer a system which can be carried on the head instead of a backpack solution which would also hinder the women to carry their baby in a sling. The research conducted in Togo revealed two different application scenarios for our envisaged system and the implications for the technology development based on the findings during the research trip differ depending on the setting of the research site:

- In an urban or suburban setting, the focus is more on the practicability of the system e.g. the water filling method to the system. The solar powering is here less important because of the availability of electricity. The system should therefore be additionally equipped with a powering plug. In addition to that, it is important to assess the saltiness of the water purified by our envisaged system, since the water available for disinfection is contaminated by sea water.
- On the countryside, the needs are different. The carrying possibilities and thus the design of the backpack should be adjustable and ways to carry it on the head should be considered and evaluated (see an example of head-carried basket in Fig. 12). Carrying the water solely on the back in a backpack would require a behavioral change and a break with long-established traditions and should therefore be accompanied by an informational and educational campaign. Giving different carrying opportunities would probably increase the later acceptance of the system. The suggested load weight of the system varies also depending on the carrying method and is higher on the head than on the back. In any case, the weight of the loaded system should not exceed 25 kg, as studied also previously in [52] and [53]. In addition to that, the solar powering of the system is important in remote areas due to the lack of electricity supply. Because of this, additional features of the backpack like a charging plug for smartphones would probably increase the user benefit.

In summary, our main findings in Togo are:

- Access to drinking clean water is still a huge problem; humans and animals share the same water source and animals additionally contaminate the water with (endo)parasites; in some cases, well water is currently purified by chlorine; therefore, affordable solutions for water access and better water purification are highly needed;
- There is no electricity access in many areas, and therefore solar-powered solutions are of high interest;
- Villagers cover large distances on foot in order to access distant water sources; standalone navigation solutions to optimize the travelled routes, extract mobility patterns and accurately mark the water sources would be

FIGURE 12. Example of a head-carried basket in an urban area in Togo.

beneficial; for example, in the dry season (summer), the rivers often have so little water that water has to be dug in the riverbed; those places need to be properly marked for an easy access.

- Everything is carried on the head, thus solutions relying on head-held baskets are likely to be more acceptable than solutions relying on a backpack; also behavioral change could be tested, such as a backpack to be carried on the front;
- Education and information will be crucial and information campaign must be properly prepared.

VIII. DISCUSSION, LIMITATIONS, AND CONCLUSION

A. WATER-DISINFECTION SOLUTIONS

Real-time and efficient water purification techniques which are portable and easy to use, are still not a reality in several countries in Africa. Togo, as one of these countries, offers plenty of raw surface and ground water sources, with relatively easy access from rural dwellings (less than 6 km), however the water quality does not meet the WHO requirements for potable water. In Algeria, the research has shown that even in urban areas where all the households are connected to the water supply, the traditions and misbeliefs lead to a rejection of the purified water and keep the people consuming water from unsafe water sources.

Water quality investigation on two water sampled in rural area (Latacopé) and peri-urban area (Agoe-Zongo) shows several no-compliance parameters such as conductivity, iron, potassium, sodium and microorganisms. Water from Haho river, like many surface waters, is under threat by contamination from natural sources and anthropogenic sources, such as bad hygiene practices, bad pesticides uses in agriculture and fishing, inorganic and organic fertilizers uses in agriculture, oxen drink during transhumance, etc. The already poor natural water quality is threatened by the transport methods, storage capabilities, and poor sanitation in rural areas. The groundwater is most often under threat from sanitation, discharges, or agricultural and industrial inputs. In the coastal sedimentary basin where Agoé Zongo is located, the groundwater is also subject to marine intrusion. In addition, the shallow depth of these drilled wells accentuates their vulnerability. Currently, the majority of diarrhoea-related deaths worldwide are explained by a lack of access to safe drinking water, or a deficiency in personal hygiene [50].

Regarding the water disinfection solutions, the UV irradiation after filtration can achieve very high levels of disinfection, and this happens due to inactivation and not killing or destruction of the germs. As a consequence, repair and recovery is possible and has been observed [54], [55]. However, the use of a relatively broad UV spectrum, as it is the case with medium pressure mercury lamps as radiation sources, can reduce or even eliminate the recovery capabilities of the irradiated micro-organisms [54], [55]. By using UV-LEDs at different wavelengths one can achieve the same effect as with medium pressure lamps and also has more flexibility regarding the amount of radiation delivered within different spectral ranges. Thus, within the framework of this project the use of combinations of LED's at different wavelengths will be investigated further, in order to identify an optimum disinfection result. Our design is based on the data provided in the literature [54], [56]. We expect that all the micro-organisms indicated in Table 6 of [56] (such as bacillus subtilis, adenoviruses, clostridium perfringens, calicivirus canine, rotaviruses, coxsackie virus, streptococcus faecalis, e-coli, legionella pneumophila, etc.) will be reduced to levels which reach at least 99.99%. However, our target is a 99.999% reduction which, for some germs like, for example, Giardia may not be achievable irrespective of the dose and spectrum which are delivered, see [56]. In this respect, one has to also keep in mind possible limitations of the disinfection unit under varying seasonal conditions. For example, for the unit to work, water has to be in its liquid phase. Thus, the unit is not expected to work below zero degrees unless we include insulation and heating in our design. Such a design would be suitable for northern climates, e.g., Finland. Likewise, very warm climates such as those in Africa are also expected to impose some limitations due to the cooling required for the LEDs to work properly. Currently, the cooling is ensured by using large surface copper radiators. However, these might prove inefficient if ambient temperatures rise above an estimate of 45 degrees Celsius. Currently, there are no provisions in our envisaged unit for determining the concentrations of different water quality parameters, as adding such measurement sensors for some parameters analysis will increase the cost of the system. However, future developments may also support additional measurement sensors.

B. SOLAR-POWERED SOLUTIONS

The mobile and handy system proposed by us can be a solution for various areas in Africa, such as the studied ones (Togo and Algeria), with some design and feature modifications to adapt the differing needs and countries. Charging options based on solar power for mobile devices can be an additional usage incentive and a variation in the ways of carrying the system to meet the different habits of the people can increase the acceptance. The system implementation should be accompanied by a well-prepared informational campaign in the countries of interest, considering the different socio-cultural and local requirements.

C. WIRELESS-POSITIONING SUPPORT

With respect to the third architectural segment, the one of low-cost wireless localization engine, this is an added-value feature, not strictly necessary in the water purification process, but very valuable for many potential broader applications, including the tracking and location of the water purification system (backpack, head basket, …), especially when displaced or stolen, potential of collecting, monitoring, and further analyzing water migration flows (e.g., the patterns and frequencies of how people access the water sources), as well as offering geofencing and geotagging solutions. The choice of Android devices for a first step in achieving localization goals has been motivated by their ease of use and ease of access to the GNSS raw data, as well as no additional system charges since the phone can be used also for other purposes, such as monitoring the whole system, etc. Our survey have shown the various challenges and limitations triggered by the use of standalone pseudoranges for forming the location estimation without the need to access a cellular of WiFi network and summarize also the various pseudorange-based positioning algorithms proposed so far in the literature. Our survey also identified a clear need of developing more powerful pseudorange-based positioning algorithms than the state-of-the-art in order to deal better with low-quality, noisy, or incomplete measurements available in standalone mode from low-power affordable devices.

D. OTHER OBSERVATIONS

Our user needs assessment study on site (in Togo) has revealed the importance of a user-centered approach in technology development, especially in less developed countries. Traditions and socio-cultural and geographical characteristics can place different demands on the system and should therefore be included in the start of the design process. In case of design limitations which hinder the system modification to adapt to the needs, an educational information campaign can foster the behavioral change. A water purification system which fits the individual user needs will not only provide reliable drinking water, but it will also support the socio-cultural and economical development by reducing water-related health issues which have a strong impact on the empowerment of women and the education of children.

To sum up, in developing countries, the low financing of drinking water infrastructures must inspire strong alternatives. Thus, we believe that the compact purification modules proposed by us constitute a viable and sustainable solution that we plan to continue developing.

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