smart cities

Review

Pseudolites to Support Location Services in Smart Cities: Review and Prospects

Tong Liu [1,2,3], Jian Liu [2,4], Jing Wang [5], Heng Zhang [6], Bing Zhang [2,3], Yongchao Ma [2], Mengfei Sun [2], Zhiping Lv [2] and Guochang Xu [1,2,7,*]

1 Key Laboratory of Urban Land Resources Monitoring and Simulation, Ministry of Natural Resources, Shenzhen 518000, China; 19b958024@stu.hit.edu.cn
2 Institute of Space Science and Applied Technology, Harbin Institute of Technology (Shenzhen), Shenzhen 518000, China; jianliu@stu.hit.edu.cn (J.L.); zhangbing@stu.hit.edu.cn (B.Z.); ma_yongchao@stu.hit.edu.cn (Y.M.); 20b958036@stu.hit.edu.cn (M.S.); lvzhiping@hit.edu.cn (Z.L.)
3 Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hong Kong 999077, China
4 Department of Aeronautical and Aviation Engineering, The Hong Kong Polytechnic University, Hong Kong 999077, China
5 Wuhan Mengxin Technology Co., Ltd., Wuhan 430073, China; jing.wang@wh-mx.com
6 State Key Laboratory of Satellite Navigation System and Equipment Technology, The 54th Research Institute of China Electronics Technology Group Corporation, Shijiazhuang 050081, China; zhhcetc@163.com
7 Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518000, China
* Correspondence: xuguochang@hit.edu.cn; Tel.: +86-183-8910-1556

Abstract: The location service is an important part of the smart city. A unified location service for outdoor and indoor/overground and underground activity will assist the construction of smart cities. However, with different coordinate systems and data formats, it is difficult to unify various positioning technologies on the same basis. Global navigation satellite system (GNSS)-based positioning is the only way to provide absolute location under the Earth-centered, Earth-fixed coordinate system (ECEF). Increasing indoor and underground human activity places significant demand on location-based services but no GNSS signals are available there. Fortunately, a type of satellite that is indoors, known as pseudolite, can transmit GNSS-like ranging signals. Users can obtain their position by receiving ranging signals and their resection without adding or switching other sensors when they go from outdoors to indoors. To complete the outreach of the GNSS indoors and underground to support the smart city, how to adapt the pseudolite design and unify coordinate frames for linking to the GNSS remain to be determined. In this regard, we provide an overview of the history of the research and application of pseudolites, the research progress from both the system side and the user side, and the plans for pseudolite-based location services in smart cities.

Keywords: pseudolite; indoor positioning; spatial datum; seamless navigation; GNSS; PNT; Internet of Things; integrated navigation

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1. Introduction

Smart cities place a significant demand on accurate location services. End-users of smart cities—typically via smartphones, vehicles, wearables, etc., with respect to the Internet of Things (IoT)—require precise location and time information [1]. For positioning, a reference datum is needed first. Positioning techniques such as ultra-wide band (UWB) [2], received signal strength indication (RSSI) [3], ZigBee [4], etc., could provide precise positioning, but only in a local coordinate system. Different from other indoor positioning methods, the GNSS receiver is the only sensor that can provide absolute positioning in the geocentric coordinate system. Thus, GNSS-based spatial data [5] could be regarded as the smart city's infrastructure for common positioning and navigation services.

Unfortunately, the GNSS can be used only in an open environment on the ground surface since the L-band signal of the GNSS cannot be transmitted directly to the subsurface. Thus, it is hard to rely only on the GNSS to complete underground data construction. Indoor positioning technologies such as UWB [6] have system differences from the GNSS and require additional receiving sensors for users [7]. Moreover, they could only provide customized relative locations in a free local coordinate system, rather than the absolute location in the Earth's coordinate system. In this case, the current indoor positioning techniques make it difficult to cooperate effectively with GNSS. Now, the indoor and underground location services based on GNSS spatial data are still lacking [8,9].

Pseudolites can emit GNSS-like signals, thus enabling continuous positioning both indoors and outdoors. If the pseudolite uses a standard-format GNSS frequency and signal, then the GNSS receiver, without any modification, can process the pseudolite signal [10]. In comparison with other methods, the pseudolite is able to provide a datum associated with the GNSS for indoor and underground positioning and seamless navigation.

In recent years, researchers have studied pseudolites from many different perspectives, including system commissioning, signal transmission, signal reception, error processing, and pseudolite-based integrated navigation. Pseudolites are becoming closer to large-scale applications, especially with the introduction of hardware solutions for signal design and reception in the field of communications, where the problems of near–far effects and clock synchronization are largely solved.

However, how to achieve the location services for smart cities under the GNSS via pseudolite has rarely been discussed. Moreover, as a technology with great potential applications, few authors have reviewed and analyzed the technical progress, existing problems, and prospects of pseudolites. The last pseudolite review article was published 20 years ago [11]. In the last 20 years, many advances in pseudolite technology have occurred and higher demand has been placed on the technology.

Facing the unification of spatiotemporal reference and seamless navigation, higher requirements for the pseudolite system's construction has become apparent. This is related to two issues: on the one hand, the unification of orbit is indispensable; current pseudolites are only used for indoor positioning, while seamless navigation requires that the orbits of pseudolites are integrated into the coordinate system of the GNSS, such as the "World Geodetic System 1984" (WGS84); on the other hand, there is the pseudolite constellation; current research is mostly tested in open indoor environments or with a well-indoor pseudolite constellation; however, there are random and multiple masks in real indoor environments such as in shopping malls which lead to poor positioning accuracy. Facing the problem of obscured signals, how to better optimize the constellation structure of pseudolites and combine multiple sensors is the key issue in making high positioning accuracy obtainable in a larger indoor area [6,11].

To further promote the application of pseudolite technology in smart cities and to serve the construction of the positioning, navigation, and timing (PNT) system, it is necessary to sort out and present the current status of pseudolite technology and its development trend. In this review, Section 2 provides a brief introduction to the development and applications of pseudolites; Section 3 reviews the status architecture and challenges on the pseudolite system side; Section 4 presents the status of the main academic and technical inspections on the receiver side; Section 5 provides a discussion of the current issues and the prospects; Section 6 describes the possible role of pseudolites in smart cities; the final section provides the conclusion.

2. Brief Development History and Existing Applications

As early as the construction of the GPS in the United States, research on pseudolite problems has been carried out. A schematic diagram of the workflow of a single pseudolite with both receiving and transmitting functions can be seen in Figure 1. The earliest pseudolite started from simulating the GPS L1 signal [12]. After that, the theory of pseudolites for positioning and navigation was discussed [13–15]. To verify the feasibility of GPS theory, a pseudolite test site in the United States named Yuma was built [16]. At that time, the above studies showed that pseudolites were used more as a technology to test GPS rather than a stand-alone positioning technology. After a period of development, by 2002, the progress of GPS-based pseudolites and the technical problems existing at that time were reviewed [11].

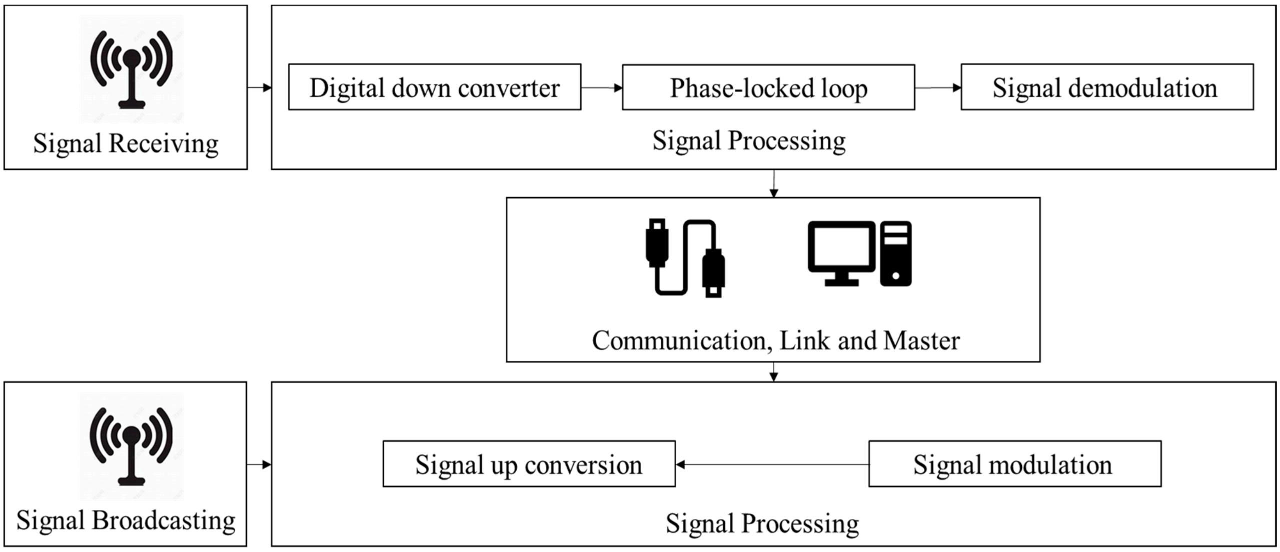

Figure 1. Schematic diagram of the workflow of a single pseudolite with both receiving and transmitting functions.

In addition to those who built the GPS, other GNSS communities have also worked on pseudolites. A Galileo satellite navigation system (Galileo) experimental test environment named GATE was built in Germany, and positioning tests were carried out by transmitting Galileo signals from six ground-based pseudolites [17]. A pseudolite signal-transmitting system based on GPS L1 signals produced by a Finnish company was tested. Although the positioning error can sometimes reach tens of meters, seamless navigation was initially achieved [18]. Pseudolites were used as an augmentation tool during the development of the European Geostationary Navigation Overlay Service (EGNOS) [19,20]. With the development of BeiDou, the airborne BeiDou-capable pseudolite system was developed [21]. Pseudolite systems combining BeiDou [22] and dual BeiDou/GPS systems [23] were developed. Along with the development of the GNSS, pseudolites have been developed for more than 40 years.

Research has shown that pseudolite positioning is a feasible technology and is applied in many fields. The application scenarios of pseudolites include location services for the public and exclusive applications for industries, as shown in Figure 2. To the best of our knowledge, the application scenarios of pseudolite positioning around location services for smart cities, in addition to common indoor positioning, include positioning of aircraft, positioning of trains or subways, underwater positioning, deformation monitoring, and deep space exploration.

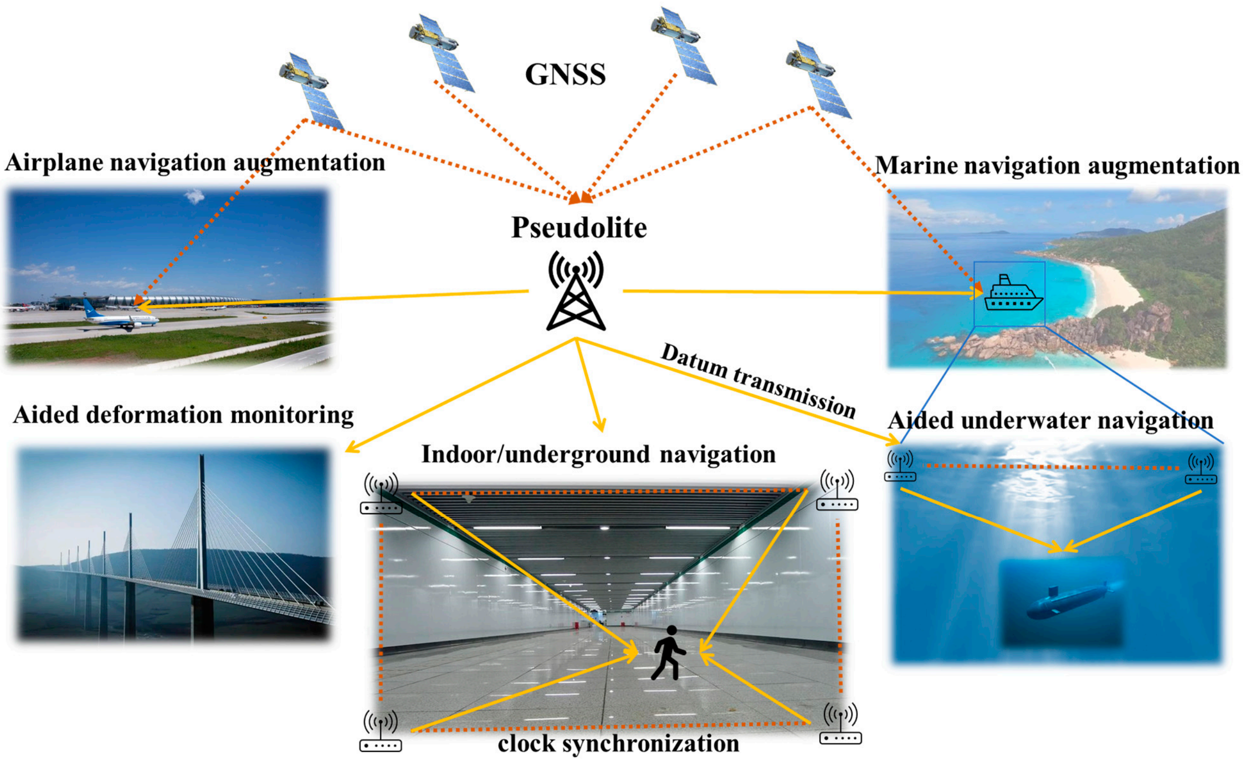

Figure 2. Schematic of pseudolite applications in smart cities.

2.1. For Aircraft Positioning

Currently, the hotspot of GNSS research in civil aviation is the theory, methods, and experiments of augmentation systems, including satellite-based augmentation systems (SBASs), ground-based augmentation systems (GBASs), and aircraft-based augmentation systems (ABASs). Since the pseudolites could not achieve the equivalent performance as GNSS augmentation systems required by civil aviation, in comparison with the augmentation systems, pseudolite-based civil aviation applications have received less attention in recent years but were studied earlier.

For civil aviation, in addition to being a tool for GPS testing, pseudolites are used for GPS augmentation, for example, to assist in aircraft approaches [24–30]. An integrated GPS, GLONASS, and pseudolite navigation approach was proposed for Category III approaches and landings [31]. A pseudolite-based augmentation system (PBAS) for civil aviation navigation was introduced. A test in Korea showed that the PBAS could improve positioning accuracy by approximately 50% [32,33].

Pseudolite applications for unmanned aerial vehicles (UAVs) were investigated. When there is a good geometry of the pseudolite placement, the performance is comparable to GPS performance [34]. Aeronautical applications of integrated navigation using pseudolites have been explored, and the results show that pseudolites help improve the vertical accuracy of aircraft [35,36]. In the aerodrome zone, the positioning geometry factor of pseudolites with GLONASS orbit simulation is discussed. Results show that the number and placement of pseudolites are the keys to improving the accuracy [37]. Moreover, pseudolites are used as a ranging method, and the results show that the clock synchronization performance is at least better than that of other distance measurement equipment (DME), though the data reception quality is slightly worse [38]. For outdoor civil aviation or UAV positioning, there is a trade-off between the improved positioning accuracy from the pseudolite and the ranging error introduced by the associated clock deviation [39]. Airborne BeiDou pseudolites have been preliminarily discussed [21,40]. At present, the exploration of ground-based BeiDou-pseudolite-based civil aviation is still almost non-existent.

2.2. For Train Positioning

The optimization of the constellation design of pseudolite positioning at railway stations was investigated [41], and an integrated train positioning system based on an integrated GNSS/pseudolite model was proposed. The performance of optimized pseudolite constellations and their impact on GNSS/pseudolite-based seamless positioning for trains was demonstrated through a case study involving a reference pseudolite constellation strategy [42]. Both studies show the importance of the placement of pseudolites at train stations or trackside. In addition to positioning on the ground, geostationary pseudolites and Doppler algorithms could be used underground for the subway [43]. Although there are rare train positioning solutions using pseudolites, these studies have demonstrated the potential of pseudolite applications in train positioning.

2.3. For Underwater Positioning

As early as 1991, the idea of pseudolite application for underwater positioning was proposed [44]. Due to severe signal attenuation in water, the attenuation model of signal transmission needs to be addressed [45]. Studies show that it is more appropriate to use acoustic and other means of localization underwater [46,47].

Although pseudolites cannot be used directly for underwater positioning, pseudolite-like devices on the surface can transmit time and space references underwater, which is of great importance for underwater mapping and navigation. As a position reference rather than a positioning method, pseudolites can be used as buoys for underwater localization [48]. Moreover, pseudolites can be used for the mutual correction of positions between buoys on the water to determine a dynamic surface positioning reference [49].

2.4. For Deformation Monitoring

Usually, for deformation monitoring of dams, reservoirs, slopes, and bridges, the GNSS is sufficient. There have been many practical cases of the GNSS being used for landslide monitoring [50–52]. However, pseudolites can still be involved due to their advantages in canyons or tree-shaded environments; for example, they can be used for ground settlement monitoring in urban canyons to supplement and validate interferometric synthetic aperture radar (InSAR) monitoring results [53,54]. A combination of GPS and pseudolites is proposed to monitor deformation in urban canyons areas. The addition of pseudolites improves the accuracy of deformation monitoring compared to GPS use alone [55]. The structural deformation of bridges was monitored using the GPS and pseudolites; when the geometry is well and multipath effects are mitigated, a millimeter-level deformation monitoring accuracy is achievable [56].

Pseudolites can also be used in conjunction with a variety of other sensor combinations for deformation monitoring [57]. For deformation monitoring using pseudolites, it is more important to determine the relative displacement rather than the absolute position, which leads to the possibility of using a different technical route than that of GNSS positioning. For example, since the pseudolite is stationary, it is possible to monitor the deformation by ranging the distance from the pseudolite transmitter to the receiver located at the displacement.

2.5. For Deep Space Positioning

In the lunar exploration project, the accuracy geometry factor could be reduced by setting pseudolites when conducting positioning on the lunar surface using the GNSS [58]. A local-area GPS pseudolite-based navigation system can be used for Mars exploration [59]. If pseudolites are deployed over a wide area on the Moon or Mars, they can assist in the orbit determination of the probe and navigation for landing [60,61].

2.6. Cases of Practical Application

Smart cities rely on outdoor GNSS positioning. Location services in smart cities are limited in GNSS-denied environments. However, several cases have shown that pseudolites can be successfully applied in GNSS denial environments.

2.6.1. The Locata System

Locata is one of the most established pseudolite systems. It was initially designed to address the multipath effect under urban canyons and was later applied indoors [62,63]. The system features a nanosecond time synchronization program [64]. In practical engineering, the Locata and GPS time synchronization performed well [65]. In its signal coverage area, Locata's positioning accuracy is much better than that of the GPS [66], especially in the up direction [67]. In particular, Locata technology can provide sub-centimeter indoor positioning in the horizontal direction by mitigating cycle slips and multipath effects [68].

In recent years, with the enhancement of processing clock differences [69,70], cycle slips [71], tropospheric delays [72], and multipath [62,73], Locata has gradually been increasingly used in more applications, such as open-cut mining [74,75], deformation monitoring [67,76], flight testing [77–81], and integrated navigation [80,81].

2.6.2. The Beidou/GPS Dual-Mode System

The 54th Institute of China Electronics Technology Group Corporation (CETC), alongside the Wuhan Mengxin Technology Co., Ltd., have developed dual-mode pseudolites and their signal receiver that can accept BeiDou and GPS signals, as shown in Figure 3. This system mainly consists of receiving antenna, forwarding antenna, time synchronization ring, and pseudolite host. A detailed presentation is available [23]. The main technical aspects include the signal design [82] of BeiDou and GPS, the processing of near–far effects [83], closed-loop clock synchronization, and integrated positioning. The pseudolite device was used for indoor positioning of the "Snow Ruyi" venue for the Beijing Winter Olympics.

Figure 3. Pseudolite Receiver: module and integrated unit.

Recently, a multi-PNT source-based positioning system [84] has been designed for GNSS signal denial environments. Its infrastructure includes mobile communication base stations, Wi-Fi networks, UWB transmitters, radio frequency identification (RFID) transmitters, and pseudolites. Its elastic PNT terminal includes a GNSS receiver, inertial unit, Wi-Fi module, 5G module, Bluetooth module, and lidar. The software embedded in the device functions for data capture, fusion, and localization. The system has been tested with sub-meter accuracy [85] and has been successfully used in the Yan Chong Expressway, which contains several tunnels.

2.7. An Underlying Positioning Technology for the Internet of Things

Alongside the outdoor applications mentioned above, in recent years, pseudolites have been considered popular candidates for indoor positioning and seamless indoor-outdoor navigation. Hot research topics include technical issues in simulating or transmitting signals, and signal- or data-oriented processing methods to improve positioning accuracy.

The Internet of Things (IoT) requires location services as its underlying technology support [86]. The positioning error sources of the IoT have been analyzed [87]. A prototype of location services for the IoT has been described [88], which essentially enables seamless indoor and outdoor navigation without the addition of other indoor positioning devices. In the IoT, pseudolites can be used as a key technology for positioning, which can provide high accuracy and GNSS connections to the outdoors. The establishment of a spatial datum based on pseudolites can realize the unification of ground–underground and indoor–outdoor spatial data and provide GNSS-like accurate location services for underground/indoor operations in megacities. In this vision, dynamic and static positioning of indoor pedestrians, cell phones, bracelets, pendants, and other belongings can be achieved, for example, in a scheme for baby positioning [89].

Location and telecommunication are the two key elements of the IoT [90]. As an essential part of IoT applications, pseudolites need to be integrated with communication solutions such as 5G [91,92] in order to further expand their capabilities. One existing success case is the construction of a low-cost regional navigation system [93,94] based on decommissioned communications satellites.

3. Architecture and Technical Issues on the System Side

The current state of research on pseudolites is divided into technical problems that could be solved on the hardware system side and the main academic/algorithmic problems to be solved at the receiver side. The issues related to pseudolite signal transmission, clock synchronization problems, and orbit problems that can be optimized from the system side are first discussed, after which the received data and their processing refinement can be addressed on the receiver side.

3.1. Signal Intensity and Near–Far Effect

Receiving a sufficiently strong signal is a prerequisite for a receiver to locate; therefore, the receiver should be able to capture weak or reflected signals at a distance [95,96]. A time-hopping (TH) pulse position detection method [97] solves the problem of low signal detection success rate in a low signal-to-noise environment. To mitigate the effects of signal degradation, a robust and general time-hopping direct sequence spread spectrum (TH-DSSS) signal acquisition method was proposed [98]. When setting up the new signal method, the number of operations should be considered at the same time to avoid low timeliness due to computational overload [99,100].

The attenuation of electromagnetic waves in the air is large. Pseudolite signals near the receiver can create power suppression of distant signals, leading to the near–far effect, as demonstrated in Figure 4. Resolving the near–far effect is the primary requirement for successful pseudolite positioning.

Traditionally, the near–far effect may be mitigated by the following [11,101]: (1) transmitting a pulse signal with a fixed period in the GPS band but with frequency offset; this scheme is feasible because by adjusting the carrier signal frequency, the pseudolite can be made to operate in a variable frequency band determined by the signal frequency [102]; (2) transmitting pseudolite signals at the frequency offset from the GPS, but within the same frequency band, or using a longer coding sequence than the GPS. In addition, a successive interference cancellation method [95] allows GPS receivers to receive pseudolite signals at 30 dB to 40 dB. New programs have been successively proposed over recent years. A general pulsing scheme based on random permutations was proposed to mitigate this effect [103]; signal orthogonality can be exploited to counteract the pseudolite signal near–far effect [104].

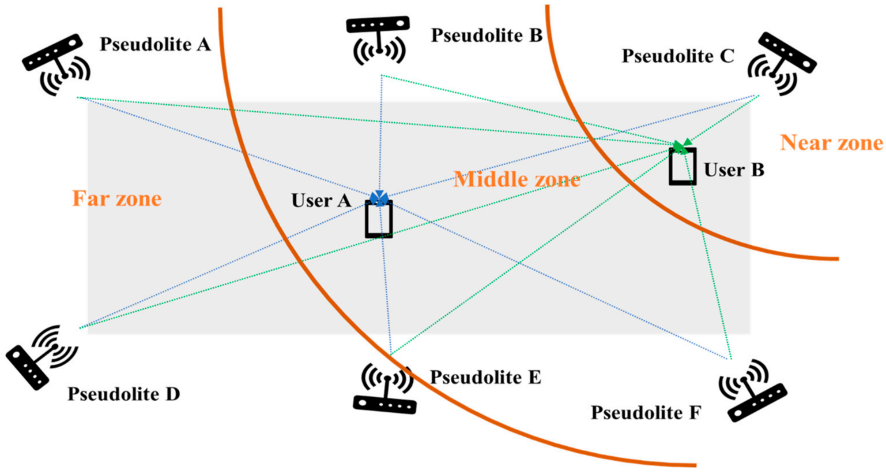

Figure 4. From the ground, different user locations and the corresponding received signal propagation paths: User B is in the near zone of pseudolite C, whose signal suppresses the distant signal of pseudolite D; User A is in the middle region of pseudolite C and can receive equal pseudolite C and distant signals pseudolite D; and in the far field of pseudolite C, the signal of pseudolite C is suppressed.

3.2. Clock Synchronization

Time synchronization is a necessary issue to be stressed for seamless navigation [105,106] since unsynchronized clocks can introduce significant positioning errors. For specific positioning algorithms and operational requirements, a targeted analysis is required to determine a reasonable solution for introducing pseudolites.

The impact of clock offset on both single-point positioning [107] and differential positioning [108] is significant. Clock discrepancies from ground-based transmitters can lead to asynchronous timing problems [109] and hinder attempts to fix integer ambiguity [110]. Unfortunately, pseudolites cannot be time-synchronized by expensive satellite-based clocks such as the GNSS, and only low-cost solutions can be adopted.

Wireless synchronization methods are favored for their flexibility in system deployment [111,112]. A tree topology for time information flow can be constructed based on the master node; thus, a pseudolite can receive signals broadcast by multiple pseudolites. For example, with the Locata system, a master transceiver synchronizes its slave transceivers over a wireless network [69]. Based on this approach, bidirectional time synchronization between multiple pseudolites over a network cable or wirelessly can be achieved [107,113].

Considering the problem of time synchronization in pseudolites, indoor precise point positioning (iPPP) [114] and iPPP with real-time kinematic (iPPP-rtk) [110] systems were proposed to address time deviation. They can reliably achieve accurate indoor positioning at the centimeter level. Time delay fluctuations can disrupt the integer properties of the carrier phase. A fractional cycle deviation correction method [107] was proposed for the case where the ambiguity of observations in pseudolites is usually estimated as a floating-point value. This method is based on bidirectional time synchronization and corrects its own bias by pseudolite network estimation.

The clock can remain synchronized in the presence of link outages or pseudolite failures. A mesh topology clock synchronization (MTCS) technique based on a mesh topology using all received signals was proposed [115]. MTCS constructs a mesh topology for time information flow, derives the coupling relationship from the clock. In addition, the temporal deviation can be estimated by putting it into the process of position decomposition in the case of clock link interruption [116]. From a hardware point of view, in addition to the use of networks, fiber optics is also a solution that can be used for clock synchronization [117–119].

Current research shows that clock synchronization only pseudolites only can be achieved through hardware and software treatments. However, the time synchronization between pseudolites and real satellites needs to the focus if the time systems defined by them are expected to be the same. In the future, the issue could be further addressed at both the system and user levels. On the hardware level, optical fibers can be used to connect the ground network of pseudolites to the BeiDou ground system [118]; on the common user level, a clock transfer technique is available [120]; for example, the Coordinated Universal Time (UTC) can be determined based on GPS code transfer and clock comparison [121]. Not only the GPS but also BeiDou can be synchronized with the clock of pseudolites via a similar method [122]. However, at present, the synchronization technology of BeiDou and ground-based pseudolites is still less researched. It is necessary to propose new synchronization schemes for BeiDou and pseudolites from a software perspective for common users who cannot deploy fiber optics in a large project.

3.3. Orbital and Ranging Problems

For pseudolites, the loss of positioning accuracy due to orbital errors is significant [123]. In open outdoor environments, users can receive the orbit information of satellites and even extrapolate the satellite orbits [124–126]. While indoors, the pseudolite orbits are fixed points. This orbit inconsistency problem between stationary pseudolites and dynamic satellites prevents indoor users from using the same method of positioning as outdoors. Unlike the near–far effect and clock synchronization problems that have been focused on in the past, there is little research related to the orbit problem of pseudolites in indoor positioning.

The solutions can be divided into two categories: one option is to disregard the outdoor satellite motion and simply treat pseudolites as technology similar to other indoor positioning technologies; although high-precision positioning can be achieved, this essentially eliminates the primary advantages of pseudolites, i.e., the seamless integration of indoor and outdoor location services and the consistency of GNSS and pseudolite spatial data; another option is to use pseudolites as both GNSS receivers and transmitters [127], replicating and forwarding ephemeris and range values; when GNSS ranging errors such as ionospheric delays, tropospheric delays, clock differences, orbital errors, antenna phase center corrections, differential code biases, tide corrections, solid tide corrections, relativistic effects, and multipath effects are adequately handled, pseudo-satellites can be used as receivers to achieve millimeter-level positioning accuracy. This approach implies that the user can receive the ephemeris and that the receiver's position can be unified under the GNSS framework. However, the range values received by the user are still provided by pseudolites and are not related to the real ephemeris. Therefore, the user's positioning is still based on the indoor datum and is not included in the GNSS framework, as shown in Figure 5.

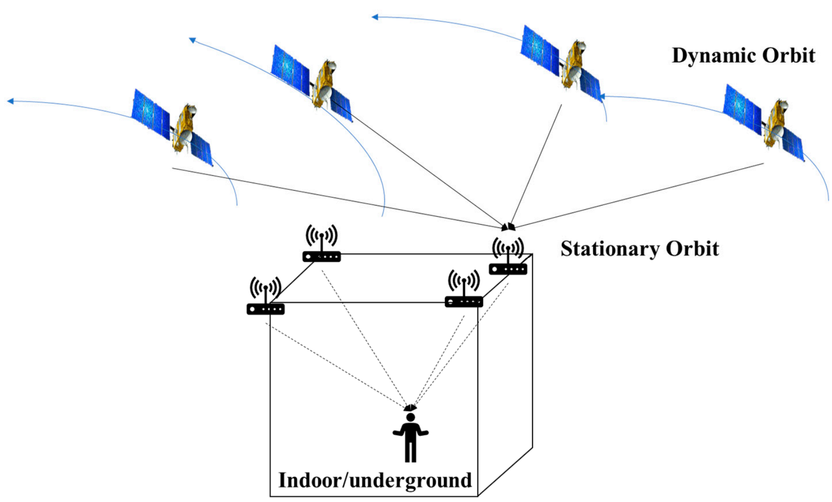

Figure 5. The dynamic orbit of real satellites and the stationary orbit of pseudolites.

When completing the integrated spatial data construction of outdoor and indoor/overground and underground activities with pseudolites, the orbit problem is unavoidable. A feasible method is to establish a two-way communication relationship between the user and the pseudolite transmitter based on the second option in the previous paragraph. The indoor positioning range values, altitude, and azimuth are returned to the pseudolite in real-time. Subsequently, the pseudolite calculates the range, altitude, and azimuth of the user and the real satellite based on its position and broadcasts them directionally.

3.4. Constellation Optimization

In addition to the method of receiver signal processing, the constellation optimization of the pseudolite is crucial to enabling sustainable signal reception and low dilution of precision (DOP). A study has identified the concept that the constellation optimization of pseudolites can influence the pseudolite positioning error [123]. The essence of constellation optimization is to make a larger number of satellites observable in more space to improve positioning precision [124,128]. The effectiveness of a multi-objective particle swarm-based approach for the deployment optimization of pseudolite systems is discussed [129]. Both theoretical and numerical analyses have shown [123] that the positioning error can be significantly reduced when the pseudolite is in an optimal position.

Moreover, the pseudolite constellation can be made more reasonable by testing the positioning accuracy of different locations of the receiver [130]. The geometric design of the pseudolite system can be determined via visual domain analysis and signal coverage time and base station accuracy factors [131].

Parameters related to the pseudolite constellation are the location of the pseudolites, the geometric space, and the obstruction condition of the signal path. An ideal constellation optimization method is to reconstruct the interior in three dimensions via visual or laser sensors beforehand. Then, the pseudolite layout that can obtain the maximum user-pseudolite viewing space is selected experimentally. Subsequently, the simulated configuration is corrected by evaluating the actual signal reception test.

4. Algorithmic and Technical Issues on the User Side

In addition to the system architecture and challenges, there are still problems to be solved via processing at signal receivers, such as poor geometry, large linearization errors, and signal reflection that cause multipath errors, leading to signal divergence. In addition, time delay fluctuations, phase center errors, and potential multipath errors disrupt the integer characteristics of the carrier phase [114]. To address these deficiencies, some algorithms can be used on the signal-receiving terminal.

4.1. Multipath

The multipath effect is the key to improving the accuracy of pseudolite positioning. The generation mechanism of the multipath effect in pseudo-satellite positioning is shown in Figure 6. In an experiment, 94% of the pseudolite positioning errors could be below 2 m when the errors introduced by multipath effects were controlled to be below 1 m [132]. In addition to a more sensible antenna design at the signal generation end, for example, two-array pseudolite antennas make the signal establish a long-distance link [133,134]. The ability to detect multiple paths at the receiver is another way to mitigate this error; for example, an area-based approach can detect more than 70% of the signal at low carrier-to-noise ratios [135].

From engineering experiments, a hardware–software complex is considered for studying the accuracy and noise immunity characteristics of pseudolite-based proximity navigation systems [136]. This complex is implemented based on the National Instruments hardware platform and the LabView coding environment. It provides a simulated navigation field and analyzes the received signals, such as signal transmission path loss and power angle distribution, which can be obtained by suppressing a ray-tracing method [137]. It also determines the error in the measurement of navigation parameters of pseudolite signals. Subsequently, the measured errors are compared with the characteristics of standard GNSS receivers.

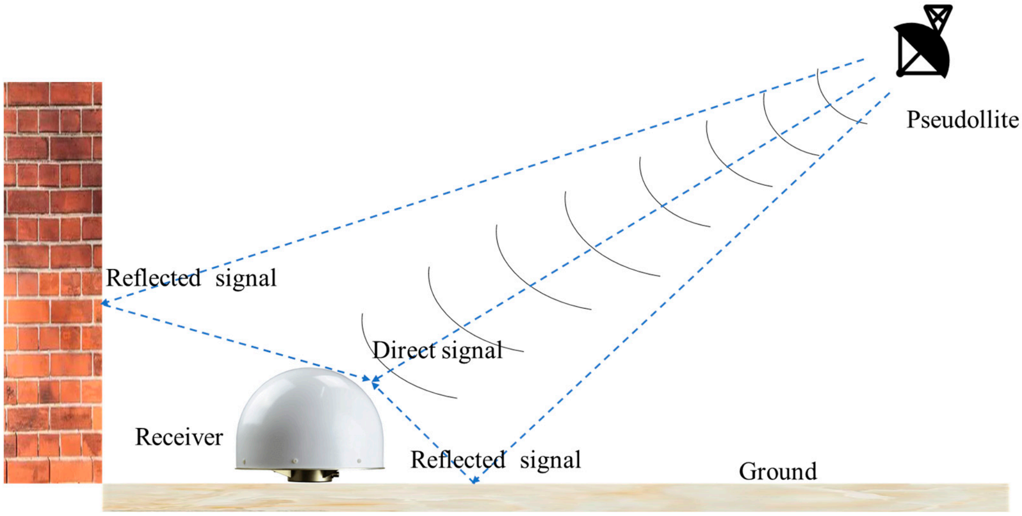

Figure 6. Multipath effects in pseudo-satellite positioning: receivers receive both direct and reflected signals at the same time.

The reduction in available observations due to barriers in the signal path exacerbates the results of multipath errors. Non-visual range cases and under-observation can be handled using a machine-learning approach [138]. In solving the problem of line-of-sight between different transmitter-receiver pairs that differs greatly while performing antenna calibration, the multipath error is severe when there is no expensive anechoic chamber. Multiple calibrations at different locations can reduce antenna phase pattern accuracy to the millimeter level due to protection from multipath error [139]. An indoor fusion localization method using the double-difference pseudo-range measurements and the pseudolite signal carrier-to-noise ratio [140] demonstrates good suppression of receiver sampling time asynchrony and multipath errors. Challenges such as the poor geometric configuration of indoor pseudolites, the large linearization error, and the multipath error can be solved by the indoor PPP algorithm with optimal floating point ambiguity in the trust region [114].

The multipath effect depends on the location and constellation of the pseudolite. In addition to simply using signal processing methods to mitigate the multipath effect, the effect of the constellation should be considered when hardware conditions are limited. Furthermore, the multipath effect is related to indoor scenes. The user can assess the upcoming scene conditions by simultaneous localization and mapping (SLAM) or visual odometry (VO) to mitigate multipath errors [141] or to estimate the upcoming line-of-sight signal and multipath errors in advance to reduce the weight of pseudolite positioning in integrated navigation.

4.2. Resilient Processing Models

The resilient model contains the function model and the stochastic model [142], which are reviewed as follows.

4.2.1. The Function Model in Positioning

The function model expressed here is the process of modeling and calculating the user's location from the data received by the receiver side. The positioning of the pseudolite can be achieved via space resection, such as via the GNSS. In general, for low-cost single-frequency pseudolite systems, the static differential pseudolite system (DPL) method [143,144] is used to quickly acquire the low-precision positioning coordinates of the roaming station. A pseudolite positioning method using the carrier phase difference [145] performs a single differential (SD) operation on the two sets of carrier phase measurements output from a dual-antenna receiver to eliminate the effect caused by the common error.

The ambiguity function method (AFM) was used to find coordinates in the corresponding ephemeris [144]. Confronting the non-linearity problem in the pseudolite system, the projection cancellation technique [146] is developed for linearizing the pseudo-range observations on the reference virtual station and user stations; the algorithm can improve the overall positioning accuracy by approximately 30% without increasing the time cost in the case of severe non-linearity. The optimal geometric factor method [147] based on the moving vector component and the multiarray pseudolite weighting factor for indoor positioning is proposed to solve problems such as single-array pseudolites and antenna aging or damage, and simulation results show that it effectively expands the high-precision positioning area. A method [144] is proposed to achieve high-precision indoor pseudolite positioning without using known point initialization (KPI), which can quickly obtain the initial coordinates and solve the ambiguity [148]. By classifying clock deviations as transmitter phase biases (TPBs) and estimating them, pseudolites can provide GNSS-like PPP-RTK services [149]. Above all, due to the similarity with the GNSS, the function model of pseudolite positioning can be borrowed from the GNSS models of several types and made adaptive modifications.

4.2.2. The Stochastic Model in Positioning

Kalman filtering and its adaptation for pseudolite positioning improvement have been studied. Although Kalman filtering can also be classified as a functional model [150], it is found that most of the pseudolite positioning methods related to error processing and gross error detection under the stochastic model are based on Kalman filtering, so it is discussed in this section. The extended Kalman filter (EKF) can be used for parameter estimation provided that the pseudolite operates properly and the number meets the positioning requirements [151]. Dynamic centimeter-level accuracy and static millimeter-level accuracy can be guaranteed through fault detection and troubleshooting. A non-linear parameter estimation method suitable for pseudolite localization [143], namely, the unscented Kalman filter (UKF), is introduced, which has high accuracy and low dependence on the initial coordinate values; the numerical results show that the computational efficiency of the EKF and UKF are basically the same, with the EKF performing slightly better. In response to the lack of resistance of the standard UKF to frequent anomalous observations, a robust UKF and partial ambiguity resolution (AR) algorithm [152] was proposed, which has the advantage of being more resistant to gross errors. A distributed algorithm based on the split covariance intersection filter (SCIF) is proposed [153] to process the newly acquired data to obtain consistently estimated states. In addition, different orbit and clock-difference correction prediction models are discussed. The performance of airborne-pseudolite (A-PL) positioning based on GNSS PPP and inter-pseudolite ranges, as well as error prediction modeling, are evaluated. The results show that GNSS PPP combined with inter-pseudolites can improve convergence localization accuracy and shorten the convergence time of GNSS PPP.

4.2.3. Next Steps

Most existing experiments show that with an adequate number of pseudolites, accomplished clock synchronization, optimized constellation, and well-handled multipath errors, although the processing methods of signals or received data are different, the positioning accuracy of dynamic centimeter and static millimeter levels can be largely achieved. In the case of bad conditions, the positioning accuracy is at the meter level. In other words, the initial theory and methods of pseudolite positioning for indoor use have been developed. The current and future research trends can be summarized via three aspects. First, new ideas for pseudolite localization in the function model, for example, Doppler observation quantities, can be used for localization [154]. Additionally, by collecting the immediate and historical carrier phase data in the indoor environment and using a training model to predict the location of the positioning terminal, higher positioning accuracy can be achieved. An indoor localization system based on homologous array pseudolite database matching could be another method [155]. Second, in new application scenarios, new problems of pseudolite positioning would appear and be solved, for example, the detection and processing of coarse differences in a stochastic model in the case of signal jamming and the dynamic localization of indoor unmanned vehicles or drones using pseudolites. A third topic is the error model and processing method of deep integration of pseudolites and the GNSS, i.e., the integration of indoor and outdoor spatiotemporal data and seamless navigation tests. This would involve specific issues such as the switching of signal channels, unification of coordinate frames, etc.

4.3. Integrated Positioning with Other Methods

Multiple sources of sensors can be used in conjunction to obtain high-accuracy positioning with advantage sharing. The positioning accuracy of the GNSS integrated with pseudolites in an obscured environment was evaluated; integrated with PPP and pseudolites, submeter-level positioning is achievable in urban canyons [156]. As one of the most common indoor positioning techniques, integrated navigation with inertial guidance is mostly discussed. The principle simulation and testing of the combination of pseudolite, GPS, and inertial navigation system (INS) platforms have been analyzed [157]. The introduction of pseudolites into existing integrated GPS/INS systems to provide higher availability, integrity, and accuracy in localized areas has been discussed [158]. Preliminary experimental results on the dynamics of a combination of pseudolite, GPS, and INS platforms have been explored from an algorithmic perspective, and the results suggest that the problem of high noise of pseudolite signals and data utilization are of concern [159]. Combining the inertial measurement unit (IMU) in a test environment can improve the pseudolite positioning accuracy from 25 cm to 18 cm [160]. By combining GPS, IMU, pseudolite, and frontal laser scanner technologies, centimeter-level positioning accuracy can be obtained in an obscured environment [161].

Furthermore, studies show that integration with an INS can assist pseudolites in measuring ambiguity [162]. A suitable stochastic model allows pseudolites to help GPS ambiguity resolution, especially when the line-of-sight vector is changing rapidly [163]. The cycle slip detection of pseudolites can be assisted by using a low-cost IMU [164]. An ultra-tight integrated model incorporating GPS, INS, and pseudolite was explored [165]. The application scope of an integrated navigation system incorporating pseudolite, GPS, and INS technologies could include civil aviation [29].

The combination of pseudolite and pedestrian dead recycling (PDR) is another approach that has been studied. The average positioning error of PDR is 5.5 m and 10 m, while the average positioning error of the integrated positioning is 2–3 m [166]. The results above show that the integrated technique of pseudolite and PDR can achieve high-accuracy positioning over a long time and long distance. In addition to PDR, synthetic marks can be taken into account [85]. Alternatively, other indoor positioning techniques can be integrated with pseudolites; for example, the performance of pseudolites and UWB transmission was evaluated [167]. Magnetometers [168] can also be included in the category of techniques for assisted positioning.

Although they are different systems and positioning principles, for the GNSS or pseudolites, inertial devices, PDR, and other methods can provide technical support for outdoor indoor and aboveground underground continuous navigation.

In an enlightening manner, it was demonstrated that SLAM can be used to assist in the construction of a dedicated pseudolite system to explore transmitter asynchrony [169]. A pseudolite multi-source fusion navigation and positioning algorithm with map information constraints was proposed to solve the localization problem in narrow indoor areas [170]; that is, the direct arrival signal of a single pseudolite can be used to correct the mobile phone position information under map constraints in order to improve the navigation and positioning performance in indoor access and corridor areas. In addition, an integrated visual–inertial odometry (VIO) and pseudolite navigation scheme was proposed [141]. However, few studies have been conducted to explore the integrated navigation of pseudolites and SLAM. SLAM allows for fast indoor modeling to obtain the locations of pseudolites. This is important for users who do not know the constellation and proximity of pseudolites to deal with the multipath and near–far effect. The fusion and application of the GNSS, pseudolites, and SLAM-containing semantics can be an important support in the framework of a smart city or meta-universe.

GNSS or pseudo-satellites can provide positions in the ECEF framework, but with low or failed positioning accuracy when the received signal quality is poor. Indoor positioning technologies such as UWB, while providing highly accurate positions, have a self-defined coordinate system that is not geo-referenced; therefore, a possible option is for GNSS to provide a rough absolute geographic position via pseudo-satellites, and later combine it with a variety of other techniques to achieve more accurate positioning, as shown in Figure 7.

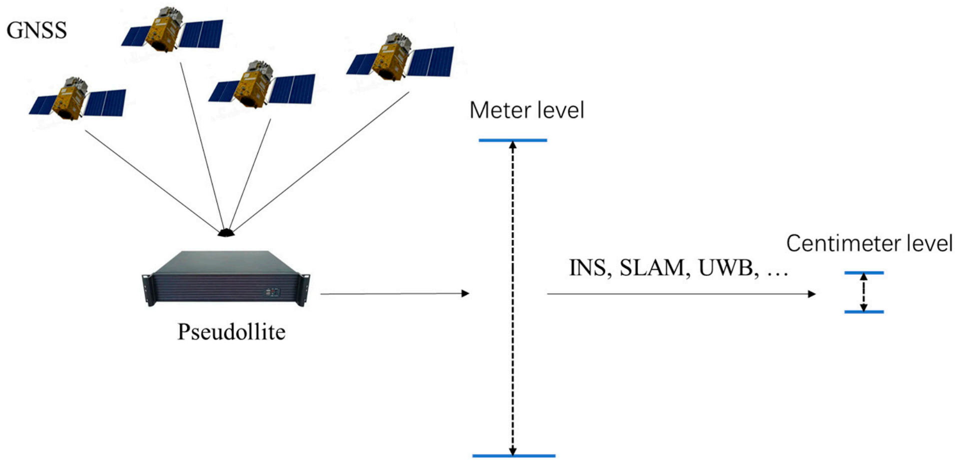

Figure 7. One possible solution: GNSS provides a rough absolute location via pseudolites, which is later integrated with a variety of other technologies to achieve more accurate positioning.

5. Pseudolites as a Spatial Reference: Discussion and Prospects

A unified, stable spatial foundation is a prerequisite for smart city construction. Nowadays, GNSS-based spatial data are available on the ground, in the case of China, for example, the "China Geodetic Coordinate System 2000" (CGCS2000) was built [171] and maintained [172,173], and the "Seafloor Geodetic Network" [174] has been gradually carried out. However, at present, industrial and subsistence activities are gradually entering the underground space, such as the mega underground construction in the Xiong'an New Area [175] and the underground high-speed railway station of Daxing Airport [176] near Beijing. The indoor/underground spatial datum and its location-based services are becoming a rigid demand. As the technical problems in pseudolites are gradually solved, it is expected to become part of the space infrastructure, as shown in Figure 8. In particular, if the orbits and clocks of the pseudo-satellites are harmonized with the GNSS, it will provide users with GNSS-like spatiotemporal information, and then location-based IoT services such as underground or indoor navigation, autonomous driving, and so on, will greatly benefit.

Regarding strict national space reference requirements and the daily needs of mass users, new problems have arisen when using pseudolites as a space reference and seamless navigation method as well as an indoor positioning method. Among them, the most important is the precise correlation of references, e.g., indoor and outdoor references. This requires that time synchronization and orbit issues be addressed in the framework of GNSS positioning and timing. For specific industries, such as the IoT and autonomous driving, pseudolite positioning solutions need to interface with pre-existing industry standards, which will spawn new solutions. In response to the specific technical issues on the system side and the user side sorted out above, some potentially useful suggestions or discussions have been organized as follows.

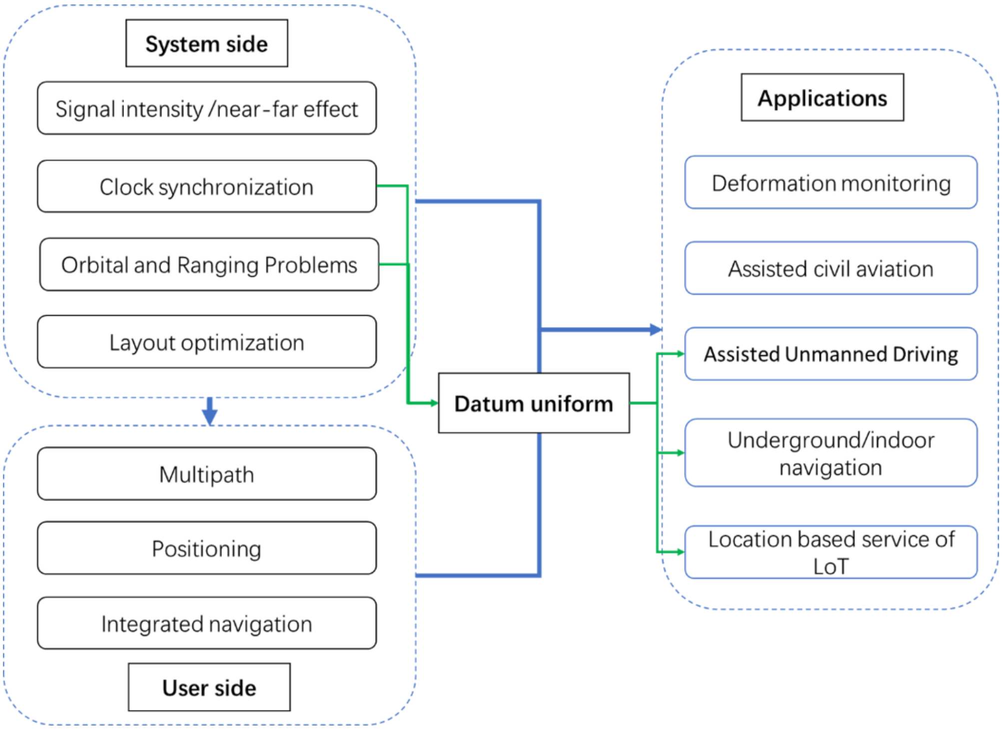

Figure 8. Key technologies and applications for pseudolites: datum unification is the intermediate link for selected applications.

From the hardware perspective, basal signal emission and capture are largely solved problems, from which the most serious and most explored is the problem of near–far effects. The near–far effect that occurs when multiple signals are received simultaneously is presented as a fundamental problem to be addressed in various ways [83,95,177–181], with most of them needing to improve or increase the signal reception equipment and mode. However, with the calling of seamless navigation, the near–far effect problem needs to be mitigated while using the most common receivers. It is worth noting that although the problems in pseudolites are divided in the above subsection, many of them need to be addressed comprehensively. The near–far effect is closely related to the pseudolite constellation. In constellation design, the PVT (position, velocity, and time) [180] as a function of the near–far effect could be evaluated. Afterward, from a geometric viewpoint, an optimal constellation could be designed [22] to maximize the number of pseudolite observations at more locations and minimize the impact of the near–far effect and multipath effect. In this process, signal transponders can be used to improve signal strength in some of the priority areas.

New test methods can be used in the process of constellation design. For example, visual sensors [182] can quantitatively sense the proximity of a pseudolite. As the sensor moves, the distance and proximity effects of the signal change. The receiver–pseudolite distance in a three-dimensional space thus constructed is related as a function of the near–far effect and the geometric accuracy factor [22,130,183], which helps in the optimization of the constellation.

The visual 3D space construction is meaningful for indoor integrated navigation [42]; it is more important to allow the user to evaluate, or even perceive, the multipath in advance. The relationship between distance and near–far effects as a function of distance can be incorporated into the algorithm of integrated navigation [184], giving more weight to the navigation of other methods when encountering near–far effects and multipath. Multiple optimization methods of intelligent PNT [185–187] can be incorporated into the integrated navigation of pseudolites.

The ranging function of the pseudolite can be used to synchronize time [23]. Each pseudolite can act as both a transmitter and a receiver. When the constellation is determined and the distance between every two pseudolites is known, the clock deviation between the pseudolites can be determined by dividing their distance measurements from each other by the speed of light.

In addition to being a positioning technique, the transfer of the GNSS datum is an important task that should be undertaken by pseudolites in seamless navigation [188]. For space–time uniform PNT or seamless navigation, there are two suggested options. One is to first set an indoor local datum, such as the north–east–up local coordinate system in Figure 9. The pseudolite acts as a GNSS positioning terminal and also as a transmitter; thus, it has different coordinates in both the WGS84 coordinate system and the local coordinate system. After that, multiple such pseudolites are used as intermediaries to complete the 3D coordinate conversion and thus transfer the user coordinates to the WGS84 frame [189]. The other option is to broadcast the satellite and user range values directly via pseudolites. In Figure 9, since the two range values, p_1 and p_2, are known, the angle between p_1 and p_2 can be calculated when the altitude angle of the outdoor pseudolite and the altitude angle of the indoor user are known. It is worth noting that this calculation needs to be performed in the plane determined by 1 and 2. The GNSS satellite-to-user range value p_3 can be calculated according to the law of cosines.

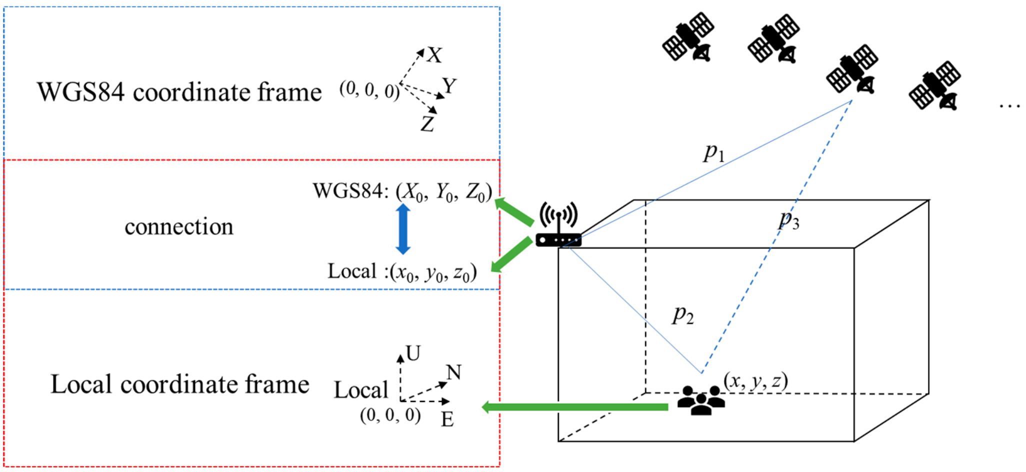

Figure 9. A schematic diagram of pseudolite-mediated frame unification.

From specific experimental scenarios, concise solutions for the practical needs of users for integrated indoor and outdoor navigation should be highlighted more often. The solution to these issues will help pseudolites move toward engineering applications to become the underlying technology of the IoT [190–192], as well as to serve the construction of new national data. Even further, as shown in Figure 8, in the future of unmanned driving, pseudolites could provide urban canyon navigation and underground garage location services and could also offer human–vehicle interconnection with the GNSS as the datum [193].

6. Pseudolite-Based Location Service: Conceived Application in Smart Cities

In the above text, some traditional application scenarios such as augmented navigation of airplanes, trains, ships, and especially indoor navigation were presented. In today's smart city context, these traditional applications can also be included in the smart city scope. In addition, there are the following predefined scenarios for pseudo-satellite-based localization to play a role.

6.1. Intelligent Transportation

Traffic congestion is one of the important problems being addressed by smart cities. Pseudolite-based location services can provide precise location information for all vehicles including those in GNSS-denied environments. In turn, it can be used by managers to obtain real-time traffic congestion conditions. In this way, scheduling is conducted to maximize the efficiency of the traffic.

Intelligent driving is developing rapidly. In smart driving, vision-based, laser-based, etc., positioning methods only allow a vehicle to obtain a position in a localized coordinate system, whereas pseudo-satellites can provide the vehicle with an absolute position. This can match vehicles with electronic maps and improve the accuracy, integrity, continuity, and availability of location services for autonomous driving.

6.2. Smart Health and Lifestyle

Pseudolite-based positioning technology can bring positive results for smart health. In outdoor exercise, people wear bracelets, watches, etc., that can count steps in various ways such as through the GNSS. However, indoors, inaccurate positioning often leads to inaccurate recording results. Pseudolite-based localization would help to improve the accuracy of exercise recordings while assisting in location-based monitoring for medical treatment.

People often become lost in large buildings such as shopping malls and airports. Traditional indoor localization only tells the user "where you are" but not "where you are going". Pseudo-satellites will help interconnect the location between people and people, between things and things, and between people and things, updating people's knowledge of space and time and their way of life.

6.3. Public Safety and Emergency Response

Public safety is an important aspect of location-based services. Law enforcement agencies can use pseudo-satellite-based location data to monitor possible criminal activities and query historical location trajectories to obtain evidence.

In addition, pseudo-satellite-based location services can assist in providing early warning of earthquakes. Although some cell phones currently have the capability to report earthquakes, their false alarm rate is high. Pseudo-satellite bodies and users are sensitive to location, and pseudo-satellites have the ability to naturally monitor building vibration. Therefore, based on the location information of the pseudo-satellite, seismic reporting capabilities will be enhanced.

7. Conclusions

This paper introduces pseudolite as a useful tool from the perspective of integrated location services in smart cities. First, the concept and development history of pseudolites were introduced; second, the possible application scenarios of pseudolites in smart cities were presented; after that, the problems on the system side of pseudolites and the methods of handling them on the user side were reviewed and analyzed; then, with the aim of applying pseudolites to smart cities, we discuss some solutions and application ideas for tackling the problems of pseudolites.

With the development of pseudolite technology over the years, indoor positioning based on pseudolites is already possible from the perspective of scientific research, especially as the problems of time synchronization, the near–far effects of signals, and multipath errors have been largely solved or mitigated. Pseudolites have already shown their application prospects with respect to smart cities. With pseudolite devices having been developed, innovation in the process of practical test applications is the next point of focus. In this process, specific issues such as constellation optimization need to be considered. Some of our ideas are summarized as follows:

On the system side: (1) facing the problem of near–far effects, the mode and intensity of transmitting signals and the hardware design of receiving devices and their anti-jamming capability should continue to be investigated; (2) for consumer-level indoor positioning, fiber optic synchronization can be adopted to replace expensive atomic clocks; (3) for the unification of indoor and outdoor coordinate frames, algorithms or methods to accurately correlate the orbit and ranging data of pseudolites with GNSS satellites should be explored; (4) for the problem of user positioning accuracy, the placement of indoor pseudo-satellites should be made more reasonable so as to allow users to obtain redundant observations to participate in the adjustment.

On the user side: (1) in indoor or underground scenarios, multipath effects seem to be unavoidable, but it is possible to study how to distinguish between direct and reflected signals, or even use reflected signals for positioning; (2) involving the processing of user-side data and fusion with other sensors in addition to positioning accuracy, the resilience, availability, and integrity of a single system or multiple systems should also be explored in the future.

We believe that as a provider of location references, indoor or underground positioning services based on pseudolites may contribute to smart cities as much as GNSS-based services in open areas.

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