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Information technology — Real time locating systems — Test and evaluation of localization and tracking systems

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National foreword

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Information technology — Real time locating systems — Test and evaluation of localization and tracking systems

Technologies de l'information - Systèmes de localisation en temps réel - Essais et évaluation des systèmes de localisation et de suivi

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Foreword

ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC technical committees collaborate in fields of mutual interest. Other international organizations, governmental and non-governmental, in liaison with ISO and IEC, also take part in the work. In the field of information technology, ISO and IEC have established a joint technical committee, ISO/IEC JTC 1.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO and IEC shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information.

ISO/IEC 18305 was prepared by Joint Technical Committee ISO/IEC JTC 1, *Information technology*, Subcommittee SC 31, *Automatic identification and data capture techniques.*

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Introduction

There exists a potentially large market for personnel / asset Localization and Tracking Systems (LTSs) in diverse application domains such as:

— emergency response;

— military;

— law enforcement;

— mining;

— E-911;

— offender tracking;

— personal vehicular navigation;

— smart phones / social networking;

— fleet management;

— asset tracking in factories / warehouses / hospitals;

— tracking the elderly / children; and

— personal navigation in museums / shopping malls.

Some applications of localization and tracking – such as personal navigation, fleet management, and asset tracking in factories / warehouses / hospitals – are commonly referred to as Location-Based Services (LBS). The use of LBS alone is expected to grow dramatically by 2020. Yet, lack of standardized Test and Evaluation (T&E) procedures has been an impediment to market growth for LTSs, because:

i) potential users cannot easily determine whether these systems meet the users' requirements;

ii) it is hard to interpret T&E results when different metrics and procedures are used to evaluate a given system or even worse to evaluate different systems; and

iii) the use of disparate minimum performance requirements by various buyers / jurisdictions forces manufacturers to develop jurisdiction-specific products, thereby raising manufacturing costs.

In contrast with LBS, there are many applications of localization and tracking that are essentially governmental functions in the sense that the government is the entity that is most concerned about the effectiveness of solutions for such applications. Examples of these applications include tracking firefighters entering a burning structure for command and control purposes and to launch a rescue mission if a firefighter becomes incapacitated, prevention of friendly fire when soldiers or Special Weapons And Tactics (SWAT) team members enter a building where either hostile forces or armed individuals threatening public safety have taken refuge, and guidance and navigation for missiles and precision-guided munitions. Many of these applications have more stringent localization accuracy and latency requirements than other applications of localization and tracking used by the general public, such as navigation in museums / shopping malls, tracking the elderly in nursing homes, ensuring children are not abducted from school grounds, and fleet management for a trucking company.

This document deals with T&E of LTSs. Once standardized T&E procedures have been established, it is possible to set minimum performance requirements for various applications of localization and tracking. For example, regulations promulgated by a government agency may require coal mine operators to have the capability to track the miners on duty within 5 m accuracy during normal mine operations and 100 m accuracy in the aftermath of a catastrophic incident in the mine, such as an explosion or a roof collapse. It makes sense to separate the T&E issue from minimum performance requirements, because the same T&E standard may be applicable to many applications of localization and tracking, but the minimum performance requirements typically vary from one application to

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another. This document deals with T&E only; it does not set minimum performance requirements for any localization and tracking applications.

T&E of LTSs is challenging for several reasons:

i) Many systems work in a "networked" fashion. That is, several devices would have to communicate with each other in order to estimate the location(s) of one or more such devices. Therefore, the LTS performance is affected by how these devices are situated with respect to each other, i.e. by the network topology.

ii) The physical environment in which the devices are situated affects communications between them and functionalities such as ranging or estimating direction of another device and hence LTS performance. For example, Radio Frequency (RF) communications in a single-family house with a wooden structure is very different from that in a large high-rise building with a steel and concrete structure.

iii) Even though it is best to take a "black-box" approach to LTS T&E, one needs to be cognizant of the failure modes of various location sensors (such as Global Positioning System (GPS), RF ranging, RF direction of arrival estimation, accelerometer, gyroscope, and altimeter) that "might" be used in an LTS in order to design a comprehensive T&E procedure.

Yet another difficulty of a different nature is that some systems rely on the availability of a networking infrastructure, such as a Wi-Fi network, or other devices, such as Radio Frequency IDentification (RFID) or Real Time Locating System (RTLS) tags, to facilitate localization and tracking in a building or structure. Some allow deployment of such devices – sometimes called "breadcrumbs" – as users enter a building. Other systems are designed to function based on the assumption that they cannot get any help with localization and tracking from the building and breadcrumb deployment is not allowed. Therefore, the T&E procedure has to account for these possibilities or classes of LTSs.

The main purpose of this document is to develop performance metrics and T&E scenarios for LTSs. LBS are envisaged in many application domains in both governmental operations and general public usage scenarios. Therefore, industry, consumers, trade, governments, and distributors are all affected by this document. Every effort has been made to write this document in such a way that it would be applicable to as many applications of indoor localization and tracking as possible. This document provides explicit instructions on how to report the T&E results, i.e. what information to document and what kind of tables and figures/plots to include to best visualize the results of the T&E effort. LTS T&E is complicated even once this document has been published, because there has to be a "network deployment" and testing in at least a few types of buildings. One should not expect that LTS T&E can be done in a laboratory. Performance results can depend on the particular building(s) used in the T&E procedure, but at least there will be a standardized way of doing the T&E, and if multiple LTSs are evaluated according to the standard in the same set of buildings, then the performance results can be compared. Localization and tracking technology has not yet matured. New systems and approaches will be developed in the next several years, but the T&E procedure can be standardized regardless of what takes place on the technology front and it may in fact foster technology development. In the absence of a T&E standard, the present uncertainties in the LTS market, where it is hard for users to ascertain whether LTS products meet their requirements and LTS vendor claims are hard to verify, will continue. Therefore, this is indeed the right time for development of this document.

Extensions of this standard to other application domains, such as miners trapped in an underground mine, navigation for submersible vehicles or tiny medical devices moving around inside a human body, may be the subjects of future standards that will be extensions of this "base" standard.

As a final note, the term "localization and tracking" has been used to denote the types of systems this document is meant to be applied to. However, this is not the only term in use for referring to such systems. ISO/IEC JTC 1/SC 31 uses the term RTLS, which also appears in the full name for this document. SC 31, in its deliberations, considered the use of the term "positioning" for the situations in which a person/object equipped with an appropriate device, uses that device possibly in conjunction with others and as part of a system to determine its own location. That is, "positioning" is for self-awareness. On the other hand, SC 31 regards "locating" as the appropriate term for the situation in which some other entity needs to determine the location of a person/object remotely. In other words,

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"locating" is for tracking and accountability purposes. There is also the possibility that a system needs to provide both "positioning" and "locating" functionalities (see 5.4.4), using the terminology just defined. "Tracking" is another frequently used term that has a time dimension to it. That is, one needs to keep track of a person/object's movements over a period of time. In its simplest form, tracking can be done by invoking a locating capability periodically over the time interval of interest. However, tracking can also take into account the mobility characteristics of the person/object being tracked. For example, it is highly unlikely that a firefighter would move faster than 1 m/s while putting the fire down in a burning building, and this information can be used to do a better job of estimating the firefighter's location at any given time. "Location System" is another term used in the literature. Yet another term, often encountered in military applications, is "navigation". In order to navigate a person/object to some destination point, it is necessary to know the person/object's starting location at a minimum. In case of navigating a missile or smart bomb, where missing the target or hitting something else can have catastrophic consequences, it is necessary to know the missile's/bomb's location continuously so that any deviations from its intended path/course can be corrected. Navigation includes computing a path to the destination. This path is not always the direct line from the starting location to the destination. For example, consider navigation in city streets or for providing guidance to a disoriented firefighter to get out of a burning building. Even though this document does not deal with navigation, it does deal with that component of navigation that has to do with where a person/object is at a given time.

This document adopted the term "localization" to capture both locating and positioning functionalities, because the person/object has to be "localized" in either case. It also adopted the term "tracking" to ensure the standard is not just about a snapshot of person/object's location, but also addresses its evolution over time. As a matter of fact, SC 31 has so far focused on purely RF–based systems, but this document considers systems that may use a variety of sensors for localization and tracking, including Inertial Measurement Units (IMUs), whose performance is indeed affected by how the person/object is moving.

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1 Scope

This document identifies appropriate performance metrics and test & evaluation scenarios for localization and tracking systems, and it provides guidance on how best to present and visualize the T&E results. It focuses primarily on indoor environments.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
entity to be localized/tracked
person / autonomous robot that needs to know its location for context-awareness / navigation purposes or person/object whose location is needed by a tracking authority at a given time instance or over a time interval

Note 1 to entry: See the abbreviation ELT in Clause 4.

3.2
location sensor
device that measures a physical quantity to facilitate estimating the spatial coordinates of a person/object in a reference coordinate system

3.3
entity localization/tracking device
equipment carried by a person or affixed to an object comprising one or more location sensors that facilitates estimating the location of the person/object at a given time instance or over a time interval

Note 1 to entry: to entry**:** See the abbreviation ELTD in Clause 4.

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4 Abbreviated terms

AOA	angle-of-arrival
AP	access point
CCD	charged coupled device
CDF	cumulative distribution function
CE95	circular error 95%
CEP	circular error probable
ELT	entity to be localized/tracked
ELTD	entity localization/tracking device
EMI	electromagnetic interference
ERP	effective radiated power
GDOP	geometric dilution of precision
GNSS	global navigation satellite system
GPS	global positioning system
IMU	inertial measurement unit
INS	inertial navigation system
ISM	industrial, scientific, and medical
IT	information technology
LBS	location-based services
LOS	line-of-sight
LTS	localization and tracking system
MEMS	microelectromechanical systems
PDOA	phase difference of arrival
PII	personally identifiable information
RF	radio frequency
RFID	radio frequency identification
RMS	root mean square
RSS	received signal strength
RSSI	received signal strength indicator
RTLS	real time locating system
SE95	spherical error 95%

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SEP	spherical error probable
SLAM	self-localization and mapping
T&E	test and evaluation
TDOA	time difference of arrival
TOA	time-of-arrival
TOF	time-of-flight
UTM	universal transverse Mercator
UV	ultraviolet
UWB	ultra wideband
VE95	vertical error 95%
VEP	vertical error probable
WGS 84	world geodetic system 84

5 LTS taxonomy

5.1 Types of location sensors

GPS has been the dominant technology for outdoor navigation and for tracking entities such as a fleet of taxicabs or trucks. Inertial Navigation Systems (INS) have been used for navigation purposes for a long time. These trends preceded the recent flurry of activities in indoor localization and tracking, which have focused primarily on RF-based methods. Two approaches have played key roles in fuelling the recent drive in development of LTSs. One is based on processing the signals received by a mobile device / smartphone from the base stations of a cellular telephony system. This approach works both indoors and outdoors, but its localization accuracy is not adequate for many applications. The other is based on the strength of signals received from Wi-Fi Access Points (APs) that are widely deployed in buildings / structures throughout the world. Once again, the localization accuracy of this approach may not be adequate in certain applications, and not all buildings have Wi-Fi APs.

These efforts were followed by exploring other RF-based methods, particularly for indoor environments where GPS receivers do not work due to the lack of Line-of-Sight (LOS) RF propagation paths to at least four GPS satellites. Since about ten years ago, researchers have significantly increased their efforts to develop various RF techniques for localization. Angle-Of-Arrival (AOA) estimation, even though it has been around for a long time, has been explored for indoor localization. Time-Of-Arrival (TOA) estimation has also been around, but it has been the subject of renewed interest due to the advent of Ultra WideBand (UWB) communications and ranging techniques. Widely used RF technologies such as Bluetooth, ZigBee, and RFID have been explored for indoor localization and tracking. Each of these technologies and approaches has its own pros and cons. Over time, it has become abundantly clear that purely RF-based approaches may not provide the desired localization accuracy or may not meet all the operational requirements of a particular application. For example, firefighters responding to a fire cannot assume that Wi-Fi APs or RFID tags/readers are available in the building that could be used for localization purposes. Therefore, there has been considerable effort lately to look at the use of other sensors for localization and tracking. Of particular interest and promise are hybrid LTSs that fuse the data from a number of location sensors to produce accurate location estimates. In this regard, one can design an LTS that employs a fixed set of location sensors or one that is sufficiently flexible to take advantage of whatever location sensors that might be available at any given time. For example, as a mobile platform such as a ground vehicle moves around, it may be able to use the signals from a radio station or TV tower together with the location of the transmitting antennae from the radio/TV stations for localization purposes. Such signals are called signals of opportunity.

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Given below is a non-exhaustive list of location sensors:

— RF-based location sensors;

— Received Signal Strength (RSS);

— proximity, including RFID;

— TOA;

— Time-Difference-Of-Arrival (TDOA);

— AOA;

— signals of opportunity;

— range / pseudo-range finder;

— GPS / Global Navigation Satellite System (GNSS);

— differential GNSS;

— accelerometer;

— gyroscope;

— magnetometer;

— IMU;

— pedometer;

— inclinometer;

— altimeter;

— acoustic sensor;

— imager;

— optical;

— infrared; and

— lidar.

More is said about these sensors and their failure modes in Annex B.

5.1.1 Unimodal systems

Some LTSs use only one type of sensor for localization and tracking purposes. An example of such a system is the widely used Wi-Fi localization system. Such a system uses the Received Signal Strength Indicator (RSSI) available on Wi-Fi receivers to estimate location. Specifically, the Entity to be Localized/Tracked (ELT), as a Wi-Fi client, uses RSSI measurements from various APs in the building to estimate its own location. Alternatively, the APs can collaborate with each other and estimate the ELT location based on the strengths of the signals they receive from it. Another example would be an LTS that uses RFID technology only. In one variation of such a system, called Reverse RFID, passive RFID tags are deployed in the building and the ELT is equipped with an RFID reader that reads all RFID tags in its vicinity. This information enables the ELT to estimate its own location.

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5.1.2 Multimodal systems

These are systems that use more than one type of location sensor. Such systems are also called hybrid systems. They use data fusion methods to combine various sensor measurements to arrive at a location estimate. The fusion process can take place on the ELT or at a designated node in the LTS. There are situations where no unimodal LTS would meet the requirements of a particular application. For example, when firefighters respond to a fire in a building, they cannot assume the building has any infrastructure (Wi-Fi APs, RFID, or other wireless technology) that could help with localization and tracking. If the firefighters and the incident command wish to have localization and tracking capability, it would have to be provided by the equipment they bring to the scene. If the building poses challenges to RF propagation, which would be the case for large buildings made of heavy construction materials like steel and concrete, then no RF-based method brought to the scene can provide the desired localization and tracking capability. (Note that firefighters are not fond of a breadcrumb solution either, because breadcrumbs may be destroyed by fire and are hard to retrieve even if they survive.) This is an example of a situation where the operational requirements of the application dictate the use of a multimodal LTS that could use GPS for outdoor tracking and inertial navigation and some form of RF ranging – even if it is not available all the time – for indoor localization and tracking.

Equipment cost might be another reason for using a multimodal LTS. There are cases where a multimodal LTS outperforms any unimodal LTS, for a given total system cost. The design of multimodal or hybrid LTSs is an active area of research and development.

5.2 Reliance on pre-existing networking / localization infrastructure

5.2.1 LTSs requiring infrastructure

A Wi-Fi localization system is an example of such a system, because it requires availability of Wi-Fi APs in the building.

Another example is LTSs that use RFID technology. There are two ways of using RFID for localization, the so-called direct way and Reverse RFID. The latter has already been described in 5.1.1. In a Direct RFID system, RFID readers are deployed throughout the building and the ELTs are equipped with RFID tags. Once a reader reads a tag, the system knows the tag is in its vicinity. If multiple readers can read/"see" a tag, then some weighted average of the reader locations would be a reasonable estimate of the tag location. Note that an RFID reader is always an active device, but the tag can be passive or active. So, there are two ways of implementing a Direct RFID system and two ways of implementing a Reverse RFID system.

It is useful to explain which type of application each system is most suited to. In a scenario where a large number of items need to be accounted for in a store, a Direct RFID system would be the appropriate choice. In this case, most likely a passive RFID tag is attached to each item and RFID readers are deployed throughout the store. This would make it possible to know the location of each item. Note that RFID readers are a lot more expensive than passive RFID tags.

On the other hand, it would be more cost effective to equip each firefighter with an RFID reader and deploy passive RFID tags throughout the building in a firefighter tracking scenario, because the number of tags that have to be deployed in any moderate to large size building in order to determine the location of firefighters with adequate accuracy is a lot larger than the number of firefighters responding to the fire that have to be tracked and accounted for. Therefore, a Reverse RFID system makes more sense in this case.

5.2.2 LTSs capable of infrastructure-less operation

Firefighters and soldiers entering a building/structure may benefit from having a localization capability, but they cannot presume that any networking/localization infrastructure is available. They need to be able to localize themselves or their comrades with the equipment they bring to the site only.

One solution in such a case is to use an INS, but the drift associated with such systems may become problematic if the user, i.e. the firefighter/soldier, spends an extended period of time moving around in

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the building/structure. A well-known solution to this problem is to occasionally provide the user with absolute location estimates to zero out the INS drift. For example, anchor nodes could be deployed outside the building/structure when the user arrives at the site. An anchor node is a transceiver whose location is known to the LTS, perhaps through a GPS receiver available at the anchor node. If the user has RF ranging capability and knows its distances from four anchor nodes, then the user's 3D location can be computed through trilateration. The INS is still needed for any decent size building/structure, because it is often not possible to determine the range to as many as four anchor nodes due to signal attenuation by walls, ceilings, and other objects. This is just one example of a design option for such an LTS. A number of other location sensors could be used, per the discussion of multimodal systems under 5.1.2.

5.2.3 Real-time deployment of nodes facilitating localization

In some applications it is acceptable to deploy auxiliary devices as the users arrive in a building. For example, emergency responders may deploy communication relay nodes to facilitate not only radio communications but also localization and tracking. One may regard an LTS operating based on this concept as something between an infrastructure-less system and one that needs infrastructure in the building to facilitate localization and tracking.

5.2.4 Opportunistic use of infrastructure/environment

There are some LTSs that can function with or without the availability of infrastructure in the building/structure. They typically perform better when infrastructure is available than when it is not. This is called opportunistic use of infrastructure/environment. One example of such an LTS is one that does not need availability of Wi-Fi signals in the building/structure in order to function, but it would use the Wi-Fi signals, when available, to offer more accurate localization. Another example is when the LTS uses the signal(s) from radio/TV station(s) and the location of the radio/TV transmission tower(s) to improve its localization performance compared to situations where such information is not available.

5.3 Off-line, building-specific training

5.3.1 LTSs requiring off-line training

The best example for this type of system is a Wi-Fi fingerprinting localization system. Suppose *n* Wi-Fi APs are deployed throughout a building. There are three approaches for implementing a Wi-Fi fingerprinting localization system. The first step in all three approaches consists of selecting a number of training points throughout the building, such that all areas in the building are covered with adequate density. The fingerprinting step in all three approaches is done off-line and before the system is used to estimate the location of an ELT equipped with a Wi-Fi client card.

The fingerprinting step in the first approach, which is called AP-based fingerprinting, involves recording the RSSI from a Wi-Fi client located at a given training point at all APs that can "hear" the client. Therefore, for each training point there shall be an *n*-tuple of RSSI values, with a default minimum value for the RSSI used when an AP does not hear the client. For each training point, the location of the point along with the *n*-tuple of RSSI values are stored in a fingerprint database. The localization process consists of comparing the *n*-tuple of RSSI values from the ELT measured by the *n* APs with all the fingerprints stored in the database and selecting the fingerprint that is "closest" to the APs' measurements according to some distance measure. The location of the ELT is estimated to be the location associated with the closest fingerprint or a combination of the locations associated with a few closest fingerprints. The location estimate is then communicated by the system to the ELT.

The fingerprinting step in the second approach, which is called client-based fingerprinting, involves recording the RSSI from the *n* APs at a Wi-Fi client located at a given training point. If the client cannot hear an AP, a default minimum value for the RSSI is used for that AP. Hence, for each training point there shall be an *n*-tuple of RSSI values. This *n*-tuple and the location of the training point are stored in a fingerprint database. The localization process consists of comparing the *n*-tuple of RSSI values measured by the ELT with all the fingerprints stored in the database and selecting the fingerprint that is "closest" to the ELT's measurements according to some distance measure. The location of the ELT is

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estimated to be the location associated with the closest fingerprint or a combination of the locations associated with a few closest fingerprints.

In the first approach the burden of localization is on the APs. The APs need to communicate their RSSI measurements to a central processor that searches the fingerprint database for the best match. This has the advantage that the ELT does not need to store or know anything about the fingerprint database and it does not have to do any work at all. The advantage of the second approach is that the APs do not need to communicate any RSSI measurements, but each ELT has to store the fingerprint database. This approach is not suitable for localizing general public visiting a shopping mall.

The third approach is a variation of the second one. The fingerprinting step is the same, but when the ELT measures the RSSIs from the *n* APs, it communicates the *n*-tuple to the localization system which returns to the ELT a location estimate for the ELT that is either the location associated with the best match in the fingerprint database or a combination of the locations associated with a few closest fingerprints. The advantage of this approach is that the ELT does not need to store the fingerprint database.

This was just one example of a system that requires off-line training, but it happens to be the one most used. In principle, it is possible to use the same procedure with other wireless technologies, such as ZigBee, Bluetooth, or even RFID.

Fingerprinting is a time-consuming process, and fingerprints change with time if:

i) new APs are installed in the building;

ii) an AP is removed; or

iii) any changes are made to the floor plans of the building by new construction or even by moving furniture around. In practice, the fingerprinting process has to be repeated once in a while and after any substantial changes in the Wi-Fi landscape.

Therefore, the need for fingerprinting is regarded as a drawback for an LTS.

Some Wi-Fi LTS developers use predictive models for signal attenuation in lieu of actually measuring RSSI values associated with each training point. The predictive model could be as simple as a power-law path loss model or as complicated as a ray tracing method. This approach is simpler than the fingerprinting methods described above, but it is not as accurate. It results in inferior localization performance, but that might be acceptable in certain applications.

5.3.2 LTSs not requiring off-line training

A Wi-Fi localization system does not necessarily need fingerprinting (off-line training). It is possible to use a formula to convert an RSSI value for an AP measured by a Wi-Fi client to a range from the client to the AP. However, such range estimates are not accurate due to the weak correlation between RSSI value and range.

One other example of a system that does not require off-line training is one that uses RF ranging. In that case, the building is equipped with a number of anchor nodes whose locations have been determined as part of the process of deploying the LTS. The ELT is equipped with an RF transceiver capable of communicating with the anchor nodes and estimating its range from them. The location of the entity is computed through ranging to different anchor nodes.

5.4 Ultimate consumer(s) of location information

5.4.1 Introduction

When the ELT has to be tracked by a tracking authority and the location estimation takes place solely at the ELT, the location estimate needs to be communicated to the tracking authority. This may be the case when the ELT is a firefighter and the tracking authority is the incident command set up outside a building on fire. In such a case, a radio link is needed between the ELT and the tracking authority.

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because it is unlikely that the two can communicate over a wired communication link. It is well-known that indoor radio performance is far from perfect. Therefore, one important failure mode for the LTS in this scenario is the breakage of the radio link between the ELT and the tracking authority. In other words, even if the location estimation is perfect, there is a problem if that information cannot be radioed to the tracking authority.

5.4.2 The ELT

A shopping mall patron may wish to know where s/he is and how to get to a particular store. In this case, the sole user of the location information is the ELT itself.

5.4.3 The tracking authority

An offender roaming city streets may need to be tracked by the police. In this case the system is not designed to help the offender navigate city streets, but to enable the police to track the offender and receive notifications whenever the offender violates the rules on his/her movements. (The offender knows in which areas he/she is expected to remain and where the exclusion zones are that he/she is supposed to stay away from.)

5.4.4 Both the ELT and the tracking authority

A firefighter entering a building on fire needs to know where in the building he is. At the same time, the incident command outside the building needs to know the location of each firefighter for command and control purposes as well as for launching a rescue operation if a firefighter is incapacitated.

6 LTS privacy and security considerations

6.1 Privacy

There are significant privacy issues associated with the use of LTSs, particularly when the ELT is a human being. In such cases it is presumed that Personally Identifiable Information (PII) will be collected. There may be universal acceptance and no concern for privacy in LTS use cases such as firefighters battling a fire in a building, where the incident command needs to know which firefighter is where, and the firefighters do not mind being tracked by the incident command. There may be less acceptance and potential privacy concerns where an LTS is used to track the elderly or children, where it may be imperative to ensure their privacy is not compromised and the location information does not end up in unauthorized hands. Therefore, in some applications the identity of individuals being tracked and even their movement patterns may need to be encrypted and the privacy of such data ensured.

One way to think about privacy and PII is the ability to correlate personal identity to activity. If the location information is not bundled or stored with identifying information, and an observer (for instance the tracking authority) cannot link a person's identity to location information, then there is no PII. This is an important distinction because it makes the difference between sniffing location information from the network "personal" or "not personal", which may either encumber or free the technology from regulatory burden.

Consequently, the implementers of this document need to be cognizant of:

— the existence of privacy and data protection risks associated with the use of LTSs;

— the broad differences in privacy and data protection legislation observed in different jurisdictions;

— the existence of both horizontal (i.e. all-encompassing/generic) and sector-specific privacy and data protection legislation which might have to be observed concomitantly;

— the potential need to observe more than one set of rules if applications operate cross-border; and

— the complex nature of assigning responsibilities in this area when more than just one actor is involved.

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Generally speaking, the implementers should consider

— Notice: data subjects should be given notice when their data is being collected;

— Purpose: data should be used only for the purpose stated and not for any other purposes;

— Consent: data should not be disclosed without the data subject's consent;

— Security: collected data should be kept secure from any potential abuses;

— Disclosure: data subjects should be informed as to who is collecting their data;

— Access: data subjects should be allowed to access their data and make corrections to any inaccurate data; and

— Accountability: data subjects should have a method available to them to hold data collectors accountable for following the above principles.

The rules relating to the collection, security, disclosure, access, and accountability for PII can be found in ISO/IEC 29100 [1] and ISO/IEC 29101 [2].

6.2 Security

The security of an LTS is even harder to assess than its privacy. An LTS, like any other Information Technology (IT) system, may be vulnerable to cyber attacks. Just like any other security problem, no one knows what all possible cyber attacks are. However, two obvious ones are discussed next. One is a RF jamming attack to disrupt the proper operation of the LTS or the radio link for communicating location information to a tracking authority. Another is when an attacker pretends to be a legitimate user that is supposed to be tracked and transmits wrong information regarding the location of the legitimate user or the kind of misinformation that adversely affects the estimation of other legitimate users' locations. Hence, it is important to protect an LTS against cyber attacks.

It is also possible that the tracking authority may be impersonated, such that authorized access is granted to value data, and used for unintended purposes.

7 T&E methodology taxonomy

7.1 System vs. component testing

7.1.1 System testing

A typical user of an LTS is interested in knowing whether the system meets the user's requirements or not. The user does not care how the system works, but how it performs. System testing means testing the LTS as a whole without any regard for the performance of individual components used in that system. This document is focused on system testing.

7.1.2 Component testing

In addition to designing (multimodal) LTSs with good performance, system developers and researchers are also interested in improving individual components that may be used in an LTS. An LTS component can be a location sensor (see 5.1) or a location sensor together with some algorithm for processing the data from that sensor. By improving a system component as much as possible, one can improve the performance of a unimodal LTS using that component only or a multimodal LTS that uses that component along with some others. For example, one may be interested in designing the best possible UWB ranging device, accelerometers with small drifts, or an effective data fusion algorithm for a multimodal LTS. Therefore, it would be important to be able to measure the performance of the components that may be used in an LTS through testing. Component testing, however, would not say anything about how the LTS would perform as a whole. Component testing is not addressed in this document.

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7.2 Knowledge about LTS inner-workings

7.2.1 T&E designed with full knowledge of LTS inner-workings

It was stated earlier that this document focuses on system testing. One can do a better job of system testing if one knows what components are used in the system and how the data from these components are processed. On one hand, this would be an expensive approach, because it implies development of custom-made T&E procedures for a given LTS. On the other hand, it can reduce the number of tests that need to be done for a given LTS and hence reduce the testing cost. For example, a purely INS solution does not need to be tested in various building types, because there are no RF propagation issues if only the user needs to know his/her location as opposed to a tracking authority.

System-specific T&E may make sense if a particular system becomes dominant in the marketplace and widely deployed. On the other hand, there may not be a need for T&E for a widely deployed system, because its performance may be well-known at that stage. This document does not address custom-made T&E procedures.

7.2.2 Black-box testing

Black-box testing is the approach taken by this document. It means system testing without the knowledge of what components are used in the LTS. The user does not care what's inside the box. For the most part, the T&E procedure is independent of what components / location sensors the LTS uses. Yet, the T&E standard has to be cognizant of the type of location sensors that *might* be used in an LTS, and one has to know the failure modes of those sensors to make sure the T&E procedure would have provisions for stressing the LTS along directions that make such failures likely.

7.3 Repeatability

7.3.1 Repeatable testing

Repeatability is the ability to reproduce the same test results when a given LTS is tested several times in the same environment. It is desirable to have repeatable LTS testing, but this is difficult due to the need for a "network" deployment covering a sizeable area. It is hard to recreate exactly the same conditions. Nevertheless, to maximize the likelihood of repeatability and enable fair comparisons between different versions of a system, efforts should be made to keep the testing conditions constant. The test environment should be monitored for external influences that should be controlled to the extent possible. These influences include, for example, RF interference. Results obtained when there are significant perturbations in the test environment should be discarded.

It is easier to have repeatable testing for LTS components, such as RF ranging, but component testing is not the focus of this document.

7.3.2 Non-repeatable testing

Every effort should be made to control the test conditions. However, if it is not possible to reproduce the same test conditions from one testing session to the next, several LTSs may be tested in the same buildings using the same T&E methodology in one session. Under these conditions, one can still compare the performance of various systems tested.

7.4 Test site

7.4.1 Building-wide testing

This is when all or large portions of several buildings/structures are used for testing. It is the approach advocated by this document.

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7.4.2 Laboratory testing

This is typically for component testing, where with proper controls one may be able to make the tests repeatable. It is very difficult, if not impossible, to test at the system level in a laboratory.

7.5 Ground truth

7.5.1 Off-line surveyed test points

One way of measuring the localization accuracy of an LTS (see Clause 8 for various metrics related to accuracy) is through establishment of a number of test points in each building used in the T&E process. Surveying is used off-line to determine the (x, y, z) coordinates of the test points with respect to some 3D Cartesian coordinate system established at the building. Test points should cover all or a large portion of the building with sufficient density. The locations of the test points shall be random, i.e. the test points should not be at a fixed distance from each other or exhibit a regular deployment pattern to eliminate the possibility that any LTS under test can use the knowledge of such regular pattern to improve its location estimates. If the LTS relies on RSS fingerprinting, it shall be ensured that the test points are different from the training points at which fingerprints were taken (see 5.3.1). During the T&E process, the LTS under test shall be asked to generate location estimates at the test points. These estimates are then compared with the "ground truth", i.e. the coordinates of the test points measured off-line, in order to assess the LTS localization accuracy performance.

The surveying process shall be done in such a way to ensure the accuracy of the 3D coordinates of the test points is at least one order of magnitude better than the expected accuracy of the LTS under test. For example, if the expected accuracy of the LTS is 3 m, then the measured coordinates of each test point should be such that the Euclidean distance between the measured coordinates and the actual coordinates of the test point is no more than 30 cm. It is recommended that precision laser surveying equipment be used to measure the coordinates of the test points. Even when precision surveying equipment is used, one has to be mindful of compounding errors, which are encountered when one uses the surveyed coordinates of one point to determine the coordinates of the next point, and so on. In order to increase the accuracy of the surveying process, one has to use closed loops. That is, one starts at a given point and keeps surveying new points, but one closes the loop and returns to the starting point. The error in the location of the starting point can then be backpropagated along the traversed path.

If the cost of the surveying equipment is an issue, another alternative is to use a tape measure if high precision floor plans of the building are available. In this case, the coordinates of each test point is measured with respect to a landmark in the building, whose coordinates can be obtained from the CAD file, as opposed to another test point. For example, a test point can be 1 m east and 50 cm north of a landmark. This will ensure that the error in measuring the coordinates of a test point with respect to a landmark using a tape measure does not propagate, leading to an accumulation of errors.

Finally, since some LTSs use the World Geodetic System 84 (WGS 84) standard to represent location information, the 3D Cartesian coordinates of the test points should be converted to WGS 84 coordinates and both sets of coordinates stored. Annex A presents procedures for establishing a local 3D Cartesian coordinate system at a test building and converting coordinates of a point from WGS 84 to local coordinates and vice versa.

7.5.2 Reference LTS

An alternative to establishing surveyed test points in a building is to use a "reference" LTS along with the LTS under test and compare the location estimates of the two systems in order to assess the localization accuracy performance of the latter. One advantage of this approach is that it does not interfere with the test subject's natural motion, because he/she would not need to press a button on the Entity Localization/Tracking Device (ELTD) to request the generation of a location estimate while the ELTD is on a pre-surveyed test point. With this approach, one shall ensure that the average accuracy of the reference system is at least one order of magnitude better than the expected accuracy of the LTS under test. This is necessary because the location estimate of the reference system is treated as the ground truth.

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The reference system can be quite expensive, depending on how accurate it needs to be. Two example solutions for the reference system are:

i) An INS with very small drift; and

ii) A UWB ranging system with many anchor nodes deployed in the building so that the UWB transceiver carried by the ELT can see at least four anchor nodes at any location in the building.

It is also possible to combine these two approaches and use a lower quality INS than the one used in (i) along with fewer UWB anchor nodes deployed in the building than with (ii).

One shall ensure that the reference system does not have any RF interference issues with the LTS under test.

8 LTS performance metrics

8.1 Introduction

Whether the T&E procedure uses off-line surveyed test points or a reference LTS, the performance analysis boils down to comparing the location estimates generated by the LTS under test at a finite number N of test points with the corresponding ground truth coordinates of those points. For i=1,2,… ,N, the following terminology is introduced for "test point" i :

ground truth coordinates: (x_i, y_i, z_i)

location estimate generated by the LTS: $(\hat{x}_i, \hat{y}_i, \hat{z}_i)$

3D error vector: $\underline{\varepsilon}_i = (\varepsilon_{x,i}, \varepsilon_{y,i}, \varepsilon_{z,i}) = (\hat{x}_i - x_i, \hat{y}_i - y_i, \hat{z}_i - z_i)$

l_2-norm or magnitude of $\underline{\varepsilon}_i$: $\left\|\underline{\varepsilon}_i\right\| = \sqrt{\varepsilon_{x,i}^2 + \varepsilon_{y,i}^2 + \varepsilon_{z,i}^2}$

horizontal error vector: $\underline{\varepsilon}_{h,i} = (\varepsilon_{x,i}, \varepsilon_{y,i})$

l_2-norm or magnitude of $\underline{\varepsilon}_{h,i}$: $\left\|\underline{\varepsilon}_{h,i}\right\| = \sqrt{\varepsilon_{x,i}^2 + \varepsilon_{y,i}^2}$

It is assumed that the z-axis corresponds to the vertical direction.

In addition, in some applications of localization and tracking, a coarse granularity is more useful for characterizing the LTS performance than performance metrics based on the terminology introduced above. Specifically, it is of vital importance to correctly guess on which floor of a building the located entity is when firefighters are tasked to extricate someone, e.g. a downed firefighter or a resident, from a burning building. Similarly, it may be adequate in certain applications to just correctly guess in which "zone" of a building floor the located entity is as opposed to estimating the horizontal location with high precision. Therefore, the appropriate performance metrics for these two cases are the probabilities of making correct guesses. To facilitate computing these probabilities, assume the building has F floors, possibly including floor(s) below ground level, and for j=1,2,…,F, introduce the following notation for floor j:

number of zones: L_j

floor zones: $S_{j,1}, S_{j,2}, \ldots, S_{j,L_j}$

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The performance metrics presented next are "estimates" of certain statistical averages and probabilities. As such, it makes sense to put a ^ above each estimate, e.g. use $\hat{\mu}_{\underline{\varepsilon}}$ as opposed to $\mu_{\underline{\varepsilon}}$. However, in order to avoid clutter, no ^ signs are introduced.

8.2 Floor detection probability

Let N_F denote the number of times the floor number is guessed correctly when the LTS is tested at the N test points. Then the floor detection probability is estimated by

$$P_F = \frac{N_F}{N}$$

Note that in order to guess the floor number when testing at test point i, one needs a mapping from $\hat{z}_i$ to the floor number. That mapping would be quite simple if the height of all floors in the building is the same and known and the height of the lowest floor with respect to the ground level is known. (It is assumed that $z = 0$ corresponds to the ground level.) The mapping would be more complicated if the floor height varies from one floor to another, the building has entrances at multiple levels, or it has split floors. In such cases, detailed floor plans of the building along with elevation data need to be made available to the LTS.

Note Some product manufacturers have coined the term 2.5D RTLS to refer to systems that generate an estimate of the horizontal location and the building floor on which the ELT is located. The floor number is regarded as a half dimension in this context, because it may not be as precise as the horizontal location estimate.

8.3 Zone detection probability

This metric is defined as a conditional probability, because most likely guessing the zone correctly would be useless if the floor is guessed erroneously. Therefore, if $N_{F,Z}$ denotes the number of times that both the floor and zone numbers are guessed correctly by the LTS, the zone detection (conditional) probability is estimated by

$$P_{Z|F} = \frac{N_{F,Z}}{N_F}$$

In order to guess the zone number when testing at test point i located on floor j, one needs to have a mapping from $(\hat{x}_i, \hat{y}_i)$ to zone numbers on floor j, i.e. $S_{j,k}$. This can be tricky depending on how complicated the partitioning of floor j by its zones is.

8.4 Means of various errors

The mean of the error vector is estimated by

$$\mu_{\underline{\varepsilon}} = \frac{1}{N}\sum_{i=1}^{N} \underline{\varepsilon}_i$$

It represents the *overall bias* of the LTS, if N is reasonably large. The performance of the LTS can be improved, in the sense of reducing the Root Mean Square (RMS) value of the magnitude of the 3D error vector, by subtracting this bias from the location estimate generated by the LTS. (The RMS values for various errors are introduced shortly.) Note that any carefully designed LTS would have zero overall bias, particularly if the bias is computed over the entirety of results obtained from testing in several buildings. In addition, one may get some insight by computing the bias separately for each building used in testing. For example, consider a situation where the initial location of a person entering a building is estimated with an LTS that is equipped with a GPS/GNSS receiver and the absolute (such as WGS 84) location of the building outer boundary is made available to the LTS. If there is significant error in the initial location estimate of the person or in the absolute location of the building, then this discrepancy

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may affect all the location estimates computed after the person enters the building. This type of problem can be detected by computing the bias for the given building.

The mean of the horizontal error vector is simply the sub-vector consisting of the first two elements of $\mu_{\underline{\varepsilon}}$.

Also, of interest are the means of the magnitudes of horizontal, vertical, and 3D error vectors estimated by:

$$\mu_{\|\underline{\varepsilon}_h\|} = \frac{1}{N}\sum_{i=1}^{N}\|\underline{\varepsilon}_{h,i}\|,$$

$$\mu_{|\underline{\varepsilon}_z|} = \frac{1}{N}\sum_{i=1}^{N}|\varepsilon_{z,i}|,$$

and

$$\mu_{\|\underline{\varepsilon}\|} = \frac{1}{N}\sum_{i=1}^{N}\|\underline{\varepsilon}_i\|,$$

respectively.

8.5 Covariance matrix of the error vector

The covariance matrix of the error vector is estimated by:

$$K_{\underline{\varepsilon}} = \mathrm{cov}(\underline{\varepsilon}) = \frac{1}{N}\sum_{i=1}^{N}(\underline{\varepsilon}_i - \mu_{\underline{\varepsilon}})^{\mathrm{T}}(\underline{\varepsilon}_i - \mu_{\underline{\varepsilon}})$$

The diagonal elements of $K_{\underline{\varepsilon}}$ are estimates of the variances of error vector components. The lower right diagonal element, for example, is the variance of the vertical error.

The trace of $K_{\underline{\varepsilon}}$, denoted by $\mathrm{tr}(K_{\underline{\varepsilon}})$, is the sum of the diagonal elements of $K_{\underline{\varepsilon}}$. $\mathrm{tr}(K_{\underline{\varepsilon}})$ is of particular interest, because it's the square of the RMS value of the magnitude of the error vector once the overall bias has been removed. $\mathrm{tr}(K_{\underline{\varepsilon}})$ is a key metric for an LTS that characterizes performance once the overall bias has been removed.

The off-diagonal elements of $K_{\underline{\varepsilon}}$ are also of interest, because they characterize the correlations between various error vector components. This information may help the LTS designer to improve the system performance by detecting strong correlations and removing them through modifications in system design.

The covariance matrix of the horizontal error is simply the upper left 2x2 sub-matrix of $K_{\underline{\varepsilon}}$.

8.6 Variances of magnitudes of various errors

The variances of the magnitudes of horizontal, vertical, and 3D errors are estimated by:

$$\sigma^2_{\|\underline{\varepsilon}_h\|} = \frac{1}{N}\sum_{i=1}^{N}\left(\|\underline{\varepsilon}_{h,i}\| - \mu_{\|\underline{\varepsilon}_h\|}\right)^2,$$

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$$\sigma^2_{|\varepsilon_z|} = \frac{1}{N}\sum_{i=1}^{N}\left(\left|\varepsilon_{z,i}\right| - \mu_{|\varepsilon_z|}\right)^2 ,$$

and

$$\sigma^2_{\|\underline{\varepsilon}\|} = \frac{1}{N}\sum_{i=1}^{N}\left(\left\|\underline{\varepsilon}_i\right\| - \mu_{\|\underline{\varepsilon}\|}\right)^2 ,$$

respectively.

8.7 RMS values of various errors

The RMS values for the error vector components are given by:

$$\varepsilon_{x,\mathrm{rms}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\varepsilon^2_{x,i}} \quad \varepsilon_{y,\mathrm{rms}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\varepsilon^2_{y,i}} \quad \varepsilon_{z,\mathrm{rms}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\varepsilon^2_{z,i}}$$

which leads to:

$$\varepsilon_{h,\mathrm{rms}} = \sqrt{\varepsilon^2_{x,\mathrm{rms}} + \varepsilon^2_{y,\mathrm{rms}}}$$

and

$$\varepsilon_{\mathrm{rms}} = \sqrt{\varepsilon^2_{x,\mathrm{rms}} + \varepsilon^2_{y,\mathrm{rms}} + \varepsilon^2_{z,\mathrm{rms}}}$$

as the RMS values for the magnitudes of horizontal and 3D errors, respectively.

Note that:

$$\varepsilon^2_{\mathrm{rms}} \geq \mathrm{tr}(K_{\underline{\varepsilon}})$$

with equality iff the overall bias of the LTS is zero (or has been removed).

8.8 Absolute mean of the error vector

When the regular mean of an error component is computed, positive and negative errors cancel each other out. This motivates the introduction of the absolute mean of the error vector estimated by

$$\mu_{|\underline{\varepsilon}|} = \frac{1}{N}\sum_{i=1}^{N}\left|\underline{\varepsilon}_i\right| = \frac{1}{N}\sum_{i=1}^{N}\left(|\varepsilon_{x,i}|,|\varepsilon_{y,i}|,|\varepsilon_{z,i}|\right)$$

8.9 Circular Error 95% (CE95) and Circular Error Probable (CEP)

$\mathrm{CE95}$ is defined as the radius of the smallest circle centred at the origin in the *xy*-plane that encloses 95% of $\underline{\varepsilon}_{h,i}$'s. Specifically,

$$\mathrm{CE95} = \min\left\{R : R \geq 0, \left|\left\{\underline{\varepsilon}_{h,i} : i = 1,2,\ldots,N, \left\|\underline{\varepsilon}_{h,i}\right\| \leq R\right\}\right| \geq 0{,}95N\right\} ,$$

where $|.|$ denotes the size of a set in this context. $\mathrm{R95}$ is an equivalent term to $\mathrm{CE95}$.

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CEP is very similar to $\mathrm{CE95}$. The only difference between the two is that CEP uses a 50% figure in its definition while $\mathrm{CE95}$ uses 95%. Specifically,

$$\mathrm{CEP} = \min\{R : R \geq 0, \left|\{\underline{\varepsilon}_{h,i} : i = 1,2,\ldots,N, \left\|\underline{\varepsilon}_{h,i}\right\| \leq R\}\right| \geq 0,5N\}$$

In general, it is a good idea to plot the empirical Cumulative Distribution Function (CDF) of the magnitude of the horizontal error. This is a staircase function of a single variable r that is zero for all $r < 0$, it jumps by $1/N$ at each empirical value for $\left\|\underline{\varepsilon}_{h,i}\right\|$, and it reaches 1 at the largest value for $\left\|\underline{\varepsilon}_{h,i}\right\|$ and stays at that level afterwards as $r \to \infty$. (Note that if there are n samples of $\left\|\underline{\varepsilon}_{h,i}\right\|$ that take the value r_0, then the height of the jump at r_0 would be n/N. Once this empirical CDF has been plotted, then $\mathrm{CE95}$ and CEP are simply the inverse values of this function at 0,95 and 0,5, respectively.

8.10 Vertical Error 95% (VE95) and Vertical Error Probable (VEP)

$\mathrm{VE95}$ is defined as the smallest nonnegative number such that 95% of the $\varepsilon_{z,i}$'s lie in the interval $[-\mathrm{VE95}, \mathrm{VE95}]$. Specifically,

$$\mathrm{VE95} = \min\{V : V \geq 0, \left|\left\{\varepsilon_{z,i} : i = 1,2,\ldots,\mathrm{N}, \left|\varepsilon_{z,i}\right| \leq V\right\}\right| \geq 0,95N\}$$

VEP is very similar to $\mathrm{VE95}$. The only difference between the two is that VEP uses a 50% figure in its definition while $\mathrm{VE95}$ uses 95%. Specifically,

$$\mathrm{VEP} = \min\{V : V \geq 0, \left|\left\{\varepsilon_{z,i} : i = 1,2,\ldots,\mathrm{N}, \left|\varepsilon_{z,i}\right| \leq V\right\}\right| \geq 0,5N\}$$

Once again, it is a good idea to plot the empirical CDF of the absolute value of the vertical error. Once this empirical CDF has been plotted, then $\mathrm{VE95}$ and VEP are simply the inverse values of this function at 0,95 and 0,5, respectively.

8.11 Spherical Error 95% (SE95) and Spherical Error Probable (SEP)

$\mathrm{SE95}$ is defined as the radius of the smallest sphere centred at the origin of the 3D Cartesian coordinate system that encloses 95% of $\underline{\varepsilon}_i$'s. Specifically,

$$\mathrm{SE95} = \min\left\{R : R \geq 0, \left|\left\{\underline{\varepsilon}_i : i = 1,2,\ldots,\mathrm{N}, \left\|\underline{\varepsilon}_i\right\| \leq R\right\}\right| \geq 0,95N\right\}$$

SEP is very similar to $\mathrm{SE95}$. The only difference between the two is that SEP uses a 50% figure in its definition while $\mathrm{SE95}$ uses 95%. Specifically,

$$\mathrm{SEP} = \min\left\{R : R \geq 0, \left|\left\{\underline{\varepsilon}_i : i = 1,2,\ldots,\mathrm{N}, \left\|\underline{\varepsilon}_i\right\| \leq R\right\}\right| \geq 0,5N\right\}$$

Once again, it is a good idea to plot the empirical CDF of the magnitude of 3D error. Once this empirical CDF has been plotted, then $\mathrm{SE95}$ and SEP are simply the inverse values of this function at 0,95 and 0,5, respectively.

8.12 Coverage

This metric, which is denoted by C, measures the percentage of the evaluation area/space in which the LTS meets its "minimum performance requirements". In other words, $C = n/N$, if the LTS meets the minimum performance requirements at n out of the N test points. It is best to compute C separately for each of the buildings used in the T&E procedure. Therefore, the proper value for N in this context

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would be the number of test points in the given building and not the total number of test points used in *all* buildings.

In order to compute this metric, one has to specify what's meant by minimum performance requirements. There are several possible choices. The LTS under test is said to meet its minimum performance requirements at test point i, if $\left\|\underline{\varepsilon}_{h,i}\right\| \le R_h$, for some $R_h \ge 0$ specified by the LTS application. Another choice is $\left\|\underline{\varepsilon}_{h,i}\right\| \le R_h$ <u>and</u> $\left|\varepsilon_{z,i}\right| \le V$ for some non-negative numbers R_h and V. Yet another choice is $\left\|\underline{\varepsilon}_{i}\right\| \le R_{3D}$, for some $R_{3D} \ge 0$.

If one is allowed to make several measurements and obtain a corresponding number of location estimates at each test point, then one can use upper bounds on RMS values of the three accuracy metrics used in the previous paragraph as the condition for meeting minimum performance requirements at a test point. Note that each RMS value for a given test point is computed over the measurements made at that test point and not those made at different test points.

In order for this metric to correctly represent the fraction of area/space, one should ensure the evaluation area/space is covered by a reasonably dense, uniform distribution of test points <u>and</u> no preference is given to one test point over another. In other words, there should be the same number, say m, of measurements made at each test point, where $m \ge 1$. This is in contrast with the way the *availability* metric, introduced later in this document, is computed.

In computing and reporting the value of coverage, one needs to specify whether the location estimate needs to be made available to the ELT or the tracking authority. The latter requires the availability of a radio link between the ELT and the tracking authority. Therefore, let C_{E} and C_{TA} denote the coverage as seen by the located entity and the tracking authority, respectively. One can also compute coverage for the case that the location estimate needs to be known at *both* the ELT and the tracking authority.

NOTE This metric is primarily intended for RF-based LTSs. If the LTS has inertial components, one may get different values for coverage depending on what path the ELT takes inside the building.

8.13 Relative accuracy

Sometimes the relative position of one ELT with respect to another one or even the distance between the two is more important than the absolute 3D coordinates of the two ELTs. This would be the case, for example, when one firefighter goes into a burning building to rescue another firefighter. If the rescuer knows that the downed firefighter is within 2 meters of him, then he can just search the area around him by touching, even in a dark, smoke-filled environment. If the distance between the rescuer and the downed firefighter is computed from the estimates of their locations, then it has to be ensured that the location estimates are obtained at approximately the same times and the rescuer knows how old that information is (see 8.14 on latency).

This metric is particularly useful if the LTS has peer-to-peer ranging, i.e. the capability for two ELTs to directly estimate the distance between them in addition to possibly distances to any anchor nodes. Note that in a cooperative localization scheme, where the system simultaneously estimates the locations of all ELTs, the "inter-ELT" distances just introduced would be useful and would improve the localization accuracy for all ELTs.

This metric, denoted by μ_{Δ}, is defined as the mean of the absolute difference between the actual distance between two ELTs and the LTS estimate of that distance. When the latter estimate is computed by finding the distance between the location estimates of the two ELTs, one has to be careful to use location estimates obtained at the same time in cases where the ELTs are in motion.

8.14 Latency

The dissemination of location information in an LTS may be based on a pull or push protocol. In the former case, either the ELT or the tracking authority sends a request to the LTS to generate an estimate

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