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

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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).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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.*

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 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, “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.

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

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

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.

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%

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.

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.

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 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 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 <u>and</u> 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, 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.

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.

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.

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.

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

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 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:

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

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 $\text{tr}(K_{\underline{\varepsilon}})$, is the sum of the diagonal elements of $K_{\underline{\varepsilon}}$. $\text{tr}(K_{\underline{\varepsilon}})$ 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. $\text{tr}(K_{\underline{\varepsilon}})$ 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:

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

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

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

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

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 $\mathrm{CE95}$.

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

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

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 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)

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

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

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

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

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 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)

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,

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

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

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

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 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 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 $\|\underline{\varepsilon}_{h,i}\| \le R_h$, for some $R_h \ge 0$ specified by the LTS application. Another choice is $\|\underline{\varepsilon}_{h,i}\| \le R_h$ and $|\varepsilon_{z,i}| \le V$ for some non-negative numbers R_h and V. Yet another choice is $\|\underline{\varepsilon}_i\| \le R_{3D}$, 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 and 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 of the ELT's location. In the latter case, the LTS automatically generates such location estimates every T seconds and makes that information available to the ELT or the tracking authority. It is also possible for an LTS to accommodate both protocols. That is, the LTS generates location estimates every T seconds, but also accommodates requests for location estimates at any time.

It is clear that outdated location information is of little value. However, what constitutes "outdated" depends on the ELT's speed of movement. In the case of a stationary object, like a piece of equipment on a factory floor, the tracking authority would be pleased if the LTS "instantly" reports the location of the equipment. Even if this is not the case and it takes the LTS several seconds to locate the equipment, the tracking authority may not be terribly disappointed. When it comes to tracking or navigating a fast moving object, such as an unmanned aerial vehicle or a fighter jet, one may not be willing to tolerate delays more than a fraction of a second in getting a location estimate. The main point is that, regardless of the LTS application at hand, the ultimate user of the location estimate does care how long it takes for the LTS to generate that estimate. That delay is called latency.

In case of an LTS with a push protocol, the latency is defined as the delay from the moment the LTS initiates the process of computing a location estimate, which happens every T seconds, until that estimate is computed and made available to the ultimate user of the location information. Note that the latency may turn out to be larger than T seconds. In addition, it makes a difference whether the ultimate user is the ELT or a tracking authority. (In some LTSs the location estimate is readily available to the ELT, but reporting it to a tracking authority could be problematic, because it requires a radio link between the ELT and the tracking authority and there can be delays in radio communications due to fades, packet transmission collisions, etc.) Therefore, let τ_{E} and τ_{TA} denote, respectively, the latency of reporting a location estimate in an LTS with a push protocol to the ELT and the tracking authority, if one is present, respectively.

In case of an LTS with a pull protocol, the latency is defined as the amount of time elapsed from the moment a request is made for a location estimate until the estimate is delivered to the requester. Once again, it is necessary to make a distinction between the ELT making the request and the tracking authority doing so. Let δ_{E} and δ_{TA} denote, respectively, the latency of reporting a location estimate in an LTS with a pull protocol to the ELT and the tracking authority, if one is present, respectively.

Naturally, it is best to collect a lot of data and report the mean and the standard deviation when computing any of the four latency metrics proposed above. That is, latency data should be collected when the LTS generates location estimates at many locations in several buildings so that there is good confidence in computing any of the latency metrics.

8.15 Set-up time

The time it takes to set up an LTS is a critical issue in certain applications. For these applications, the LTS should be easy to set up. For example, when firefighters go to the scene of a fire, they cannot spend half an hour, or even 15 minutes, to set up an LTS before entering a burning building, because lives are in danger. Therefore, the time it takes to set up the LTS until it is operational needs to be measured and reported.

8.16 Optional performance metrics

8.16.1 Location-specific accuracy

One would have more confidence about LTS localization accuracy at a given location by making several measurements and examining the statistics of those measurements as opposed to making just one measurement. There are two problems with this, however. First, making several measurements at each test point would make the testing procedure more expensive. Second, this is not just a matter of making several measurements at each location. It may matter also how the ELT approaches a given test point: from which direction and with what speed and mode of mobility (walking, crawling, etc.). These attributes affect localization accuracy if the LTS has an IMU, for example.

As a compromise, one can compute this type of metric when the goal of the LTS is to locate a stationary object. In that case, the object can be placed at a given test point and several measurements made at that location. One can then compute the RMS values for the magnitudes of horizontal, vertical, and/or 3D errors, as was suggested in the “coverage” subclause. One can even compute metrics such as $CE95$, $VE95$, or $SE95$ with the measurements made at a given test point.

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.

8.16.2 Availability

One can compute the percentage of area/space in which the LTS meets its “minimum performance requirements”, as is done in the “coverage” subclause, or the percentage of time. The latter is the basis for computing availability, where one has to allow the possibility that the ELT may be found at certain locations in the evaluation area/space more often than at the others. In other words, not all locations are created equal! Therefore, in order to compute availability, one needs to have some idea of the probability distribution of the sojourn time of the ELT over the evaluation area/space. It is difficult to determine such a distribution and, hence, this metric has been designed as optional. Note that the value of the metric depends on the probability distribution of the sojourn time.

In practice, all that one needs is the probability, $p_i, i = 1, 2, \ldots, N$, of the ELT being at test point i when the LTS tries to estimate its location. Since it is assumed that the test points cover the evaluation area/space with sufficient density, assume that these probabilities add up to one. (This excludes the possibility that the entity is at any location other than the test points.) If G is the subset of indices of test points at which the LTS meets its minimum performance requirements, then availability is simply given by

$$a = \sum_{i \in G} p_i$$

Once again, one has to specify what’s meant by the LTS meeting its minimum performance requirements at a given test point. Any of the six criteria proposed in the “coverage” subclause can be used for this purpose. (Three of them work with RMS values and the rest do not.) In addition, in computing and reporting availability, 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.

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

9 Optional performance metrics for LTS use in mission critical applications

9.1 Introduction

It is important to pose some “what if” questions when lives are in danger and to have some idea of how LTS performance may be degraded in such scenarios. For example, when firefighters enter a burning building, the LTS equipment they deploy may get destroyed by the fire. The same thing may happen in a coal mine as a result of an explosion and a subsequent roof collapse. There may be even mundane environmental factors that affect LTS performance. This clause deals with such issues.

These are important issues, but they are also application dependent. That is, what can go wrong in a coal mine and tracking coal miners is quite different from what may go wrong in a submarine and how that may affect its navigation system. For these reasons, computing the two performance metrics proposed in this clause is optional. If the user of this T&E standard decides to compute these metrics, he/she should specify what performance metrics he/she is using and more importantly delineate under which mitigating conditions the tests are being carried out.

9.2 Susceptibility

This metric measures the degradation in "system performance" due to events that may happen during normal operations at the site where the LTS is to be used. For example, certain machinery may get turned on during routine operations in a coal mine that could affect the LTS performance. System performance may be characterized by any of the performance metrics proposed in Clause 8.

9.3 Resilience

This metric measures the degradation in "system performance" due to incidents / catastrophic events at the site where the LTS is to be used. The scope / extent of the incident needs to be specified, so that one would have some idea of which components of the LTS may be compromised as a result of the incident. For example, an explosion in a coal mine may destroy half of the anchor nodes used by the LTS. The question is whether the LTS will meet its post-incident performance requirements. One can emulate such a post-incident environment by disabling a fraction of the anchor nodes. However, conducting such an analysis often requires information regarding the internal mechanisms of the LTS. This is not possible in black-box testing. Once again, system performance may be characterized by any of the performance metrics proposed in Clause 8.

10 T&E considerations and scenarios

10.1 Building types

10.1.1 Introduction

Many LTSs use one or more RF components to facilitate localization and/or use a radio to (i) enable the ELT to report its location estimate to a tracking authority when the estimate is computed at the ELT or (ii) let a centralized data processing node or tracking authority communicate the location estimate to the ELT when the estimate is computed at that node or the tracking authority. It is well-known that RF propagation inside buildings and structures is affected by the size of the building/structure, its floor plan and layout, number of floors, construction material used, what's inside the building/structure, and the locations of the transmitting and receiving RF devices. The construction material and the contents of the building/structure may also affect the performance of the magnetometer, if one is used in the LTS. Therefore, it is important to use multiple buildings in the T&E procedure when assessing the performance of an LTS. However, it shall be ensured that none of these buildings would constitute an "explosive environment". Needless to say, it is imperative to ensure that the RF emissions from the LTS under test would not cause any explosions in the building.

This clause proposes five types of buildings for this purpose and presents them in roughly the order of challenge they pose to LTSs. All five building types shall be used in any LTS T&E exercise compliant with this document. Unless noted otherwise, testing shall be done in ALL areas of the five building types specified next.

10.1.2 Wooden structure single-family house

This is the simplest type of test site in terms of the challenges that it poses to many RF-based LTSs. It represents a typical single-family house. If an LTS cannot do well in this type of building, it is unlikely that it would do well in the next four types described in the following subclauses. Testing in this type of building is important, because people spend a significant portion of their lives in their homes.

The test site shall be a two-story building with a floor plan of at least 100 m^2 per floor. If possible, it is recommended that the floor plan should be 200 m^2 or larger. The building should not be narrow, e.g. 8 m x 25 m. It is preferable that the building would have a basement so that RF propagation from below ground level is also included in the test. However, since residential buildings do not have basements in certain regions of the world, it is acceptable to test in a building without a basement as long as this fact is stated in the T&E report. In addition, wooden structures are not used in certain regions of the world. In that case, a building with the commonly used type of construction material should be used.

10.1.3 Medium-size brick & concrete office building

This type of building represents the next level of difficulty for the LTS under test. Many people work in office buildings and spend many hours a day in their offices. A brick and concrete type of construction is heavier than a wooden construction. An office building may also have metal studs.

It is recommended that at least a three-story building covering at least 2 000 m^2 of area per floor be used. The building shall also have at least one level below ground level (basement, parking lot) in addition to the three floors above ground level.

10.1.4 Warehouse/factory

There are also many people who work in factories, industrial plants, and warehouses. Such buildings would have open floor plans and may house heavy machinery or may have aisles of metallic shelves up to the ceiling posing a challenge to RF propagation and communications.

A structure with a single floor above ground level covering at least 5 000 m^2. of area with a ceiling no less than 5 m high shall be used in this category.

10.1.5 High-rise steel structure

Determining on which floor of a high-rise building an ELT is poses a great challenge to many LTSs, unless the building has infrastructure on every floor to facilitate localization. In many LTS applications, getting the floor right is more important than knowing with good accuracy where on that floor the ELT is.

A building with at least ten floors above ground level and one basement level (below ground) with each floor covering at least 1 000 m^2. (preferably 2 000 m^2) of area shall be used in this category. Metal is naturally heavily used in this type of building, and the building would certainly have elevator(s). If at all possible, the LTS should be tested inside elevator(s) at various heights.

In order to keep the burden/cost of the T&E procedure manageable, it is OK to not test at all floors of this type of building. If such a strategy is adopted, some of the highest floors shall be included in the testing procedure because many LTSs have problems with location estimation far off the ground. In addition, some adjacent floors should be used to test whether the LTS can detect changes of height by one floor only. If at all possible, it would be preferable to test in a building that has half-floors also, i.e. floors that are off from regular floors by half the height of a regular floor.

10.1.6 Subterranean structure

Just as high floors of a high-rise building pose a challenge to many LTSs, so do subterranean structures, such as parking structures that have several levels below ground level and underground metro stations. For example, if the LTS uses RF components and has anchor nodes at the ground level, those anchor nodes would have difficulty communicating with an ELTD several levels below ground level. Other examples of subterranean structures include underground mines and some caves and tunnels.

A subterranean structure with an area of at least 2 500 m^2 and at least 6 m (preferably 10 m) below ground level shall be used in this category. If the structure has many levels below ground level, it is desirable to test the LTS at all those levels to determine whether there is a degradation in performance as the ELTD moves / is moved to deeper levels of the structure.

10.2 Effects of mobility

10.2.1 Introduction

The performance of an LTS that estimates the location of an ELT without any regard for its movement history is not affected by the movements of the ELT. For example, when RF ranging is used to estimate the distances from an ELT to several anchor nodes and trilateration is used to estimate the ELT's location, then it does not matter whether the ELT is moving or stationary, as long as the distances to various anchor nodes are estimated at approximately the same time[1]. On the other hand, IMUs are used in many LTSs and they measure the characteristics of the ELT's motion, such as linear acceleration and angular speed, and convert these measurements into an absolute location using dead-reckoning. Video cameras take advantage of an ELT's motion history by examining several video frames to do a better job of estimating the ELT's location.

A motion model is assumed whenever motion history is used to estimate the ELT's location. The most common assumption is that the ELT is either stationary or a human walking in a building. Some LTSs use a pedometer, which counts the number of steps. If the ELT's motion is anything other than those just mentioned, then the LTS may do poorly in estimating the ELT's location. Since this document treats the LTS under test as a black-box and does not assume the tester is aware of what components and methods are used by the LTS, it is important to test the LTS under different mobility conditions.

10.2.2 Stationary object/person

Most objects or assets do not move on their own. Even a person may be stationary over relatively long periods of time. Therefore, it is important to assess the performance of the LTS for stationary ELTs.

10.2.3 Walking

Humans walk at a speed of roughly 5 km/h, which corresponds to approximately 1,4 m/s. Test scenarios involving a walking person should be included in the LTS T&E procedure, but the walking speed does not have to be controlled to be exactly 1,4 m/s.

10.2.4 Running

Running can be problematic for LTSs that are not designed to handle such fast motion. The fastest speed recorded for humans is about 10 m/s corresponding to the world record in 100m dash. However, people typically do not run that fast inside buildings. Therefore, a running speed of about 2,5 m/s, corresponding to 9 Km/h and about 10,7 minutes per mile, is suggested for LTS T&E purposes.

10.2.5 Backward walking

Firefighters may engage in this type of behaviour when pulling a water hose. Naturally, this is going to be slower than normal walking. Including this type of mobility in the T&E procedure is important, because it may affect the performance of any IMU(s) in the LTS. A speed of 0,5 m/s is suggested for backward walking for LTS T&E purposes.

10.2.6 Sidestepping

Firefighters may engage in this type of behaviour when pulling a water hose. Naturally, this is going to be slower than normal walking. Including this type of mobility in the T&E procedure is important, because it may affect the performance of any IMU(s) in the LTS. A speed of 0,75 m/s is suggested for sidestepping for LTS T&E purposes.

10.2.7 Crawling

Firefighters and warfighters may crawl in buildings. This certainly poses challenges to any IMU component. Therefore, it would be a good idea to include a little bit of crawling – albeit it is hard on the testers – in the T&E procedure. A speed of 0,1 m/s is suggested for crawling for LTS T&E purposes.

1) In practice, the distances (ranges) are never estimated at exactly the same time. The estimation times depend on the MAC layer protocol used by the ranging radios and the ranging protocol used. If the difference between the earliest time that a range is estimated and the latest one is small compared to the speed at which the ELT is moving, then "for all practical purposes" the times at which the ranges are estimated are the same and no significant error is introduced in the trilateration process. For example, this would be the case if the ELT is a person walking in a building and the difference between the earliest time a range is estimated and the latest one is only one tenth of a second, during which the ELT cannot move by more than 14 cm.

10.3 Failure modes and vulnerabilities of location sensors

A non-exhaustive list of location sensors was provided in 5.1. These are sensors that could be used to facilitate localization and tracking. There may be others that qualify as “location sensors”, particularly as new sensors are developed in the future. Each of the location sensors included in this document works properly under certain conditions and not so well under other conditions. It is important to (i) identify the circumstances under which a location sensor does not work well or outright fails, and (ii) ensure the LTS T&E scenarios include vignettes where those failures are likely to happen. This is essential in order to ensure the fairness of the T&E process. Particularly, when several LTSs are tested side by side, it is important to know the strengths and weaknesses of each system and the extent by which the weaknesses affect the localization and tracking performance. The only exception to the requirement on including the failure modes of all location sensors in the T&E scenarios is if we know for a fact that one or more particular sensors are not used by any of the LTSs under test. For example, if none of the systems under test use an optical still/video camera, then there is no need to test the systems in areas that are dark or have poor lighting, because none of the systems would be affected by such environmental conditions.

Admittedly, identifying and characterizing the failure modes of location sensors and translating these into action items on designing LTS T&E scenarios is the most challenging aspect of this document. Annex B describes how each location sensor included in this document works and facilitates localization and tracking. It also provides a qualitative discussion of the failure modes of each sensor. These failure modes shall be taken into account by the test administrator that designs LTS T&E scenarios and included as vignettes in the scenarios.

10.4 T&E scenarios

An LTS T&E scenario for a given test building/structure is a specification of how many ELTs are involved, whether they are stationary or moving (different types of mobility needs to be considered), and whether at any given time the ELTs are at the same location in the building or at different locations.

In case of LTSs meant for tracking, one needs to specify the location of the tracking authority. The tracking authority would typically be at a central location in the building in an asset management application. It might be located outside the building in a firefighting scenario. Table 1 specifies the minimum required separation between a tracking authority/station and a face of each building type to be used for LTS T&E in firefighting scenarios. This distance is larger in case of taller buildings for safety reasons. If there is potential for building collapse, it makes sense for the tracking station to be set up farther away from the building in case of tall buildings.

Table 1 — Minimum required separation between various building types and the tracking station in firefighting scenarios

Building number	Building type	Minimum separation (in metres)
1	Wooden structure, single-family house	5
2	Medium-size brick & concrete office building	10
3	Warehouse/factory	10
4	High-rise steel structure	20
5	Subterranean structure	10

Table 2 describes the scenarios under which an LTS could be tested. In other words, not every scenario may be used for testing a given LTS. The scenario descriptions assume the availability of pre-surveyed test points in the buildings used for testing (see 7.5.1). The notion of ELT type has been introduced in the table to provide general guidance on which testing scenario should be used for which type of ELT. The three types of ELT are:

— **Object-** In the context of this document, an object cannot move on its own. It can be at rest (stationary) or in transition, being moved by a person, cart, or forklift truck, to name a few.

— **Person-** A person can be stationary or on the move. It can change its location on its own (walking, running, walking backwards, sidestepping, or even crawling) or it can travel indoors using a golf cart, Segway, wheelchair, or some other vehicle.

— **Robot-** A robot can be stationary or on the move by itself. It is the latter that makes it distinct from an object. This category has been included for completeness, but no T&E scenario is offered for robot navigation or tracking in Table 2.

There are some LTSs that are strictly meant for one type of ELT. For example, a boot-mounted inertial LTS is intended to help people navigate or to make it possible to track people provided that the ELTD is equipped with a radio to report the location information to a tracking authority. It cannot be used for tracking objects, because they do not walk. Therefore, it does not make sense to test such an LTS in scenarios meant for tracking objects. Similarly, it does not make sense to test an LTS meant for tracking objects in a scenario involving crawling, even though in principle an object being tracked could be in the pocket of a person crawling on a floor. It makes more sense to talk about localizing the person in that case. The business case for an LTS meant for asset management does not include tracking an asset that is in the pocket of a crawling person. The test administrator or a user of this document should take the suggestions of the product manufacturer into account in order to decide which scenarios to use for a given LTS. Of course, the T&E report will show which scenarios were used for testing the given LTS.

Table 2 — LTS T&E scenarios

Scenario number	Scenario description	ELT type			Building type				
		Object	Person	Robot	Wooden structure, single-family house	Medium-size brick & concrete office building	Warehouse / factory	High-rise steel structure	Subterranean structure
1	A person carrying an ELTD or wearing one walks along a pre-determined course in a building, stops at certain test points on the course, waits for 3 s, prompts the LTS (through the ELTD) to generate a location estimate, moves on to the next test point, and so on. (No use of elevators or escalators.)	•	•		•	•	•	•	•
2	A person carrying an ELTD or wearing one smoothly walks along a pre-determined course in a building, prompts the LTS (through the ELTD) to generate a location estimate at certain test points on the course, moves on to the next test point, and so on. (No use of elevators or escalators.)	•	•		•	•	•	•	•
3	A person smoothly pushes an ELTD placed on a cart along a pre-determined course in a building, prompts the LTS (through the ELTD) to generate a location estimate at certain test points on the course, moves on to the next test point, and so on. (No use of elevators or escalators.)								

Table 2 *(continued)*

Scenario number	Scenario description	ELT type			Building type				
		Object	Person	Robot	Wooden structure, single-family house	Medium-size brick & con-crete office building	Warehouse / factory	High-rise steel structure	Subterranean structure
4	A person drives a forklift truck carrying an ELTD along a pre-determined course in a building, prompts the LTS (through the ELTD) to generate a location estimate at certain test points on the course, moves on to the next test point, and so on. (No use of elevators or escalators.)	•				•	•	•	
5	A person wearing an ELTD drives a golf cart or a Segway along a pre-determined course in a building, prompts the LTS (through the ELTD) to generate a location estimate at certain test points on the course, moves on to the next test point, and so on. (No use of elevators or escalators.)	•					•		
6	A person pushes a cart with 5 ELTDs placed tightly next to each other on the cart along a pre-determined course in a building, stops at certain test points on the course, waits for 3 s, prompts the LTS (simultaneously through the ELTDs) to generate location estimates for the ELTDs at certain test points on the course, moves on to the next test point, and so on. (No use of elevators or escalators.)		•				•		

Table 2 *(continued)*

Scenario number	Scenario description	ELT type			Building type				
		Object	**Person**	**Robot**	**Wooden structure, single-family house**	**Medium-size brick & concrete office building**	**Warehouse / factory**	**High-rise steel structure**	**Subterranean structure**
7	Two people, each wearing an ELTD, smoothly walk together along a pre-determined course in a building, prompt the LTS (through their ELTDs) to generate location estimates at certain test points on the course, move on to the next test point, and so on. (No use of elevators or escalators.)	•				•	•	•	
8	Two people, each wearing an ELTD, enter a building from different entrances or at different times, walk along pre-determined courses, prompt the LTS (through their ELTDs) to generate location estimates at certain test points on their respective courses, move on to the next test points along their respective courses, and so on. (No use of elevators or escalators.)		•		•	•	•	•	•
9	A person carrying an ELTD or wearing one walks along a pre-determined course in a building, prompts the LTS (through the ELTD) to generate a location estimate at certain test points on the course, moves on to the next test point, and so on. The person uses an elevator to go up and down between building floors, sometimes changing multiple floors.		•			•	•	•	•

Table 2 *(continued)*

Scenario number	Scenario description	ELT type			Building type				
		Object	Person	Robot	Wooden structure, single-family house	Medium-size brick & con-crete office building	Warehouse / factory	High-rise steel structure	Subterranean structure
10	A person carrying an ELTD or wearing one smoothly walks along a pre-determined course in a building, prompts the LTS (through the ELTD) to generate a location estimate at certain test points on the course, moves on to the next test point, and so on. The person leaves the building and re-enters twice, possibly through different entrance doors, before finally leaving the building for a third time at the end of the scenario. (No use of elevators or escalators.)	•	•			•	•	•	•
11	A person wearing an ELTD runs for 50-100 m along a long corridor/pathway in a building and prompts the LTS (through the ELTD) to generate location estimates at certain test points in the corridor/pathway.		•				•	•	

Table 2 *(continued)*

Scenario number	Scenario description	ELT type			Building type				
		Object	Person	Robot	Wooden structure, single-family house	Medium-size brick & concrete office building	Warehouse / factory	High-rise steel structure	Subterranean structure
12	A person wearing an ELTD side-steps for 20-30 m along a corridor/pathway in a building and prompts the LTS (through the ELTD) to generate location estimates at certain test points in the corridor/pathway.		•			•		•	
13	A person wearing an ELTD walks backwards for 20-30 m along a corridor/pathway in a building and prompts the LTS (through the ELTD) to generate location estimates at certain test points in the corridor/pathway.		•			•		•	
14	A person wearing an ELTD crawls on the floor for about 20 m along a straight line in a building and prompts the LTS (through the ELTD) to generate location estimates at certain test points on the line.		•			•		•	

The following guidance shall be followed in deployment of test points and design of LTS T&E scenarios:

1. A test point shall be deployed in every 5-10 m^2 of area in the single-family house described in 10.1.2 and in every 50-100 m^2 of area in each of the other building types used for LTS T&E. For example, a three-story building with an area of 5 000 m^2 per floor shall have 50-100 test points per floor and 150-300 test points in the entire building.
2. The test points shall be deployed randomly in each building, but yet in such a way that the distribution of the test points is not far from a uniform distribution. In other words, the test points shall not be deployed according to a regular pattern or at equal distances from each other. They shall be deployed in the entirety of each building.
3. At least half the test points deployed in each building shall be used in each LTS T&E scenario. Each test points shall be used in at least one scenario. In other words, the entire set of test points shall be used by the time all scenarios have been executed.
4. To the extent possible, the course followed in each building in each scenario shall be designed in such a way that the test subject will go over each test point used the same number of times, and that number shall be specified in the T&E report (see Clause 11). This is to ensure that no area of the building will be given preference over the others.
5. It shall be ensured that at least two test buildings would have significant amount of metal inside. For example, this could be in the form of walls that are entirely made of metal sheets or large rooms that house lots of metal cabinets. The purpose of this requirement is to cause any RF ranging component used in the LTS under test to fail.
6. In T&E scenarios that involve mobility, it shall be ensured that the course used in at least two test buildings shall go by a room or area housing a lot of metallic objects to throw off any magnetometers used in the LTS.
7. In T&E scenarios that involve mobility, it shall be ensured that the course used in at least two test buildings shall have a straight linear segment of length at least 50 m to gauge the drift of any potential IMU used in the LTS.
8. In T&E scenarios that involve mobility, it shall be ensured that, for the most part, the course followed by the test subjects in each building does not start and end at the same point to avoid the cancellation/reduction of the drift in any potential IMU used in the LTS. Nevertheless, it is a good idea to have one scenario in each building where the starting and ending locations are the same to gauge how far the LTS is from closing the loop.
9. If the LTS under test has any optical cameras, it shall be ensured that half the T&E scenarios in each building is executed under poor lighting conditions.
10. If the LTS under test has any imaging components, it shall be ensured that there are cluttered areas in at least two of the buildings used for testing.

11 T&E reporting requirements

11.1 Introduction

A comprehensive LTS T&E procedure is not all that useful unless it is accompanied by an equally comprehensive report that not only describes the tests performed and presents the test results but also documents a number of other facts about the LTS that require no testing but yet without which one would not have a complete picture of the effectiveness, merits, and drawbacks of the LTS under test. This clause specifies in painstaking details what should be recorded in the T&E report. The goal is to have a report that is comprehensive and yet accessible so that it can be easily followed. To that end, recommendations are made on best practices in presenting the T&E results, specifically on what kinds of graphs, tables, and images to include. In addition, a comprehensive T&E report makes it easier to compare various LTSs in a fair manner as opposed to comparing apples with oranges.

One important aspect of an LTS is the types and quantities of equipment that it needs in order to function. Typically, the ELTD has to be carried by any mobile entity (person or robot) that needs to know its location or be tracked by someone else and affixed to any asset (stationary object) that needs to be localized[2]. In addition, the LTS may require deployment of some other equipment inside and/or outside the building. That equipment may be deployed ahead of time and before the LTS is used to locate/track any ELTs. Examples of such equipment include Wi-Fi APs and RFID tags/readers. Alternatively, the equipment may be deployed by the users of an LTS at the same time they use the system for localization/tracking. For example, firefighters arriving at a building on fire may deploy some equipment outside the building before they enter and/or deploy some inside, wherever necessary.

Therefore, it is important to document what LTS equipment, if any, needs to be deployed ahead of time and/or at the time of use. The equipment deployed ahead of time inside the building is typically referred to as localization infrastructure. The installation process for the equipment to be deployed at the time of use ought to be simple and fast. It is for that reason that the "set-up time" metric was introduced in 8.13. Furthermore, it is necessary to have a description of the set-up procedure in the T&E report so that the reader would know how complicated this process is, how many people are needed to carry it out, and how long it would take. In addition to installing equipment, there may be a need to calibrate some of the equipment at the site before use. All this needs to be reflected in the report.

Yet another aspect of an LTS that has to be documented is the extent of information it needs about a building in order to function.

It would be quite difficult for an LTS to provide user-friendly information about the location of an ELT inside a building if no information whatsoever is available about the building, i.e. when neither the floor plans for the building nor the absolute (such as WGS 84) coordinates of its corners are available[3]. Such a situation can arise, for example, when a group of firefighters arrive at a burning building about which little they know. In some cases, they may not know how many floors the building has. Even worse, it may have different numbers of floors on different sides, and it may not be possible to detect this by visually inspecting the building from the outside. A reasonable thing to do under such circumstances is to establish a local coordinate system upon arrival at the site. This will take some time to do; hence it is important to document the required procedure as part of the set-up in the T&E report. If the ELTD is equipped with a GPS/GNSS receiver, it can provide an estimate of the firefighter's location before he enters the building. If the ELTD happens to have an IMU also, then it can use dead-reckoning and the initial location and direction of movement (3D velocity vector) of the firefighter to continue to estimate his location and report it in the WGS 84 coordinate system. This by itself would not be user-friendly, because it is not easy to deduct from this information where in the building the firefighter is. However, given that a local coordinate system is established before firefighters entered the building, the WGS 84 coordinates can be converted into more user-friendly local coordinates. If the ELTD is not equipped with a GPS/GNSS receiver, then the LTS may work by deploying a few RF anchor nodes outside the building whose coordinates have to be measured with respect to the local coordinate system. Once again, this procedure needs to be documented in the T&E report. Note that even if the building has its own RF-based localization capability based on Wi-Fi or some other RF technology, that capability would not be helpful to the LTS because such a system would use a local coordinate system that, based on the operating assumption for this paragraph, the LTS knows nothing about.

If the ELT is an object that is housed inside the building, such as in an asset localization and management application, then there has to be a local coordinate system that is known to the LTS.

A common feature of all the cases discussed above is the presence of a local coordinate system that has to be established during an initialization process at the site or it may already exist and the LTS has full knowledge of it.

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2) One exception is the case of a multi-camera tracking system. Video cameras with overlapping fields of view can be used to not only identify people moving around inside a building, or outdoors for that matter, but also to track their movements. In this case, the people being tracked do not need to carry ELTDs.

3) Knowing the coordinates of the corners of a building, for example in counter-clockwise order staring with one corner, makes it possible to uniquely specify all the faces / outer boundaries of the building, if all the faces of the building are planar. However, the building may have some faces that have curvature, in which case the coordinates of the corners are not adequate for knowing the outer boundaries.

Yet another way of handling a situation where nothing is known about the building is to use a Self-Localization And Mapping (SLAM) technique that not only determines the location of a mobile entity entering a building but also creates a 3D floor plan for the building in real-time.

In certain cases, all that is available to the LTS is the shape of the outer boundary of the building and possibly its location on the earth and orientation[4]. The floor plans of the building may not be available due to a variety of reasons:

i) floor plans were never made;

ii) they are out of date due to renovations in the building since original floor plans were prepared; or

iii) floor plans do exist but are simply not available to the LTS. Knowledge of the outer boundary shape enables the LTS to visualize and display the location of the ELT with respect to the building outer boundary, which is indeed helpful. In order for this to happen, a local coordinate system known to the LTS should exist a priori or one has to be established at the time the LTS is used.

If the absolute (such as WGS 84) coordinates of the outer boundary is known – which implies the knowledge of the boundary shape – and if the ELTD has a GPS/GNSS receiver, then the LTS would be able to visualize and display the ELT's location with respect to the outer boundary without any need for a local coordinate system. Albeit imprecise, Google Earth™[5] can be used to obtain the shape and absolute coordinates of the building outer boundary.

Note that a good LTS design would take advantage of the knowledge of the outer boundary shape, because an ELT known to be inside the building cannot be outside the outer boundaries. The LTS can use this fact to improve its localization accuracy.

If the floor plans of the building are available to the LTS, then the LTS would be able to visualize and display the ELT's location on a detailed floor plan making it possible to know in which subarea of the building, such as a room, the ELT is located. If the ELTD is equipped with a GPS/GNSS receiver and if the goal is to localize/track an ELT entering the building, then the ELT's WGS 84 coordinates and velocity prior to entry may have to be converted to local coordinates implied by the floor plans.

Once again, a good LTS design would significantly benefit from the knowledge of building floor plans, because the ELT that is known to be inside the building cannot be outside its outer boundaries and it cannot cross any internal walls[6] if the ELT is moving around in the building.

Finally, suppose that not only the building floor plans but also the outer boundaries' absolute coordinates are available to the LTS. If the ELTD has a GPS/GNSS receiver, then the LTS can continue to use the WGS 84 coordinate system inside the building and visualize and display the ELT's location on the floor plan. Otherwise, and in the case of an ELT entering the building, its initial location and perhaps 3D velocity vector with respect to the local coordinate system implied by the floor plans may have to be determined.

To summarize, it is important to document how much information about a building an LTS needs in order to function, because it would not be fair to compare an LTS that needs, for example, full building information (floor plans and absolute coordinates) with one that does not need any information about the building. It is also important to document the set-up procedure, because its complexity can vary significantly from one LTS to another.

The rest of this clause specifies exactly what needs to be recorded in an LTS T&E report.

4) One way to specify the location and orientation without any ambiguity is to provide the WGS 84 coordinates of a sufficient number of corners of the building. In most cases, the shape, location, and orientation can be specified by the WGS 84 coordinates of all corners of the building starting with one corner and proceeding counterclockwise. Some other method would have to be used for buildings that have curved outer walls.

5) Google Earth is the trademark of a product supplied by Google™. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO and IEC of the product named.

6) The ELT would be able to cross an internal wall if it has burned down, but this is an exception to the norm.

11.2 Test place and date

The street addresses for all the buildings in which the LTS was tested as well as the date(s) on which the LTS was tested shall be recorded.

11.3 Environmental conditions

The temperature, humidity, barometric pressure, and lighting conditions at the test sites shall be recorded.

11.4 LTS product tested

The name of the company that manufactured the LTS and the specific model for the product tested shall be recorded.

11.5 Equipment used by the LTS

It is important to list all the equipment, other than ELTDs that are handled under the next subclause, the LTS uses or relies on in order to function. The answers to the following questions shall be recorded in the T&E report:

— Does the LTS need the existence and availability of certain infrastructure – i.e. equipment that is embedded in the building or permanently installed outside to facilitate localization/tracking and/or report location estimates to a tracking authority – in order to function? This includes, but is not limited to, Wi-Fi APs, RF anchor nodes, and RFID readers / (active/passive) tags. Describe in detail what is needed and how many units of each needs to be present. Does this equipment need to use wires and cables to get connected to each other or the building networking infrastructure or is it wireless? Is the equipment battery-operated or does it need AC power? If it is battery-operated, how long do the batteries last? For equipment embedded in the building, specify the numbers needed for every 100 m^2 of building area.

— Is there any need for the users to install any equipment outside or inside the building, in addition to the equipment covered by the previous bullet, at the time they wish to use the LTS? (This arises only in situations like firefighters arriving at a building on fire or warfighters tasked to carry out certain mission, such as a mop up operation, in a building.) Describe in detail what needs to be installed, how many of each, and where.

— Does the LTS have the capability to opportunistically use any infrastructure that can facilitate localization and tracking? Describe what the LTS can use opportunistically and what extra information it needs in order to do so.

11.6 ELTD features

The ELTD is particularly important, because there may be many such devices in an LTS. The following features of the ELTD shall be documented:

— size; specifically, dimensions in cm

— weight in grams

— in case of ELTDs carried by human users, the place on the body the ELTD should be worn (on the boots, on the belt, in the hands of the user, etc.)

— battery type needed and how many

— charged battery life in hours, days, or months

— battery charging time

— whether the ELTD is a typical smartphone and whether it can work without a connection to the cloud or a backend server

— the capability to send an alarm to the tracking authority when the remaining battery life drops below certain threshold and becomes critically low[7)]

— Hazardous Location (HazLoc) Certification[8)]; it shall be specified whether or not the ELTD is certified for use in hazardous environments. If so, the Certifying Body (e.g. UL (Underwriters Laboratories) [3], Factory Mutual [4], ATEX (Appareils destinés à être utilisés en ATmosphères Explosives) [5], etc.) and the area classification of the certification shall be identified.

11.7 Location data format

The T&E report shall indicate whether the LTS uses an open source or proprietary format for location data and whether the data is easily displayable in popular mapping software.

11.8 Location update rate and system capacity

An LTS typically updates the location estimate for an ELT in a periodic manner. The faster the update rate in case of an ELT that is in motion, the better the quality of tracking. If the update rate is not sufficiently fast relative to the ELT speed, the motion of the ELT on the ELTD or tracking authority display would look jerky. A faster update rate, however, implies increased computational burden on the LTS, faster depletion of the ELTD battery, and possibly increased use of the RF bandwidth, which otherwise could be used for data communications. Therefore, the location update rate is a key characteristic of an LTS.

In asset management and tracking applications, the ELTD attached to an asset may be equipped with a motion sensor. A higher location update rate is used when the asset is in motion than when it is stationary. The ELTD may even go to sleep when the ELT is stationary to improve its battery life.

Even for generating a single location estimate, many RF-based LTSs make several measurements followed by filtering/averaging. For example, an RF ranging system may repeat the range estimation process several times and report the average of the estimates to improve the ranging accuracy. Likewise, in RSS-based localization, it helps to average several measurements to get rid of the temporal variations of the RSS at a given location.

Another LTS characteristic that is closely related to location update rate is system capacity, namely the number of ELTs the system can handle (locate or track) simultaneously. In fact, there is a coupling between these two characteristics. For example, the LTS may be able to handle 100 ELTs with a location update rate of 10 Hz or 1 000 ELTs with an update rate of 1 Hz. Therefore, it may be meaningless to talk about one of these characteristics without talking about the other.

The T&E report shall document the pairs of values for location update rate and system capacity that the LTS under test can support as well as the actual values used during the T&E process. If the set of pairs of values documented in the report are based on vendor claims as opposed to independent verification and validation during the T&E process, that fact should clearly be stated in the T&E report.

11.9 RF emission and interference issues

It is important to ensure that the LTS under test does not cause Electromagnetic Interference (EMI) to any RF systems that might be in use at the test site. More importantly, it has to be ensured that such RF systems do not cause EMI to the LTS under test, thereby adversely affecting its operation and performance.

7) This is an important feature in tracking assets, firefighters inside burning buildings, and offenders, to name a few.

8) In some applications of localization and tracking, for example in buildings on fire or in coal mines, the ELTD power consumption should not exceed certain levels so that it would not cause explosions.

The manufacturer of the LTS under test shall provide a written declaration of the RF emissions of their product that shall be included in the T&E report. This declaration shall include the following information:

i) the frequency bands in which the LTS emits RF energy;

ii) the Effective Radiated Power (ERP) in each frequency band;

iii) the duty cycle or air time for RF emissions in each band, because while some LTS components may emit RF energy on a regular basis, others – such as the radios used for communications between the ELTDs and the tracking authority – may become active on an irregular and as needed basis only; and

iv) compliance with any appropriate regional regulations on RF emissions (e.g. FCC Part 15 or ETSI regulations) and approval for operation. This declaration shall be made available to the individuals in charge of the RF systems or any scientific experiments that might be carried out in the building and permission for LTS testing obtained from those individuals *prior* to any testing is done.

Similarly, information related to the RF systems in use at the test site, including frequency bands and respective ERPs, shall be documented in the T&E report and made available to the LTS manufacturer *prior* to any testing to ensure the LTS is not affected by the RF systems in the building.

11.10 Set-up procedure

There are two types of set-up. One is for the permanent infrastructure in the building and the other is for the equipment that has to be installed at the time of LTS use, as in the firefighter and warfighter scenarios discussed in 11.5. While 11.5 focuses on the types/quantities of equipment needed by the LTS, this subclause deals with the complexity of installing that equipment and getting the LTS ready for use.

The set-up procedure shall be described in sufficient detail in the T&E report. For example, in the case of permanent infrastructure, is there a need for RSS fingerprinting throughout the building? Is there anything else that needs to be done?

The set-up procedure at the time of LTS use is an even more critical issue, because typically in these scenarios the user cannot afford to wait a long time before he/she can use the LTS. It was mentioned earlier that the user may have to install a few RF anchor nodes outside the building, establish a local coordinate system, and/or determine the WGS 84 coordinates of a few building corners. All these tasks take time. Hence, it is important to document everything that has to be done and how many people are needed to do the required work in the T&E report.

11.11 Building information needed by the LTS

The following questions shall be answered in the T&E report:

— Does the LTS require the establishment of a local coordinate system at the building and providing information about that coordinate system to the LTS before the LTS is used? For example, the local coordinate system may be characterized by stating that its origin is at a certain corner of the building at the ground level, the *x*-axis extends from the origin at the ground level in certain direction along certain face of the building, the *y*-axis extends from the origin at the ground level in certain direction along another building face that is perpendicular to the first face, and the *z*-axis is along a vertical direction with larger z values corresponding to the higher floors of the building.

— If the LTS needs the establishment of a local coordinate system at the building ahead of time, does it need to know the relationship between that coordinate system and an absolute coordinate system, such as WGS 84? This relationship can be specified by, for example, the WGS 84 coordinates of the points with local coordinates, $(0,0,0)$, $(1,0,0)$, $(0,1,0)$ and $(0,0,1)$.

— Does the LTS need to know the shape of the outer boundaries of the building?

— If the LTS needs to know the shape of the outer boundaries, does it also need to know the location and orientation of the building with respect to some absolute coordinate system such as WGS 84?

— Does the LTS need to know the floor plans of the building?

— If the LTS needs to know the floor plans, does it also need to know the location and orientation of the building with respect to some absolute coordinate system such as WGS 84?

— Does the LTS require the knowledge of an RSS fingerprint catalogue collected at the building prior to the LTS being used?

— Any other information about the building required by the LTS shall be documented in the T&E report.

11.12 LTS GUIs

11.12.1 ELTD GUI

The ELTD would not necessarily have a GUI. For example, in a hospital asset management application, the ELTD is simply a tag attached to the equipment being tracked. Such a tag would not have a GUI. On the other hand, in scenarios where firefighters/warfighters enter a building, they would benefit from knowing where in the building they are. In that case, the ELTD may have a GUI.

GUI encourages adoption and usage. If people cannot see a "thing" is on or working, then they often don't believe as readily in the benefits. Device vendors and system owners should carefully assess the cost of GUI with business benefits around usage and adoption, especially when the users of location information are wearing or directly using the ETLD.

A description of the ELTD GUI, if there is one, should be included in the T&E report to document how user-friendly the ELTD is. For example, one useful feature for an ELTD GUI is to provide a measure of confidence in the ELT's horizontal location estimate. This is typically shown with a circle centred at the horizontal location and with a radius that is related to the estimate's confidence. A large circle indicates a poor estimate and low confidence. This description should include the type of information presented by the GUI. It would be useful to include a few screenshots of the GUI to show how that information is presented.

11.12.2 Tracking authority GUI

The tracking authority would most likely have a GUI, particularly if it is tracking several entities. The GUI may display not only the locations of the entities being tracked on floor plans of the building or a 3D display of the building structure, but also some additional information about the ELTs. For example, in the case of an incident command at a fire scene, the GUI may display the physiological health status of the firefighters (breathing rate, heartbeat rate, core body temperature, blood oxygen level, etc.), oxygen tank level, firefighter gait, and whether he/she is moving or has been staying at one location for a significant amount of time.

The issue of what information the GUI should show and in which form gets into the realm of usability, which is beyond the scope of this document. However, it would be useful if the T&E report includes a description of the tracking authority GUI and a few screenshots of the GUI.

11.13 Maintenance

When an LTS is used in a building for an extended period of time, then it may require certain maintenance procedures, in addition to the initial LTS installation and set-up. Maintenance is an issue in, for example, a hospital asset management and tracking application, but not in the scenario where firefighters/warfighters arrive at a building for a certain one-time mission. In the latter case, there may not be a need for maintenance during the mission, but it still has to be ensured that all the LTS equipment is in working condition prior to arriving at the scene.

The T&E report should include a description of all the procedures that need to be followed to keep the LTS in working condition and how often each procedure needs to be performed. This, in a sense, is an indirect cost of using the LTS that needs to be taken into account.

11.14 Floor plans of test buildings

The floor plans of all the buildings used for testing shall be included in the T&E report. For each building, floor plans shall be given for all floors used for testing. Figure 1 shows the floor plan of a single-story building that has been used for LTS testing.

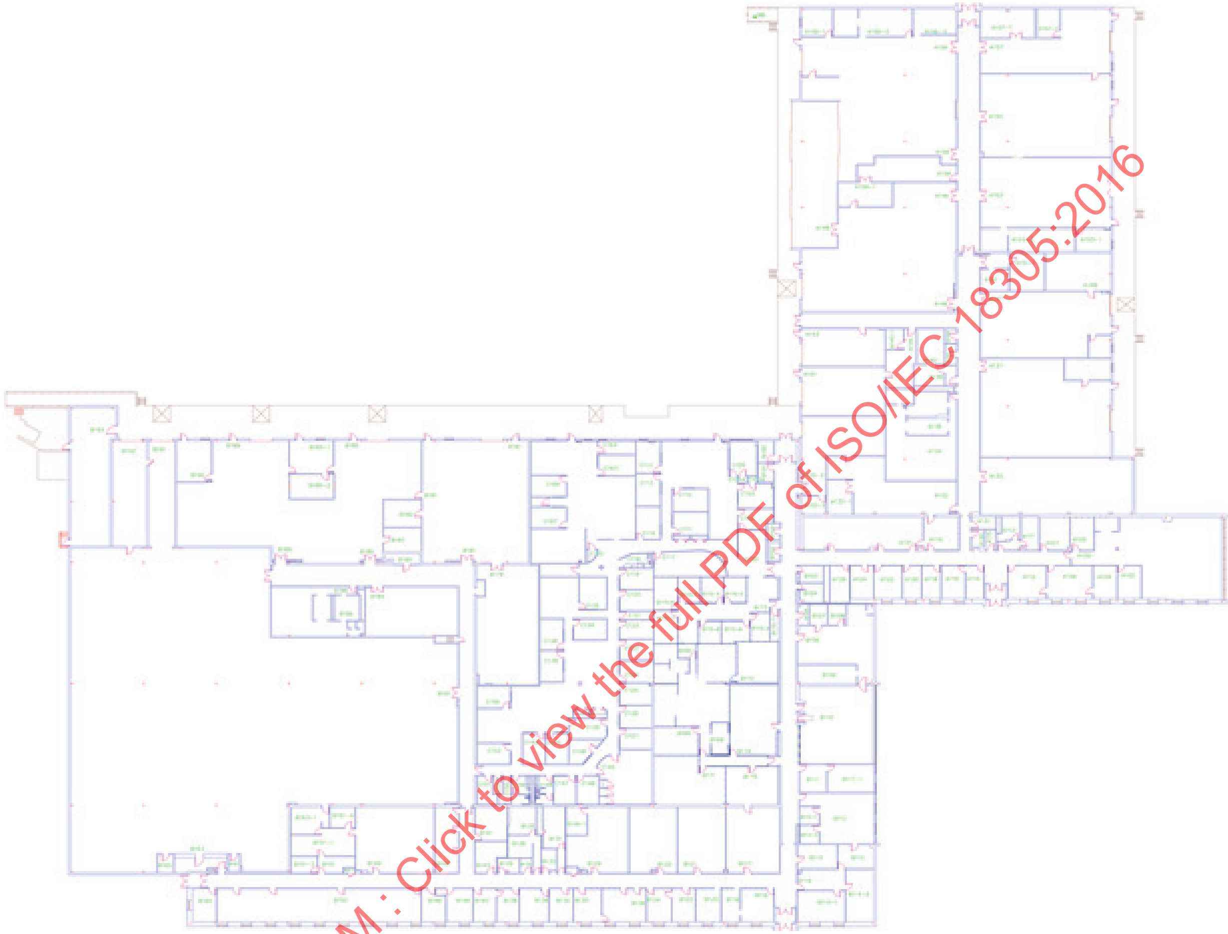

Figure 1 — Floor plan of a building used for LTS testing

11.15 Characterization of T&E scenarios involving entities in motion

The locations of the test points in the buildings used for testing shall not be disclosed, because it is desirable to be able to use the same test points in future LTS T&E events and naturally it is best that the manufacturers of any LTSs to be tested not know the ground truth locations of the test points. Establishing new test points for each T&E event is expensive, because the surveying process needed to determine the locations of the test points with sufficient precision is quite laborious and expensive.

In the case of T&E scenarios where one or more human test subjects equipped with ELTDs move around in a test building, the course they follow in the building shall be documented in the T&E report. This includes scenarios in which one or more test subjects walk together in a building and follow a particular course as well as scenarios in which several test subjects enter a building, possibly from different entrances and at different times, and each test subject follows certain course specified for that test subject. In the latter case, not only the courses shall be specified, but also the time each test subject enters the building relative to the time the first test subject entered the building shall be specified. Any move involving a test subject going from one floor of a building to another shall also be specified. Finally, test scenarios involving running, walking backwards, sidestepping and crawling shall also be unambiguously characterized. Figure 2 shows the course, denoted by the solid black line, which two tests subject followed in the building whose floor plan was given in Figure 1. (To see all the details presented in Figure 2, it is highly recommended that the reader of this document view this figure on a computer monitor using 400% magnification.) Each test subject entered the building using a door at the inner corner of the L-shaped building, walked towards the bottom of the figure, followed a complicated course covering all areas of the building and the diversity they presented in terms of floor plan layout and very different objects they housed, and left the building through another door close to the starting point. Note that the test subjects left the building sometime in the middle of the course through a door at the lower left part of the building, walked for about 20-30 m outside, making it possible for a GPS fix, and then walked back into the building through the same door. (Other coloured lines in the figure shall be described later in this document.)

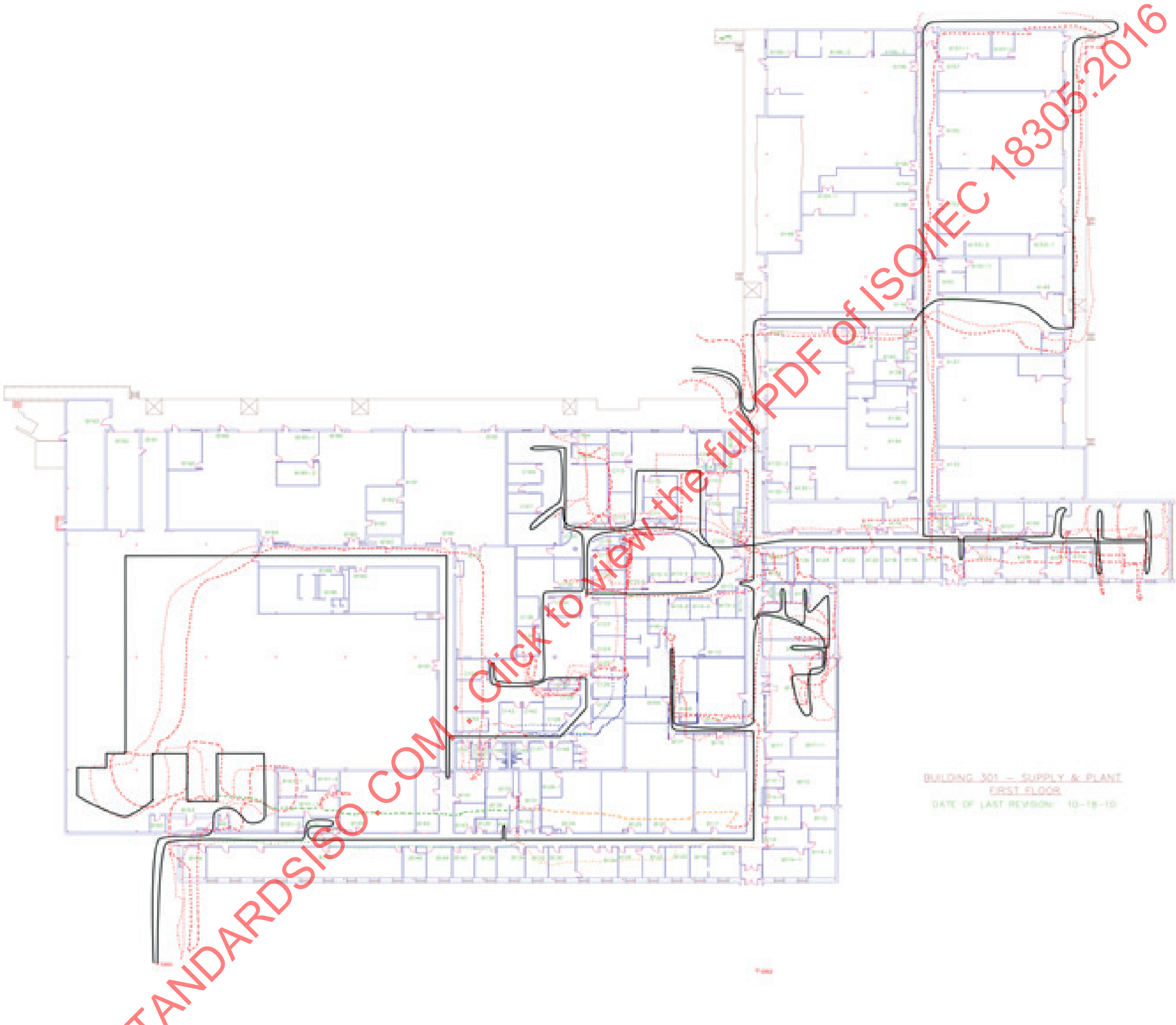

Figure 2 — The course travelled by two test subjects and the LTS estimates of the course for the test subjects

11.16 Presentation of numerical T&E results

Even though there is a large volume of T&E results that needs to be presented in the T&E report, every effort is made to make it as easy as possible for the reader of the T&E report to get a good grasp of the results by proposing a number of tables with appropriate formats.

Since it would be too unwieldy to present all the T&E results for even one building in a single table, the T&E results shall be presented in four types of tables each with one row for each T&E scenario. Tables 3-6 show the column headings for each table and a blank row as a space holder for presenting the numerical values for various performance metrics for the given scenario. Note that each row in Tables

4-6 is really a compound row consisting of two rows. Except for the two probabilities in Table 4, the units for the entries in these tables shall be metres, m^2, or seconds.

Table 3 — Template for recording the LTS performance metrics, for a given test building, that are not affected by whether the overall bias is removed or not

Scenario number	μ_{Δ}	μ_{τ_E}	σ_{τ_E}	$\mu_{\tau_{TA}}$	$\sigma_{\tau_{TA}}$	μ_{δ_E}	σ_{δ_E}	$\mu_{\delta_{TA}}$	$\sigma_{\delta_{TA}}$
1	NA								
2	NA								
3	NA								
4	NA								
5	NA								
6									
7									
8									
9	NA								
10	NA								
11	NA								
12	NA								
13	NA								
14	NA								
Average over all scenarios									

A number of points/clarifications need to be made regarding Tables 3-6:

— In practice, Table 3 may not include all the columns shown in the template, because not all LTSs support both the pull and push protocols for disseminating location information (see 8.14). If the LTS employs the pull (push) protocol only, the latency metrics related to the pull (push) protocol only shall be presented in the Table. If the LTS supports both protocols, the latency metrics for both protocols shall be presented, just as shown in Table 3. In addition, it matters who the ultimate consumer of the location information is (see the three cases in 5.4). If there is no tracking authority, there is no need to include latency metrics as experienced by the tracking authority. On the other hand, if the sole user of location information is the tracking authority, the latency metrics as experienced by the tracking authority only shall be included.

— Tables 4-6 shall be prepared depending on who the ultimate consumer of location information is. If the ELT (tracking authority) is the sole consumer, the accuracy metrics shown in these tables shall be computed based on location estimates presented to the ELT (tracking authority). If the LTS delivers location estimates to both the ELT and the tracking authority, each of Tables 4-6 shall be included twice, once for the ELT and once for the tracking authority.

— Note that relative accuracy can be computed only when there are multiple ELTs in a building simultaneously, in which case every possible pair of ELTs should be considered in the computation. This means that relative accuracy can be computed in Scenarios 6, 7, and 8 only (see 10.4). The computation is straightforward in Scenario 2, because the ELTs are placed at one test point and the location estimated by all the ELTs, and then this process is repeated at the next test point, and so on. The pairwise distance between any pair of ELTs should be roughly zero in this case, depending on how close to each other the ELTs can be placed. The computation is a bit tricky in Scenarios 7 and 8, because the two ELTs involved are in motion and hence it is challenging to determine the ground truth range between them. The uncertainty in the ground truth range can be reduced if the range estimation process is initiated when at least one of the two ELTs is located at a test point with known ground truth location.

The second ELT would most likely not be at a test point at that instant in time. So, what is known at this stage is the range estimate, the time at which this estimate was obtained, and the ground truth location of the ELT that initiated pairwise ranging. What is not known is the ground truth location of the second ELT and hence the ground truth range between the two ELTs. The ground truth location of the second ELT can be obtained through linear interpolation by knowing the time instants at which that ELT was on top of the last test point it visited before the ranging operation and the first test point it visited afterwards, and the path the second ELT took between those two test points. The drawback of the procedure just described for determining the ground truth range is the assumption that the second ELT moves at a constant speed between the two test points, which may not be realistic. Note that the clocks at the ELTs are assumed to be synchronized. The range estimation process is straightforward if the ELTs have peer-to-peer ranging capabilities. Otherwise, the initiating ELT has to send a request to the LTS to estimate the location of the second LTS and hence the range between the two ELTs.

Table 4 — Template for recording the first group of LTS performance metrics, for a given test building, that are affected by whether the overall bias is removed or not

Scenario number	Before/after removing overall bias	$\mu_{\underline{\varepsilon}}$	$K_{\underline{\varepsilon}}$	$\mathrm{tr}(K_{\underline{\varepsilon}})$	P_F	$P_{Z\|F}$	$\mu_{\\|\underline{\varepsilon}_h\\|}$	$\mu_{\|\varepsilon_z\|}$	$\mu_{\\|\underline{\varepsilon}\\|}$
1	Before								
	After								
2	Before								
	After								
3	Before								
	After								
4	Before								
	After								
5	Before								
	After								
6	Before								
	After								
7	Before								
	After								
8	Before								
	After								
9	Before								
	After								
10	Before								
	After								
11	Before								
	After								
12	Before								
	After								
13	Before								
	After								
14	Before								
	After								
Average over all scenarios	Before								
	After								

Table 5 — Template for recording the second group of LTS performance metrics, for a given test building, that are affected by whether the overall bias is removed or not

Scenario number	Before/after removing overall bias	CE95	CEP	VE95	VEP	SE95	SEP	$\sigma_{\lVert\underline{\varepsilon}_h\rVert}$	$\sigma_{\lvert\varepsilon_z\rvert}$	$\sigma_{\lVert\underline{\varepsilon}\rVert}$
1	Before									
	After									
2	Before									
	After									
3	Before									
	After									
4	Before									
	After									
5	Before									
	After									
6	Before									
	After									
7	Before									
	After									
8	Before									
	After									
9	Before									
	After									
10	Before									
	After									
11	Before									
	After									
12	Before									
	After									
13	Before									
	After									
14	Before									
	After									
Average over all scenarios	Before									
	After									

Table 6 — Template for recording the third group of LTS performance metrics, for a given test building, that are affected by whether the overall bias is removed or not

Scenario number	Before/after removing overall bias	$\varepsilon_{x,\mathrm{rms}}$	$\varepsilon_{y,\mathrm{rms}}$	$\varepsilon_{z,\mathrm{rms}}$	$\varepsilon_{h,\mathrm{rms}}$	$\varepsilon_{\mathrm{rms}}$	$\mu_{\lvert\underline{\varepsilon}\rvert}$
1	Before						
	After						
2	Before						
	After						
3	Before						
	After						

Table 6 *(continued)*

Scenario number	Before/after removing overall bias	$\varepsilon_{x,\text{rms}}$	$\varepsilon_{y,\text{rms}}$	$\varepsilon_{z,\text{rms}}$	$\varepsilon_{h,\text{rms}}$	ε_{rms}	$\mu_{\lvert\underline{\varepsilon}\rvert}$
4	Before						
	After						
5	Before						
	After						
6	Before						
	After						
7	Before						
	After						
8	Before						
	After						
9	Before						
	After						
10	Before						
	After						
11	Before						
	After						
12	Before						
	After						
13	Before						
	After						
14	Before						
	After						
Average over all scenarios	Before						
	After						

Aside from having one row for each T&E scenario, Tables 3-6 shall have one special row at the bottom that shall present the respective performance metrics averaged over all T&E scenarios. In case of Tables 4-6, these average values are presented before/after the overall bias computed over all T&E scenarios has been removed.

In addition, there shall be four more tables similar to Tables 3-6, but only with one row each, that have not been shown. These tables shall present all the performance metrics shown in Tables 3-6 when they are computed as averages over not only all T&E scenarios, but also over all test buildings used.

Table 7 is the template for set-up times that shall be included in the T&E report. Set-up time shall be reported in seconds.

Table 7 — Set-up times in various test buildings

Building 1	Building 2	Building 3	Building 4	Building 5	Average

Note that certain performance metrics proposed in 8 have not been included in the tables proposed in this clause. There are various reasons for such omissions. Coverage was not included, because it depends on what is meant by "minimum performance requirements". The same is true for availability. However, availability has been designated as an optional performance metric in this document anyway. If it is known in which application the LTS under test shall be used and there is a precise definition for "minimum performance requirements", then it is straightforward to measure coverage for each building using T&E Scenario 1 only. It is also possible to compute an average of the coverage figures to arrive at an overall coverage number for an LTS.

Location-specific accuracy, being an optional performance metric, was not discussed either. The performance metrics of Clause 9, being application-dependent, were not discussed at all. However, this should not preclude testing organizations from devising and performing appropriate tests and reporting the results on performance metrics that were not included in Tables 3-6.

11.17 Visualization of T&E results

It is often said that a picture is worth a thousand words. Therefore, it is important to find creative and informative ways of presenting the T&E results using appropriate plots and figures in addition to the tables proposed in 11.16. This will make it easier to understand the T&E results. The figures and plots presented below shall be included in the LTS T&E report for each T&E scenario and each test building.

Figure 3 is a display of horizontal error vectors resulted from testing an LTS at about 100 test points in a building. The colour chart at the left is used to show the progression of time from the beginning of the T&E scenario to the end. In this scenario, a human subject entered the building, mostly walked in the building, and exited the building from where he entered and ended up at the starting point of the test. Since the course taken in the building is known, if a bunch of error vectors with the same colour are close to the circle representing CE95, which in this case happened to be 6,573 m, then one concludes the LTS did relatively poorly in a particular area of the building corresponding to a certain time window during the test. The figure also shows the mean and standard deviation of the magnitude of the horizontal error.

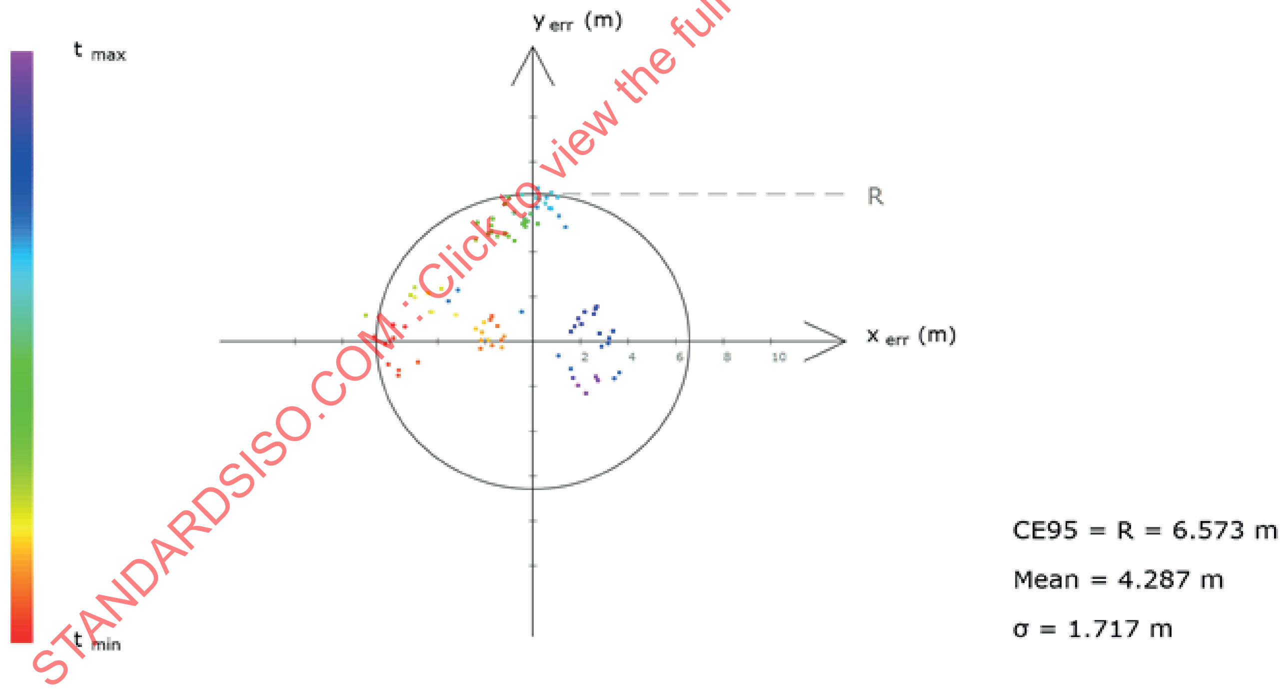

Figure 3 — Spatial distribution of horizontal error with colour-coding to show evolution with test time

Figure 4 presents roughly the same information as Figure 3. It shows the magnitude of the horizontal error as a function of test time in addition to CE95 and the mean and standard deviation of the magnitude of the horizontal error.

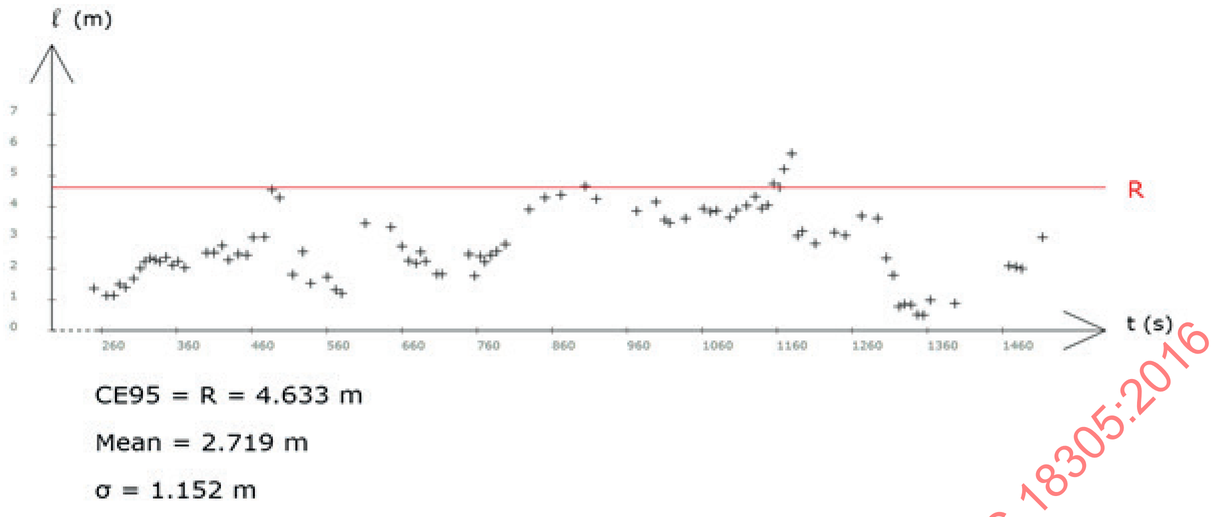

Figure 4 — Horizontal error as a function of test time

Figure 5 depicts the evolution of vertical error as a function of test time. It also shows VE95 and the mean and standard deviation of the absolute value of the vertical error.

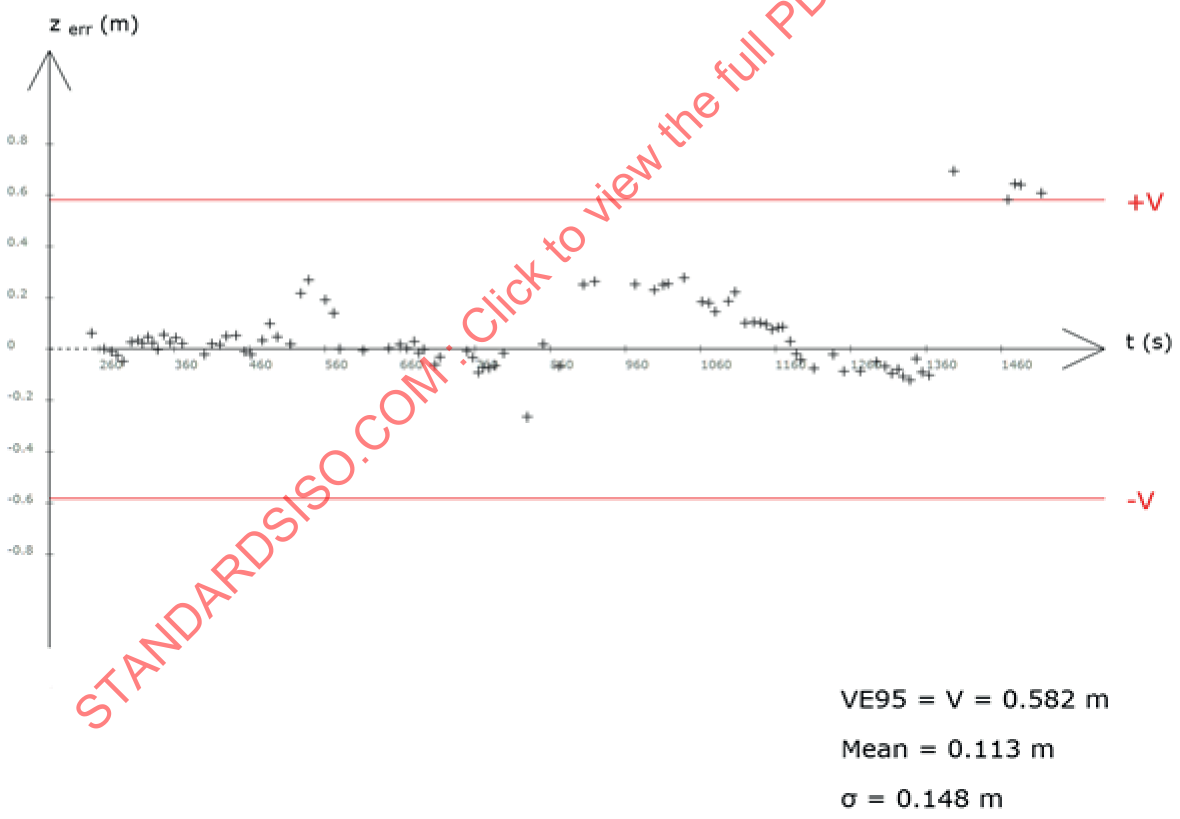

Figure 5 — Vertical error as a function of test time

As mentioned earlier, the solid black line in Figure 2 shows the course followed by two test subjects that walked together in the building. The dashed and dotted red lines depict the LTS estimates of the test subjects' trajectories depicted. This is yet another way of showing in which areas of the building the LTS did poorly. Note that the colours of the dashed and dotted lines turn to orange, green, and blue. These colours correspond to areas in the buildings that the test subjects walked backwards, sidestepped, and crawled on the floor, respectively.

Figure 6 depicts location-specific accuracy at various test points inside a building. Specifically, the radius of the circle at each test point is proportional to the CE95 of several measurements made at that test point. Alternatively, one can let the radius of the circle be proportional to the RMS value of the magnitude of the horizontal error for several measurements.

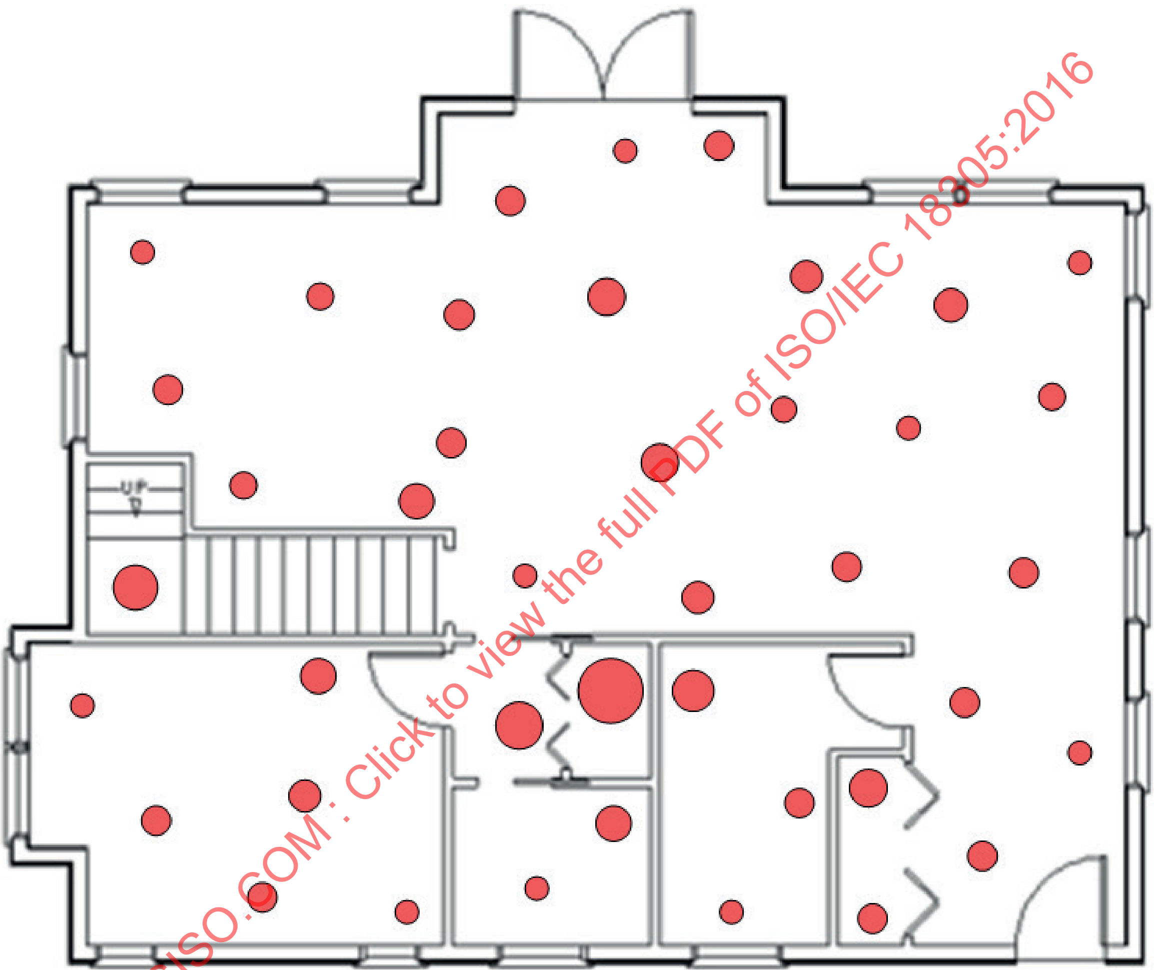

Figure 6 — Location-specific accuracy depicted by circles of various sizes

Figure 7 shows the locations of test points used inside a building with either a white or black circle at each test point. A white (black) circle implies that the aggregate test results at that test point meets (does not meet) the minimum performance requirements. For example, the CE95 or the RMS value of the magnitude of the horizontal error at a test point may be below (above) a user-specified threshold depending on the circle colour.

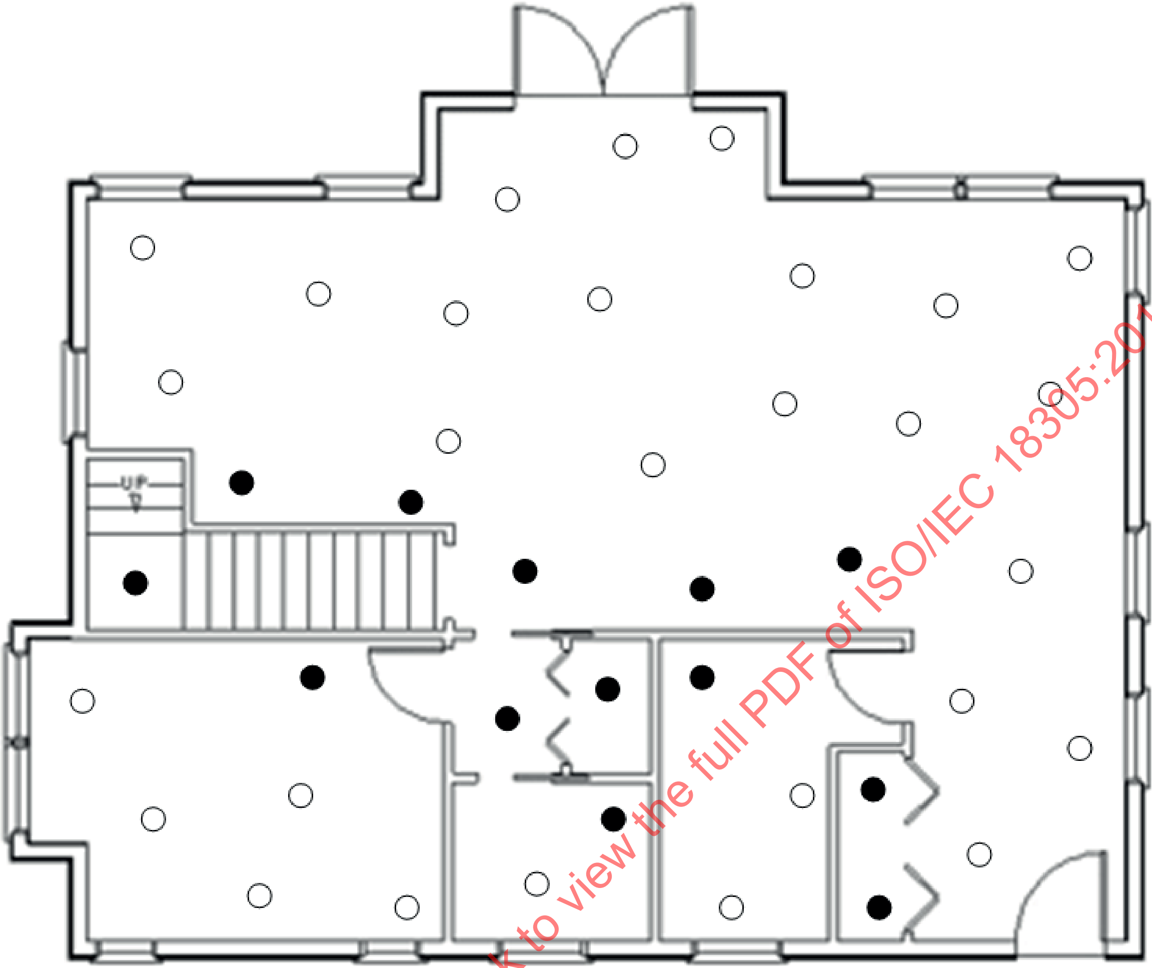

Figure 7 — White (black) circles depict test points at which location-specific minimum performance requirements were (not) met.

Figures similar to Figures 6 and 7 can be generated using VE95 or the RMS of the absolute value of the vertical error for several measurements made at each test point inside a building.

Annex A
(normative)

Conversions between local Cartesian and WGS 84 coordinates

A.1 Introduction

This annex describes two procedures for coordinate conversion and provides MATLAB code for each:

— the procedure to convert the local 3D Cartesian coordinates of a point inside or outside a building to WGS 84 coordinates

— the procedure to convert the WGS 84 coordinates of a point outside a building or on its roof to the local 3D Cartesian coordinates established at the building[9)]

Before these procedures can be described, we need to go over some preliminary steps.

A.2 Establishing a local 3D Cartesian coordinate system and other preliminaries

Assume the building has at least one planar exterior wall. The vast majority of buildings satisfy this requirement. There are, however, exceptions, such as circular or elliptical buildings.

If the building has more than one planar exterior walls, pick the longest one, and let the *x*-axis of the local 3D Cartesian coordinate system be parallel to that wall. The *x*-axis itself could be either at the ground level or on the roof of the building.

Specifically, pick two points outside the building or on its roof such that

— they both have LOS views of several GNSS satellites,

— they are as far away from each other as possible, and

— they are along the longest planar exterior wall such that the line connecting them is parallel to the wall[10)], but not necessarily horizontal. Point 2 will have a larger *x*-coordinate than Point 1.

Use precision laser surveying equipment to establish the *y*-axis in such a way that the *xy*-plane becomes horizontal, with the *y*-axis at 90 degrees counterclockwise from the *x*-axis when viewed from above. Points 1 and 2 will have the same *y*-coordinates, but that coordinate will not necessarily be zero.

The *z*-axis would be perpendicular to the *xy*-plane at the origin and hence in the vertical direction. Using the right hand rule, let the higher *z* values correspond to higher elevations.

Precisely measure the coordinates $\left(x_i y_i z_i\right), i = 1,2$, of the two points using laser surveying equipment.

Precisely measure the WGS 84 coordinates $(\text{lat}_i, \text{long}_i, \text{alt}_i), i = 1,2$, of the two points using differential GNSS equipment, such D-GPS.

9) We assume the point is at a location with LOS views of a sufficient number of GNSS satellites so that its WGS 84 coordinates can be measured. Such a point cannot be inside the building, because the GNSS signal would be either unavailable or weak.

10) Strictly speaking, this does not have to be the case. One can devise procedures for coordinate conversions similar to those presented in this annex for any arbitrary pair of points that are far away from each other. However, for the sake of simplicity, we opted for presenting conversion algorithms that assume the line connecting the two points is parallel to the wall.

Convert the latitude and longitude coordinates of the two points to the Universal Transverse Mercator (UTM) coordinates. This is basically a 2D (easting, northing) coordinate system. Let $(e_i, n_i), i = 1, 2$, denote these UTM coordinates. Figure A.1 shows a MATLAB code that can do that type of conversion.

```
function  [x,y,utmzone] = deg2utm(Lat,Lon)
% ------------------------------------------------------------------------
% [x,y,utmzone] = deg2utm(Lat,Lon)
%
% Description: Function to convert lat/lon vectors into UTM coordinates (WGS 84).
% Some code has been extracted from UTM.m function by Gabriel Ruiz Martinez.
%
% Inputs:
%    Lat: Latitude vector.   Degrees.  +ddd.ddddd  WGS84
%    Lon: Longitude vector.  Degrees.  +ddd.ddddd  WGS84
%
% Outputs:
%    x, y , utmzone.   See example
%
% Example 1:
%    Lat=[40.3154333; 46.283900; 37.577833; 28.645650; 38.855550; 25.061783];
%    Lon=[-3.4857166; 7.8012333; -119.95525; -17.759533; -94.7990166; 121.640266];
%    [x,y,utmzone] = deg2utm(Lat,Lon);
%    fprintf('%7.0f ',x)
%      458731  407653  239027  230253  343898  362850
%    fprintf('%7.0f ',y)
%     4462881 5126290 4163083 3171843 4302285 2772478
%    utmzone =
%      30 T
%      32 T
%      11 S
%      28 R
%      15 S
%      51 R
%
% Example 2: If you have Lat/Lon coordinates in Degrees, Minutes and Seconds
```

```
%   LatDMS=[40 18 55.56; 46 17 2.04];
%   LonDMS=[-3 29  8.58;  7 48 4.44];
%   Lat=dms2deg(mat2dms(LatDMS)); %convert into degrees
%   Lon=dms2deg(mat2dms(LonDMS)); %convert into degrees
%   [x,y,utmzone] = deg2utm(Lat,Lon)
%
% Author:
%   Rafael Palacios
%   Universidad Pontificia Comillas
%   Madrid, Spain
% Version: Apr/06, Jun/06, Aug/06, Aug/06
% Aug/06: fixed a problem (found by Rodolphe Dewarrat) related to southern
%   hemisphere coordinates.
% Aug/06: corrected m-Lint warnings
%-------------------------------------------------------------------------

% Argument checking
%
error(nargchk(2, 2, nargin));  %2 arguments required
n1=length(Lat);
n2=length(Lon);
if (n1~=n2)
error('Lat and Lon vectors should have the same length');
end


% Memory pre-allocation
%
x=zeros(n1,1);
y=zeros(n1,1);
utmzone(n1,:)='60 X';

% Main Loop
```

```
%
for i=1:n1
la=Lat(i);
lo=Lon(i);

sa = 6378137.000000 ; sb = 6356752.314245;

%e = ( ( ( sa ^ 2 ) - ( sb ^ 2 ) ) ^ 0.5 ) / sa;
e2 = ( ( ( sa ^ 2 ) - ( sb ^ 2 ) ) ^ 0.5 ) / sb;
e2cuadrada = e2 ^ 2;
c = ( sa ^ 2 ) / sb;
%alpha = ( sa - sb ) / sa;           %f
%ablandamiento = 1 / alpha;   % 1/f

lat = la * ( pi / 180 );
lon = lo * ( pi / 180 );

Huso = fix( ( lo / 6 ) + 31);
S = ( ( Huso * 6 ) - 183 );
deltaS = lon - ( S * ( pi / 180 ) );

if (la<-72), Letra='C';
elseif (la<-64), Letra='D';
elseif (la<-56), Letra='E';
elseif (la<-48), Letra='F';
elseif (la<-40), Letra='G';
elseif (la<-32), Letra='H';
elseif (la<-24), Letra='J';
elseif (la<-16), Letra='K';
elseif (la<-8), Letra='L';
elseif (la<0), Letra='M';
elseif (la<8), Letra='N';
elseif (la<16), Letra='P';
```

```
elseif (la<24), Letra='Q';
elseif (la<32), Letra='R';
elseif (la<40), Letra='S';
elseif (la<48), Letra='T';
elseif (la<56), Letra='U';
elseif (la<64), Letra='V';
elseif (la<72), Letra='W';
else Letra='X';
end

a = cos(lat) * sin(deltaS);
epsilon = 0.5 * log( ( 1 +  a) / ( 1 - a ) );
nu = atan( tan(lat) / cos(deltaS) ) - lat;
v = ( c / ( ( 1 + ( e2cuadrada * ( cos(lat) ) ^ 2 ) ) ) ^ 0.5 ) * 0.9996;
ta = ( e2cuadrada / 2 ) * epsilon ^ 2 * ( cos(lat) ) ^ 2;
a1 = sin( 2 * lat );
a2 = a1 * ( cos(lat) ) ^ 2;
j2 = lat + ( a1 / 2 );
j4 = ( ( 3 * j2 ) + a2 ) / 4;
j6 = ( ( 5 * j4 ) + ( a2 * ( cos(lat) ) ^ 2) ) / 3;
alfa = ( 3 / 4 ) * e2cuadrada;
beta = ( 5 / 3 ) * alfa ^ 2;
gama = ( 35 / 27 ) * alfa ^ 3;
Bm = 0.9996 * c * ( lat - alfa * j2 + beta * j4 - gama * j6 );
xx = epsilon * v * ( 1 + ( ta / 3 ) ) + 500000;
yy = nu * v * ( 1 + ta ) + Bm;

if (yy<0)
yy=9999999+yy;
end

x(i)=xx;
y(i)=yy;
```

```
utmzone(i,:)=sprintf('%02d %c',Huso,Letra);

end
```

Figure A.1 — MATLAB code for converting WGS 84 (lat, long) coordinates to UTM coordinates

Define a new set of UTM coordinates for Point 2 by moving the origin of the UTM coordinate system to Point 1 using the following equations:

$$\hat{e}_2 = e_2 - e_1$$

$$\hat{n}_2 = n_2 - n_1$$

The rotation angle of the $\hat{x}$ -axis with respect to the $\hat{e}$-axis can be computed by

$$\theta = \begin{cases} \arctan(\hat{n}_2 / \hat{e}_2) & ; \text{ if } (\hat{e}_2, \hat{n}_2) \text{ belongs to the 1st quadrant} \\ \pi + \arctan(\hat{n}_2 / \hat{e}_2) & ; \text{ if } (\hat{e}_2, \hat{n}_2) \text{ belongs to the 2nd or 3rd quadrants} \\ 2\pi + \arctan(\hat{n}_2 / \hat{e}_2) & ; \text{ if } (\hat{e}_2, \hat{n}_2) \text{ belongs to the 4th quadrant} \end{cases}$$

Note that, $0 \le \theta < 2\pi$ and θ is measured counterclockwise.

The following equation establishes the relationship between the $(\hat{x}, \hat{y})$ coordinates of any point (not necessarily Points 1-2 introduced earlier) and its $(\hat{e}, \hat{n})$ coordinates:

$$\begin{pmatrix} \hat{e} \\ \hat{n} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} = \begin{pmatrix} \hat{x} \\ \hat{y} \end{pmatrix}$$

Figure A.2 shows the relationship between these two coordinate systems and others pictorially. Also shown are Points 1 and 2 with black solid circles, with Point 1 on the left side and Point 2 on the right.

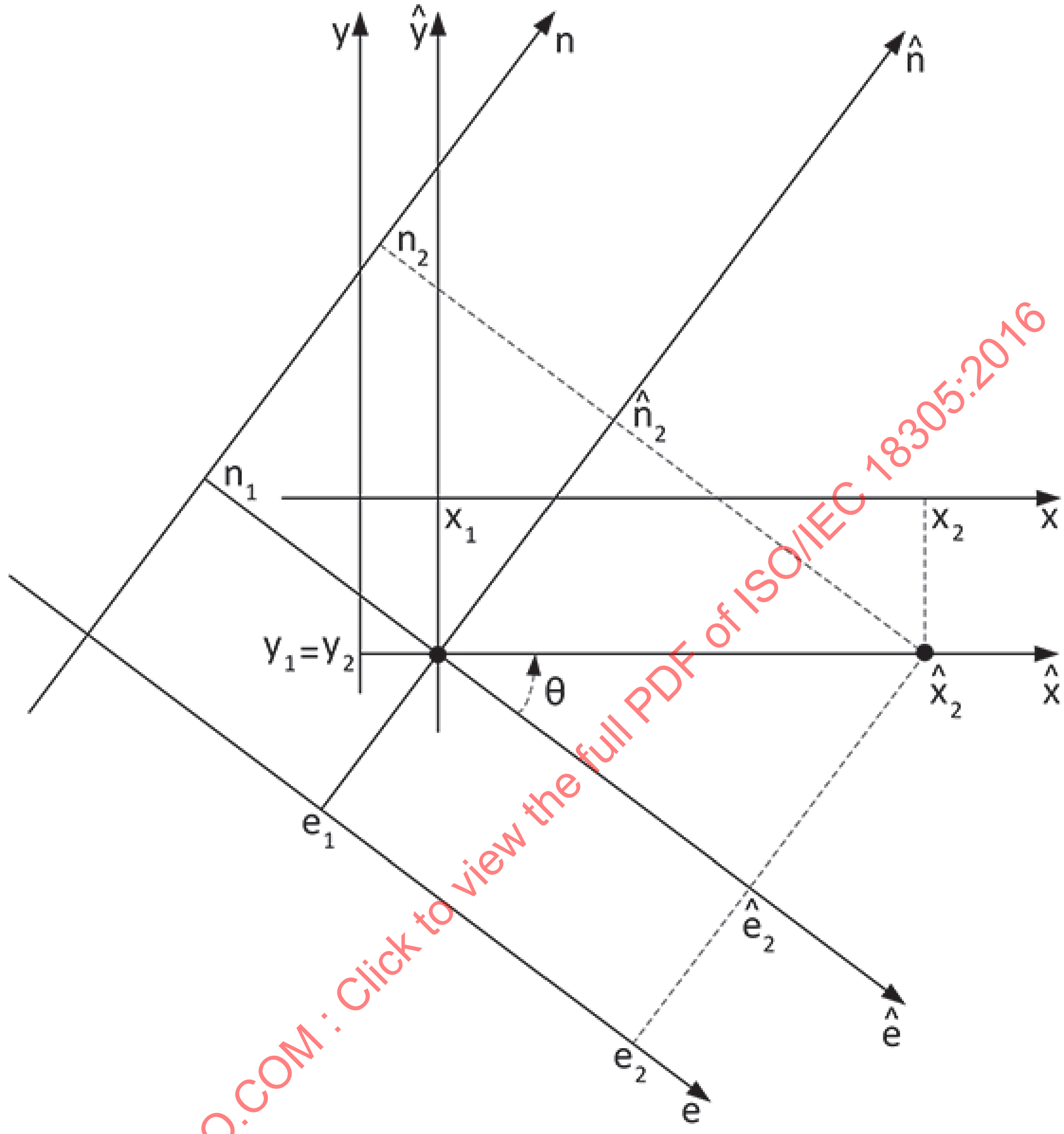

Figure A.2 — Relationship between various coordinate systems

A.3 Conversion from WGS 84 coordinates to local 3D Cartesian coordinates

Given the WGS 84 coordinates of a point outside the building or on its roof, a procedure is given in this clause to convert those coordinates to the local 3D Cartesian coordinates. Most of the work is in converting the $(\text{lat}, \text{long})$ coordinates to (x, y). The conversion of altitude to z is simply a shift using the altitude of the *xy*-plane, which corresponds to $z = 0$.

The first step in the process is to convert the $(\text{lat}, \text{long})$ coordinates of the point to the $\left(e, n\right)$ UTM coordinates using the code given in Figure A.1.

Translate these coordinates to the $(\hat{e}, \hat{n})$ space using

$$\hat{e} = e - e_1$$

$\hat{n} = n - n_1$

Convert these to $(\hat{x}, \hat{y})$ using the matrix equation given at the end of A.2.

Finally, convert $(\hat{x}, \hat{y})$ to (x, y) by a simple translation:

$x = \hat{x} + x_1$

$y = \hat{y} + y_1$

The MATLAB code given in Figure A.3 converts the WGS 84 coordinates of a set of points stored in an Excel spreadsheet to local 3D Cartesian coordinates and writes the results to another Excel spreadsheet. Note that the code calls the algorithm presented in Figure A.1.

```
%% This script is used to convert points from WGS 84

% (lat,Long,Alt) coordinates to Cartesian coordinates (x,y,z)

% Needed inputs:

% 1) An excel file of WGS 84 points in (lat,Long,Alt). For example: points_WGS84.xls

% 2) x,y,z coordinates for a reference WSG84 point

% 3) Row index of the reference point: For example: point 1.


% Script output: A Excel file consisting of x,y,z coordinates for the WGS 84 points.

% For example: points_xyz.xls


% Note: x,y,z shall be in meters

%%


% First, we need to convert points from WGS 84 to UTM

clear all;

format long;

AA = xlsread('points_WGS84.xls');


[BB(:,1),BB(:,2),z] = deg2utm(AA(:,1),AA(:,2));


CC = xlsread('known_waypoints.xls');


[DD(:,1),DD(:,2),z] = deg2utm(CC(:,4),CC(:,5));
```



```
% Save the UTM coordinates (Easting and Northing) into the same
% file points_WGS84.xls in columns 4 & 5.

% xlswrite('points_WGS84',B,'D1');

% Calculate rotation angle relative to Norht from known_waypoints % by
% picking the two farthest known waypoints on the same side(assume that we
% pick % points 1 and 2 from the known_waypoints
% file)

theta = atan((DD(1,2)-DD(2,2))/(DD(1,1)-DD(2,1)));


% Move the Origin of the UTM coordinates to the reference point (assume that is Point 1)

BB(:,1) = BB(:,1) - DD(1,1);
BB(:,2) = BB(:,2) - DD(1,2);


% Rotate new UTM coordinates with the (-)theta angle into x,y

cosin_matrix = [cos(theta), sin(theta); -sin(theta),cos(theta)];

[m,n] = size(BB);
for i=1:m
   BB_rotated(i,:) = ((cosin_matrix)*BB(i,1:2)')';
end


% Add x,y,z of the reference point (assume that is point 1 in known_waypoints) into
% the B_rotated to create the x,y,z coordinates for all of the WGS 84 points.
```

```
points_xyz1(:,1) = BB_rotated(:,1) + CC(1,1);

points_xyz1(:,2) = BB_rotated(:,2) + CC(1,2);

points_xyz1(:,3) = AA(:,3) - CC(1,6) + CC(1,3);


% Save the x,y,z coordinates into a file named


xlswrite('points_xyz1',points_xyz1);


% End.
```

Figure A.3 — MATLAB code for converting the WGS 84 coordinates of a set of points to *(x, y, z)*

A.4 Conversion from the local 3D Cartesian coordinates to WGS 84 coordinates

The procedure presented in this clause does the inverse of the procedure given in A.3. That is, it converts the local 3D Cartesian coordinates of a given point to WGS 84. Most of the work is in the conversion from (x, y) to $(\text{lat}, \text{long})$. The conversion from z to altitude is simply a shift, i.e. adding the altitude of the *xy*-plane to the *z*-coordinate.

The first step is to convert (x, y) to $(\hat{x}, \hat{y})$ through

$$\hat{x} = x - x_1$$

$$\hat{y} = y - y_1$$

These coordinates are converted to $(\hat{e}, \hat{n})$ using the matrix equation given at the end of A.2.

Next we convert these coordinates to (e, n) by a simple translation:

$$e = \hat{e} + e_1$$

$$n = \hat{n} + n_1$$

The last step is a conversion from UTM coordinates to WGS 84, which can be done using the MATLAB code given in Figure A.4.

```
function  [Lat,Lon] = utm2deg(xx,yy,utmzone)

% -------------------------------------------------------------------------

% [Lat,Lon] = utm2deg(x,y,utmzone)

%

% Description: Function to convert vectors of UTM coordinates into Lat/Lon vectors

% (WGS 84).

% Some code has been extracted from UTMIP.m function by Gabriel Ruiz Martinez.
```

```
%
% Inputs:
%    x, y , utmzone.
%
% Outputs:
%    Lat: Latitude vector.   Degrees.  +ddd.ddddd  WGS84
%    Lon: Longitude vector.  Degrees.  +ddd.ddddd  WGS84
%
% Example 1:
% x=[ 458731;  407653;  239027;  230253;  343898;  362850];
% y=[4462881; 5126290; 4163083; 3171843; 4302285; 2772478];
% utmzone=['30 T'; '32 T'; '11 S'; '28 R'; '15 S'; '51 R'];
% [Lat, Lon]=utm2deg(x,y,utmzone);
% fprintf('%11.6f ',lat)
%    40.315430   46.283902   37.577834   28.645647   38.855552   25.061780
% fprintf('%11.6f ',lon)
%    -3.485713    7.801235 -119.955246  -17.759537  -94.799019  121.640266
%
% Example 2: If you need Lat/Lon coordinates in Degrees, Minutes and Seconds
% [Lat, Lon]=utm2deg(x,y,utmzone);
% LatDMS=dms2mat(deg2dms(Lat))
% LatDMS =
%    40.00         18.00         55.55
%    46.00         17.00          2.01
%    37.00         34.00         40.17
%    28.00         38.00         44.33
%    38.00         51.00         19.96
%    25.00          3.00         42.41
% LonDMS=dms2mat(deg2dms(Lon))
% LonDMS =
%    -3.00         29.00          8.61
%     7.00         48.00          4.40
%  -119.00         57.00         18.93
```

```
%  -17.00      45.00      34.33
%  -94.00      47.00      56.47
%  121.00      38.00      24.96
%
% Author:
%  Rafael Palacios
%  Universidad Pontificia Comillas
%  Madrid, Spain
% Version: Apr/06, Jun/06, Aug/06
% Aug/06: corrected m-Lint warnings
%-------------------------------------------------------------------------

% Argument checking
%
error(nargchk(3, 3, nargin)); %3 arguments required
n1=length(xx);
n2=length(yy);
n3=size(utmzone,1);
if (n1~=n2 || n1~=n3)
  error('x,y and utmzone vectors should have the same number or rows');
end
c=size(utmzone,2);
if (c~=4)
  error('utmzone should be a vector of strings like "30 T"');
end



% Memory pre-allocation
%
Lat=zeros(n1,1);
Lon=zeros(n1,1);
```



```
% Main Loop
%
for i=1:n1
  if (utmzone(i,4)>'X' || utmzone(i,4)<'C')
    fprintf('utm2deg: Warning utmzone should be a vector of strings like "30 T", not "30 t"\n');
  end
  if (utmzone(i,4)>'M')
    hemis='N';   % Northern hemisphere
  else
    hemis='S';
  end

  x=xx(i);
  y=yy(i);
  zone=str2double(utmzone(i,1:2));

  sa = 6378137.000000 ; sb = 6356752.314245;

%   e = ( ( ( sa ^ 2 ) - ( sb ^ 2 ) ) ^ 0.5 ) / sa;
  e2 = ( ( ( sa ^ 2 ) - ( sb ^ 2 ) ) ^ 0.5 ) / sb;
  e2cuadrada = e2 ^ 2;
  c = ( sa ^ 2 ) / sb;
%   alpha = ( sa - sb ) / sa;             %f
%   ablandamiento = 1 / alpha;   % 1/f

  X = x - 500000;

  if hemis == 'S' || hemis == 's'
     Y = y - 10000000;
  else
     Y = y;
  end
```



```
  S = ( ( zone * 6 ) - 183 );
  lat =  Y / ( 6366197.724 * 0.9996 );
  v = ( c / ( ( 1 + ( e2cuadrada * ( cos(lat) ) ^ 2 ) ) ) ^ 0.5 ) * 0.9996;
  a = X / v;
  a1 = sin( 2 * lat );
  a2 = a1 * ( cos(lat) ) ^ 2;
  j2 = lat + ( a1 / 2 );
  j4 = ( ( 3 * j2 ) + a2 ) / 4;
  j6 = ( ( 5 * j4 ) + ( a2 * ( cos(lat) ) ^ 2) ) / 3;
  alfa = ( 3 / 4 ) * e2cuadrada;
  beta = ( 5 / 3 ) * alfa ^ 2;
  gama = ( 35 / 27 ) * alfa ^ 3;
  Bm = 0.9996 * c * ( lat - alfa * j2 + beta * j4 - gama * j6 );
  b = ( Y - Bm ) / v;
  Epsi = ( ( e2cuadrada * a^ 2 ) / 2 ) * ( cos(lat) )^ 2;
  Eps = a * ( 1 - ( Epsi / 3 ) );
  nab = ( b * ( 1 - Epsi ) ) + lat;
  senoheps = ( exp(Eps) - exp(-Eps) ) / 2;
  Delt = atan(senoheps / (cos(nab) ) );
  TaO = atan(cos(Delt) * tan(nab));
  longitude = (Delt *(180 / pi ) ) + S;
  latitude = ( lat + ( 1 + e2cuadrada* (cos(lat)^ 2) - ( 3 / 2 ) * e2cuadrada * sin(lat) * cos(lat) * ( TaO - lat
) ) * ( TaO - lat ) ) * ...
            (180 / pi);

  Lat(i)=latitude;
  Lon(i)=longitude;

end
```

Figure A.4 — MATLAB code for converting UTM coordinates to WGS 84 (lat, long) coordinates

The MATLAB code given in Figure A.5 converts the local 3D Cartesian coordinates of a set of points stored in an Excel spreadsheet to WGS 84 coordinates and writes the results to another Excel spreadsheet. Note that the code calls the algorithm presented in Figure A.4.

