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Comparison of time-difference-of-arrival and angle-of-arrival methods of signal geolocation

SM Series

Spectrum management

International Telecommunication Union

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REPORT ITU-R SM.2211-2

Comparison of time-difference-of-arrival and angle-of-arrival methods of signal geolocation

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1 Introduction

This Report compares the strengths and weaknesses of time-difference-of-arrival (TDOA) versus angle-of-arrival (AOA) methods of signal geolocation. While this Report focuses on TDOA, it should be noted that other geolocation techniques exist[1]. The AOA method determines the angle of arrival of a wave at a measurement point. AOA methods have been commonly used in many direction-finding applications, and have some advantages but also some disadvantages related to antenna requirements, for example. TDOA methods, on the other hand, compute the time difference of arrival of a wave at multiple measurement points, and calculate the source point based on timing and wave comparisons. TDOA methods have not been widely used in spectrum monitoring, but have become increasingly useful due to the availability of inexpensive and compact computing power, more advanced radio receiver technology, ready availability of data links, and accurate distributed timing signal availability. The paper will provide a short overview of TDOA technology and some comparison of the strengths and weaknesses of the TDOA method compared to more traditional AOA methods.

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[1] Power of arrival (POA) uses the measured power ratio of a signal at multiple measurement points to compute the source point. POA is often used for indoor geolocation. Frequency-difference-of-arrival (FDOA) uses the frequency Doppler shift of a moving source (and/or multiple receivers) to calculate the source point. FDOA is often used in conjunction with TDOA for airborne applications.

2 Overview of TDOA technology

The TDOA technique measures the time of arrival of an RF signal at several points in space and compares the time difference between each receiver. The traditional approach to estimating TDOA is to compute the cross-correlation of a signal arriving at two receivers. The TDOA estimate is the delay which maximizes the cross-correlation function. By knowing the location of each receiver, an estimate of the location of the source of the emissions can then be deduced provided all receivers are time synchronized. The complement to an AOA system's line-of-bearing (LoB) is a hyperbolic line of constant time difference of arrival referred to as an isochron or line-of-position (LoP). A more complete discussion of TDOA methods is contained in the ITU Handbook on Spectrum Monitoring, Edition 2011, Chapter 4.7.3.2.

TDOA methods have been used in radiolocation tasks in some defence applications, and more recently in some specific applications such as location of mobile cellular telephones for emergency responses (fire, ambulance, etc.) The main obstacle in the past to more pervasive civil deployment has been the required nanosecond-level time synchronization. As electromagnetic radiation travels at approximately 30 cm/ns, any significant timing jitter between receivers will translate directly into the dilution of location accuracy. Today, the advent of satellite navigation systems (GPS, Galileo and GLONASS) provides one such accessible and inexpensive means of maintaining time synchronization. As a result, TDOA-based systems are now available today from several vendors in different countries around the world.

3 Strengths and weaknesses of TDOA compared with traditional AOA

To better understand TDOA we present a short comparative survey of its strengths and weaknesses with regard to AOA. It should be noted that TDOA and AOA are complementary techniques for geolocation. A geolocation system that combines both may outperform either alone [1]. Also, having an alternate and confirming method of geolocation can be crucial for spectrum enforcement actions.

To simplify the discussion, we assume that the TDOA system uses cross-correlation based detection, and that measurement receivers relay sampled signals to a central server for TDOA processing. For most spectrum monitoring applications, this method will be preferred for both its location performance and flexibility. To further simplify the discussion, we compare TDOA against a correlative interferometer (CI) AOA system. Correlative interferometry is a widely implemented AOA technique in modern radio monitoring. The correlative interferometer is introduced and discussed in Chapter 4.7.2.2.5 of the ITU Handbook on Spectrum Monitoring, Edition 2011.

(NOTE 1 – "Chapter" references in Tables 3-1 and 3-2 refer to the ITU Handbook on Spectrum Monitoring, Edition 2011. Numbers in parentheses in Tables refer to References listed in § 6.)

TABLE 3-1

TDOA strengths

Simpler antenna requirements	The antenna is low cost, low complexity, and may be small in size. TDOA receivers may employ a single simple antenna (such as a monopole or dipole). Unlike AOA systems, the antenna does not require high mechanical tolerances and electrical precision, and does not require operational test and measurement for calibration. An added benefit is that the antenna may be made small in size and made inconspicuous. This is important when deploying monitoring systems in historical or architecturally restricted sites or when negotiating siting agreements with 3rd parties.
Simpler siting and calibration requirements	Siting requirements are less restrictive than AOA and require little to no calibration. This allows more flexibility in choosing TDOA sites. As a result, TDOA installations are faster to deploy. In urban installations, additional TDOA receivers may be placed to overcome the shadowing effects of tall structures. In contrast, AOA sites must be chosen to minimize wave front distortion due to re-emanation from local obstacles, ground reflections, and ground conductivity changes. Some AOA antenna arrays must be calibrated after site installation to minimize the resulting frequency and direction dependent errors. Antenna array calibration is one of the most important performance limiting issues in AOA [2]. AOA siting issues are discussed in further detail in Chapters 4.7.2.3.1.2 and 2.6.1.3.
Wideband, low SNR signals, and short duration signals	TDOA performs well for new and emerging signals with complex modulations, wide bandwidths, and short durations. AOA typically performs well on narrow-band signals, but advanced AOA methods can be applied for locating any signals including wideband, complex, and short duration. TDOA performance is a strong function of signal bandwidth. AOA performance is roughly independent of signal bandwidth provided that the FFT channel spacing is similar to the signal bandwidth. TDOA performance generally improves as signal bandwidth increases. Both TDOA and AOA perform better on higher SNR signals and with longer integration times. The processing gain from correlation allows TDOA techniques to detect and locate low (and even negative) SNR signals. In addition, the correlation processing gain enables additional TDOA receivers to participate in a geolocation although they may have very low or negative SNR. Basic AOA techniques cannot detect and locate negative SNR signals, and may have issues locating low SNR signals. Advanced AOA techniques such as advanced resolution or data aided correlative AOA techniques (reference DF) can process these signals. Although basic AOA does not benefit from processing gain by signal correlation, it benefits to some degree from the system gain which comes from the use of multiple antenna elements and receiver channels. Geolocation of short duration signals requires coordinated receivers, time synchronized to a fraction of the inverse signal bandwidth. This capability is fundamental to TDOA systems. In addition, TDOA can geolocate using very short duration measurements on longer duration signals. If AOA antenna elements are commutated, then the required integration duration will be decreased.

TABLE 3-1 (*continued*)

System complexity	The TDOA receiver and antenna are less complex than the typical AOA antenna array and dual or multi-channel receiver. A TDOA receiver requires at least one real time RF channel for gap free processing and highest probability of signal interception(1). This may result in a less complex receiver in simple radio environments. Advanced TDOA processing techniques are necessary when using a simple receiver in complex radio environments. Efficient methods for time synchronization (GPS) and data link interfaces are readily available.
Rejection of uncorrelated noise and interference	The correlation processing used in TDOA can suppress co-channel, time coincident noise and interfering signals that are uncorrelated between sites. This property enables the system to geolocate signals with low signal to interference + noise ratios (low SINR). Time coordinated measurements are made at all receivers. Signals that are not common to two or more receivers are suppressed. With advanced processing, a TDOA system may geolocate using only correlations with the best observation of the emitted signal. A related application of cross correlation techniques for interference analysis is given in Chapter 4.8.5.5. Advanced AOA systems may mitigate the effects of uncorrelated time coincident co-channel interference through the use of correlation with reference signals. Other advanced processing techniques such as MUSIC can be robust to uncorrelated noise and interference. However, such techniques are computationally expensive and not widely used for spectrum monitoring.
Indoor, stadium, and campus geolocation	With advanced processing techniques, TDOA may be used to geolocate high bandwidth signals indoors and outdoors at short range (< 100 m on a side) and in high multipath environments [4]. AOA systems typically do not perform well under these conditions. The challenge of accurate indoor timing synchronization may be overcome with IEEE-1588 compatible Ethernet switches and TDOA receivers. It should be noted that an alternate geolocation technique using POA, generally outperforms TDOA in high multipath, short range environments, especially for narrowband signals.
Mitigates coherent co-channel interference (multipath) under certain conditions	Both AOA and TDOA methods are compromised by multipath, also known as coherent co-channel interference. Each method is impacted differently by the position of the sensor in relation to the multipath reflections. With sufficient signal bandwidth, TDOA is less sensitive to wave front distortion from local obstacles (local multipath). TDOA may require advanced signal processing to resolve location ambiguities caused by distant obstacles (distant multipath). Advanced processing can further filter the correlation pairs used in the TDOA geolocation to improve results under high multipath conditions. With advanced TDOA processing, time resolved multipath between sites can be suppressed [5], resulting in good performance in dense urban environments(2).

TABLE 3-1 (*end*)

Geometry considerations	Both TDOA and AOA are most precise when the signal source is centred within a perimeter of measurement sites. Geolocation precision in TDOA is determined by geometric dilution of precision (GDOP), time synchronization quality, and TDOA estimation quality. The location uncertainty is not directly related to the baseline distance between TDOA receivers [6]. This can be advantageous under certain conditions. In contrast, the precision of AOA methods is directly related to the distance between the source and each AOA receiver. AOA position uncertainty is a function of bearing angle uncertainty and distance from the receiver to estimated position. When the source is far outside the perimeter, TDOA approximates a line of position similar to AOA's line of bearing. In this situation, the uncertainty in location and bearing grows similarly with distance for both methods.
Well suited to use in RF sensor networks	For both TDOA and AOA, more receivers lead to better results through proximity gain and improved statistics. TDOA is well suited to multiple receiver deployments due to its lower complexity, size, power, simpler antenna, and simplified siting requirements. A higher density of remote monitoring stations, referred to as RF sensors above, brings the monitoring receiver closer to the signal of interest. The resulting reduction in path loss, sometimes referred to as 'proximity gain', improves detection and geolocation performance [7]. In addition, the processing gain from correlation in TDOA techniques enables additional sensors to participate in a geolocation although they may have very low or negative SNR.
Full offline analysis possible at central server	TDOA systems can store and catalogue time coordinated signal measurements from all receivers, so full offline analysis is possible at a central server. This includes spectral analysis of each receiver's signal, cross correlation measurements, and geolocation. AOA systems may also store and catalogue some signal measurements (such as bearing results and bearing confidence) at a central server. These measurements are time coordinated to the degree of time synchronization achievable in the AOA system. Measurements such as spectral analysis and cross correlations are not typical as they require similar backhaul data rate requirements as TDOA.

(1) Typical correlative interferometry systems employ time-division multiplex (TDM) to reduce the number of receivers required. These systems require two to three receivers switched among the 5, 7, or more antennas. These systems are less complex than fully parallel DF systems but require a longer minimum signal duration for location.

(2) TDOA has been reported to geolocate narrowband (30 kHz) AMPS cell phone signals in dense urban environments to less than a few hundred feet r.m.s (5).

TABLE 3-2

TDOA weaknesses

Narrowband signals	Slowly varying signals, which include unmodulated (CW) carriers and narrowband signals, may be impossible or difficult to locate with TDOA techniques. TDOA performance is a strong function of signal bandwidth and performance degrades as signal bandwidth decreases. Also, multipath is potentially more of an issue for narrow bandwidth signals when the signal's temporal characteristics are wide relative to the delay spread. Under these conditions the pulse-shape distortion caused by the multipath is harder to discriminate, adding error to the time-difference estimation. The minimum signal bandwidth for acceptable performance will vary by application. For example, TDOA has been reported to geolocate narrowband (30 kHz) AMPS cell phone signals in dense urban environments to less than a few hundred feet RMS [5]. Higher SNR conditions and longer observation times can improve TDOA location for some narrowband signals. AOA systems perform well for narrowband and unmodulated signals as well as wideband signals.
Single station homing and standoff not possible	A minimum of two TDOA stations, with at least one of those being mobile, and a data link are required for the homing and standoff methods(1). AOA homing and standoff geolocation methods are possible with just one portable station. This allows for geolocation in environments where networked TDOA receivers are impractical or not cost effective. These methods are described in Chapter 4.7.3.3.
Higher data rate communication links	TDOA systems that transmit sampled waveforms from receivers to a central server require high data rate communications links. The receiver's networking needs are asymmetric with upload bandwidth exceeding download bandwidth. Advanced processing, including signal compression, can reduce the data transmitted. TDOA systems that establish TOA at the receiver will have more modest date rate requirements. TDOA data link requirements are discussed further in Chapter 4.7.3.2.4 "Network Considerations". AOA systems require lower data rates because only some signal characteristics such as bearing angle, frequency, and time, are transmitted to a central site.
Sensitive to sources of signal de-correlation	A TDOA system must carefully mitigate all potential sources of signal de-correlation between receivers. These include relative reference frequency offsets between receivers, relative signal frequency offsets (Doppler shift) due to moving sources or local environment. The maximum coherent integration time will be bounded not just by the signal duration, but also the receiver's reference oscillator stability and the dynamics of the wireless channel. High quality TDOA systems will include tracking loops to maintain frequency and time coherence. Automatic Doppler correction is essential for compensating the de-correlation effects of Doppler shifted sources. Basic AOA systems and some advanced resolution AOA systems (using MUSIC) are not sensitive to signal de-correlation between measurement sites. Advanced AOA systems which correlate with reference signals are sensitive to signal de-correlation.

TABLE 3-2 (*end*)

More accurate time synchronization	TDOA requires high quality time synchronization relative to the inverse bandwidth of the signal of interest. TDOA receiver time synchronization better than 20 ns is achievable with current technology (e.g. GPS). AOA systems have less demanding time synchronization requirements. These can be as loose as a few seconds between receivers. In practice, some signals of interest such as short duration or hopping signals demand higher levels of AOA station synchronization.
Signals containing periodic elements	While unlikely, under some conditions TDOA algorithms may generate incorrect answers for signals that contain periodic elements. Examples of such signals include repeating data sequences or synchronization pulses. This problem and a way to minimize it are further described in Chapter 4.7.3.2.3 “Factors Affecting Accuracy”. Since basic AOA systems do not perform signal cross-correlation, they are not susceptible to this issue.
Geolocation computation speed	Sampled signals are typically transmitted to a geolocation server for computation. This places demands on networking capacity and speed. A slow link can significantly delay geolocation compute time. Typical geolocation rates may be on the order of up to 1 fix per second for TDOA (best case) versus 100 fixes per second for AOA. Use of higher bandwidth data links can improve TDOA geolocation speed. Use of shorter observation times and/or advanced compression techniques can also reduce the data bandwidth requirements. Once measurements have been transmitted to a central server, recomputed TDOA geolocations are significantly faster since they operate on stored local data.
Not well suited to concurrent geolocation of many emitters	Some AOA systems support concurrent geolocation of many frequency separated signals. This is often referred to as wideband DF. This capability is possible with but not amenable to TDOA, primarily because of the much higher data transmission requirements. Data transmission may be reduced for TDOA in the data aided case by performing signal synchronization (establishing TOA) at each receiver.
Single Site Location (SSL) not possible	A minimum of 2 sensors are required to generate LoP, and a minimum of 3 sensors are needed for geolocation in 2-D, and 4 for geolocation in 3-D. AOA can be used for single site location.
Geometry considerations	Both TDOA and AOA are most precise (best GDOP) when the signal source is within a perimeter outlining a group of interacting sensors and/or direction finding (DF) stations. Immediately outside this perimeter, the location precision and effectiveness decrease more rapidly for TDOA than for AOA (See Annex 1 and [8]). When the source is far outside this perimeter, TDOA may approximate a line of position similar to AOA’s line of bearing (See Annex 1 and [8]). AOA achieves geolocation (i.e. indicates the intersection of two lines of bearing) within zones where the coverage areas of two DF stations overlap. For information related to RF detection range and geolocation coverage area of TDOA and AOA networks, see Annex 1.
Offline analysis with single site measurements	With AOA, the line of bearing can be analysed offline using measurements from just a single site. Offline analyses of TDOA lines of position are not possible with measurements from a single site.

(1) POA approaches may be used for homing and standoff with just one portable station.

4 Hybrid systems

TDOA may be combined with one or more additional geolocation technologies to produce what can be called a hybrid system. TDOA and AOA technologies may be combined at one or more stations, resulting in hybrid AOA/TDOA systems. TDOA may also be combined with other geolocation technologies, such as POA amplitude ratio technique, resulting in a hybrid TDOA/POA system.

Hybrid AOA/TDOA systems consist of a minimum of two sites, at least one of which has both AOA and TDOA measurement capability, and the remaining sites with TDOA measurement capability. The two TDOA sensors produce one hyperbolic line representing the time-difference values as described in the ITU Handbook on Spectrum Monitoring, Edition 2011, Chapter 4.7.3.2. The AOA system produces LoB. The intersection of the line of bearing and the TDOA hyperbolic line identifies the emitter location. These systems are discussed in more detail in Annex 2 and Annex 3.

5 Summary

TDOA is a complementary geolocation technology that is not widely used for radio monitoring. TDOA has become increasingly useful due to the availability of inexpensive and compact computing power, more advanced radio receiver technology, ubiquitous data connectivity, and accurate distributed timing synchronization. It has certain strengths with respect to AOA, particularly in detection and geolocation of modern wideband signals, simpler antenna requirements, ability to process close range multipath propagation in urban environments, and amenability to low cost sensor network deployments. It also has weaknesses with respect to AOA, especially in locating narrowband and unmodulated signals, usually more demanding data backhaul requirements, and it requires at least 2 receivers for line of position information and at least 3 receivers for location in 2-D. Modern signal monitoring is experiencing a trend toward ever increasing signal bandwidths and decreasing power spectral densities. Use of complementary geolocation technologies such as TDOA can improve probability of detection and location of modern signals in many environments. Hybrid AOA/TDOA systems may neutralize some of the weaknesses of each technique alone, while realizing the advantages of each. Mobile TDOA stations are effective only in the case of hybrid use with AOA.

6 References

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Annex 1

Factors affecting RF detection range and geolocation coverage area for monitoring stations

1 Introduction

There are several deployment considerations for monitoring stations that affect its RF detection range and geolocation coverage area. The overall effectiveness of any monitoring station – regardless of performance characteristics – will be impacted by constraints or advantages offered by the equipment selection, installation and the site.

In real world deployments, spectrum monitoring systems (SMS) will likely be comprised of both AOA and TDOA stations deployed in combinations of fixed and mobile platforms. Selection of the geolocation technology used for a monitoring site has a number of considerations and will typically be based on:

– Site access to power and network.
– Proximity to signal energy – both desired and undesired. Placement of monitoring sites in close proximity to wireless services or industrial grade electrical equipment has become necessary in many metropolitan areas.
– Terrain and line of site to the area being monitored.
– Emitter density and nature of spectral traffic.
– Importance of the user base in the area being monitored (i.e. critical infrastructure or government installations, etc.).
– Duration of the monitoring activity. Some monitoring products are well suited to short duration monitoring activities (less than 12 hours) due to small size, battery operation and ease of setup and tear down.
– Site Installation factors, including equipment size, power availability and usage, network connectivity, site lease, equipment calibration and maintenance.

Further, an SMS may be comprised of older and newer technology (for example, augmentation of existing stations with newer equipment), as well as the condition and function of existing monitoring equipment. Selection of one technology to address all possible scenarios is impractical. Each geolocation technology has aspects that work well in certain cases but not in all.

Simulations with a specific set of conditions are used here to illustrate the impact that design choices and emitter characteristics have on RF detection range and geolocation coverage area. The simulations that follow are based on industry standard propagation models developed between 2004 and 2007[2]. They do not take actual 3D terrain data into account, and so RF coverage is modelled

[2] Models developed in Wireless World Initiative New Radio consortium (WINNER I and II) coordinated by Nokia Siemens Networks.

uniformly from each monitoring site. This provides the ability to see the various impacts of emitter bandwidth, power and antenna height under ideal conditions. The simulations use a software tool that is routinely used to answer the question, “Roughly how many monitoring stations will I need to cover an area of interest?”

2 General considerations

It is important to first define radio frequency (RF) detection range and geolocation coverage area:

– RF detection range is defined to be the furthest distance (in km) from the monitoring station that an emitter can be detected with positive SNR. The detection range can be different in different directions depending on terrain, building features, and other factors.

– Geolocation coverage area is defined as the geographic area over which an emitter can be reasonably located using available methods (i.e. AOA, TDOA, hybrid, POA).

It is important to note the difference between RF detection range – which requires a positive SNR at the monitoring station, and geolocation coverage area, which does not require a positive SNR at every monitoring station. TDOA geolocation methods, which correlate the signal received at different sites, allows one to locate emitters with signals below the noise floor. The noise power received at the sites does not correlate. For more detailed information regarding the operation of TDOA geolocation methods, refer to §§ 4.7.3.2.2 and 4.7.3.2.3 of the ITU Handbook on Spectrum monitoring.

The geolocation coverage area for groups of fixed AOA DF stations and TDOA sensors may be analysed by considering AOA and TDOA monitoring networks consisting of up to three interacting stations, since these give rise to zones in which the coverage areas of three and two stations overlap as well as areas covered by only one station.

We shall consider geolocation coverage for three fixed sensors, identified in Fig. 1 as S1 to S3, and three fixed DF stations, identified in Fig. 2 as DF1 to DF3, having the exact same geometry, but operating in TDOA and AOA networks, respectively. The networks are also assumed to be equipped with mobile monitoring stations, identified on Figs 1 and 2 as MS, using equipment with the exact same technology as both the fixed sensors and DF stations. Individual RF detection range of each fixed station is depicted in Figs 1 and 2 using different coloured contours. Shown in yellow is the area of RF detection common to all the fixed stations within which the emission source (hereinafter referred to as the “transmitter”) has a positive SNR. Since TDOA sensors use time synchronous cross-correlation, the corresponding geolocation coverage area of the sensor network S1 to S3 in Fig. 1 is larger than that of the DF stations DF1 to DF3 in Fig. 2.

It should be noted that the RF detection range and geolocation coverage areas in both figures are notionally constructed based on a certain test transmitter with a specific power and antenna height. If these parameters are modified, this will inevitably alter the contours of the coverage areas to some extent. This is described in more detail in § 3.

For a TDOA network, the transmitter coordinates are determined on the basis of the area of intersection of the three lines of position, as shown in Fig. 1 in relation to transmitter T1, where lines of position 1-2, 3-1 and 3-2 intersect. For an AOA network, geolocation using only fixed DF stations is performed by all three DF stations, as shown in Fig. 2 (bearing lines 1 to 3 effectively locate transmitter T1). The AOA network is also effective in areas covered by only two DF stations, as shown in the same figure in relation to transmitter T2 (bearing lines 4 and 5).

FIGURE 1

Geolocation coverage area in a TDOA network

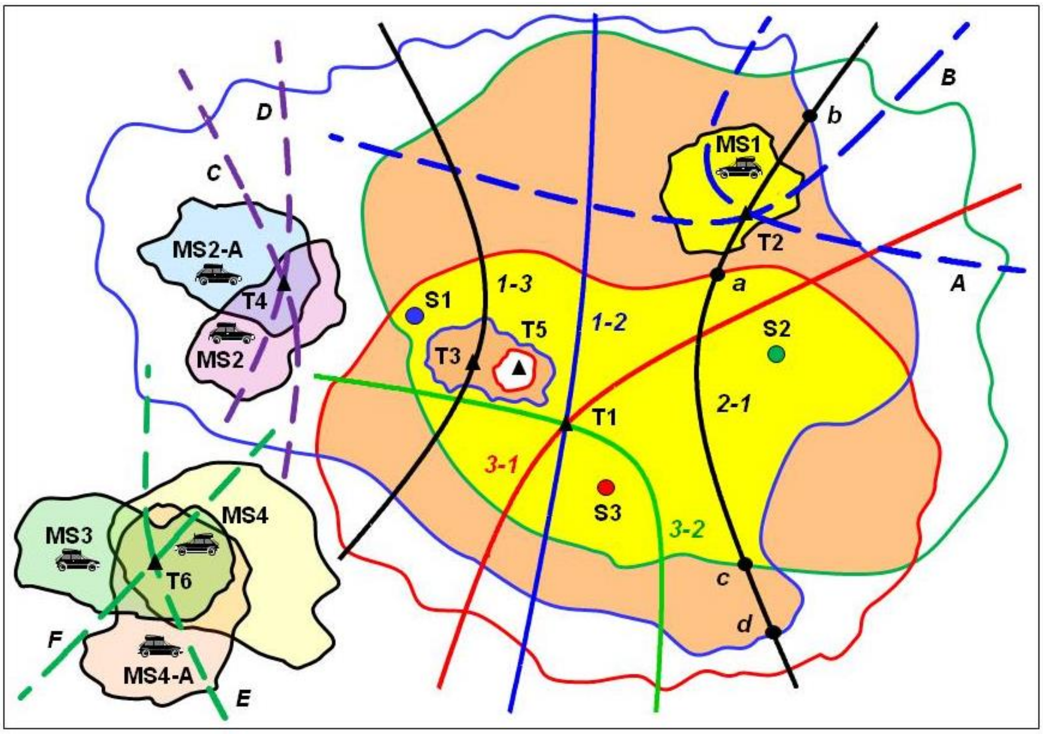
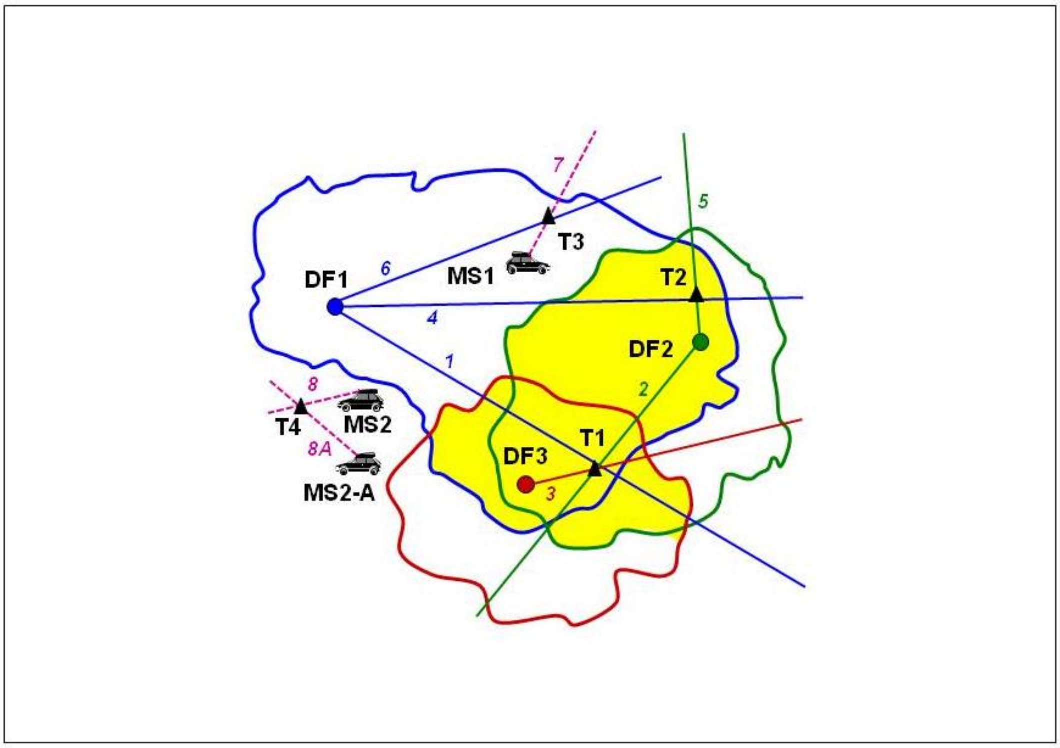


FIGURE 2

Geolocation coverage area in an AOA network



If, in a TDOA network, the transmitter of interest is situated in one of the areas outside the sensor boundary (brown colour in Fig. 1), the system may produce only one LoP, as depicted by line 2-1 in relation to transmitter T2 or a line of bearing to the transmitter. In this case, the transmitter coordinates must be determined with the help of a mobile station (MS1 in Fig. 1), interacting with the two fixed sensors. This is shown in Fig. 1 by the intersection of the LoP 2-1 with two others established by this mobile station (LoP A and B, depicted by broken lines in order to highlight their variability as the station moves around).

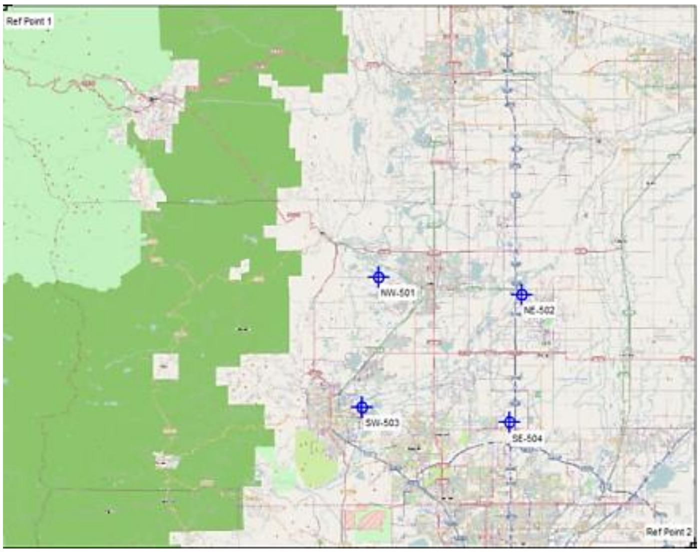
The transmitter of interest has to be in the RF detection range of one of the TDOA stations if it is intermittent (thus requiring a triggered measurement). If the transmitter is persistent, it may not need to be within the RF detection range of any of the TDOA sensors, but within the geolocation coverage area, to produce an estimation of location. The exact location can be determined with the help of mobile stations, but that can take significant time in some cases. Mobile stations often have a limited RF detection range because of the low antenna height. There are techniques, however, for elevating the antenna of a mobile station by using publicly available structures such as parking garages or terrain.

Other TDOA and AOA coverage cases which follow from Figs 1 and 2 as well as examples of the interaction of fixed and mobile stations are discussed in [8].

3 Simulations of factors affecting RF detection range in TDOA and AOA monitoring stations

FIGURE 3

Simulation area in Boulder, CO



For the examples in this section, a region in the state of Colorado in the U.S. is used, as shown in Fig. 3. Four stations (NW-501, NE-502, SW-503 and SE-504) are spaced roughly 18 km apart. The simulations will illustrate RF detection range for traditional AOA and TDOA stations operating alone. For the purposes of this simulation, detection range is defined to be the furthest distance (in km) from the monitoring station that an emitter can be detected with positive SNR.

The simulations show probability of detection in colour – red being high and blue being low. This section will highlight factors which can impact the RF detection range. Some of these factors are within the control of the operator such as:

– Monitoring Station antenna height and gain.
– RF feedline cable type and length, signal conditioning such as attenuation, filters, etc.
– RF noise environment local to the station.
– Physical surroundings (including nearby terrain).

Conversely, some factors have no relationship to the monitoring station but are strictly dependent upon the characteristics of the emitter:

– Carrier frequency.

– Power output.

– Signal bandwidth.

– Elevation of emitter antenna.

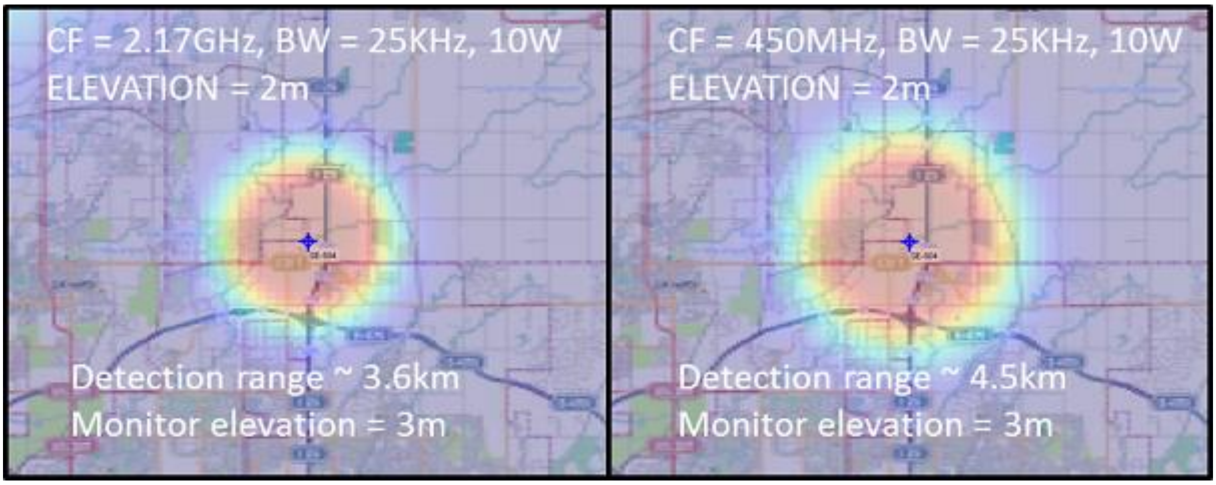
The simulation tool used in this report allows the user to modify any or all of these factors to determine the impact on RF detection range and geolocation coverage area (for cross-correlated TDOA geolocation measurements). For simplicity, a rural line-of-sight (LoS) terrain model is employed here. The simulation tool has other terrain models for Urban, Suburban, Indoor and Indoor/Outdoor scenarios. It also includes LoS and non-line-of-sight (NLoS) propagation models.

3(a) Effects of emitter carrier frequency

In Fig. 4, SE-504 is shown on a plot that measures 17.2 km North to South and 21.8 km East to West (this plot will be used in all the simulations in this section dealing with RF detection range). This station is assumed to operate with a noise floor of –150 dBm/Hz, antenna gain of 0 dB, antenna height of 3 m with a 2 m LMR-400 RF cable connecting the receive antenna to a RF sensor. For the left simulation, the emitter carrier frequency is 2.17 GHz, signal bandwidth is 25 kHz, output power is 10 W and the antenna elevation is 2 m. The simulation on the right shows the effect that reducing the emitter carrier frequency to 450 MHz has on the RF detection range[3].

FIGURE 4

Rural LoS propagation model, emitter and monitoring station both close to ground level



Higher frequency bands (above 3 GHz) are beginning to be used for cellular telephony and other licensed services. Monitoring of these services from fixed sites will be increasingly difficult because of the number of monitoring locations needed to provide coverage. For this reason, technologies based on networks of fixed, mobile and re-locatable monitoring stations may become increasingly important.

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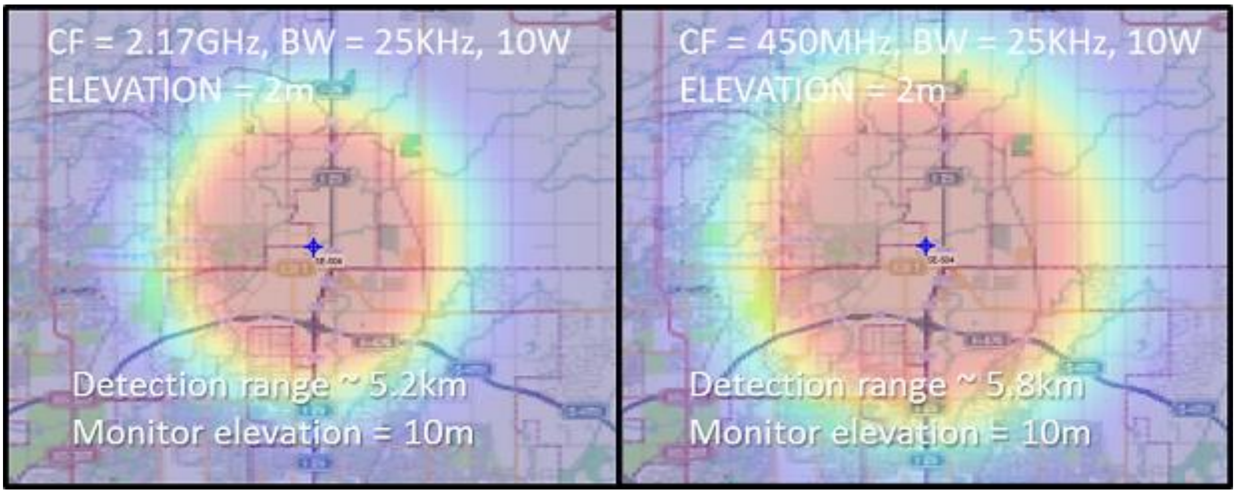
[3] Propagation losses are lower at lower frequencies, resulting in a larger RF detection range.

3(b) Effects of monitoring station antenna elevation

In Fig. 5, the monitoring station elevation is raised to 10 m and all other factors remain the same. There is a significant increase in the expected RF detection range due to improved chance for line of sight to target emitters. Elevation of the emitter antenna has a similar effect.

FIGURE 5

Rural LoS propagation model, emitter close to ground, monitoring station elevated



3(c) Effects of signal bandwidth

In Fig. 6, all elements remain the same as in Fig. 5, but the signal bandwidth is increased from 25 kHz to 200 kHz. Notice how the detection range is reduced due to lower power spectral density.

FIGURE 6

Same as Fig. 5 except signal bandwidth changed from 25 kHz to 200 kHz

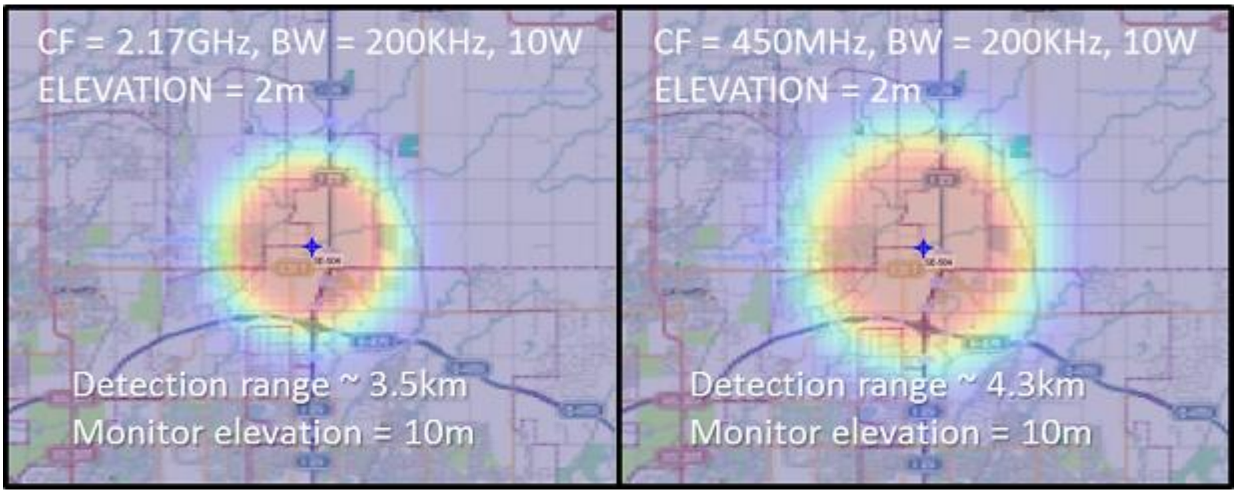
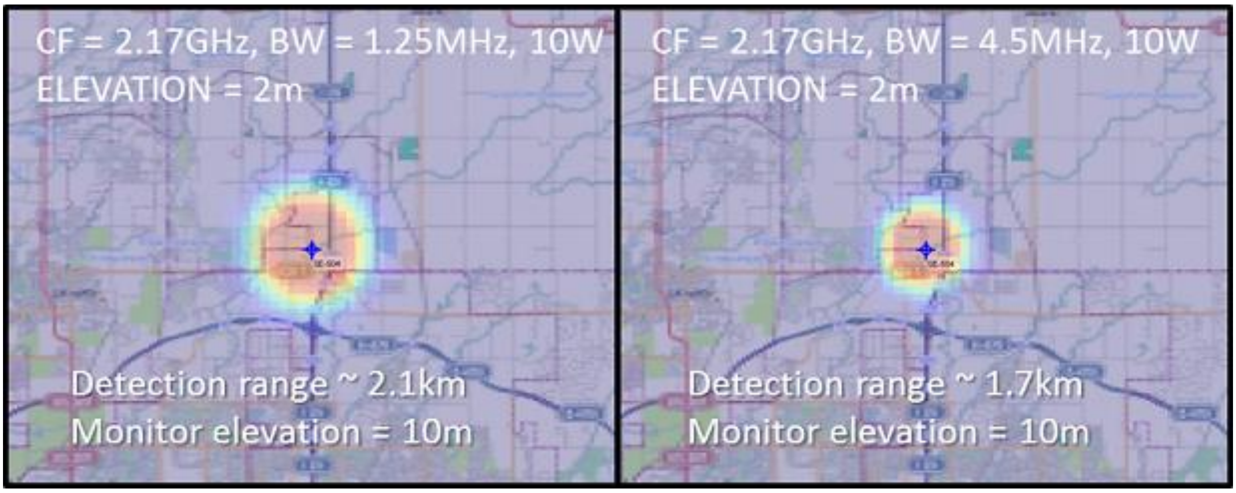


Figure 7 shows results of simulations that build on the 2.17 GHz example and increase the signal bandwidth to 1.25 MHz and 4.5 MHz respectively. All other variables are the same as in Fig. 5 (left). It is very clear how signal bandwidth impacts an emitter's ability to propagate over distance and the corresponding decrease in a monitoring station's RF detection range.

FIGURE 7

Signal bandwidth changed to 1.25 MHz and 4.5 MHz bandwidth while emitter power, elevation and carrier frequency are kept the same



3(d) Effect of antenna gain

Figure 8 shows results of a simulation in which 6 dB of antenna gain was added to illustrate the use of a directional antenna. The signal bandwidth was set back to 25 kHz. These results offer an indication of expected coverage range for some traditional AOA stations which have gain associated with their antenna system, or from a TDOA station equipped with a directional antenna. The map scale has remained the same for all simulations thus far.

FIGURE 8

Antenna gain was increased to 6 dB and emitter bandwidth reduced to 25 kHz with 2.17 GHz and 450 MHz carrier frequency, respectively

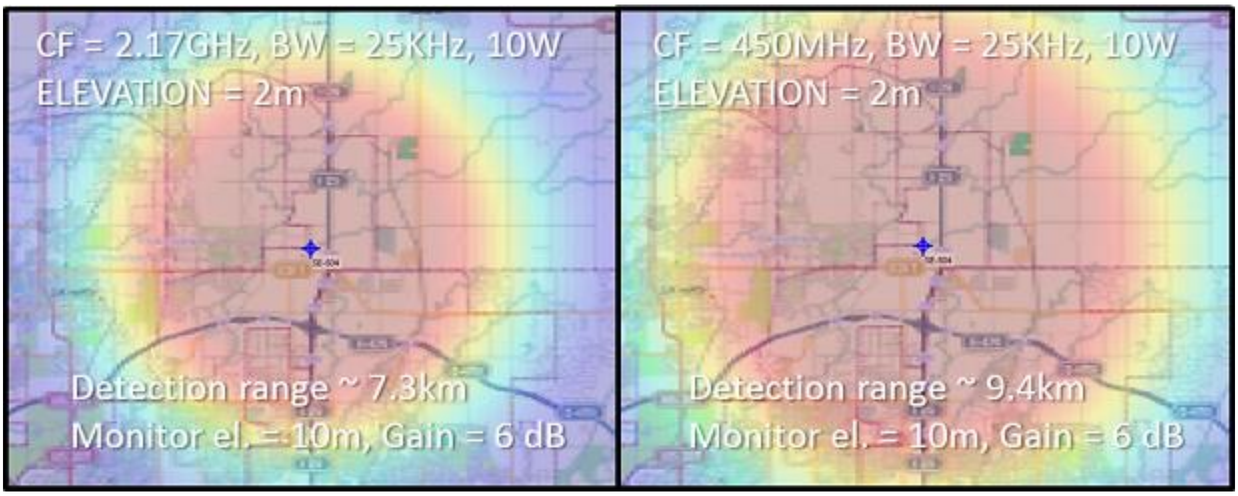
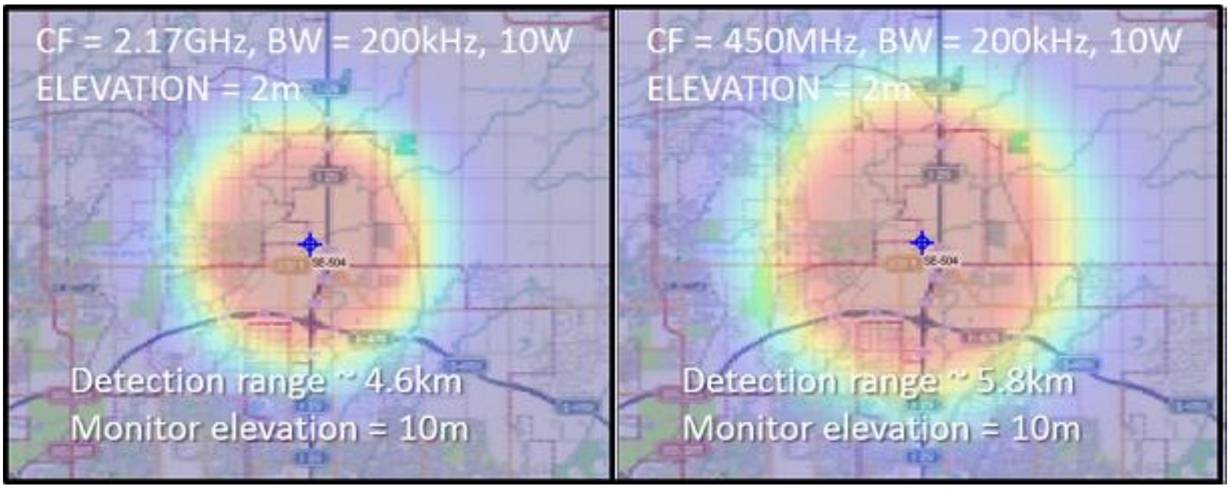


Figure 9 shows results of the same simulation in Fig. 8 except the emitter bandwidth was increased to 200 kHz.

FIGURE 9

Same as Fig. 8 except signal bandwidth was increased to 200 kHz

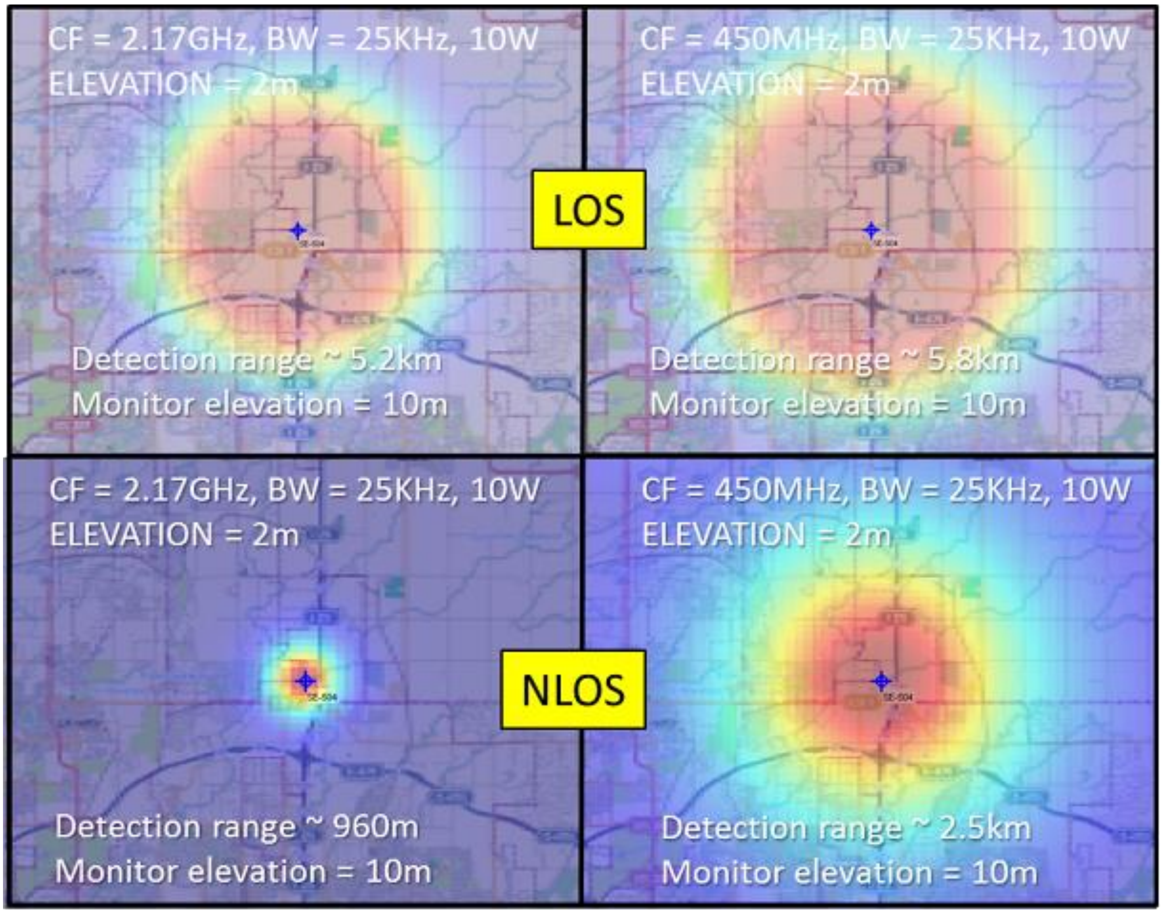


3(e) Effects of terrain and LoS

Figures 4 through 9 show results of simulations meant to illustrate the impact different design factors and emitter characteristics have on the RF detection range of a single monitoring station operating alone. Shadowing effects of buildings and terrain are not illustrated in the simulations above. To demonstrate this impact on detection range, Fig. 10 shows Rural LoS versus Rural NLoS propagation models. The same scenario from Fig. 5 is repeated here in the upper simulations contrasted with the NLoS propagation model in the lower. This shows very graphically the effects LoS may have on RF detection. It also serves to highlight the important role of mobile and re-locatable stations for modern spectrum monitoring systems. These factors must be considered when selecting the site and designing a monitoring station that will be used for emitter location measurements.

FIGURE 10

Impact on RF detection range of LoS versus NLoS propagation



4 Simulations of factors affecting geolocation coverage area in TDOA and AOA monitoring stations

In this section, an expanded geographic area is plotted and four monitoring stations are shown. Simulations on the left show the RF detection range of the individual monitoring stations operating independently. Simulations on the right show the geolocation coverage area for cross-correlated TDOA measurements.

Geolocation coverage area is defined as the geographic area over which an emitter can be reasonably located using available methods (i.e. AOA, TDOA, hybrid, POA). It is important to note the difference between RF detection range – which requires a positive SNR at the monitoring station, and geolocation coverage, which does not require a positive SNR at every monitoring station.

Figure 11 shows results of a simulation where the emitter is set to 2.17 GHz but the power level is reduced to 1W. With the emitter at 2 m elevation (and still using the Rural LoS propagation model without terrain data), the detection range of the monitoring station is about 2.6 km – and this is very optimistic considering the signal, in practice, will likely be shadowed by buildings or terrain. The TDOA geolocation coverage area, shown on the right, is estimated to be far greater since it uses cross-correlated measurements with the entire network of monitoring stations[4]. The simulation assumes correlation between four pairs of monitoring stations.

FIGURE 11

RF detection range of four individual monitoring stations (left) versus geolocation coverage area using TDOA (right)

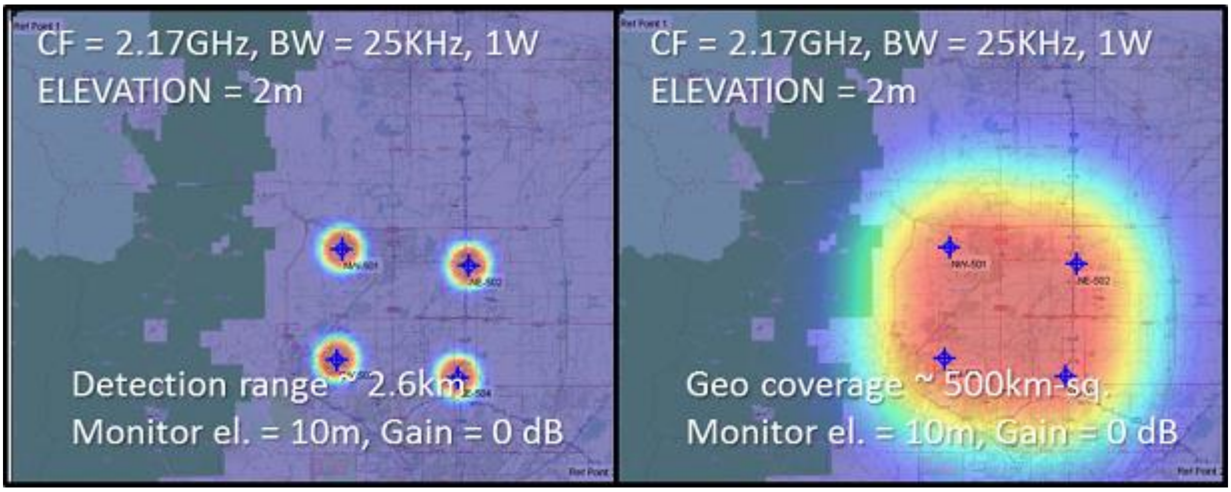
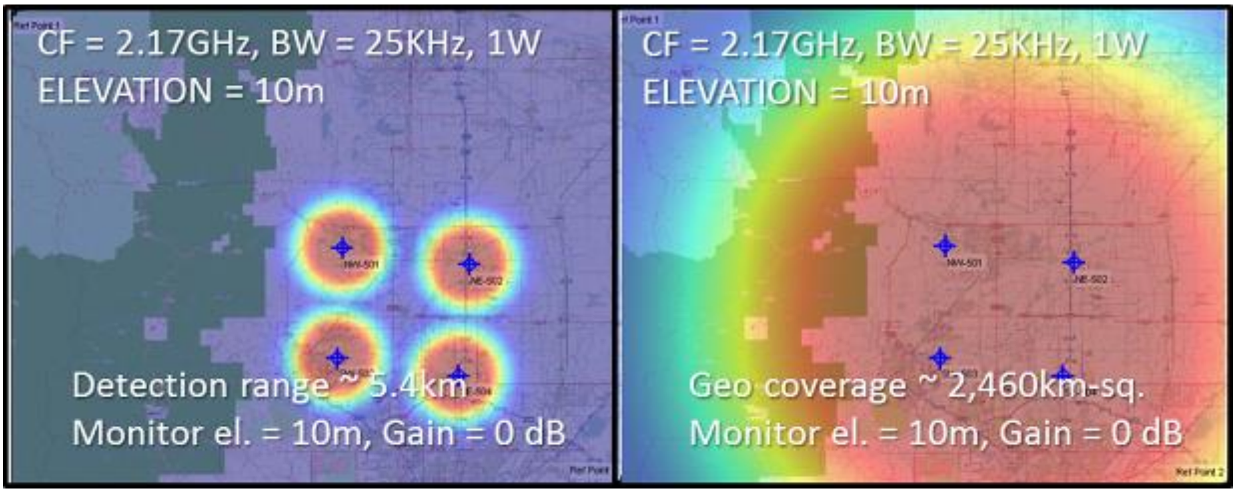


Figure 12 shows results of a simulation which raises the emitter elevation to 10 m. This shows improved RF detection range for AOA and TDOA systems. The TDOA geolocation coverage area (on the right) is also enhanced. An important consideration in this simulation is the Geometric Dilution of Precision (GDOP) associated with the station geometry relative to the emitter location. It is used to state how errors in the measurement data will affect the final estimation of location (it is shown graphically in § 5, Fig. 14). GDOP for TDOA networks increases as the emitter location moves outside the area bounded by the monitoring stations. Therefore, the accuracy of TDOA is expected to decrease outside the sensor network. While the simulation shows a large area where geolocation measurements are possible, it does not show the effect of GDOP on the expected accuracy.

[4] In the case of TDOA measurements, the same transmitted signal from two separate sensors is cross-correlated resulting in a suppression of the independent noise characteristics. In the theoretical limit of long cross-correlation times, the receiver and environmental noise is not a factor and the system's detection performance becomes less limited by the individual receiver's performance, including noise figure.

FIGURE 12

Same scenario as Fig. 11 except emitter elevated to 10 m



Processing gains achieved by advanced TDOA algorithms can provide emitter location capabilities over an area greater than the RF detection range of the individual stations.

5 Comparison of simulated and real RF geolocation measurements

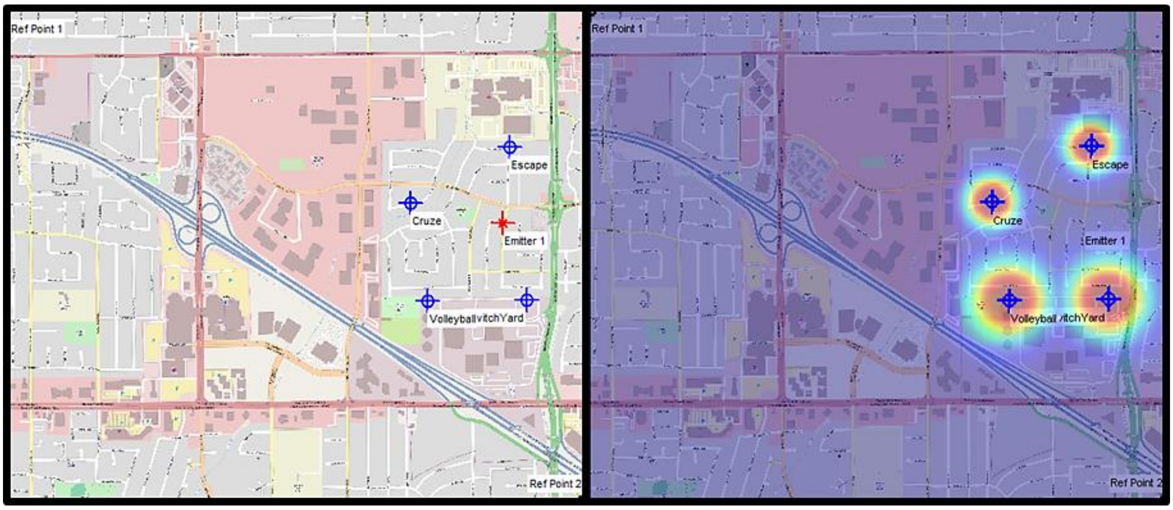
The trial described below was conducted for the specific purpose of locating low power emitters of the same nature as mobile phones. As such, the separation between monitoring stations was less than 1 km. While this scenario may not apply directly to tasks typical of spectrum regulation, it serves as a good example to compare simulated measurements with actual field measurements.

The area where this trial was conducted is Santa Clara, CA and the terrain is typically suburban with some light industrial surroundings (five to six-story office buildings, hospital, parking garages, retail, etc.). In the simulation model, we used a "Suburban NLoS" model for terrain. The "Volleyball" and "SwitchYard" stations were temporary – but fixed with both omnidirectional and patch directional antenna elements. These were on 2.5 m tripods and powered by small lithium ion batteries. The "Escape" and "Cruze" stations were mobile – installed in vehicles with magnetic mount antennas and all were battery-powered. The transmitter was moved around the area bounded by the monitoring stations.

Figure 13 (left) shows the arrangement of monitoring stations and one test emitter location. In these examples, the emitter was a mobile phone transmitting a UMTS uplink at 2 W on 831 MHz (signal bandwidth approximately 4.5 MHz) from a vehicle. The right figure shows the expected RF detection range of the monitoring stations. As can be seen, the emitter is outside the RF detection range of each individual station assuming the Suburban NLoS terrain model.

FIGURE 13

Santa Clara emitter location test setup and expected RF detection range



The detection range of the two southernmost monitoring stations is greater due to slightly higher elevation and directional antennas pointed north. All monitoring stations were connected via cellular modems to a geolocation server with routable IP address located in an office building in Santa Clara. Control of the sensor network was accomplished via laptop from the vehicle carrying the emitter.

Figure 14 (left) shows an estimated representation of Geometric Dilution of Precision (GDOP) for this deployment of monitoring stations. Notice how the low (good) GDOP extends outside the boundary of the network in some directions but not all. In practice, the ability of a TDOA network to determine a line of position/direction to an emitter can extend well outside the perimeter of the monitoring stations[5]. The figure on the right shows the expected hyperbolic lines of constant time difference between sensor pairs. Geolocation accuracy is expected to improve in regions of low GDOP (shown in red) and perpendicular crossing of the hyperbolic lines.

[5] A “line of position” produced from a cluster of multiple TDOA stations is analogous to a single AOA bearing from one AOA site, but does not give a geolocation result. It only provides the direction of the emitter (when the emitter is outside the area bounded by TDOA stations).

FIGURE 14

Santa Clara site GDOP and TDOA hyperbolic line display

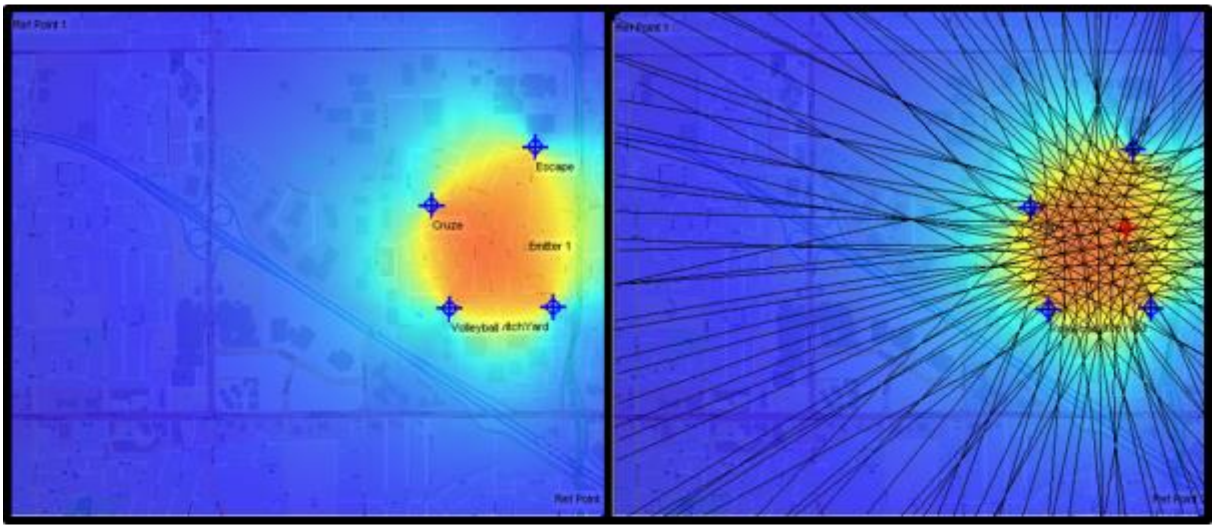


Figure 15 (left) shows the expected geolocation coverage area (assuming correlation of up to four sensor pairs) and the hyperbolic lines to the emitter location. The right figure shows an actual measurement of the emitter location. Several measurements were made at this location with the TDOA error less than 50 m.

FIGURE 15

Estimation of geometric coverage area and actual emitter location measurement

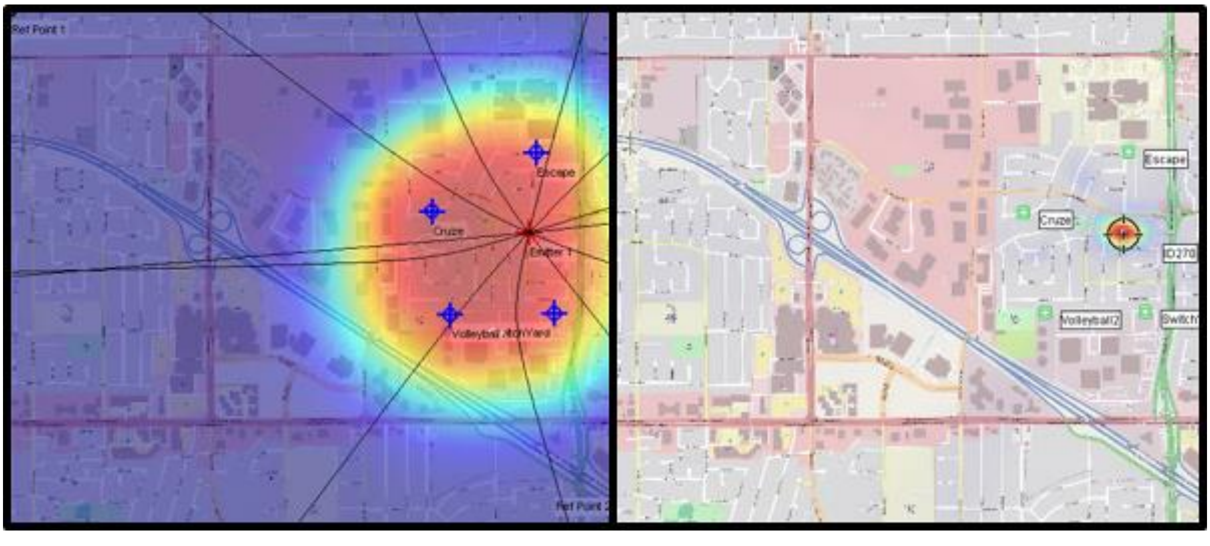
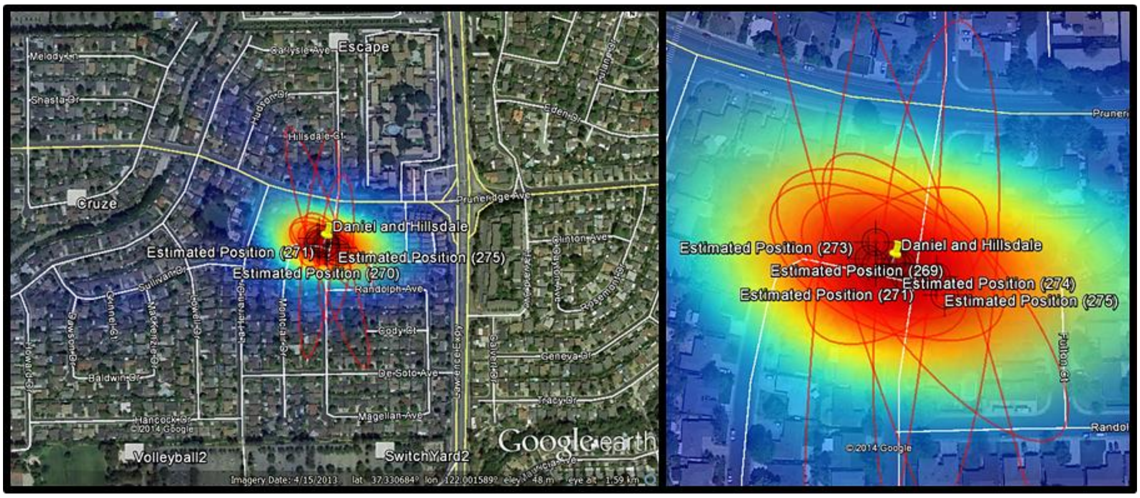


Figure 16 displays several geolocation results overlaid onto Google Earth ® with associated colorization of the likelihood, elliptical error probability (EEP) and estimated emitter position (EP). The yellow pin shows the actual location of the emitter.

FIGURE 16

Geolocation measurements overlaid onto Google Earth. A zoomed in view is shown on the right

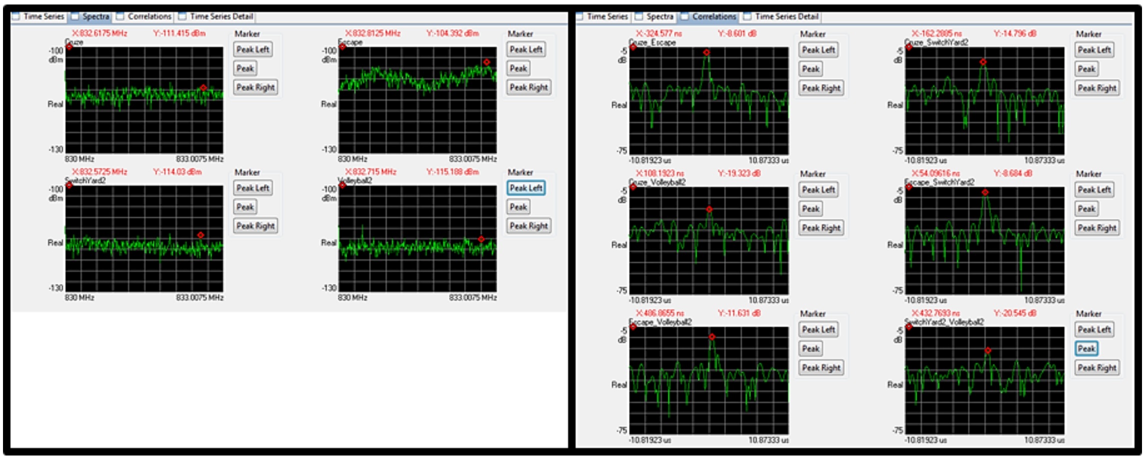


In this case, the simulations and measurements are in agreement.

Figure 17 (left) shows that the emitter only reached one monitoring location with positive SNR (escape). However, the ability to geolocate the emitter with TDOA was very strong as evidenced by the good cross-correlations between sensor pairs as shown in Fig. 17 (right).

FIGURE 17

Typical spectral and correlation plots for the UMTS device measured in a 2013 field trial



The point of these simulations and measurements is to illustrate the difference between RF detection range and geolocation coverage area and the conditions that impact them. RF detection range is subject to many different factors and is influenced by design choices and siting constraints. Geolocation coverage area is influenced by limitations imposed by the RF detection range but varies depending on the method of geolocation (i.e. AOA, TDOA, POA, etc.). These are all important considerations when selecting the method of geolocation and the location for a monitoring station site.

6 Conclusions

TDOA networks may be more effective for serving large cities and industrial centres, where a large number of sensors may be installed enabling automation of the monitoring process, including the transmitter geolocation function.

Conversely, relatively small towns and their neighbouring suburbs as well as isolated industrial centres may be more effectively served by a small number of DF or hybrid AOA/TDOA stations, separated by relatively large distances. In this case, the use of only two stations may be effective for performing geolocation of transmitters.

Detection of all signal activity over an entire metropolitan area is not realistically achievable with any fixed geolocation or monitoring technology. Regulators usually have priorities for monitoring parts of the spectrum in specific areas and during specific times/events that are important. Deploying a system that meets a majority of the needs with the flexibility to relocate and reconfigure when necessary is vital in today’s spectrum environment.

Deploying the right type of monitoring station based on the conditions of the area will minimize the number of stations while maximizing coverage and effectiveness. For example, in open rural areas with no large reflectors, AOA or AOA/TDOA (hybrid) stations will be highly effective. However, in dense urban or crowded mixed environments where close-in reflectors are densely packed into city blocks, use of a TDOA network with the ability to also use POA and hybrid geolocation algorithms may be more effective.

Annex 2

A simulation study of geolocation accuracy and coverage area for hybrid AOA/TDOA monitoring stations

1 Introduction

This Annex compares geolocation accuracy of hybrid AOA/TDOA radio monitoring stations with stand-alone AOA and TDOA systems, based on results obtained from a realistic computer simulation.

The study uses computer simulations to model the accuracy and coverage area obtained by radio monitoring stations capable of implementing hybrid AOA/TDOA techniques. Compared to stations based on AOA techniques alone or TDOA techniques alone, these simulations indicate that a hybrid AOA/TDOA system may provide coverage of a larger area of interest using a smaller number of stations, as well as increase geolocation accuracy, inside and outside the area surrounded by the monitoring stations.

2 Geolocation methods

Typical geolocation processing combines measurements from several sites to produce an estimate of emitter location. The quality of the location estimate is specified in terms of miss-distance (given in meters). Smaller values of miss-distance indicate a better location estimate.

As the emitter density increases, the capability of a spectrum monitoring/DF system to *accurately* geolocate emitters becomes an important characteristic, especially when dealing with interference problems.

There are many different methods available for geolocation processing. Discussed here are three different geolocation methods. The first method combines AOA measurements from multiple sites that use direction-finding antenna arrays to determine AOA. The second method combines TDOA measurements from a minimum of three sites (three pairs of TDOA measurements are required for geolocation). The third method combines a hybrid of both AOA and TDOA measurements to perform geolocation processing (a minimum of two sites are needed: one with both AOA and TDOA measurement capability, and one with TDOA measurement capability). For simplicity these three methods are referred to as AOA, TDOA, and hybrid AOA/TDOA.

Note that a monitoring site capable of AOA measurement is called an AOA site; a monitoring site capable of TDOA measurement is called a TDOA site, and a monitoring site capable of both AOA and TDOA measurements is called a hybrid AOA/TDOA site.

The main characteristics of the three geolocation methods are listed in the Table 1 below.

(See Report ITU-R SM.2211 for a more detailed discussion of the advantages and limitations of TDOA systems.)

TABLE 1

Geolocation System Characteristics	**AOA ONLY**	**TDOA ONLY**	**Hybrid AOA/TDOA**
Minimum number of sites required for geolocation	2 Stations	3 Stations	2 Stations, hybrid AOA/TDOA. One station can be TDOA only
Geolocation Accuracy	Linear decreasing as the distance to monitoring station increases	Approximately constant in between the TDOA sites Deteriorate rapidly in the area outside the TDOA sites	Same as TDOA in the area between the hybrid sites Similar to AOA in the area outside the sites
Accuracy decreases with increasing distance to emitter	Yes	Only for transmitters in the area outside the TDOA sites	Only for transmitters located far away from the hybrid sites.
Independent of signal modulation	Yes	TDOA does not work against unmodulated signals Difficult for narrowband signals	Yes, if there are at least two hybrid sites
Data communication requirement	Low, 10-30 kbit/s	Medium to High, 120 kbit/s – 2 Mbit/s	Can be as low as AOA, if only AOA is used or slightly higher than TDOA, if AOA and TDOA are simultaneously used

TABLE 1 (*end*)

Siting constraints (See § 3)	Larger antenna may be harder to erect, possibly limiting site availability	Simple Omni, easier to erect	Same as AOA for hybrid sites
Antenna complexity	Multi-element antenna	Single antenna	Multi-element and/or Single-element antenna
Calibration requirements	Sometimes (depends on AOA system)[6]	No	Sometimes (depends on AOA system)

As the Table shows, there are a number of advantages and disadvantages to each method. In a specific application, (urban/suburban, permanent/temporary, flat terrain/mountainous, etc.), the requirements for the deployment will determine the optimum configuration.

3 Simulation of geolocation accuracy using a specific example

A detailed computer simulation has been conducted of geolocation accuracy in and around the city of Belo Horizonte in Brazil. Different spectrum monitoring system (SMS) configurations, including AOA, TDOA, and hybrid AOA/TDOA are simulated and the results compared in terms of the expected geolocation accuracy performance.

The simulation was conducted using a software tool that combines geolocation calculation with hearability of the target signal at different stations under consideration, based on transmitter power and signal propagation effects using 3D terrain. The simulation includes specific assumptions about number of sites, receiving antenna height, emitter antenna height, and other parameters as given in Table 2.

TABLE 2

Parameters used in computer simulation results presented

Centre frequency:	450 MHz
Signal bandwidth:	25 kHz
Transmitter output power:	10 W or 1 W (e.r.p.) (see text)
Transmit antenna height:	10 m (above average terrain)
Receive antenna height:	30 m (above average terrain)
Receive antenna gain:	0 dB
Receiver noise figure:	12 dB
Received SNR at receiver:	+10 dB
Minimum number of stations receiving at specified SNR	2 Stations for AOA and hybrid, 3 Stations for TDOA

NOTE – Unless otherwise stated in the Table, the same parameters were used for all geolocation techniques: AOA, TDOA, and hybrid.

The geolocation accuracy was evaluated on the basis of miss-distance.

[6] Some AOA systems self-calibrate and require no further calibration adjustments unless changes are made.

4 Specialized software analysis tool

For this example, the complete software tool includes the following simulations:

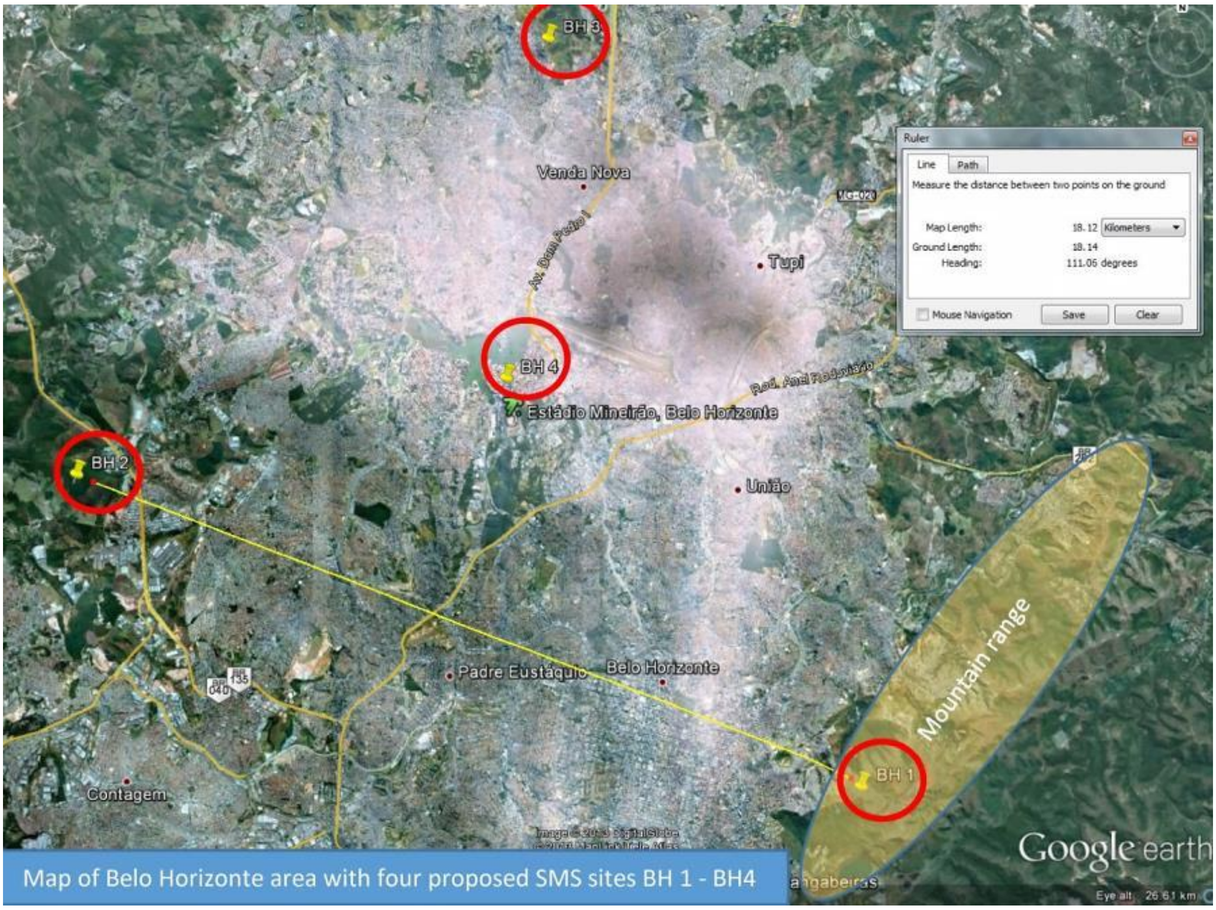
Coverage – Coverage analysis shows number of sites that can receive ('hear') emitter transmitting from the particular location at different power levels.

Geolocation accuracy – AOA, TDOA and hybrid AOA/TDOA geolocation accuracy analysis shows the performance of different geolocation methods.

Optimization of system configuration – This analysis shows the number of sites required for different geolocation methods to achieve comparable geolocation accuracy.

4(a) Example of geographic location

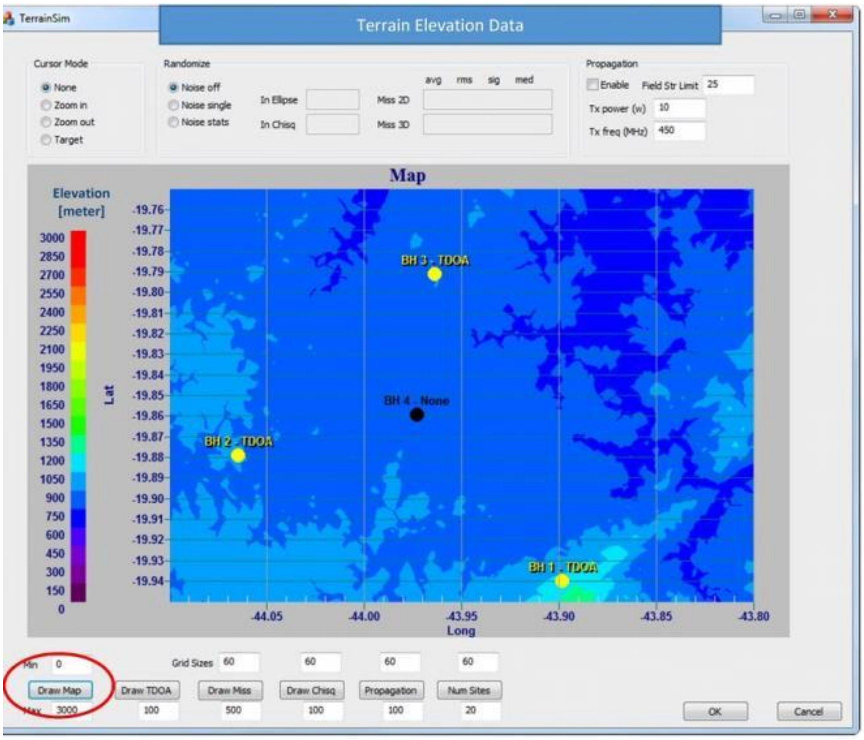
The figure below shows the locations of the four sites selected for analysis and identified as BH1, BH2, BH3 and BH4 in and around Belo Horizonte on Google maps. Site separation is approximately 18 km and terrain is relatively flat except for the mountain ridge near the BH1 site.



Map of Belo Horizonte area with four proposed SMS sites BH 1 - BH4

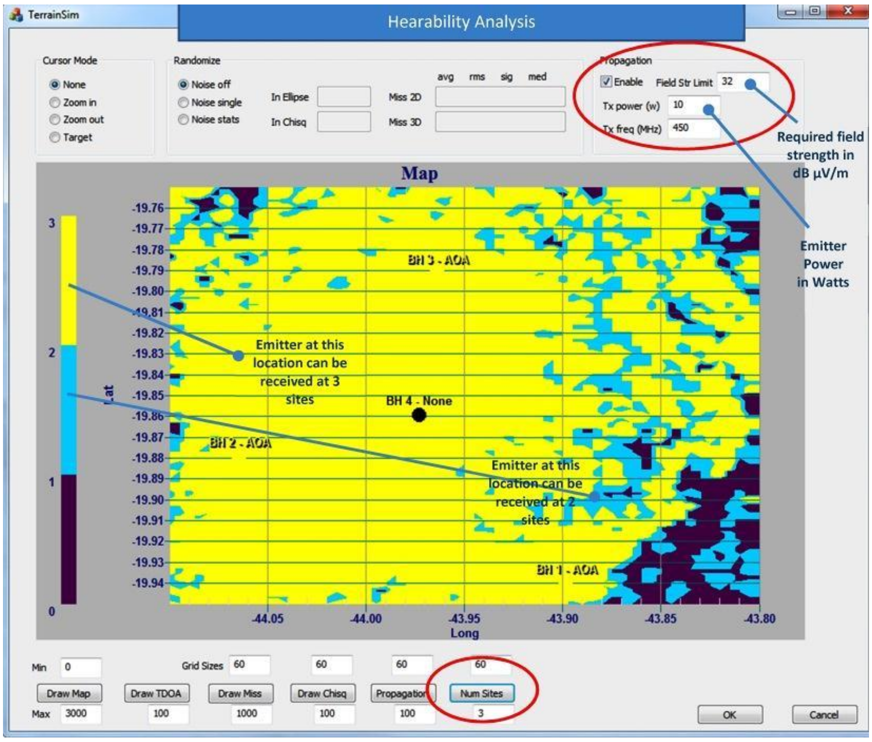
4(b) Example of terrain elevation data

The display shown below is the terrain elevation data. Also displayed are four site locations with their names and their geolocation capability. In this sample display, all sites are selected with TDOA capability. Terrain data is used both in propagation and geolocation calculation.



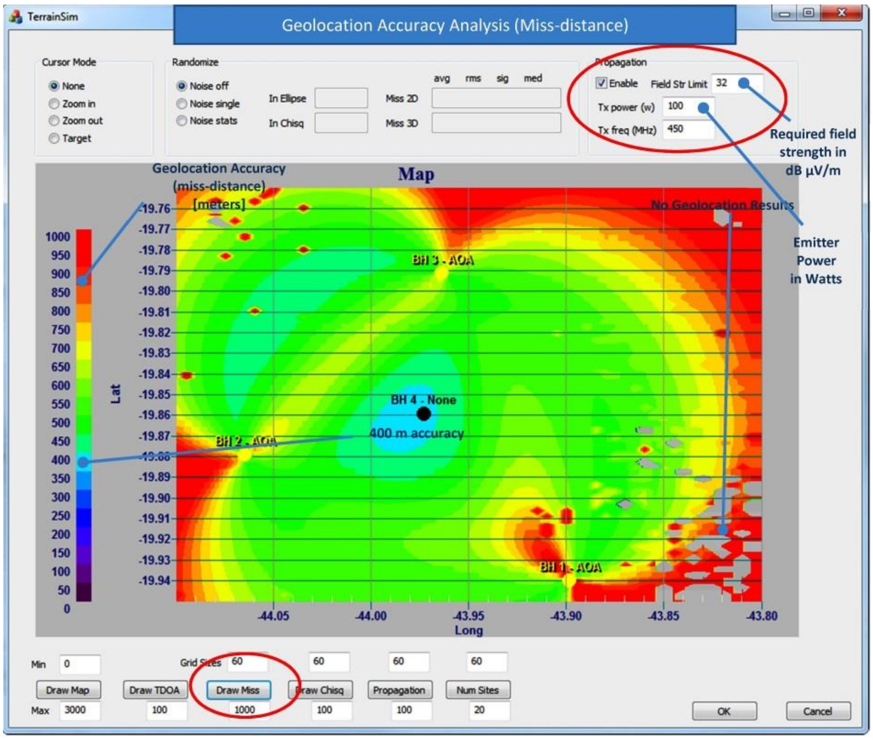
4(c) Example of hearability analysis

The next display shows the 'hearability' contours. In this display the colour coding indicates number of stations that can receive emitter signals at the required field strength. This display includes effects of both terrain elevation variations and transmitter power level. In this sample display all sites are selected with AOA capability.



4(d) Example of miss-distance plot

The next display shows the geolocation accuracy contours in terms of miss-distance (given in meters). Again, the miss-distance is calculated for the specific required field strength. In this sample display all sites are selected with AOA capability.

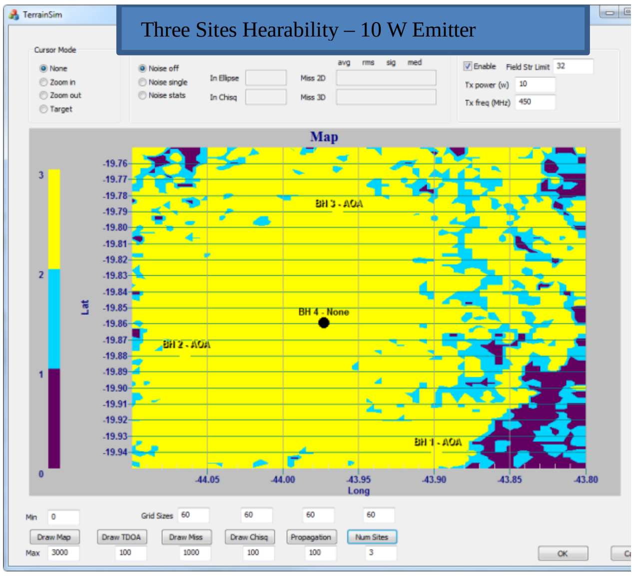


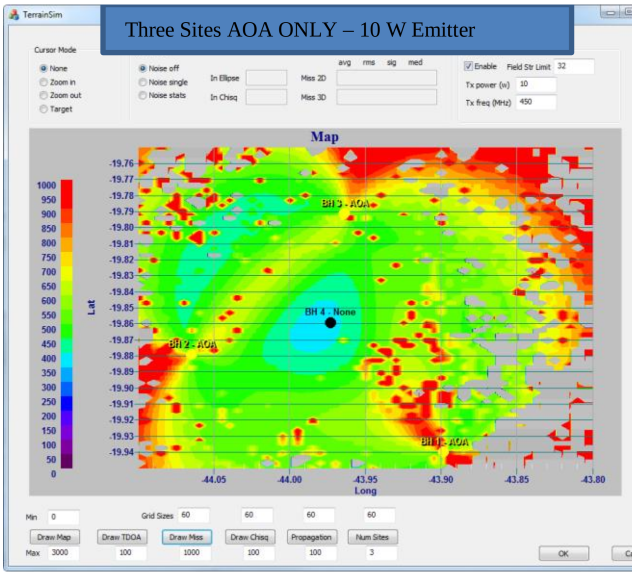
5 Results of simulations

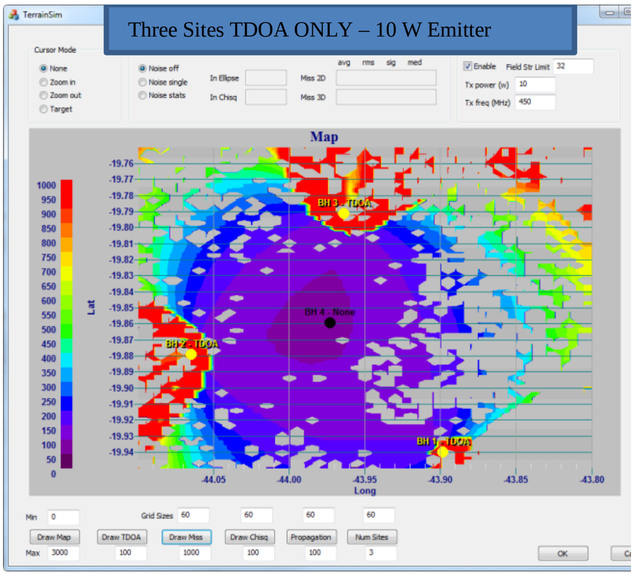
This case study was conducted under a variety of conditions, such as number of stations involved in the spectrum monitoring network, power of transmitter varied between 1 W and 100 W with different propagation conditions and different geolocation techniques. The following paragraphs give a summary of the principal results derived from this study using 10 W and 1 W scenarios.

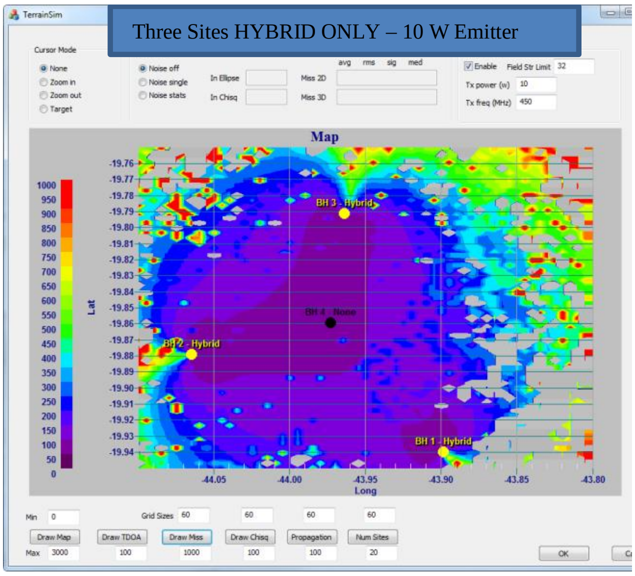
5(a) Network of three monitoring stations

The following figures present the comparison of AOA, TDOA and hybrid AOA/TDOA geolocation systems for the case of a 10 W transmitter. The first plot shows the hearability by each of the three stations of a 10 W transmitter located over the entire area of interest.









5(b) Summary of simulation results (3 stations)

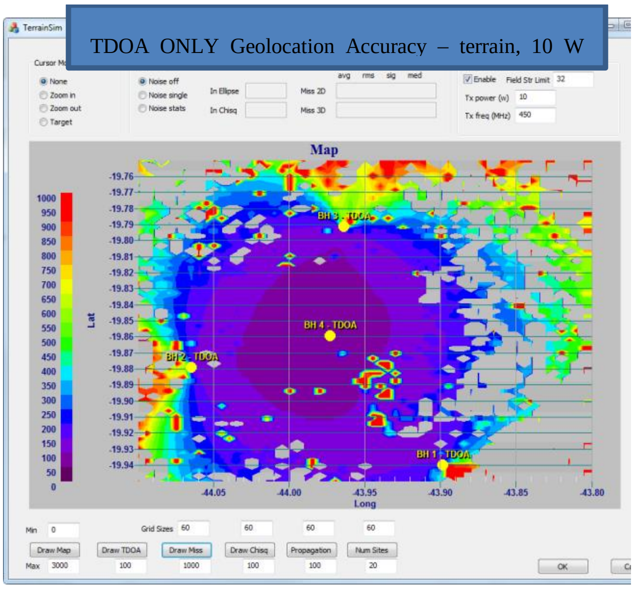
A system consisting of three AOA Stations covers the entire area of interest, but geolocation accuracy is poor for distant transmitters. However, AOA stations can provide LoB even if only one station intercepts the transmitter.

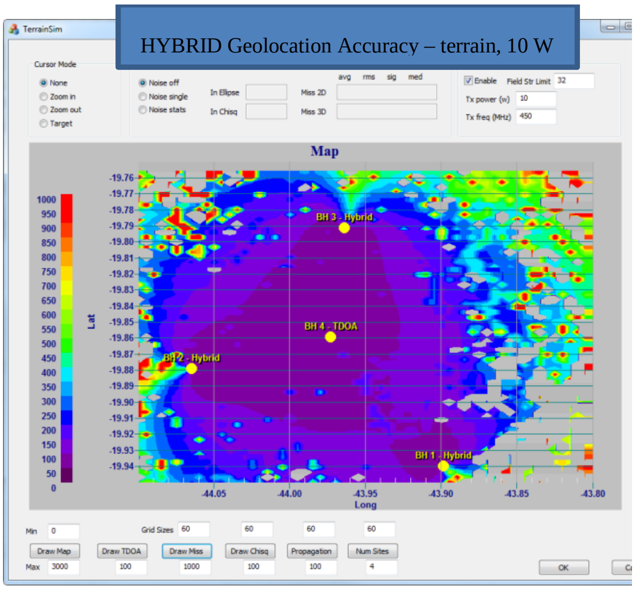
A system consisting of three TDOA stations provides good accuracy in the area bounded by the stations. However, as expected, geolocation accuracy degrades outside this area. In this simulation there are also large gaps (gray areas) where no geolocation result is expected, since TDOA geolocation coverage is partially dependent on site geometry as well as separation distance. Coverage for transmitters of 1 W or lower decreases as would be expected if only three TDOA stations are used at this separation distance (18 km) or if the emitter is not sufficiently close to at least one station. This simulation assumes a minimum of three sites with positive SNR are required. It doesn’t account for any ability to correlate into the noise floor (Both AOA and TDOA can generate a result with only one of the stations having positive SNR using correlative techniques).

For this example, a hybrid system using both AOA and TDOA techniques is expected to have better geolocation accuracy over a larger coverage area.

5(c) Network of four monitoring stations

The following figures present the comparison of geolocation results for systems based on TDOA and hybrid AOA/TDOA stations, for the case of a 10 W transmitter.





5(d) Summary of simulation results (4 stations)

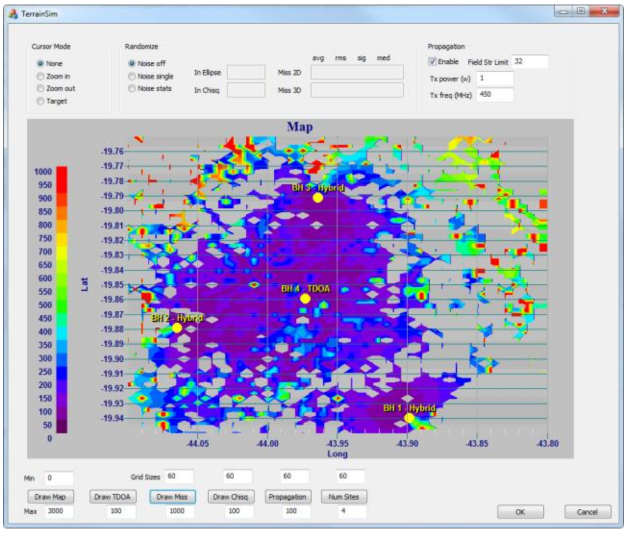
The results with a network of four stations are consistent with the results obtained with three stations, but with improved coverage results. Using only TDOA stations provides good accuracy in the area surrounded by the four stations, but geolocation accuracy degrades outside this area. There are also some gaps (grey areas) where no geolocation result is available. With four TDOA stations, coverage for transmitters of 1 W or lower decreases (for the same reasons discussed in the 3 station case).

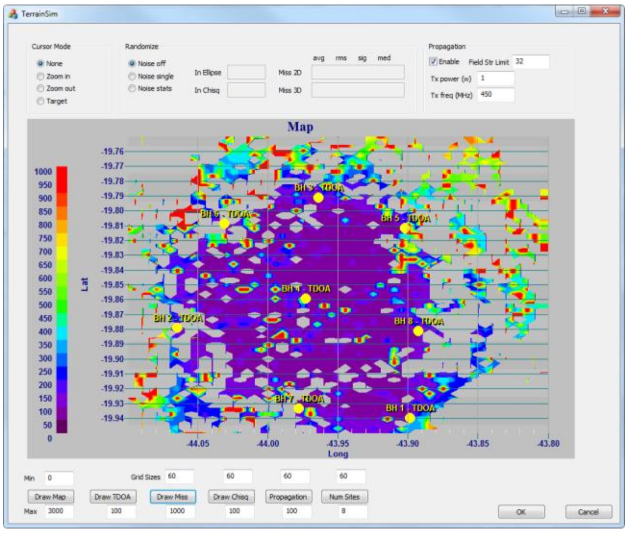
As in the three station example, this simulation shows that a hybrid system using both AOA and TDOA techniques may provide better geolocation accuracy over a larger coverage area.

5(e) Comparison of number of stations in network

The discussion in the previous paragraphs shows that the coverage area of a hybrid system using both AOA and TDOA techniques can be larger than the coverage area of an equal number of TDOA ONLY stations. In order to quantify the benefits of implementing a hybrid AOA/TDOA system, the number of TDOA ONLY stations required to provide coverage equivalent to that of a network of three hybrid AOA/TDOA stations plus one TDOA station has been modelled, for the case of a 1 W transmitter.

In the following figures, four hybrid stations are simulated on the left, and eight TDOA ONLY stations on the right.





Four Sites HYBRID (3xHYBRID + 1xTDOA)

Eight Sites TDOA ONLY

Based on this computer simulation, a hybrid AOA/TDOA geolocation solution is expected to require fewer stations than a TDOA ONLY geolocation solution to achieve the same or better coverage and same or better accuracy. Based on the assumptions in this simulation, a hybrid system using both AOA and TDOA techniques may offer a lower installation cost and lower recurring cost. Since each situation is different, careful consideration should be given to coverage requirements, terrain, site constraints and other factors in Table 1, in order to determine the optimum arrangement for a particular application.

6 Conclusion

Based on the computer simulations, a hybrid AOA/TDOA geolocation solution may offer a number of advantages over TDOA and AOA systems. In the example presented, a combination AOA/TDOA solution provides better coverage with fewer monitoring site locations.

Annex 3

A trial study of utilization of a TDOA system with an existing AOA system

1 Introduction

TDOA-based grid monitoring[7] provides affordable coverage of complex environments along with sophisticated capabilities for spectrum monitoring and emitter location. However, there are certain disadvantages of TDOA when compared with AOA systems and vice versa. Utilization of existing

[7] Grid monitoring is composed of monitoring sensors, antennas and supplementary accessories, which refers to monitoring a large district divided into several small monitoring areas (grids).

AOA system with TDOA system provides a useful complementary solution for these disadvantages of both types of systems.

The experimental programme of simple monitoring using both TDOA and AOA sensors was launched in Tokyo, Japan in 2016, to study the effectiveness of such a complementary monitoring system.

2 Objectives and test scenarios

The objective of the program was to determine how to best configure the TDOA system with an existing AOA system considering the strength and weaknesses of both systems.

2.1 Collocation of TDOA and AOA sensors

TDOA sensors were placed at the same location as existing AOA sensors around the Tokyo bay area and were used to determine test emitter locations. Both systems were used to make the measurements.

TDOA sensors were connected to omnidirectional antenna and used a wired LAN network.

A test transmitter signal from a known location was used in the experiment.

Figure 18 shows the location of the AOA and TDOA sensors (3 AOA and 3 TDOA sensors).

FIGURE 18

Location of AOA and TDOA sensors

2.2 Collaboration between fixed AOA and mobile TDOA sensors

Since the AOA system cannot estimate the emitter location unless two or more lines of bearing can be obtained, in the case where only one line of bearing can be obtained, the location of emitter location can be estimated by utilizing mobile TDOA sensors.

To implement this for the trial, a fixed TDOA sensor was deployed one by one at the same location as each AOA sensor. In addition, one mobile TDOA sensor was used.

The concept of this monitoring system is that the mobile TDOA station would move along the line of bearing measured by the AOA sensor.

3 Results

3.1 Collocation of TDOA and AOA sensors

The signal from a known emitter position was captured and the emitter position was estimated by using AOA system. Coloured lines (White, yellow and blue as shown in the figures) are the lines of bearing calculated by the AOA method. During some measurements, the lines of bearing did not intersect at one point as shown in Fig. 19.

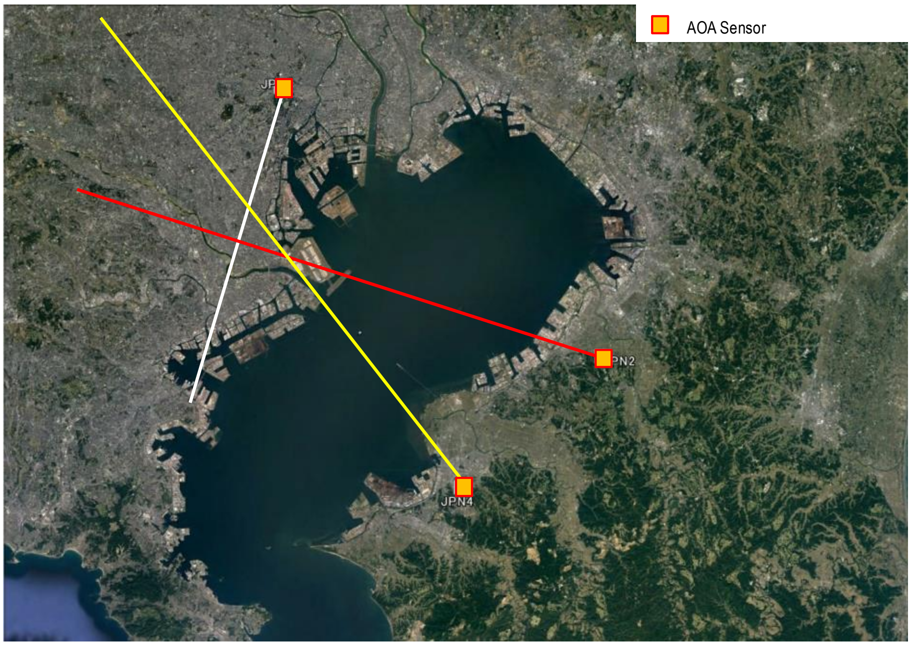
The reason for this could not be determined, but it may have been due to a close reflector or other wave front distortion.

Known emitter signal profile is as follows at this case:

Frequency	1 020.0 MHz
Occupied Bandwidth	500 kHz

FIGURE 19

Result obtained by AOA method



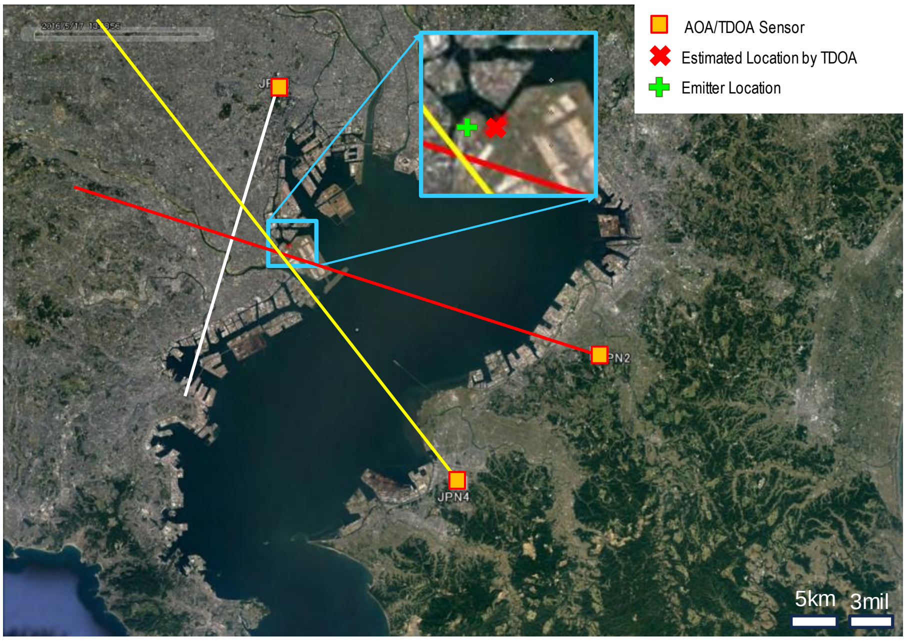
The same signal was captured by the TDOA sensors and the estimated position was calculated.

To narrow down the emitter position and minimize the ambiguity, the results of both TDOA and AOA were shown.

Figure 20 shows the estimated position by both AOA and TDOA overlaid.

FIGURE 20

Estimated position by TDOA and AOA method



These results show that the simultaneous measurements both AOA and TDOA can reduce the ambiguity and/or improve the accuracy of emitter location measurements.

In some cases, it was found that one AOA with two TDOA sensors works well to locate the emitter.

In order to successfully estimate the emitter position, at least two AOA sensors or three TDOA sensors are needed if either method is used standalone (AOA or TDOA). However, due to multipath, obstacles, weak signal etc., it might not be possible to detect the emitter signal on a sufficient number of sensors.

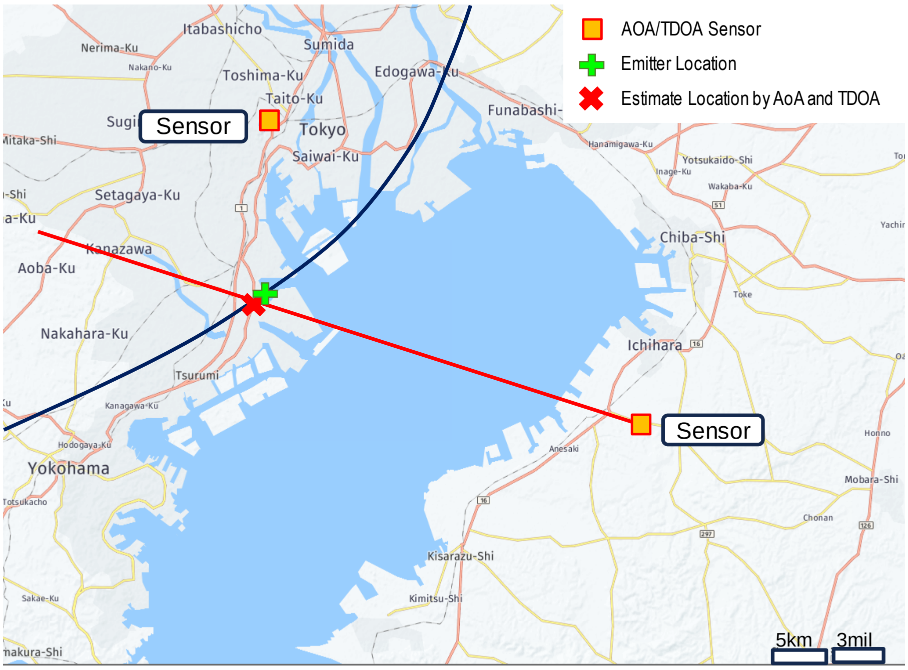
To address this situation, it was found that a combination of the AOA and TDOA methods can successfully estimate the emitter position even when a sufficient number of sensors could not receive adequate signal level.

Figure 21 shows the actual measurement results obtained with one AOA station and two TDOA sensors. The red line is the line of bearing and the blue line is the hyperbolic line formed by two TDOA sensors.

This shows that one line of bearing and one hyperbolic line can locate the emitter position. The estimated emitter location (Red x) can be derived from the intersection of the two lines.

FIGURE 21

Combination result with one AOA sensor and two TDOA sensors



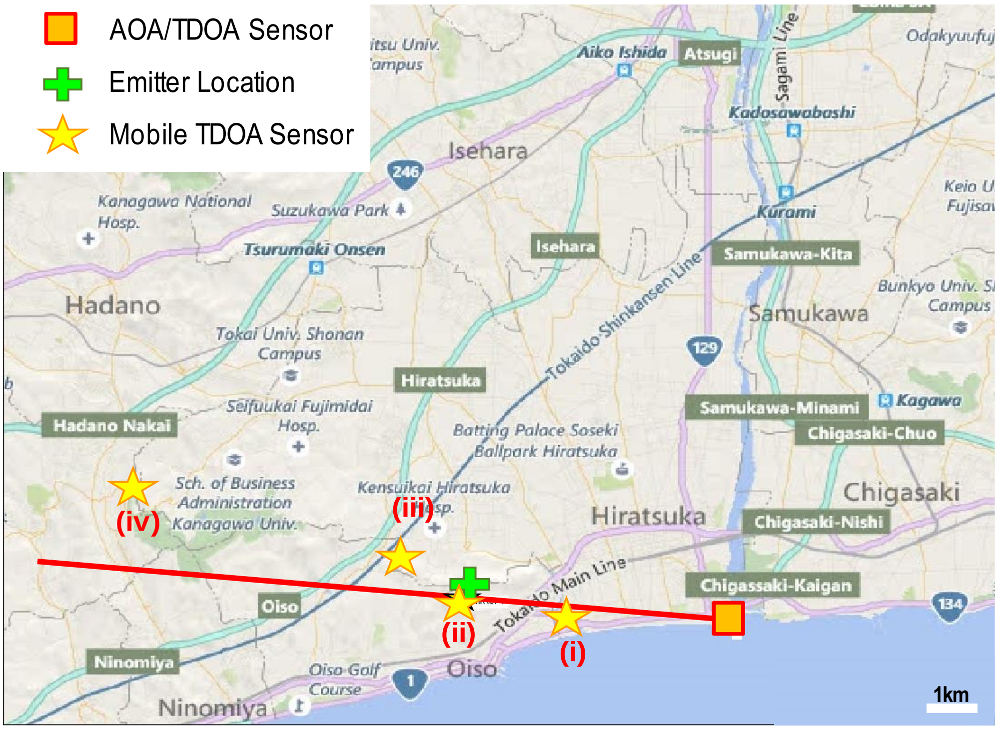
3.2 Utilizing mobile TDOA sensors with fixed AOA sensor

If a line of bearing is obtained from one AOA sensor, it can be assumed the emitter is located along the line of bearing. In that case, a mobile TDOA sensor can move on the line of bearing starting from near the AOA sensor to the far end and the hyperbolic lines formed with another fixed TDOA sensor located at the AOA sensor can estimate the emitter location.

Figure 22 illustrates this concept.

FIGURE 22

Concept with an AOA sensor and a mobile TDOA sensor



The line of bearing obtained by AOA is the red line in Fig. 22.

The mobile TDOA sensor moved from near to the AOA sensor position toward the far end of the line of bearing. This was done to home the emitter location (from location (i) to location (iv), shown in Figs 23 to 26) and the hyperbolic lines were calculated at each position.

Figures 23, 24, 25 and 26 show the results of the estimates of the emitter position with one AOA sensor and two TDOA sensors.

FIGURE 23

Estimated position at location (i)

FIGURE 24

Estimated position at location (ii)

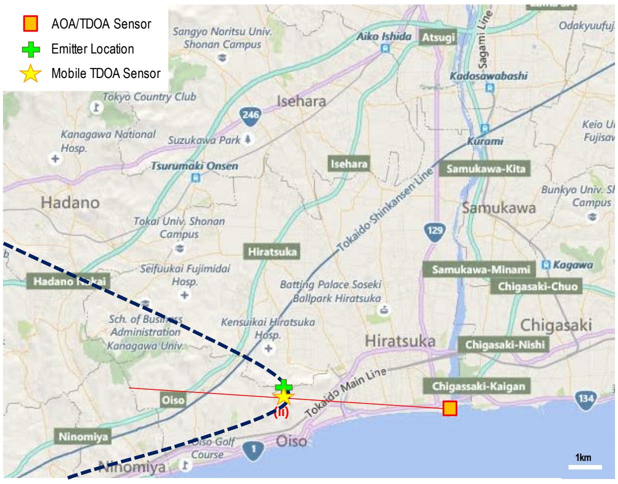
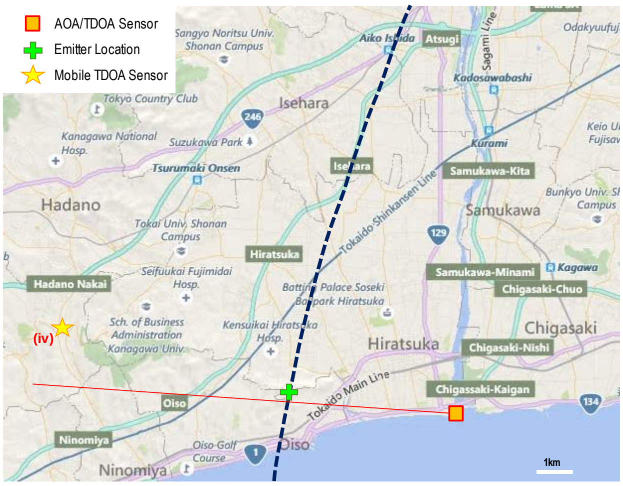


FIGURE 25

Estimated position at location (iii)

FIGURE 26

Estimated position at location (iv)



The result calculated at location (i) does not show a valid position, because the calculated time of difference exceeded the time associated with the radio wave transit between the TDOA sensors.

The distance between TDOA sensors on Fig. 23 was 3.0 km and along with 10 us of radio wave transit time. Calculated time of difference by TDOA algorithm were 9.99 us.

This means that location of the emitter could not exist in between two sensors where emitter location could be determined by the TDOA sensors.

The distance between TDOA sensors on Fig. 24 was 5.0 km along with 16.7 us of radio wave transit time. Calculated time of difference by the TDOA algorithm was 16.6 us.

Results calculated for location (iii) and (iv) was good, because the emitter location computed consistently in between two the sensors.

The distance between TDOA sensors on Figs 25 and 26 were 6.6 km and 12.55 km along with 22 us and 41.7 us of radio wave transit time. Calculated time of difference by TDOA were 11.74 us and −8.42 us.

4 Conclusion and future subject

In some areas where AOA systems have already been deployed, a TDOA monitoring system could be complementary.

In this Annex, it was demonstrated how to collaborate the TDOA monitoring system with an existing AOA sensor. As a result, several advantages from the collaboration of TDOA and AOA were found:

– Advantage 1: The ambiguity of the estimated location of an emitter can be decreased by comparing the results of both TDOA and AOA.

– Advantage 2: Combining the line of bearing obtained by AOA and the hyperbolic line obtained by TDOA makes it possible to estimate the position of the emitter with a smaller number of sensors.

– Advantage 3: Even when the physical TDOA sensor network cannot be available, collaboration of AOA and TDOA system to locate emitter position can be deployed by one AOA sensor and two more TDOA sensors (at least one of those must be mobile TDOA sensor).

The experiments described in this annex were carried out without a permanent network connection or sensor installation for the TDOA system.

Mobile TDOA system may not receive the signal simultaneously at every measurement location, but works well if the hyperbolic lines are combined with AOA result and could locate the emitter position.

In addition, this may extend the robustness of existing AOA monitoring station/networks with additional TDOA sensors.