Issues and Approaches for Navigation Using Signals of Opportunity

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Biography

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ABSTRACT

There are many situations in which GPS is either unable to provide the desired level of accuracy or is unavailable, particular in urban or indoor environments. One alternative to GPS is to navigate using signals of opportunity (SoOP)—signals that are intended for purposes other than navigation.

This paper describes the benefits and drawbacks of navigation using SoOP and identifies typical SoOP system configurations. Three different types of SoOP measurements are described, including ranging through signal strength, angle of arrival, and time-difference of arrival (TDOA) measurements. Positioning algorithms, ambiguity resolution issues, and measurement quality and geometry are also addressed.

INTRODUCTION

Over the past couple of decades, there have been a number of navigation trends that have driven the desire to improve our ability to navigate in all environments. Table 1 notionally represents these trends. Previously, the primary desire was to navigate single, stand-alone systems (such as a car), but now, the desire is increasingly to have simultaneous navigation awareness of multiple interdependent systems (such as a traffic notification system in a car). Previously, navigation capability was not always counted on, but increasingly navigation is considered to be an assumed infrastructure (like knowing the lights will come on when you turn on the light switch). Previously, navigation accuracy of 5-10 m seemed almost extravagant when other worldwide navigation options prior to GPS (namely, Omega [1] and stand-alone

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inertial) had accuracies more on the order of 1-2 km. Now, there are many applications that require meter or sub-meter level accuracy (such as precision agriculture). Previously, due to cost, power, and size constraints, it was generally only feasible to know where the "big things" are (such as airplanes). Now, navigation is desired on more and more, smaller and smaller objects (such as cell phones).

Table 1. Navigation Trends

Then	→	Now
Single, stand-alone systems	→	Multiple interdependent systems work together to achieve goal (requires navigation)
Precise navigation as a "nice-to-have" entity	→	Complete dependence on reliable navigation (navigation as an assumed infrastructure)
Navigation accuracy: 5-10 m is sufficient	→	Sub-meter to cm-level accuracy desired ("Accuracy is addictive")
We want to know where the "big things" are	→	We want to know where everything is

While GPS has been the driving factor behind most of these trends, there are limitations to GPS that have become more evident over time as we have increasingly come to rely on navigation. The shortfalls in GPS could be called the "navigation gap", as depicted notionally in Figure 1. The horizontal axis in this figure represents the continuum between urban/indoor and rural/open environments. The vertical axis roughly represents altitude, from ground level all the way up to space. GPS does a great job of covering much of this two-dimensional trade space (indicated by the solid blue shape), but GPS by itself is not sufficient when moving close to the bottom left corner. Recent advancements in high-sensitivity GPS have helped to decrease the size of this gap (indicated by the striped blue shape), but there still remains a gap where availability, accuracy, or reliability of GPS by itself is not sufficient for many applications. Ironically, it is in just such urban/indoor locations where many people spend most of their time. (In fact, odds are that you would have a hard time obtaining a high accuracy GPS fix wherever you are reading this paper!)

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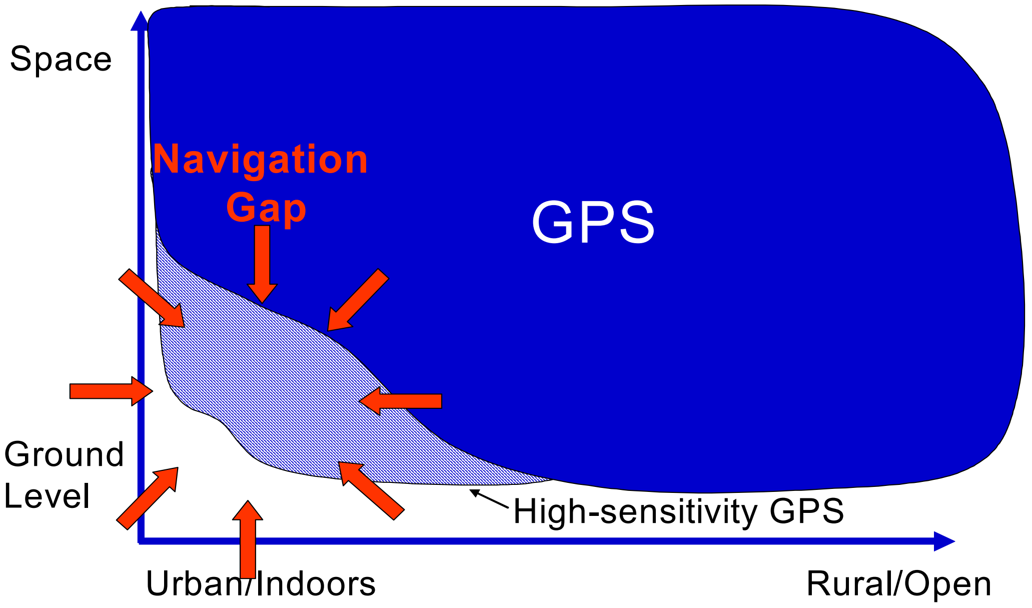

Figure 1: The Navigation Gap

Alternative Navigation Techniques

For the reasons described above, alternative navigation techniques have been and are currently being developed to help fill this navigation gap. At least three broad categories of alternative navigation techniques exist:

1. **Image/lidar/Doppler/DR aiding of inertial.** These techniques attempt to use an inertial system, but constrain the drift by incorporating another source or sources of aiding. Such systems are typically self-contained. Examples include image-aided inertial navigation [2], lidar-aided inertial navigation [3], and pedometry-based DR-aiding of inertial [4].

2. **Beacon-based navigation (including pseudolites)**. If the GPS signal is not adequate for navigation in a particular environment, it is possible to transmit an additional signal or signals that are specifically designed for navigation purposes. If the transmitted signals are similar to GPS signals, then such beacon transmitters are usually called "pseudolites." Examples of beacon-based navigation systems for indoor navigation can be found in [5] and [6].

3. **Navigation using signals of opportunity (SoOP)**. Signals of opportunity, as defined in this paper, are radio frequency (RF) signals that are not intended for navigation. Examples from previous research include digital television [7], analog television [8], and AM radio [9,10].

This paper is focused on the third category listed above—navigation using signals of opportunity. Focusing on SoOP does not imply that the other alternative navigation approaches are inferior to SoOP. There are strengths and weaknesses to each approach, and selecting the appropriate approach requires knowledge of the constraints and requirements of a specific application.

REASONS TO USE SIGNALS OF OPPORTUNITY

There are many SoOP available for navigation. There is potential for incredible signal diversity, in both direction and frequency, when using signals of opportunity. Depending on the location, there can be dozens of potential SoOP signals. There are some locations where there many not be many SoOP available, but such signals are much more plentiful in typical urban environments (where the navigation gap is). Also, because of the large number of signals at different frequencies and different directions, there is potential to mitigate some of the errors that vary as a function of frequency and direction (such as multipath).

SoOP can be relatively high power and are able to penetrate buildings. This concept can be exemplified by comparing GPS received signal power to a typical FM radio station. A GPS satellite transmits at 282W effective isotropic radiated power (EIRP) from a distance of approximately 20,000 km (if the satellite is directly above the receiver). In contrast, consider an FM radio station with an effective radiated power of 50,000W at a distance of 20 km. The combined difference in radiated power and path loss means that the FM radio station will have over 82 dbW/m^2 more received power density (i.e., a received power density that is 1.8×10^8 W/m^2 higher than that of GPS). This is much more power margin available to penetrate walls and buildings. (This is part of the reason why a typical FM radio will work inside a building but a typical GPS receiver will not!)

No infrastructure is required to transmit the signals. SoOP are already being transmitted for other purposes (by definition), so they are essentially “free” to the navigation user. There is no need to set up transmitters in order to navigate using signals of opportunity.

Advances in radio technology are making navigation using SoOP more feasible. Relatively recent improvements in radio technology have made it more reasonable to consider building a radio that receives and processes data simultaneously from many different signals. For example, there are more examples of software-defined cognitive radios that are able to quickly switch frequencies as needed to avoid interference (usually for communication purposes) [11]. These are the type of capabilities that would be important for a practical SoOP radio. Additionally, the size and power requirements for radios has decreased and battery technology have improved (consider the modern cell-phone in contrast to the 1980’s vintage equivalent).

All of the reasons stated above indicate why navigation using SoOP is promising; however, this is not the complete picture. There are some very real difficulties in this approach, and these are described in the next section.

CHALLENGES OF USING SIGNALS OF OPPORTUNITY

SoOP are not optimized for navigation. Unlike GPS and other signals transmitted for the purposes of navigation, SoOP are usually not designed with navigation in mind. One of the most important factors is timing. In order to use the time of arrival to determine position, the transmission time must be known. However, most communication systems are not time-synchronized to an accuracy of several nanoseconds (like GPS), which would be required in order to navigate without an additional reference receiver.

Availability varies by location. Signals of opportunity are not uniformly available throughout the world. While many signals of opportunity tend to exist in urban areas, the exact nature of these signals can vary between various countries, due to different broadcasting and communication standards.

Transmitter locations must be known. In order to navigate using signals of opportunity, the locations of the transmitters must be known. (If the transmitter is far from both the mobile receiver and a reference receiver, then just the direction of the transmitter is required.) Knowing the location of stationary transmitters is normally relatively easy to accomplish. However, if the transmitters are moving, then they may not be as useful as a potential signal of opportunity for navigation.

There are challenges in building reasonable SoOP navigation radios. One of the advantages of signals of opportunity is that there are a wide variety of signals in different frequency bands. However, for a radio to receive a wide variety of signals, it must have 1) a wideband antenna, 2) a wide bandwidth front-end, and 3) adequate signal processing to handle the wide bandwidth front end data (high sample rates, etc.). For example, a radio that tracks a single television channel only needs to be able to process a signal with a 10 MHz bandwidth (the spacing between television channels). However, if a radio is to simultaneously track many television signals, then it must be able to process signals between 45.25 MHz (the low end of the broadcast VHF signals) and 801.25 MHz (the high end of the broadcast UHF band). It should be made clear that these difficulties can be overcome by more advanced hardware design techniques, higher-end hardware, faster samplers, etc., but that doing so generally requires larger, more costly, more power consuming hardware than what is required for tracking a single signal.

Multipath and non line-of-sight (NLOS) problems are significant. When considering indoor or heavy urban environments, it is likely that many of the RF signals that can be tracked by a receiver will be reflected or scattered signals. For communication purposes, such reflected signals do not pose a significant problem, because the same information is present in the reflected signal as in the direct signal. However, when using the signals for navigation, it is the *timing* of the signal that is most important, and the timing is very much changed when a reflection occurs. Any reflected signal is a non line-of-sight (NLOS) signal, and tracking such signals will cause problems if they are not recognized to be NLOS signals. (Even if they are known to be NLOS signals, they are of limited usefulness unless the point of reflection can be determined). While this is perhaps the greatest challenge with using SoOP for navigation, the multipath/NLOS problem is faced by any other system (such as beacon navigation systems) that uses RF-based signals for position determination.

MEASUREMENT TYPES

It is possible to infer both position and velocity information from signals of opportunity. Velocity can be determined by measuring the frequency (or phase change) of a signal, if the transmission frequency of the signal is well-known. Velocity can be very helpful in a variety of situations, including integrated systems (where it can be used to constrain the drift of inertial systems), but it is not very useful for directly determining position, so it will not be described in this paper.

There are three primary ways that signals of opportunity can be used for positioning: 1) range via signal strength, 2) angle of arrival, and 3) time-difference of arrival (TDOA). Each of these will be described below.

Ranging via signal strength. This method uses the fact that signal strength decreases as a function of distance from a transmitter. If the transmit and received signal powers are known, and there is a good model for the path loss, then it should be possible to determine the range from the transmitter. This approach is often used to determine relative location in ad-hoc sensor networks [12]. However, for many practical signal of opportunity navigation scenarios, particularly in urban environments, this method is not adequate, since there can be many things (such as buildings) that affect the signal propagation. Who has not experienced good cell phone coverage on one side of a room but very poor coverage on another side of the same room? This exemplifies that signal strength is not, by itself, always useful for determining range to the transmitter.

Angle of arrival. Multiple-element antennas can be used to determine the angle of arrival of a signal, and knowing the angle of arrival from multiple transmitters enables the user to use triangulation to determine position, as shown in Figure 2. The position accuracy worsens as the distance to the transmitter increases, reducing the usefulness of this approach for anything but very close-in SoOP (such as WiFi transmitters). While performing triangulation using angle of arrival measurements may not be feasible, knowing the angle of arrival can still be very valuable for distinguishing between direct and NLOS signals.

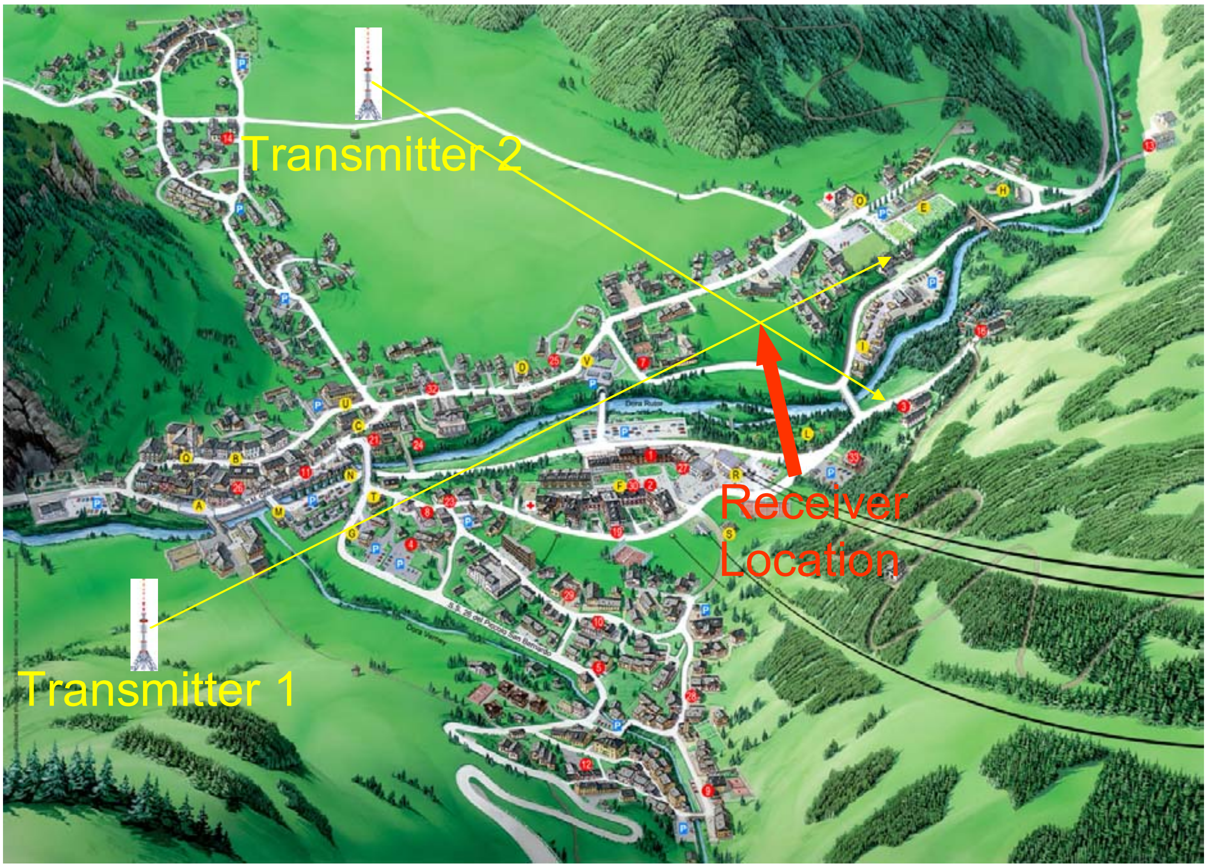

Figure 2: Example of Triangulation Using Angle of Arrival Measurements

Time-difference of arrival. Time-difference of arrival (TDOA) measurements calculate the difference in arrival time between two different receivers. Figure 3 shows the general concept behind TDOA measurements. This figure does not account for clock errors in the reference or target receiver, which would induce a bias in the TDOA measurement. TDOA measurements have potential of giving high accuracy position information that can be used to determine the mobile receiver's position. The rest of this paper will focus primarily on TDOA measurements.

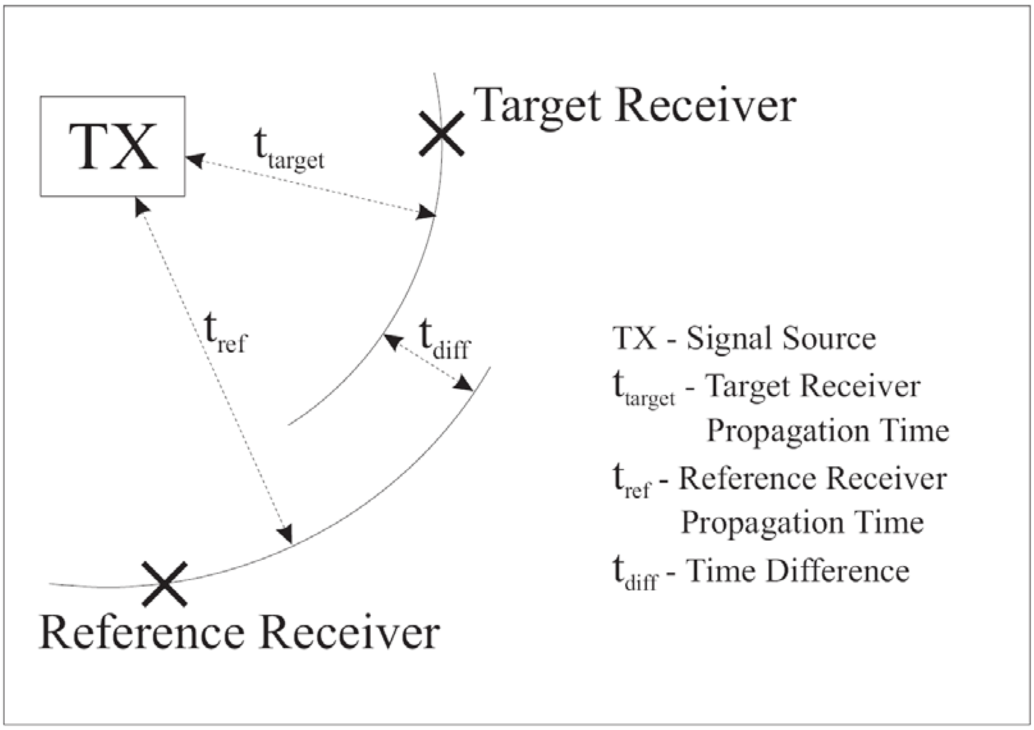

Figure 3: Illustration of TDOA Measurement [13]

TDOA POSITIONING SYSTEM ARCHITECTURE

Figure 4 shows a typical system architecture for positioning a mobile receiver in a fictitious city using a single reference receiver and several signal transmission sources. Each source is transmitting a signal of opportunity, which is received at both the mobile and reference receiver (shown by the two arrows from each source). There is a backchannel communication link that enables the mobile receiver to determine the time-difference between the signal's arrival at the mobile and the same signal's arrival at the reference. (The next section will describe methods of doing this). The reference receiver is needed in order to determine (and ultimately remove) the effect of the transmitter clock error, since for a typical SoOP, the transmitter clock error is normally not known. The backchannel communication link is necessary for this type of system to work in real-time, and the TDOA measurement cannot be formed without it. This adds to the complexity of a SoOP navigation system relative to standalone systems like GPS.

TDOA MEASUREMENT FORMATION

TDOA measurements are typically formed in one of two ways. The first method is to perform a direct cross-correlation between samples from the reference receiver and samples from the mobile receiver. The time offset corresponding with the peak of this cross-correlation is then the TDOA measurement, indicating the delay at which the signal most closely correlates between the two receivers. A big advantage of this direct cross-correlation technique is that the exact signal structure does not need to be known in order to obtain the TDOA measurement. This may be particularly useful in the SoOP case, because the user has no control over the signals being transmitted. For example, an encrypted signal can still be used to determine a TDOA measurement, even if the encryption prohibits extracting the information out of the signal. The primary disadvantage of the direct cross-correlation technique is that it requires significant bandwidth over the backchannel to move the raw samples from the reference to the mobile receiver, because the raw samples are taken at a very high sampling rate. (At an absolute minimum, the sample rate should be at least twice the front end bandwidth to avoid aliasing).

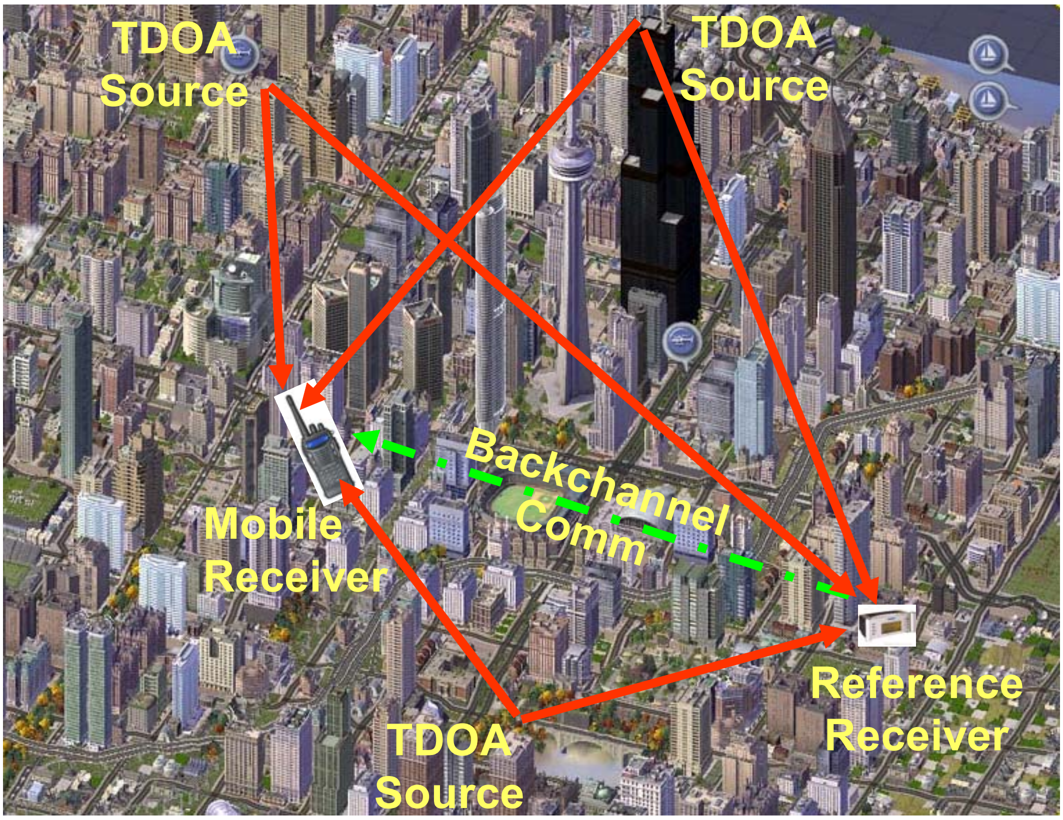

Figure 4: Typical TDOA Positioning System Architecture

The second way to form a TDOA measurement is to separately detect signal "features" in each receiver, and then share only the time at which those features were detected. For example, Figure 5 shows the synchronization pulses that occur at the beginning of each frame for typical analog television transmissions. (At the beginning of each frame, the electron beam starts at the top of the screen and starts scanning downward). These synchronization pulses are a "feature" in the signal which can be observed and timed by a receiver. The reference receiver can determine the start time of this pulse sequence and send that start time to the mobile receiver through the backchannel communications link. The Mobile receiver measures its own start time for its own synchronization pulses and differences it with the reference receiver start time to form the TDOA measurement. This same concept can be applied with any type of signal that has known, measurable features in the time domain. This approach requires minimal backchannel communications bandwidth, because only measurement time is passed (rather than the raw samples as in the direct cross-correlation case).

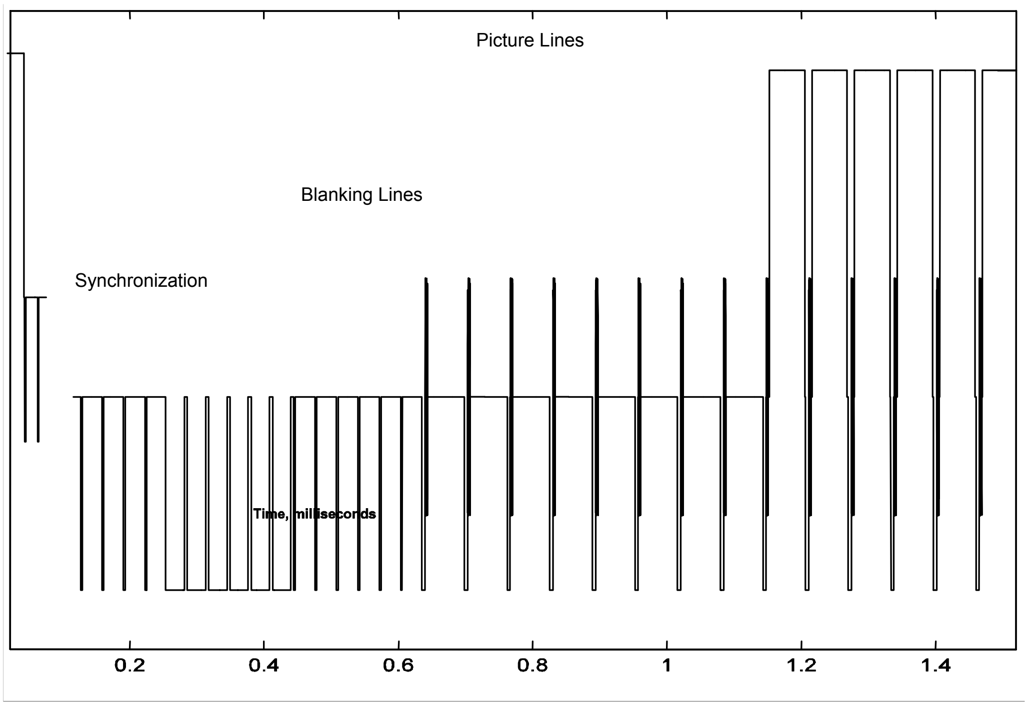

Figure 5: Synchronization Pulses and Blanking Lines for Analog Television Signal [13]

TDOA POSITIONING ALGORITHM

There are a number of methods for determining position from a set of TDOA measurements. This section describes the approach given in [14].

Figure 6 shows a base (reference) station and a rover for a generic signal of opportunity transmitter. The TDOA measurement represents the difference between the time of arrival (TOA) of the signal at the rover and the base:

$$TDOA^i = TOR_r^i - TOR_b^i \qquad (1)$$

Recognizing that there are clock errors that affect each of the TOR measurements, this can be converted to

$$TDOA^i = \frac{d_r^i}{c} - \frac{d_b^i}{c} + \delta t_r - \delta t_b \qquad (2)$$

where d_r^i and d_b^i are the distances from the rover and base station to the SoOP, δt_r and δt_b are the clock errors in the rover and base receivers, and *c* is the speed of light. Rearranging terms yields

$$\underbrace{cTDOA^i + d_b^i}_{\text{"Pseudorange"}} = \underbrace{d_r^i}_{\text{range}} + \underbrace{c\left(\delta t_r - \delta t_b\right)}_{\text{clock error}} \qquad (3)$$

As indicated in Equation (3), if the distance between the base station and the SoOP source (d_b^i) is subtracted from the TDOA measurement (after converting units from time to distance), then the result is the distance between the rover and the SoOP source plus the differential clock error. This is essentially the same as a GPS pseudorange measurement, which describes the distance between the user and the satellite plus a receiver clock error. Note that in the TDOA case, the differential clock error will be the same for all simultaneous TDOA measurements, just as the receiver clock error is the same for all simultaneous pseudorange measurements.

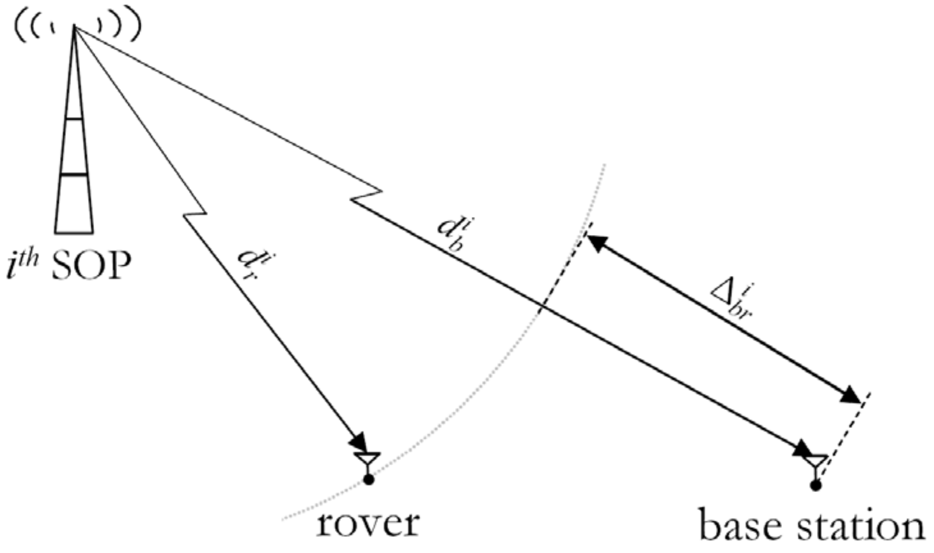

Figure 6: Geometric Interpretation of TDOA Measurements [14]

Because the TDOA measurement can be converted into a pseudorange measurement in this way, all of the methods for computing position based on pseudorange measurements can be applied in the TDOA case. Not only does this approach provide a convenient way to solve for position, but it also provides valuable insights into the number of measurements that are required for TDOA positioning with signals of opportunity, as well as the effects of measurement geometry.

For example, in order to solve for a three-dimensional position, at least four TDOA measurements are needed (to solve for three position and one clock error). However, the SoOP transmitters and the receiver are nearly coplanar (a common condition with ground-based SoOP and receivers on the ground), then there will be poor observability in the vertical direction. In this case, additional constraints or measurements must be applied. For ground-based systems (such as vehicles), a reasonable approach is to constrain the solution to the surface of the ground [15].

AMBIGUITY RESOLUTION

For people familiar with navigation technology, the term "ambiguity resolution" often applies to the need to resolve the integer ambiguities in GPS carrier-phase measurements in order to obtain the highest level of accuracy for GPS. When using SoOP, there can sometimes be ambiguities in the TDOA measurements as well. Ambiguities occur when there are parts of the signal of opportunity that repeat in time. For example, for the analog television signal shown in Figure 7, the synchronization pulses occur at the beginning of each frame. Each synchronization pulse sequence repeats at a rate of 30 Hz.[1] This means

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[1] The analog television signal actually consists of two interlaced frames each refreshing at a 30 Hz rate, for a combined refresh rate of 60 Hz. However, each individual frame (Frame 1 or Frame 2) has a unique synchronization sequence which repeats at a 30 Hz rate.

that, if the synchronization sequence at the rover was incorrectly compared to the subsequent synchronization sequence at the base (reference), then there would be an ambiguity error of 1/30th of a second, which is equivalent to approximately 10,000 km. In this case, the TDOA measurement would be approximately 10,000 km off from the correct value. It is easy to correct for this large of an ambiguity, because usually there is at least some rough idea of where the receiver is located, and all that's important is to know this approximate location more precisely than the ambiguity. For analog television, simply assuming that one is within reasonable range of the transmission tower would suffice.

The problem is more difficult for other signals of opportunity, however. Consider AM radio, which consists of an amplitude-modulated sinusoidal carrier signal. Because the AM signal is primarily dominated by a fixed-frequency carrier, there is a significant amount of replication, even with the varying amplitude. As a result, it is possible to associate one carrier cycle in the rover with another carrier cycle in the base receiver, resulting in an ambiguity error in the TDOA measurement. AM radio has wavelengths between approximately 175-575 m, so it may not be possible to know an initial position precisely enough to determine the ambiguity error directly, as in the television case. In this case, ambiguity resolution techniques similar to those used by GPS may need to be employed. Note that, for a static roving receiver, there is no geometry change when using fixed TDOA measurements, so the benefits of geometry change experienced with GPS (due to the moving satellites) will not be experienced with SoOP.

MULTIPATH AND NON LINE-OF-SIGHT ERRORS

As described earlier, multipath and non line-of-sight (NLOS) errors can be significant when using RF signals for urban or indoor navigation. This is probably the largest hurdle to overcome before SoOP navigation accuracy approaches GPS accuracy. For the purposes of this paper, multipath will be defined as a delayed signal causing a distortion in the received signal, such that an error is induced in the TDOA measurement. This is somewhat different than a non line-of-sight error, in which the delayed signal is being used exclusively to form the TDOA measurement, and the delayed signal is not present or not detected. Both multipath and non line-of-sight errors, however, are caused by the same underlying phenomenon—signals arriving at the receiver after reflected off of other objects.

The receive antenna gain pattern and orientation can have a significant impact on multipath and NLOS errors. If the antenna gain in the direction of the reflected signal is different than the gain in the direction of the direct signal, then the reflected signal will either be amplified or attenuated relative to the direct signal. This effect was observed with analog television research previously conducted at the Advanced Navigation Technology (ANT) Center at the Air Force Institute of Technology (AFIT) [13]. In one particular test, TDOA measurements were collected from two nearby commercial "rabbit-ears" television antennas located in an indoor environment. These measurements were collected on a dual-input high rate A/D converter, so there was no relative clock error between them (i.e,. both were driven by the same clock with simultaneous sampling in both channels). One of the antennas was held in place but rotated in increments of 30 degrees. The other antenna was completely stationary during the entire test.

The TDOA measurement as a function of rotation is shown in Figure 7. In all cases, the true TDOA measurement should be zero. Three different data sets are shown, along with three different methods of generating a TDOA measurement (XCORR, HOLE, and ZERO). Details of these methods can be found in [13], although they are not significant for this current discussion. Note that the antennas were not translated during any of these tests—the only difference was the orientation of one of the antennas. The significant variations in TDOA measurement accuracy as the antenna was rotated were due to the effects of multipath and the differential antenna gain between the direct and reflected signal directions. This demonstrates the dramatic impact that multipath can have on the solution.

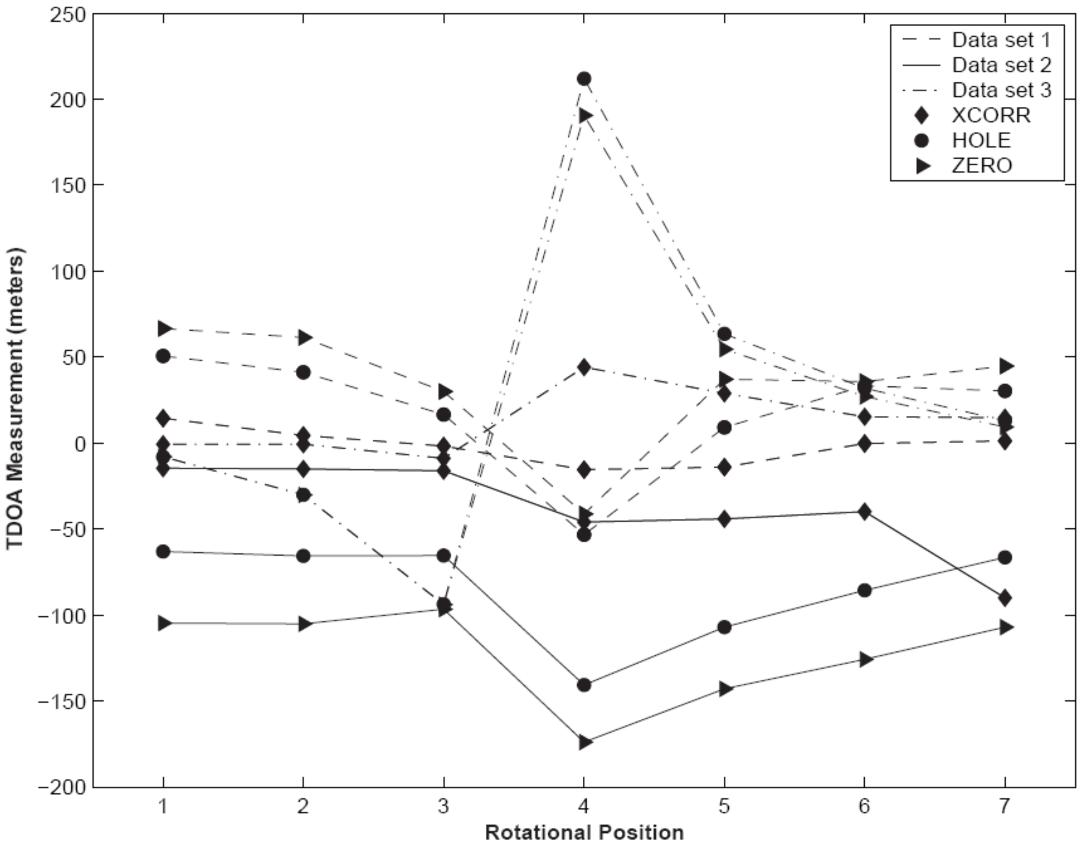

Figure 7: Analog Television TDOA Antenna Rotation Test

CONCLUSION

Navigating in indoor and highly urban locations is a “navigation gap” where GPS cannot currently perform, and the use of signals of opportunity is one potential way to fill that navigation gap. There is a wide diversity of signals available, and many are transmitted at a power much higher than GPS, enhancing the ability to penetrate into buildings. There are still significant challenges to the use of signals of opportunity for navigation, however, including hardware design issues and multipath/NLOS mitigation.

DISCLAIMER

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S Government.

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