Navigation Using Pseudolites, Beacons, and Signals of Opportunity

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ABSTRACT

This paper describes the use of RF signals for navigation, using signals designed for this purpose (pseudolites and beacons) as well as signals that are not intended for navigation (signals of opportunity). Advantages and disadvantages of each system type are presented. Common challenges faced, as well as solutions, for these types of systems are covered, including the near/far problem, measurement types, TDOA measurement formation, positioning algorithms, ambiguity resolution, and multipath. Additionally, some of the unique challenges of navigating using signals of opportunity are described. Examples of navigation using pseudolites, beacons, and signals of opportunity are be presented. The opportunities and challenges of these types of systems for a military environment are also described.

1.0 INTRODUCTION

Over the past couple of decades, there have been a number of trends that have driven the desire to improve our ability to navigate in all environments. 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 could not always be 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 inertial) had accuracies more on the order of 1-2 km. Now, many applications 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).

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!)

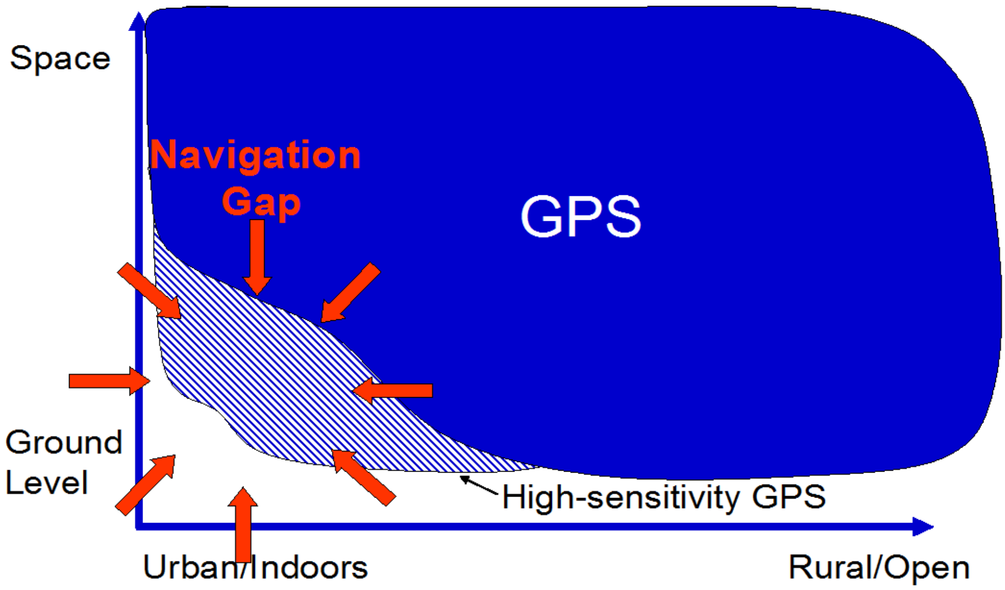

Figure 1: The navigation gap.

In addition to the spatial challenges faced by GNSS as represented in Figure 1, military users of GNSS are always concerned about GNSS availability due to intentional or unintentional jamming. As a result, for a military user, even the blue space shown in Figure 1 is potentially an area where GNSS alternatives are required for mission success.

For the reasons described above, alternative navigation techniques have been and are currently being developed to help fill this navigation gap. This paper will describe three different (but related) categories of non-GNSS radio frequency (RF) navigation:

- **Pseudolite-based navigation.** Pseudolites are defined as RF transmitters that emit GNSS-like signals. Pseudolites can be placed in locations where they can either augment or replace GNSS signals coming from satellites. The signals are sufficiently similar to GNSS signals that GNSS receivers can use them with minimal modification.
- **Beacon-based navigation**. 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, but that are different from standard GNSS signals. Examples of beacon-based navigation systems for indoor navigation can be found in [2] and [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. Some examples from previous research include digital television [4], analog television [5], and AM radio [6], [7].

This paper will be organized as follows. First, the advantages and disadvantages of each of the three methods (pseduolites, beacons, and SoOP) will be described. After that, some of the challenges faced by these systems, as well as solutions to some of these challenges, will be described. Finally, examples of navigation using pseudolites, beacons, and SoOP will be given. This paper is based in part upon [8] and [9].

2.0 ADVANTAGES AND DISADVANTAGES OF PSEUDOLITES, BEACONS, AND SIGNALS OF OPPORTUNITY

While there are certainly common aspects to pseudolites, beacons, and SoOP, each of these approaches does have some unique advantages and disadvantages. In this section, these advantages and disadvantages will be described for each category of non-GNSS RF navigation.

2.1 Advantages of Navigation Using Pseudolites

Pseudolite signals require relatively few receiver modifications. Since pseudolite signals, by definition, are similar to standard GNSS signals, any receiver that receives GNSS signals should be able to track a pseudolite signal with only minor modifications. One modification that must be made is not in the tracking loops themselves but in the algorithm that calculates the satellite position when used for positioning. A normal GNSS receiver uses satellite ephemeris data to calculate the position of the transmitting satellite for any desired time of transmission. In contrast, a pseudolite must communicate its position using something other than a standard ephemeris message, and in the case of a stationary pseudolite, the position doesn't change.

Pseudolites can operate as an augmentation as well as a stand-alone system. Since the same receiver tracks both the pseudolite signals and GNSS signals, any combination of pseudolite/GNSS signals can be used to form a position solution. As a result, even adding one or two pseudolite signals to existing GNSS signals can have a significant effect in cases with poor GNSS coverage. Beacons and SoOP, on the other hand, would often collect data with a different receiver system, significantly complicating the ability to combine with GNSS signals.

Compared to GNSS, pseudolites can transmit signals that are much stronger at the receiver. In weak signal environments (such as indoors or under trees), pseudolites can potentially transmit at higher power levels to enable penetration to the receiver. (Of course, this advantage is shared by beacons and SoOP to some extent as well).

2.2 Disadvantages of Navigation Using Pseudolites

Potential for interference is high. Pseudolites are susceptible to what has been called the "near-far" problem [10]. If a receiver is near to a pseudolite, then the pseudolite power will be large relative to other, farther away pseudolites (or GNSS satellites), and the strong signal power will interfere with the weaker signals to the point that they can no longer be tracked. Of course, if the receiver is too far from a pseudolite, then the pseudolite cannot be tracked. As a result, a user must not be too near or too far from the pseudolite—hence the name "near-far" problem. There are three ways that the near (interference) part of the near-far problem can be overcome [11]: 1) Introducing a frequency offset, 2) Using different pseudorandom noise codes, and 3) implementing a pulsing scheme. These can be used in combination with each other if desired, and all of them are effective at reducing the interference from a pseudolite, but they each come with their own complications in terms of receiver design, pseudolite network design, or regulatory compliance.

Pseudolites must be deployed in the local area in order to be useful. GNSS is extremely convenient because the user need only have a receiver to determine their position. If that same user wants to add in pseudolites, they will need to deploy them, get them synchronized with GPS time, survey them, and provide this information to the user. This is much less convenient and may not be practical for many applications, particularly since ground-based pseudolites only have a limited range for ground-based receivers. From a military standpoint, the need to deploy and survey pseudolites is a highly undesirable and impractical requirement for many types of operations.

2.3 Advantages of Navigation Using Beacons

Like pseudolites, beacons can transmit signals at much higher signal strengths than GNSS. This yields the same benefits as those described for pseudolites in Section 2.1

Beacons enable maximum design flexibility to customize for specific navigation requirements. Unlike pseudolites, which are limited to GNSS-like signals, or SoOP, which are limited to the signals that already exist, beacons effectively can use just about any type of signal structure to meet the desired objectives (within the limits set by regulatory requirements and physics, of course!). For example a beacon navigation system designed by Locata has which four spread spectrum signals are transmitted from each individual beacon—two different frequencies each transmitted from two different antennas (with each signal having a unique spreading code) [12]. This system is a good example of what is possible when one breaks out of the paradigm of just having a single signal per transmitter. Other examples include ultra-wideband pulsed frequency modulated continuous wave (FMCW) signal [13] and a white Gaussian noise signal [14].

2.4 Disadvantages of Navigation Using Beacons

Like pseudolites, beacons must be deployed in the local area in order to be useful. This brings along some of the same additional complexity when using beacons compared to a GNSS-only solution.

Use of a beacon for navigation will generally require an additional receiver. Unless the beacon signal is very similar to a GNSS signal (in which case we would call it a pseudolite), then a receiver separate from the GNSS receiver must be used to take advantage of the beacon. Depending on the system, the additional receiver may be small and could conceivably be packaged along with the GNSS receiver, but doing this will still require additional size, weight, power, and cost relative to a GNSS-only receiver. Worse, if not packaged as part GNSS receiver, a beacon receiver becomes an additional box to mount, carry around, etc.

2.5 Advantages of Navigation Using 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 may not be many SoOP available, but such signals are much more plentiful in typical urban environments (where the navigation gap is).

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.

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) [15]. These are the type of capabilities that would be important for a practical SoOP radio.

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.

2.6 Disadvantages of Navigation 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.)

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 band- width front-end, and 3) adequate signal processing to handle the wide bandwidth front end data (high sample rates, etc.), all of which are costly. For example, a radio that tracks a single television channel only needs to be able to process a signal with a 10 MHz bandwidth. 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).

3.0 COMMON ASPECTS OF PSEUDOLITES, BEACONS, AND SOOP

In the previous section, unique advantages and disadvantages for each of the three measurement types were described. However, pseudolites, beacons, and SoOP are all based on RF signals, so there are many common aspects to using these systems. This section will describe several issues which must be considered for these types of systems to be used effectively.

3.1 Measurement Types

It is possible to infer both position and velocity information from RF signals. 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 as useful for directly determining position, so it will not be described in this paper.

There are three primary ways that RF signals can be used for positioning: 1) range via signal strength, 2) angle of arrival, 3) time-difference of arrival (TDOA), and 4) pseudorange measurements. Each of these will be described below.

3.1.1 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 [16]. 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.

3.1.2 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.

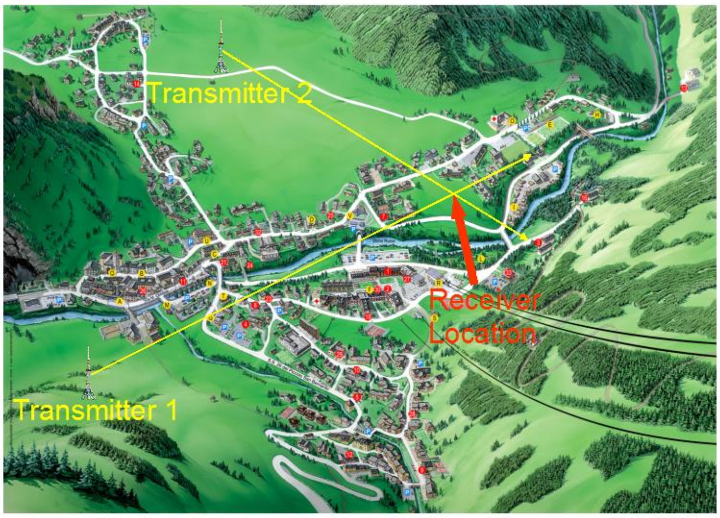

Figure 2: Example of triangulation using angle of arrival measurements.

3.1.3 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.

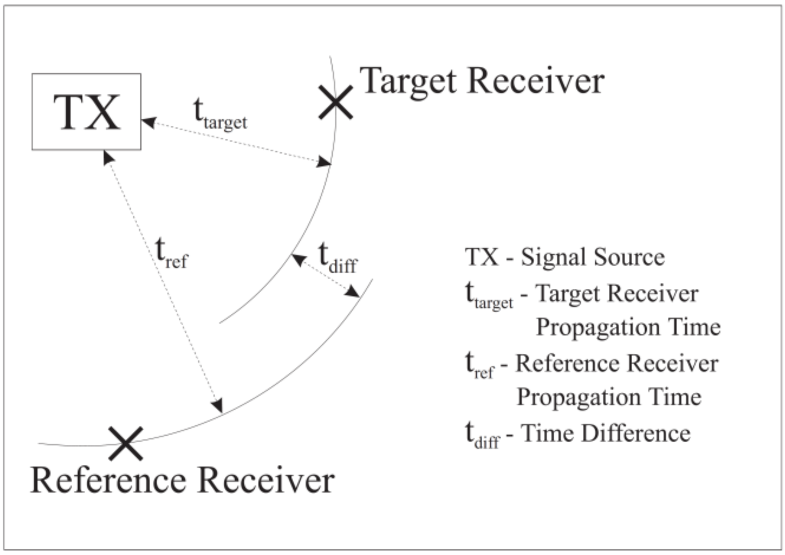

Figure 3: Illustration of TDOA measurement [17].

3.1.4 Pseudorange Measurements

If the time of transmission, the time of reception, and the velocity of a signal are all known, then these quantities can be converted to a range. However, in most applications, the time of reception is not known precisely, due to receiver clock errors. As a result, rather than a range measurement, there is a *pseudorange* measurement which is a combination of both the range and the receiver clock error. This is the primary measurement that is used in the GPS system, and is well-understood in that context [18]. In order for a pseudorange to be used with a pseudolite, beacon, or SoOP system, the transmit time of the signal must be precisely known. This can be accomplished through various means, including 1) use of GNSS to determine time (requires that GNSS is available), 2) Synchronization using a common reference signal (often one of the pseudolites or beacons), and 3) Measurement and correction of the transmitter clock using a reference station. This third approach ends up being very similar in nature to a TDOA measurement.

3.2 Use of TDOA Measurements for Navigation

Since TDOA measurements are commonly used with RF-based navigation, particularly for SoOP, the overall concept of operation for the use of these measurements will be described in this section.

3.2.1 TDOA Positioning System Concept of Operation

Figure 4 shows a typical concept of operation 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.

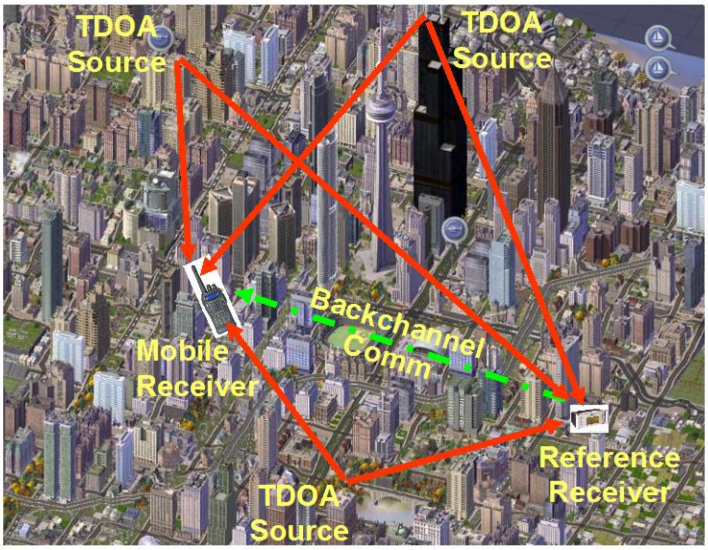

Figure 4: Typical TDOA Positioning System Concept of Operation.

3.2.2 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).

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. By way of example, Figure 5 shows the synchronization pulses that occur at the beginning of each frame for typical analog television transmissions. While analog television is no longer in use in the United States, it still provides a good example of a signal "feature"). 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).

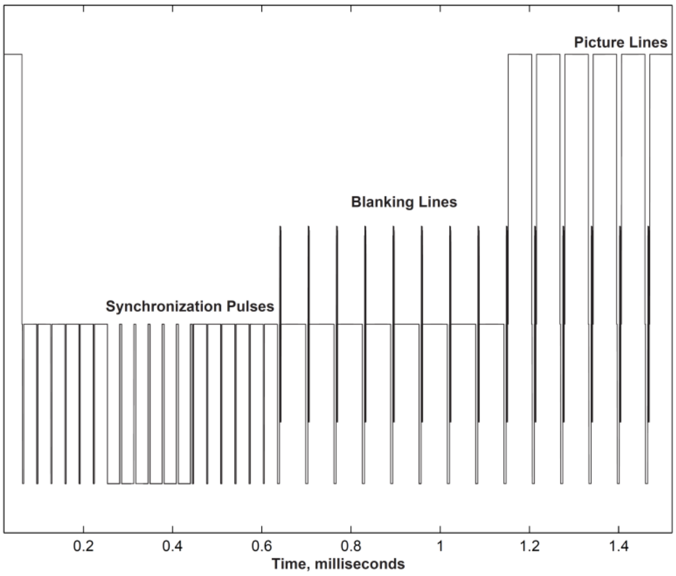

Figure 5: Synchronization pulses and blanking lines for an analog television signal [17].

3.2.3 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 [19].

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 (TOA_r^i) and the base (TOA_b^i):

$$TDOA^i = TOA_r^i - TOA_b^i \tag{1}$$

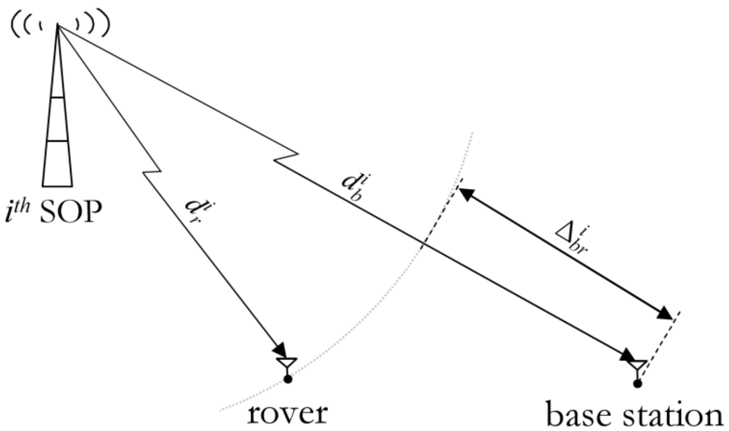

Figure 6: Geometric interpretation of TDOA measurements [19].

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

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

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, respectively, and c is the speed of light. Rearranging terms yields

$$cTDOA^i + d_b^i = d_r^i + c(\delta t_r - \delta t_b) \quad (3)$$

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 (left hand side of Equation 3), then the result is the distance between the rover (i.e., range) 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.

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 [20].

3.3 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 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.

[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.

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.

3.4 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, and can also be a very significant issue for pseudolites and beacons. 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 ranging 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 being 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) [17]. 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 was 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 [17], 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.

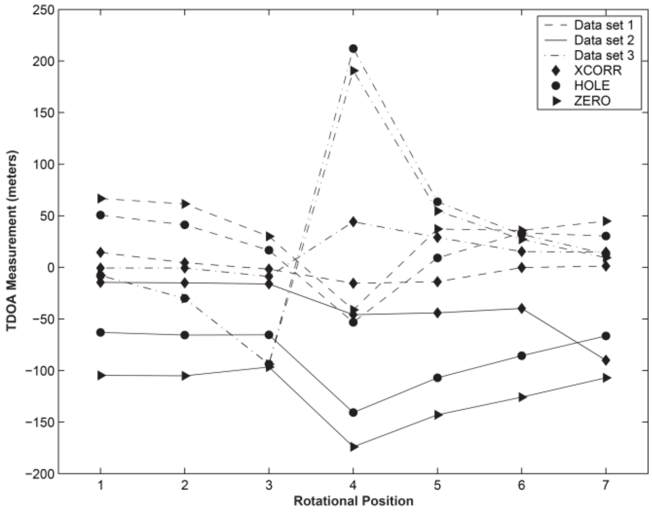

Figure 6: Analog television TDOA antenna rotation test—true TDOA is zero.

4.0 IMPLEMENTATION EXAMPLES

This section will give an example for the three different system types described in this paper. These are intended to be summarized descriptions, and the reader is referred to the source documents referenced in the section titles to obtain more detailed information.

4.1 Pseudolite Example [21]

In 1995, the 746th Test Squadron at Holloman Air Force Base, NM was attempting to develop a flight reference system that would be immune (or at least resistant) to jamming broadcast toward a flying aircraft. The thought was to build a system like that shown in Figure 7, in which a mobile pseudolite on an aircraft is received by several receivers on the ground in order to determine the position of the aircraft. Note that there was a need for a "reference pseudolite" in order to remove the effect of clock errors in each of the receivers through a differencing method.

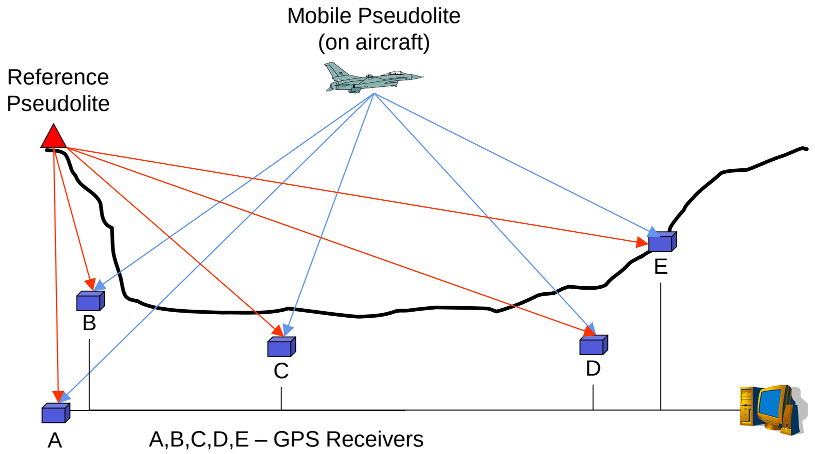

Figure 7: Inverted pseudolite system design concept.

In order to test this concept, a ground based proof of concept demonstration was conducted using 6 GPS L1 receivers, a fixed pseudolite, and a mobile pseudolite mounted on top of a test vehicle. Figure 8 shows the geometry of the test setup.

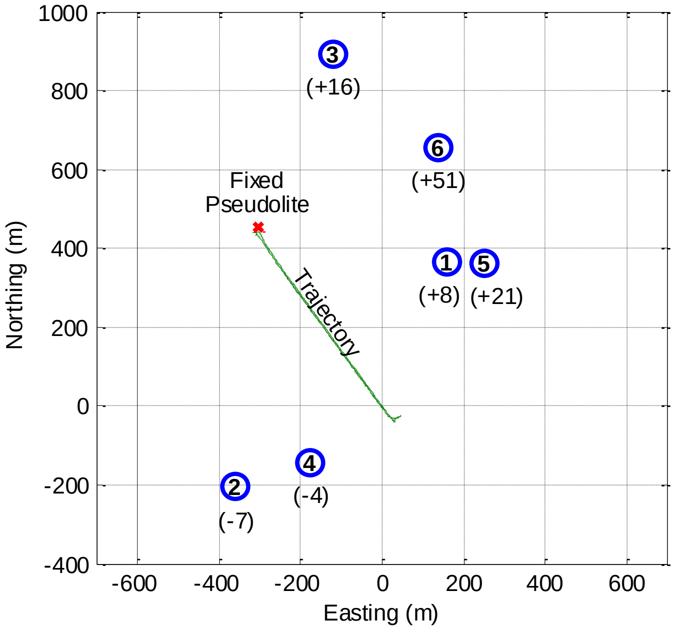

Figure 8: Positions of six stationary receivers and fixed pseudolite with respect to test route. (Nominal altitude above test route shown in parentheses).

There was a GPS receiver mounted on the roof of the test vehicle next to the pseudolite transmitter, but due to the near-far problem, the GPS receiver could not receive any GPS signals if the pseudolite was on. As a result, it was not possible to obtain a precise GPS-based truth trajectory when the pseudolite was operating. In order to evaluate performance, the test vehicle was driven out and back along the same stretch of road for two complete round trips, first with the pseudolite on, then with the GPS receiver on. Figure 9 shows a comparison between the pseudolite-derived position and the GPS-derived position. The vertical accuracy appears to be on the order of 0.5 meters or better, and there is no discernible difference between the pseudolite and GPS cross-track trajectories. It is not surprising that the vertical error is a little larger, considering that the vertical dilution of precision (VDOP) was 10 or higher over the entire route, in constrast to a horizontal dilution of precision (HDOP) value of approximately 1.5. For a description of DOP values, see [18]. This test provided a clear demonstration of the ability to get extremely accurate positioning using ground-based pseudolites.

4.2 Beacon Example [12]

In 2011, the 746th Test Squadron conducted another test, this time of a beacon navigation system developed by the Locata corporation. This system used beacons (called LocLites) that operated in the 2.4 GHz ISM band and involved four spread spectrum signals transmitted from each individual beacon—two different frequencies each transmitted from two different antennas (with each signal having a unique spreading code). This frequency and spatial diversity was present in order to help mitigate multipath, which is almost always a challenge in any type of terrestrial-based navigation system. Unlike the pseudolite example in Section 4.1, this test involved the positioning of aircraft over a much larger area, as shown by the laydown diagram shown in Figure 9.

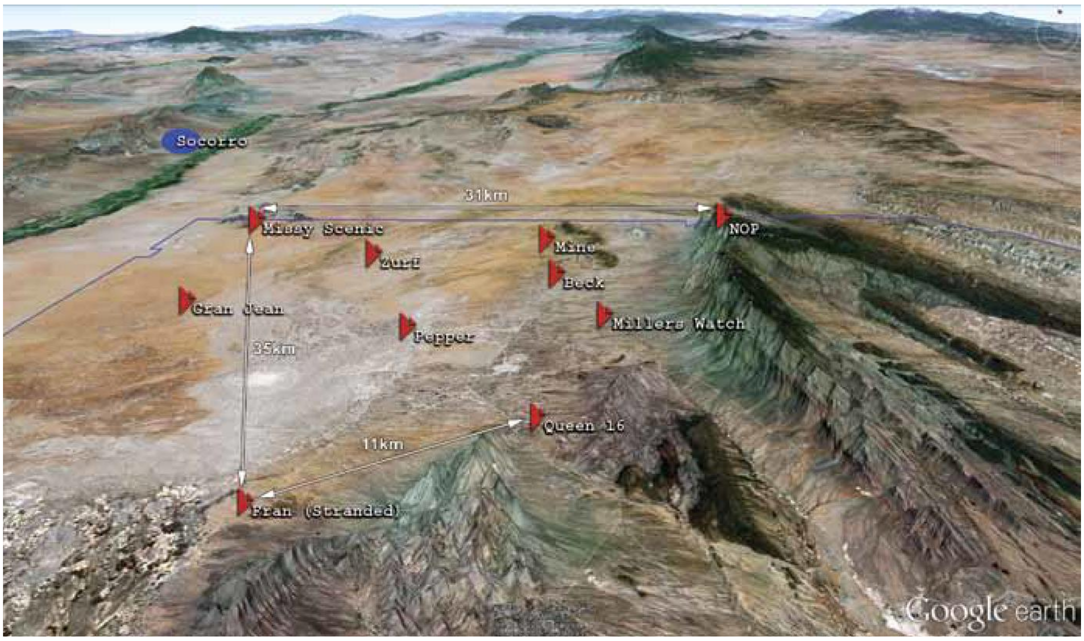

Figure 9: Test configuration of Locata flight test at Holloman AFB [12].

A C-12J was flown in a racetrack pattern at 25,000 feet over the LocLite network (shown on the left side of Figure 10), and the measurements were processed to determine a trajectory. This trajectory was differenced with a trajectory obtained using standard carrier-phase differential GPS processing, and the difference is plotted on the right side of Figure 10. This demonstration showed the beacon-based navigation systems can provide accuracies comparable with precision GPS positioning.

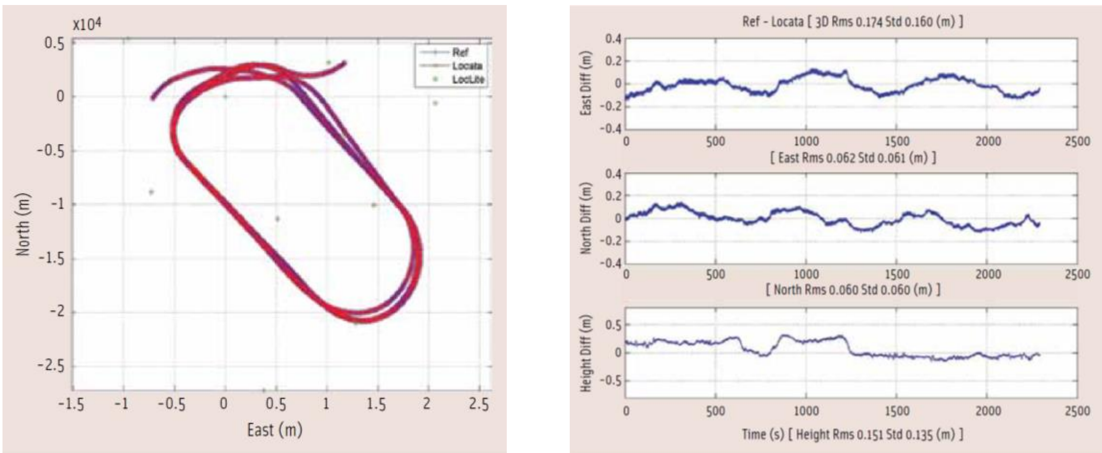

Figure 10: Aircraft racetrack (left) and difference between Locata and differential carrier-phase GPS solution (right) [12].

4.3 Signal of Opportunity Example [22]

The final example in this paper is a system which was designed to generate TDOA measurements from a SoOP—namely broadcast amplitude modulated (AM) radio stations. While the results shown here are based on [22], another good example of the same basic approach can be found in [6] and [23].

The goal was to measure the relative phase between two receivers who were monitoring the same AM radio station. A test setup was developed using analog AM radio front ends along with an older version of the Universal Software Radio Peripheral (USRP) in order to downsample and digitize the signals. Figure 11 shows a path that was traversed in a field near the Air Force Institute of Technology (left side) and a comparison between the true TDOA measurements and the TDOA measurements obtained from the AM radio signals for this path (right side). While the AM radio-based TDOA measurements are somewhat noisy, they clearly do follow the trends in the true TDOA measurements.

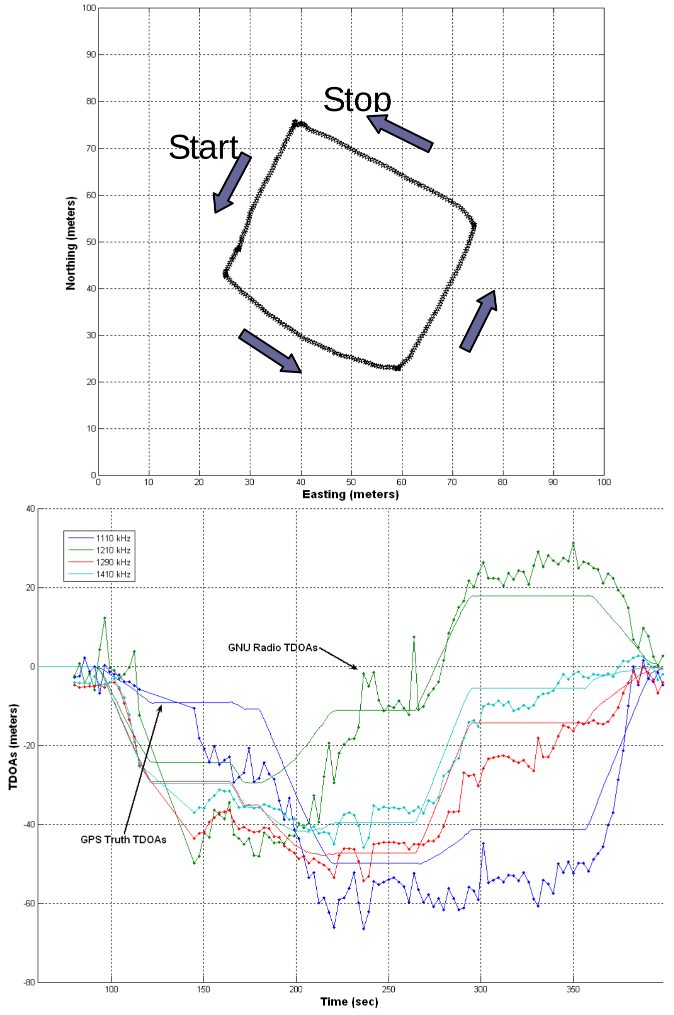

Figure 11: AM radio SoOP test traversed path (left) and comparison between true and measured TDOA measurements (right).

5.0 CONCLUSION

This paper described three different categories of non-GNSS RF-based navigation—beacons, pseudolites, and SoOP. There are advantages and disadvantages for each of these categories, but together they form a powerful set of possibilities for navigating when GNSS is not available. There are a number of issues that must be worked out when using these systems, and one of the most challenging of these is multipath, which can have a significant, negative impact if not mitigated. Finally, examples of all three categories were presented, demonstrating the real-world application of these types of systems.

6.0 DISCLAIMER

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

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