Fusion of Inertial Sensors and OFDM Signals of Opportunity for Unassisted Navigation

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***Abstract*—The advent of the global positioning system (GPS) has provided worldwide high-accuracy position measurements. However, GPS may be rendered unavailable by jamming, disruption of satellites, or simply by signal shadowing in urban environments. Thus, this paper considers fusion of Inertial Navigation Systems (INS) and Orthogonal Frequency Division Multiplexed (OFDM) Signals of Opportunity (SoOP) for navigation. Typical signal of opportunity navigation involves the use of a reference receiver and uses time difference of arrival (TDOA) measurements. However, by exploiting the block structure of OFDM communication signals the need for the reference receiver is removed.**

***Index Terms*—inertial navigation, OFDM, signals of opportunity.**

I. Introduction

One alternative method of navigation that has been proposed recently is "Navigation via Signals of Opportunity." The idea is to use existing radio frequency signals that were not intended for navigation, and leverage knowledge of the transmitter locations to determine the position of the receiver. Some signals investigated thus far include the National Television System Committee Broadcast Signal, AM and FM signals [1,2,3]. This problem is the converse of the source localization problem, hence similar mathematical methods can be used to extract a position estimate.

Measurements that can be taken to aid in positioning include the angle of arrival (AOA), the received signal strength (RSS), or the time difference of arrival (TDOA) at multiple receivers. We focus on TDOA, since it is difficult to get sufficient position accuracy from AOA or RSS [4]. One difficulty encountered with using TDOA is that there must be either two transmitters sending the same signal or two spatially separated receivers measuring the same transmission. Usually only one transmitter is available, hence a reference receiver must be placed at a known location, and the mobile (whose position is to be determined) must cooperate with the reference in some way. A second difficulty is that TDOA measurements generally require some form of correlation between the two received signals. This requires that the reference retransmit much of its received signal to the mobile, using significant bandwidth. Recent previous work has shown how OFDM modulation can alleviate the bandwidth constraint [5].

By using the same blind block synchronization described later a received time for each OFDM block can be obtained for both a reference and mobile receiver. After individual blocks are distinguished, statistical features such as mean and standard deviation of each block can be calculated. These statistical features along with received times for the corresponding block are then transmitted from the reference receiver to the mobile receiver instead of transmitting the entire signal, greatly reducing required bandwidth. These statistical features are then correlated with statistical features calculated at the mobile receiver. Correlating the features allows a time difference to be obtained [5].

In this paper, we leverage the previous work to show how OFDM signals of opportunity can be combined with an inertial navigation system (INS) to remove the need for a reference receiver almost entirely, with the "almost" caveat remaining because a reference receiver is still occasionally needed to account for transmitter clock drift. This TDOA measurement system is shown in Figure 1 for a single transmitter, though in general multiple transmitters would be used.

INS systems are strong candidates for non-GPS navigation because they have high accuracy over short periods of time. However, they are subject to gradual drift. The use of a signal of opportunity can mitigate this drift. Specifically, we show that an

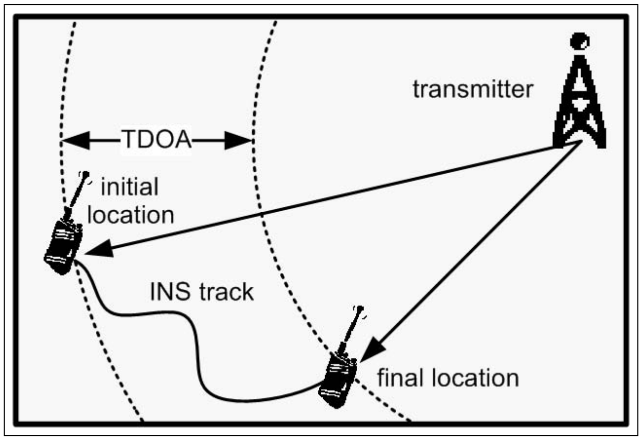

Fig. 1. TDOA geometry. The TDOA is computed by calculating block arrival times at the initial location, and at the final location. The time difference can be obtained by differencing these two measurements.

INS can be used to obtain multiple relative position estimates at relative times. Then the proposed fusion process can compare the expected and actual times of reception of the OFDM system's block structure to extract TDOA information. Specifically, the receiver can locate the start of each OFDM block in blind fashion by looking for the repetition induced by the cyclic prefix of OFDM systems. The receiver can compare the measured reception times of sequential blocks to the known block length, and a change in the expected vs. measured time indicates if the receiver is moving towards or away from a given transmitter. With enough transmitters, a position track can be obtained.

II. INS System Model

The INS model used in this research was a simple two dimensional model. Two accelerometers (f_{xb} and f_{yb}) and one gyroscope ($\dot{\Theta}$) were used to obtain acceleration and angular rotation rate in a plane. Additive white Gaussian noise (AWGN) was added to the accelerometer and gyroscope measurements. AWGN added to these measurements had a standard deviation (σ) of $0.1\frac{m}{s^2}$ for the accelerometer and $0.1\frac{rad}{s}$ for the gyroscope. One accelerometer started pointing in the positive X direction, and the other in the positive Y direction. This system is shown in Figure 2. The body accelerations were resolved in the X and Y directions using the formulas found in [6] which are:

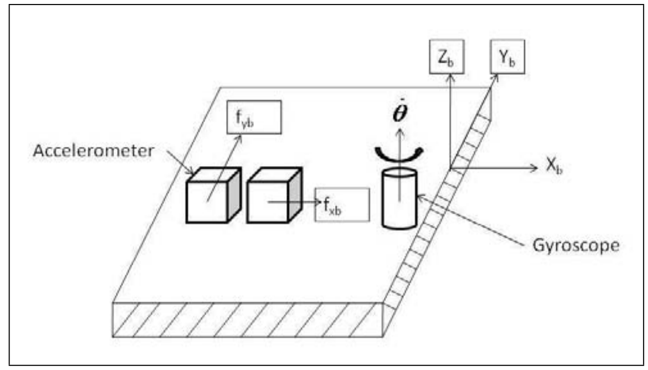

Fig. 2. INS model used in the simulation. A two dimensional model with two accelerometers and one gyroscope. Position is obtained in the X and Y directions

$$f_{xi} = f_{xb} \cdot \cos(\Theta) + f_{yb} \cdot \sin(\Theta) \tag{1}$$

$$f_{yi} = -f_{xb} \cdot \sin(\Theta) + f_{yb} \cdot \cos(\Theta) \tag{2}$$

where f_{xb} and f_{yb} are measured acceleration in the X_b and Y_b body frame. Θ is the rotation angle obtained by integrating $\dot{\Theta}$. f_{xi} and f_{yi} are accelerations resolved in the X and Y directions. INS measurements were taken at 50Hz. X and Y position were then obtained via the formulas:

$$v_{xi} = \int f_{xi} \tag{3}$$

$$v_{yi} = \int f_{yi} \tag{4}$$

$$X = \int v_{xi} \tag{5}$$

$$Y = \int v_{yi} \tag{6}$$

Although the AWGN added to the simulated measurements was zero mean, these errors cause an error drift due to the fact that they are integrated twice. This causes errors in INS position solution to grow over time. Because of these continuously growing errors, INS systems are typically aided by some sort of measurement system. Here we will use OFDM signals of opportunity to aid the INS system through the use of a Kalman filter. Truth data was obtained by integrating the simulated INS measurements without adding AWGN.

III. OFDM System Model

The first step in an OFDM communication system occurs at the bit level. Data bits to be transmitted go through an interleaving process and are then encoded. The use of a convolutional encoder is common, but not necessarily required. The encoding rate may also be varied depending on transmission bit rate requirement. This serial bit stream is then converted into a parallel bit stream. These parallel bits are then mapped to a signal constellation which depends on modulation type used by the transmitter. Modulation type can vary depending on transmission bit rate requirement, but typically include BPSK, QPSK, 16 QAM, and 64 QAM. These constellation mappings are then applied to numerous carriers. This simulation included $N = 64$ carriers. Then an N point Inverse Fast Fourier Transform (IFFT) is performed on the data modulated carriers to get the data from the frequency domain to the time domain. This action produces N time domain samples. These N samples are then demultiplexed from parallel to serial. Once in serial a cyclic prefix is added to the beginning of the signal. This is done by copying the last v time domain samples and appending them to the front of the original N time domain samples. This creates an $M = N+v$ sample OFDM symbol. This symbol is then modulated at the carrier frequency and transmitted over the air. A block diagram of an OFDM communication system is shown in Figure 3.

The cyclic prefix (CP) is of particular importance to these experiments because it is the sole piece that allows for the removal of the reference receiver. The addition of the CP was originally designed to mitigate the effects of multipath, specifically intersymbol interference (ISI) and intercarrier interference (ICI). The use of the CP removes these effects [7]. Because the CP is an exact replica of the last section of the symbol, an autocorrelation algorithm will produce a well defined peak at the point when these two sections of the symbol are correlated. This peak becomes even more distinguishable when several symbol peaks are averaged. Finding the index of where this peak occurs allows for a TDOA measurement to be obtained without the need for a reference receiver. This process will be explained in the next section.

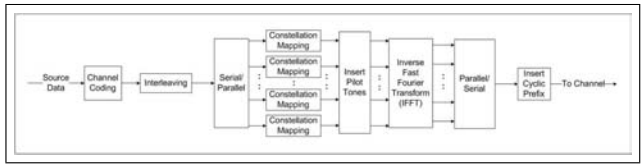

Fig. 3. OFDM communication block diagram. After coding and interleaving, bits to be transmitted are mapped using a signal constellation onto multiple carrier frequencies. An IFFT is then performed on the carrier frequencies. Once in the time domain a cyclic prefix is added and the symbol is transmitted over the channel.

IV. TDOA Computation

In this section we discuss how TDOA measurements are obtained from the OFDM signals. To do this a receiver estimates block boundaries within the signal. This is a common method of blind block synchronization and is derived in [8]. Thus given a received signal the maximum likelihood (ML) estimate of the block boundaries is

$$\hat{\delta}_{ML,rx} = \arg \max_{0 \leq m \leq M-1} \Re\{\gamma_{avg}(m)\} \tag{7}$$

where

$$\gamma_{avg}(m) = \sum_{k=0}^{K-1} \sum_{i=m+1}^{m+v} y_{rx}(Mk+i) y_{rx}^{*}(Mk+i+N) \tag{8}$$

and $\Re$ is the real operator, K is the number of blocks averaged over, M is the symbol length, k is the index of the OFDM block, and i is the index of the sample within the OFDM block.

Finally, once $\hat{\delta}_{ML,rx}$ is obtained the TDOA can be calculated using the formula

$$TDOA = (\hat{\delta}_{ML,rx} - \delta_{initial}) \cdot T_s \tag{9}$$

where T_s is the sampling interval. Note that in these simulations $\delta_{initial}$ is always zero, and all TDOA measurements are measured from the initial point (0,0).

V. Simulation Results

This section illustrates performance of the TDOA aided INS system. Note that no transmitter or receiver clock errors were modelled in the simulation. For the simulations the OFDM signal used $N = 64$ carriers with a cyclic prefix length of $v = 16$. This produced an $M = 80$ sample OFDM symbol. These lengths are consistent with the IEEE 802.11

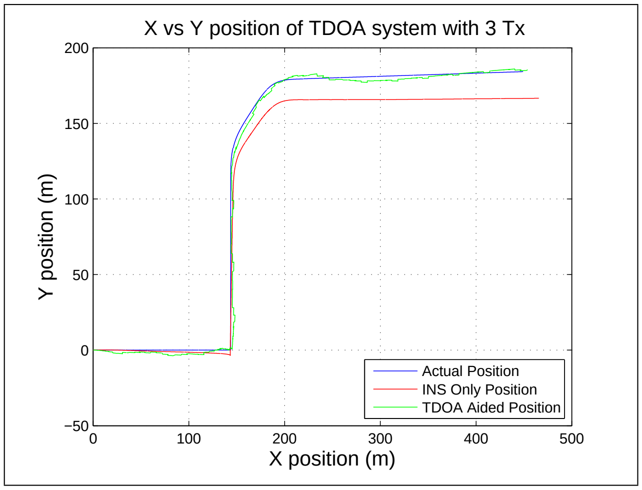

Fig. 4. TDOA aided INS position. Three transmitters were used to obtain TDOA measurements and aid the INS through the use of a Kalman filter.

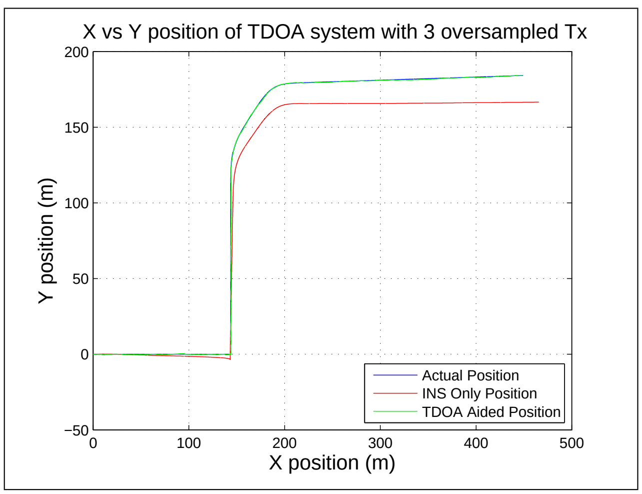

Fig. 5. 15× oversampled TDOA aided INS position. Again three transmitters were used to obtain TDOA measurements. These measurements used oversampling of the OFDM signal producing more accurate measurements.

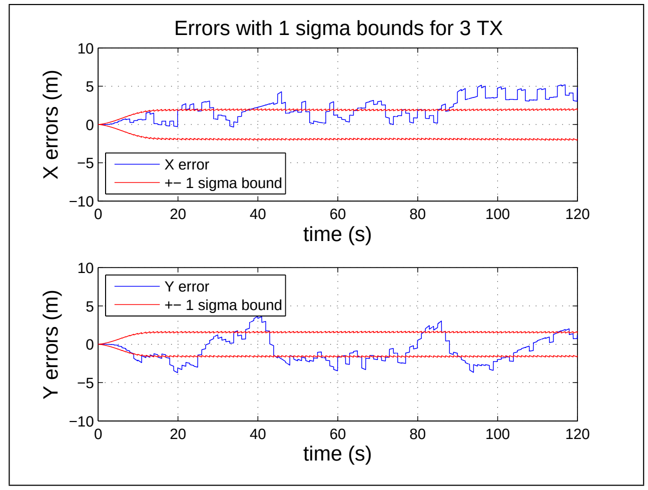

Fig. 6. Errors with 1σ error bounds. Error bounds shown for X and Y position are used to ensure the Kalman filter is operating properly.

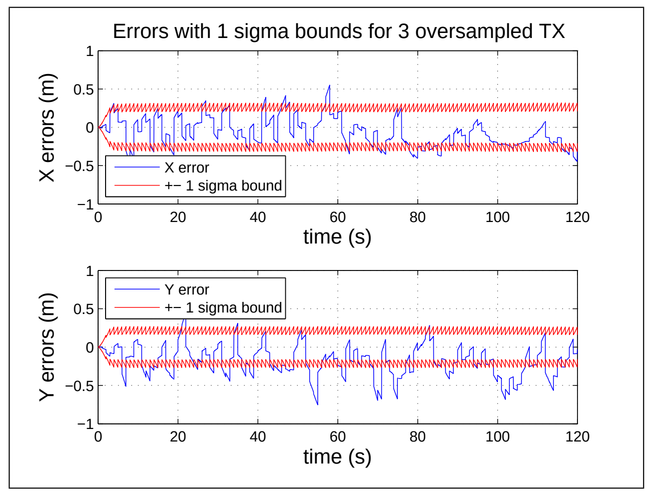

Fig. 7. Oversampled errors with 1σ error bounds. Error bounds shown for X and Y position are used to ensure the Kalman filter is operating properly. Error bounds from the oversampled system are smaller than error bounds of the regular system.

standard. The transmitter locations were assumed to be known in relation to the receiver, and the receiver position was initialized to (0,0). Three transmitters were used and stationed in a triangular fashion around the receiver. Once INS measurements and TDOA measurements had been simulated using MATLAB, a Kalman Filter also implemented in MATLAB was used to output an optimal position estimate. Figure 4 shows the position result from the output of the Kalman filter. It can be seen that after a short period, the aided system performs better than the INS alone.

This simulation was rerun using an oversampled TDOA system. This system used a sampling rate 15× greater than the original system. Figure 5 shows the position result from the output of the Kalman Filter when the OFDM signal is oversampled by 15 times. This oversampled system clearly produces better position estimates than compared to the first simulation. Oversampling the system produces more sample measurements with independent noise values. If there were any time correlated errors in the TDOA measurement there would be less of

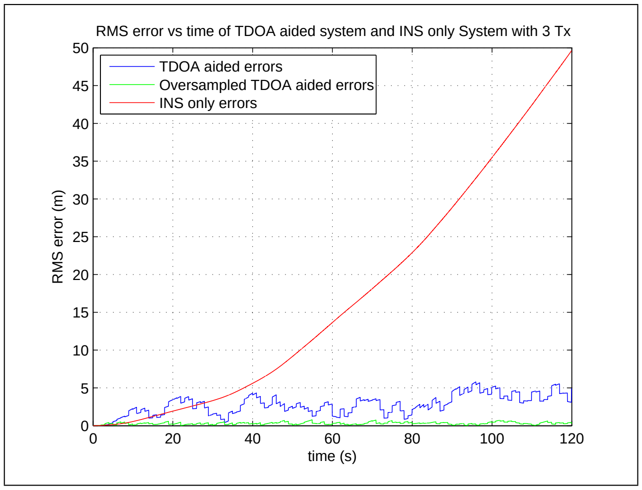

Fig. 8. RMS error with 3 transmitters. The above simulations were run 10 times each and RMS errors were calculated. INS errors grow over time, while the TDOA aided system are much lower.

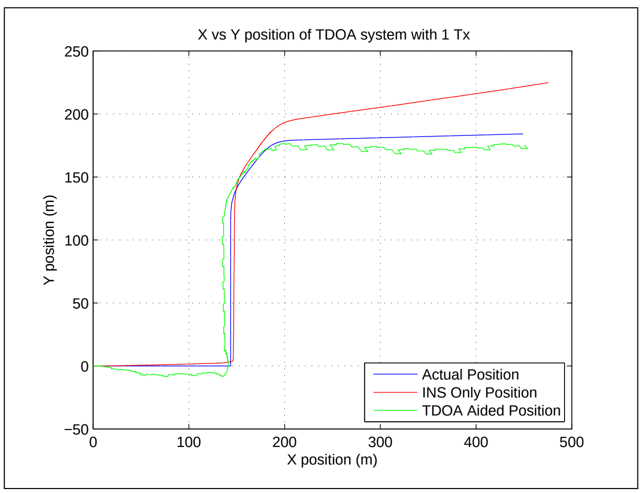

Fig. 9. TDOA aided INS position. One transmitter was used to obtain a TDOA measurement and aid the INS. When compared to Figure 4 this one measurement is less accurate than using three measurements.

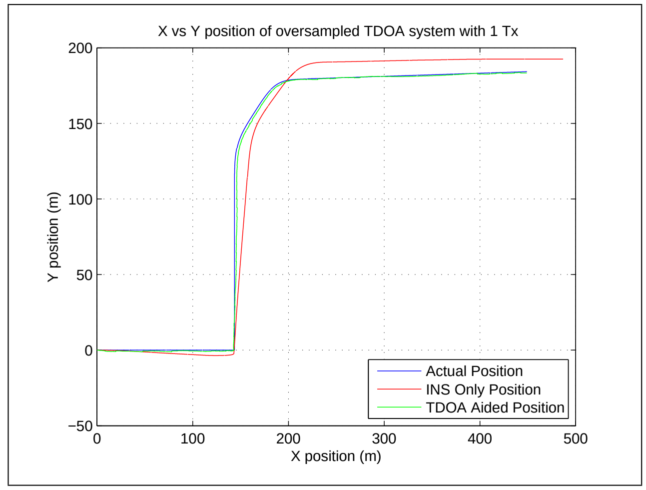

Fig. 10. Oversampled TDOA aided INS position. Again only one transmitter was used to obtain a TDOA measurement. This measurement used oversampling of the OFDM signal producing a more accurate measurement. When compared to Figure 9 this oversampled measurement is more accurate than the non-oversampled system.

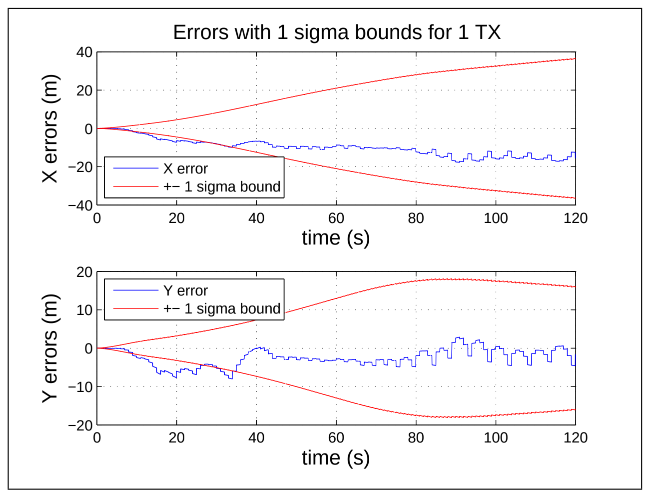

Fig. 11. Errors with 1σ error bounds. Error bounds shown for X and Y position are used to ensure the Kalman filter is operating properly.

an improvement.

The errors in the X and Y directions of the two systems were also plotted along with 1σ error bounds. These plots are shown in Figures 6 and 7. Both simulations were then run ten times and the average RMS error for each case over time was computed and compared with the average RMS error of the INS only system. Average RMS error for all three systems are shown in Figure 8.

Simulations were also run using only 1 OFDM transmitter. Results from the regular system are shown in Figure 9 and results from the oversampled system are shown in Figure 10. Errors and error bounds of the X and Y position are shown in Figures 11 and 12 Once again, average RMS error over 10 runs was compared with the INS only case. These results are shown in Figure 13.

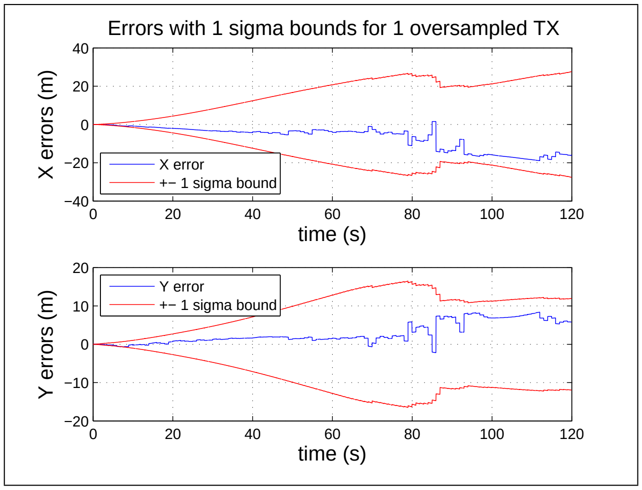

Fig. 12. Oversampled errors with 1σ error bounds. Error bounds shown for X and Y position are used to ensure the Kalman filter is operating properly.

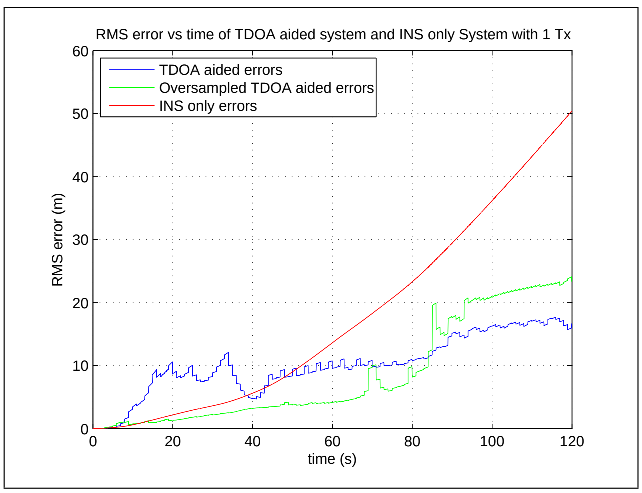

Fig. 13. RMS error with 1 transmitter. Systems used in Figures 9 and 10 were run 10 times and RMS error was calculated. When compared to Figure 8 the RMS error is higher with only 1 transmitter.

VI. Conclusions and Future Work

The use of OFDM modulated signals of opportunity has been shown as a viable option to aid inertial navigation systems. Furthermore exploitation of the block structure allowed the removal of the reference receiver typically needed to calculate time difference of arrival measurements. The accuracy of these measurements has also been shown to improve with the use of oversampling. This oversampling causes smaller sampling intervals and thus a finer TDOA measurement can be obtained. This more accurate measurement fed into the Kalman filter causes a more accurate position estimate. Overall position accuracy also increases as the number of transmitters increases. This is expected as more measurements contain more information about the receivers position.

The models used thus far have been greatly simplified from that of an actual system. Future work will consider effects of receiver clock errors and clock drift, as well as transmitter clock errors and clock drift which are known to cause significant errors in positioning. Future efforts will also incorporate a rigorous 3D INS model, and use actual INS measurements with differential GPS truth data to simulate TDOA measurements.

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