Design and Test of Algorithms and Real-Time Receiver to use Universal Access Transceiver (UAT) for Alternative Positioning Navigation and Timing (APNT)

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ABSTRACT

The FAA Alternative Positioning Navigation and Timing (APNT) effort is developing technologies to provide navigation service capable of sustaining operations in the event of the loss of Global Navigation Satellite Systems (GNSS). APNT will utilize existing ground infrastructure to support this capability. One effort is to examine the use of the Automatic Dependent Surveillance Broadcast (ADS-B) ground infrastructure for ranging. This paper examines the use the one of transmitted ADS-B signals, Universal Access Transceiver (UAT). UAT signal is designed with passive range capability. This paper first discusses how to obtain the range from UAT. Then, a prototype UAT receiver is designed to implement the concepts. Finally, a ground test uses the transmitted, on-air signal to examine the ranging and positioning of the receiver. The field test results are presented demonstrating the ability of UAT to support APNT.

INTRODUCTION

As air traffic continues to grow, the Global Navigation Satellite System (GNSS) plays an increasingly important role in enabling the air space to efficiently handle the higher traffic loads. In fact, GNSS be the primary and often the only system capable of supporting key capabilities for the future airspace. However, GNSS is vulnerable to radio frequency interference (RFI) and spoofing, so an alternative positioning, navigation and timing (APNT) system that also enables many of GNSS derived capabilities is necessary for aviation user [1].

Universal Access Transceiver (UAT) was developed to support aviation surveillance and provide important traffic and weather data to aviation users. With about 660 automatic dependent surveillance broadcast (ADS-B) ground stations in the conterminous United States (CONUS) supporting UAT, significant infrastructure exists to ensure that users in most of US airspace can receive this information. Additionally, UAT was designed with a simple passive ranging capability. This capability of interest for the FAA APNT program as it seeks to develop terrestrial radio navigation system capable of sustaining operations in the future national airspace even with the absence of GNSS [2]. UAT from ADS-B ground stations represent an important radio navigation source to support targeted APNT capabilities, and can be used with other transmissions such as distance measuring equipment (DME). APNT at a minimum needs to support area navigation (RNAV) or Required Navigation Performance (RNP) operations of one nautical mile (nm) – RNAV/RNP 1.0. However, it is desirable that APNT support RNP operations of 0.3 nm which requires position accuracy 307.2 m [3]. The resulting range accuracy requirement is 108.6 m under good geometry – horizontal dilution of precision (HDOP) of 2.8 or less.

The current UAT performance is evaluated in several ways. The time synchronization of the transmission is examined. UAT transmissions are nominally synchronized to UTC. However, specifications allow the transmission to vary up to 500 nanoseconds from UTC. After evaluating the time synchronization of some ground sites, the ranging capability of the signal is assessed. Direct and differential assessments are used to evaluate the performance. Then, position domain evaluation is conducted using measurements from two local stations.

While UAT has a built-in basic passive ranging feature, supporting APNT may require capabilities beyond those currently specified. This paper starts from introduction of UAT signal and then examines how to leverage the existing design of UAT to support high rate, high accuracy ranging. It is desirable that UAT support frequent range updates, authentication, ground station location, and integrity. Currently UAT provides roughly 1 Hz range updates. This paper discusses how the ground station signals can be used to support higher update rates. Specifically, it examines how the existing signals: automatic dependent surveillance broadcast (ADS-B), traffic information service broadcast and flight information services broadcast (FIS-B) may be used as additional pseudoranging transmissions.

The final area covered is the design of a prototype UAT navigation receiver that we are developing to test these concepts. It discusses the receiver hardware and software design. A method for improving range resolution is also addressed. A ground test is conducted for evaluate the performance of ranging and positioning. Both static and dynamic scenarios are tested. Both positioning and ranging results are examined.

INTRODUCTION TO UAT SIGNAL

UAT is a new signal developed specifically for ADS-B and described in the UAT minimum operational performance standards (MOPS) [4]. It uses a DME channel that is unused in the United States and is organized using time division multiple access (TDMA). Specific message start opportunities (MSOs) are used by UAT transmissions. As a result of the channel organization and proper assignment of transmission slots, there should be little intersystem interference sources. The organization of the UAT channel is seen in Figure 1. UAT transmissions are organized around a one second long frame that starts on the Coordinated Universal Time (UTC) second. Two segments of the frame are defined: ground and ADS-B.

The ground segment is dedicated to transmissions from ground stations. It is organized such that ground segment transmissions from proximate stations should not interfere with each other. There are 32 MSOs used in the ground segment. The time difference between each used MSO is 5.5 milliseconds (ms) which provides enough time for the message (~4.1 ms providing 3392 bits of data) and some buffer so as to not interfere with messages transmitted in adjacent MSOs. These transmissions support pseudo ranging and provide FIS-B to the aircraft. The basic ground payload is seen in Figure 2 where the slot being the ordinal of the MSO used (e.g., slot 1 is the 1st MSO that can be used in the ground segment). UAT timing is maintained through the use of GPS at the GBT [5]. Other information in the ground uplink message needed for passive ranging is ground station latitude/longitude. The allocated bits allows the station location to be represented within 1 meter. There is a flag showing whether the transmission is UTC coupled. If the flag is true, the transmission timing accuracy is within ±500 ns of UTC.

The ADS-B segment supports ADS-B and TIS-B. These are shorter transmissions and adjacent MSOs are 250 µsec apart. These signals were not designed to support pseudo ranging. This effectively limits UAT ranging rates to about 1 Hz unless ADS-B segment signals can be used to provide pseudo ranging.

The UAT signal modulated using continuous phase frequency shift keying (CPFSK) where the signal frequency varies by ±312.5 kHz. This keeps the transmitted energy mainly within the 1 MHz DME channel. An increase of 312.5 kHz (Δf) indicates a “1” bit while the same decrease indicates a “0” bit. Each UAT transmission uses a synchronization header consisting of thirty-six 0.96

µsec long bits. The synchronization bits used for the ADS-B segment are the inverse of those used in the ground segment.

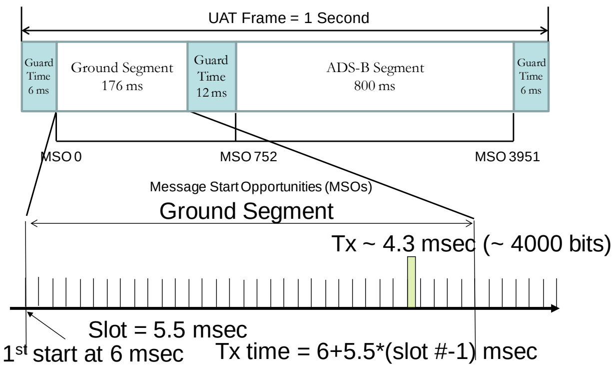

Figure 1. UAT Frame and Organization

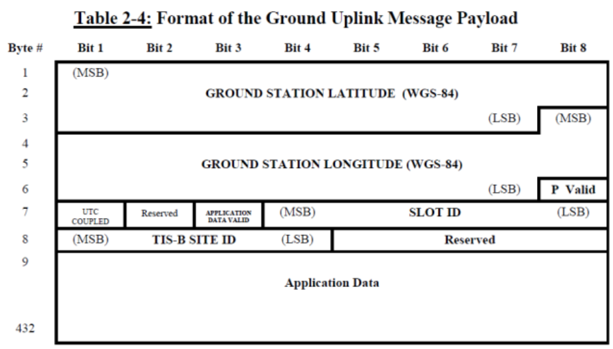

Figure 2. Ground Uplink Message (UAT ground segment) from DO-282B [4]

PASSIVE RANGING

Passive ranging or pseudo range (PR) is calculated by taking difference between time of arrival (TOA), as measured by the user/aircraft (TOA_{AC}) and time of transmission (TOT), as indicated by the ground station (TOT_{GS}). This is shown in Equation 1.

$$PR = TOA_{AC} - TOT_{GS} \qquad (1)$$

For the transmission in the ground segment, the time of transmission is indicated by the slot ID in the message [4]. Equation 2 shows the calculation of the TOT_{GS} of the ground segment message in milliseconds (ms) from the start of the UTC second. Normally, there are two or three ground segment transmissions for each ground station. However, if higher rate is demanded, ADS-B segment must be developed to provide pseudo ranging. As discussed in Figure 3, ADS-B segment messages do not contain necessary information for pseudo ranging. The most critical information not supplied are TOA and ground station source. One way of supplying this information is to develop and transmit new ADS-B segment pseudo ranging messages. However, using existing messages is beneficial for several reasons: 1) more ranging messages, 2) better use of spectrum and 3) no modifications to existing infrastructure. Hence, we examine how this information can be determined from existing messages so that no new messages

$$TOT = 6 + 5.5 \cdot (slot\ number - 1)\ msec \qquad (2)$$

Both TOA and ground station source can be estimated using the information from the ground segment pseudo range message. This can be done simultaneously as we know the stations visible and approximate corresponding pseudo ranges from the ground segment transmissions. Denote the pseudo range from the ground and ADS-B segments as PR_{GND} and PR_{ADSB}, respectively. PR_{GND} has been determined while we cannot immediately calculate PR_{ADSB} because there is no TOT information. By design, TOT must occur at a specified MSO. Furthermore, for a given station PR_{GND} and PR_{ADSB} should be close. Hence, we can estimate PR_{ADSB}. One way is shown in Equation 3 to start with an initial estimated MSO and determine one can add or subtract an integer number of 250 microseconds (µs) that would result in a pseudo ranges consistent for each station available. If that is possible, then both the transmitting station and pseudo range should be close, i.e. Equation 4 should hold. Of course, differentiating stations is predicated on the premise that the available stations have different pseudo ranges, modulo 250 µs or 75 km. This is generally true but could occasionally pose an issue. This can be resolved by not using ADS-B segment pseudo ranges for stations whose pseudo ranges from ground segment transmissions (which have station identification) are close, modulo 250 µs. We conducted analysis of static data from two local ADS-B ground stations to verify this technique.

$$PR_{ADSB} = TOA_{AC} - est\ MSO - N \cdot 250\ \mu s \qquad (3)$$

$$PR_{ADSB,station\ N} \cong PR_{GND,station\ N} \qquad (4)$$

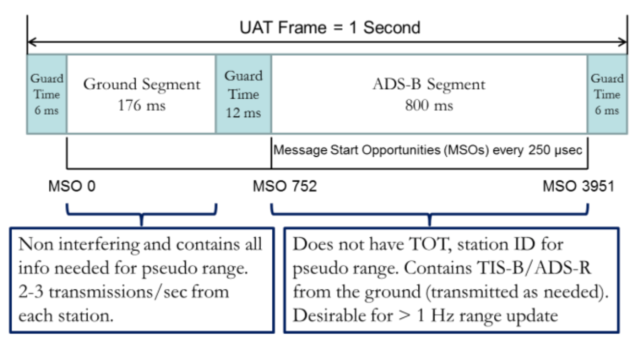

Figure 3. Passive ranging in UAT

DEVELOPMENT OF UAT RECEIVER

To evaluate the passive ranging capability of UAT, a prototype receiver is developed. The receiver equipment is capable of receiving and collecting UAT and GPS signals. The receiver calculates UAT pseudo ranges as well as a GPS truth solution. Calculating a UAT derived position solution is challenging there are only two ADS-B stations in San Francisco Bay Area. To get an additional measurement, we employ a workaround by using GPS to provide a time estimate. When we incorporate other potential APNT measurements from the many local DME stations, this workaround will not be necessary. This is especially true if DME provides both true and passive ranges, allowing for clock synchronization with only one station [6].

The hardware architecture of receiver is depicted in Figure 4. This receiver was designed to be carried on small autonomous platforms so that it should be lightweight, hardened to interference (such as from electric motors) and not requiring external power. The hardware contains GPS antenna, UAT antenna with surface acoustic wave (SAW) filter, computer, solid state drive (SSD), RF front-end, battery and DC to ATX power converter. The received GPS and UAT signals pass to RF front-end. A SAW filter TA0689A manufactured by Tai-saw technology [7] is used to filter out the unwanted signal close to 978 MHz. The RF front-end is Loctronix's ASR-2300[8] which features the dual-channel separated transceivers supporting wideband range between 300 MHz and 3.8 GHz. The center frequencies of those two channels are set as 1575.42 MHz for GPS and 978 MHz for UAT. These two channels are synchronized, so the samples from both channels are aligned within 20 ns. Also, the front-end has 12 bit I/Q sampling, so it provides enough dynamic range to avoid the near-far problem for receiving the terrestrial signal. Currently, the achievable sampling rate for this front-end is 4 MHz, so the direct range resolution of each sample is around 250 nanoseconds (ns) or 75 meters. In the following section, a method to improve the range resolution is shown. Our receiver is software-based and may be required to compute multiple types of signals (GNSS, UAT, etc.) in real-time and process multiple inputs, so the computer should be powerful. Another requirement of computer is low power consumption to allow long running time. Hence, the used computer is Supermicro's X10SBA [9]. Its central processing unit (CPU) is Intel Celeron processor J1900 which features four cores and has 10W power consumption. The computer runs the Ubuntu distribution of Linux and our internally developed software defined radio (SDR). For evaluation purposes, the raw Intermediate Frequency (IF) data stream from the front-end is stored to a SSD and then the data can be post-processed. The pseudorange is used to perform horizontal positioning with the barometer providing altitude estimates. In our receiver, altitude measurement is provided by Pixhawk's barometer [10]. Figure 5 shows a picture of the UAT/GPS prototype receiver.

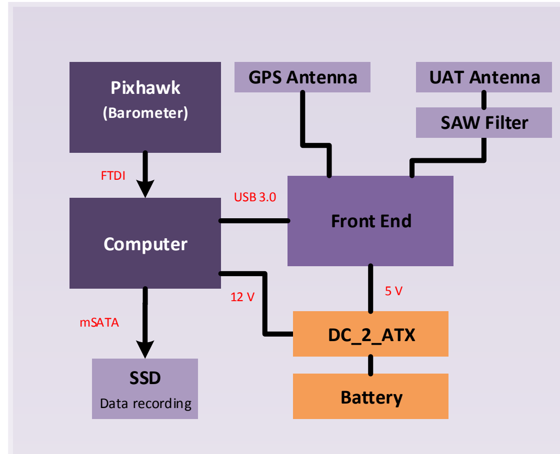

Figure 4. Block diagram of UAT receiver

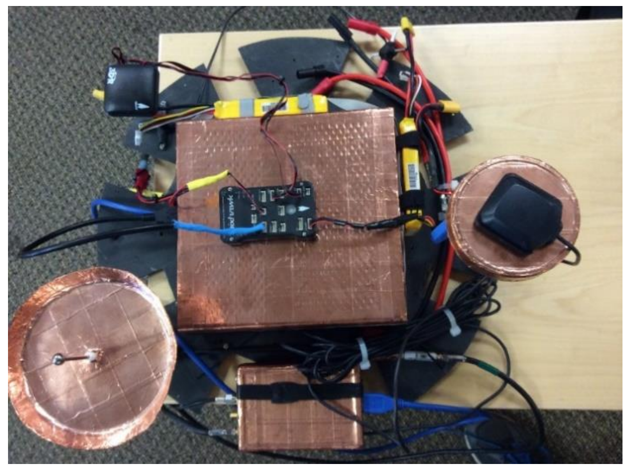

Figure 5. UAT receiver

SOFTWARE ARCHITECTURE

To efficiently use all resources in the computer, the software distributes the tasks into 4 threads with each of thread is distributed to run a separate CPU core. Figure 6 shows the software architecture of UAT receiver. First thread processes the GPS data stream for each one-millisecond long from the front-end. Eight tracking channels are implemented for tracking signals from GPS satellites. This implementation is based on our previous work in [12][13][14][15][16]. The receiver's GPS position can be calculated every 20 ms, if more than four GPS pseudoranges are measured Positioning at high rate 50 Hz is required to keep timing precisely accounting for receiver's clock drift. Second thread processes the UAT data stream from the front-end. The thread starts from signal detector which sets a threshold to detect the UAT signal from the noise floor and checks the synchronization header. Then, data demodulation is performed to obtain the data bit from CPFSK. Forward error correction is to detect and correct errors in the demodulated data. After a full message is received, decoding is performed to get the required information such as the position of ground station and slot identification. Final step in the second thread is TOA determination which uses the timing from GPS and a method in the following section to get better resolution in time. Applying the GPS time make the TOA an estimated true range. This implementation is based on previous works in [17]. Third thread performs the APNT positioning. Every 1 second, the altitude data is obtained from Pixhawk and all UAT pseudoranges occurring within this 1 second time frame are collected. Then, a filter is performed on these pseudoranges to get noiseless range. Final step is to do APNT positioning using UAT pseudorange and barometer height. The fourth thread is configured to run the main function for controlling overall system and other data transfer between computer and front-end.

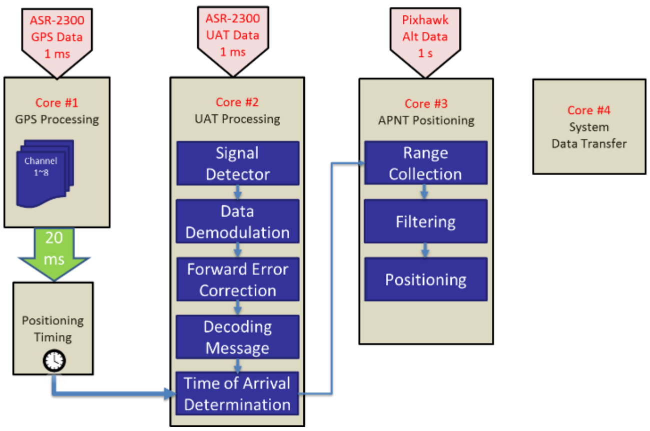

Figure 6. Software Architecture of UAT receiver

IMPROVING RANGE RESOLUTION

Due to the limitation on low sampling rate, a method based on correlation is used to improve range resolution. Figure 7 shows an example of UAT incoming signal in the synchronization header. The sequence of synchronization header is defined in [3], so local replicas with detailed delays can be built beforehand and pre-loaded into memory. Figure 8 shows the multiple local replicas with 3 meters resolution between 1 and -1 sampling time. Different colors indicate the local replica with different delays. The correlation between incoming signal and local replicas is

$$Z[j]=\sum_{i=1}^{n} x[i]\times y[i-j\frac{2T}{(M-1)}] \qquad (5)$$

where x is incoming signal, y is local replica, T is sampling time, M is the number of local replicas, n is the number of samples in the synchronization header, and j represents index of local replica from –(M-1)/2 to (M-1)/2 . Figure 9 shows an example of correlation outputs with M = 51. With a sampling rate of 4 MHz, the range resolution is around 3 meters. The index of maximum correlation indicates the optimal TOA.

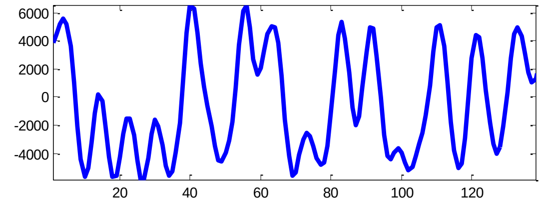

Figure 7. UAT incoming signal

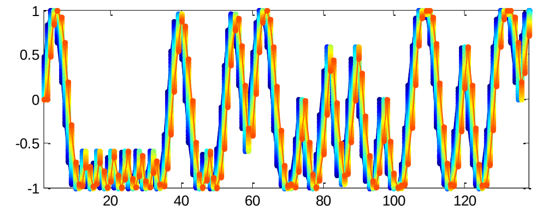

Figure 8. Local replicas for UAT signal

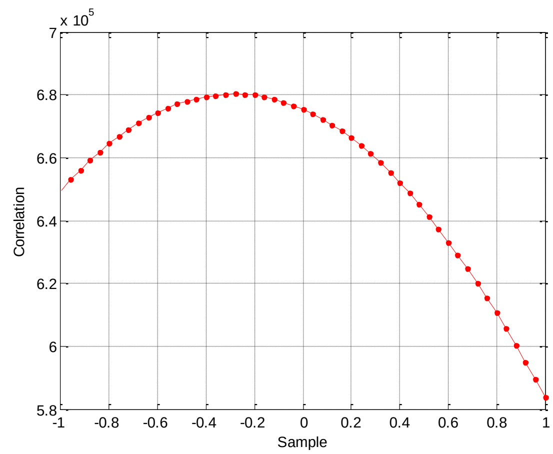

Figure 9. Correlation results

POSITION CALCULATION

The minimum requirement for positioning is with two UAT ranges (as GPS time turns the TOA measurements into true ranges) and one barometric altitude. Its procedure is shown in Figure 10. Position is calculated by solving following nonlinear equations

$$\begin{aligned} c\times(TOA_1-TOT_1) &= \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} \\ c\times(TOA_2-TOT_2) &= \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} \\ h &= F(x,y,z) \end{aligned} \qquad (6)$$

where c is speed of light, TOA_k is the time of arrival of k^{th} ground station, TOT_k is the time of transmission of k^{th} ground station, x,y,z is the receiver's position to be solved, x_k,y_k,z_k is the surveyed position of k^{th} ground station, h is barometric altitude, and F is the function to transfer earth-centered earth-fixed (ECEF) Cartesian coordinate frame (x,y,z) to the h in ellipsoidal coordinate .

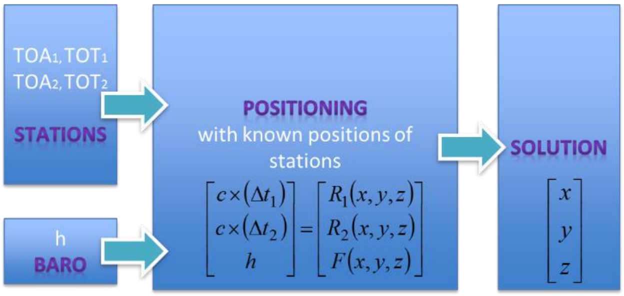

Figure 10. Positioning procedure

DRIVE TEST SETUP

In order to evaluate the capability of ranging and positioning using UAT receiver, initial drive test is conducted in Stanford campus. Figure 11 shows the receiver setup. The receiver is mounted on the top of a Sport Utility Vehicle (SUV). The SUV was driven on the top level of a parking garage as shown in Figure 12. The size of parking is 120m × 100m. Driving test starts by staying at each corner of parking garage for two minutes and then taking two round trips counterclockwise. In this test, available UAT signals from two ADS-B ground stations, Woodside and San Jose, are shown in Figure 13. The ground station in San Jose is farther away from Stanford (40 km away) and has lower height 283 m. As a result, the San Jose UAT signal is sometimes blocked by surrounding structure.

Figure 11. Drive test setup

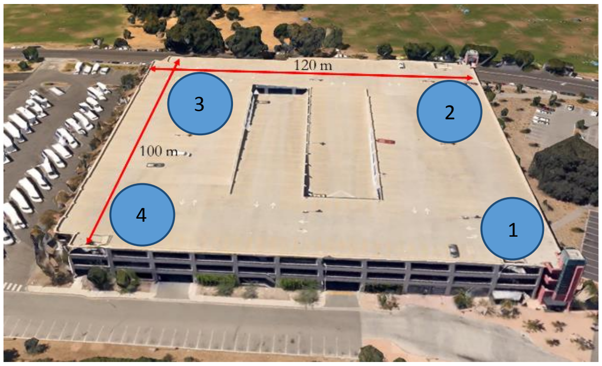

Figure 12. Parking garage in the drive test

Figure 13. Local ADS-B ground stations in San Francisco Bay area

PSEUDORANGE AND HEIGHT MEASUREMENT

The UAT ranges results from both of ground stations are shown in Figure 14. The UAT range outputs are updated in the discrete time when signal is available. The GPS range outputs are calculated by our GPS SDR and thought to be true. In the range from San Jose, UAT signal is unavailable in the fourth corner due to blockage. Both of ranges have biases compared to the GPS determined truth. Figure 15 shows the histograms of range error from both ground stations. The biases from San Jose and Woodside are 76 and 138 m, respectively. Both of biases are within 500ns (150m) which are resulted from timing accuracy in the ground station. The standard deviation of range is around 12 m.

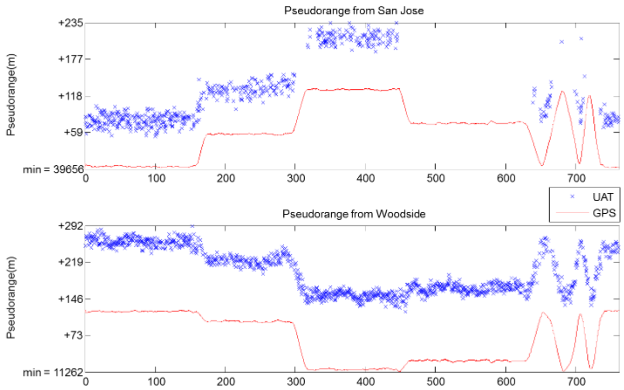

Figure 14. UAT ranges with time from ground stations San Jose (top) and Woodside (bottom)

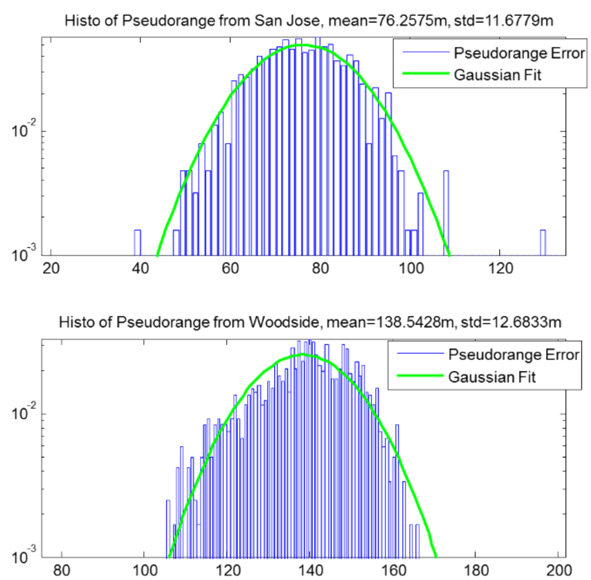

Figure 15. UAT range errors from ground stations San Jose (top) and Woodside (bottom)

There are three height measurements available on our platform: GPS SDR, commercial ublox GPS receiver and barometer. Figure 16 shows the comparison between three heights. The height should not change much because the whole driving route is on the same level. It is noted that the second corner has higher height than expected from GPS. The difference between first and second corners from both GPS receiver is around 8 meters. It is much higher than height difference of barometer which is only 2 meters. There is an elevator structure next to the second corner. Hence, it is suspected that there is a high level of GPS multipath in the second corner.

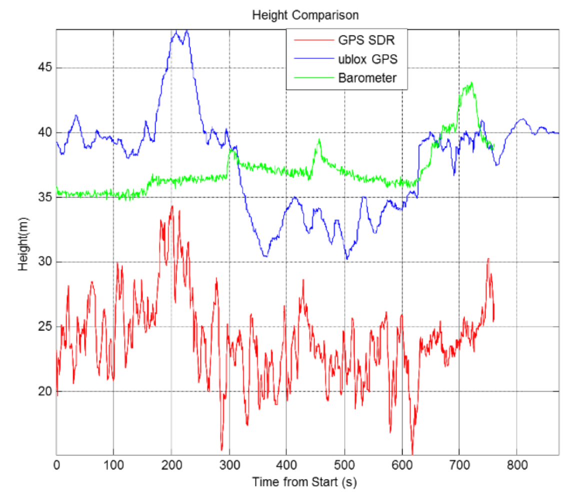

Figure 16. Height outputs comparison between barometer and GPS receivers

POSITIONING RESULT

UAT positioning using the procedure described in the previous section are divided into static and dynamic cases. The biases in the UAT ranges are removed before positioning. Figure 17 shows the results in the static cases while the SUV stays in the four corners. There is only one UAT range available in the fourth corner, so no position fix is available. Figure 18 shows the position fixes in the first corner. Its 95% horizontal accuracy is 37.2 m. It has the best performance among the four corners. Figure 19 shows the position fixes in the second corner. It has the worst performance due to UAT multipath. There is an obvious bias in position fixes, so the 95% horizontal accuracy increases to 72m. For the dynamic case, Figure 20 is the positioning result and only half of loop has position fixes. Also, a large bias exists in the second corner.

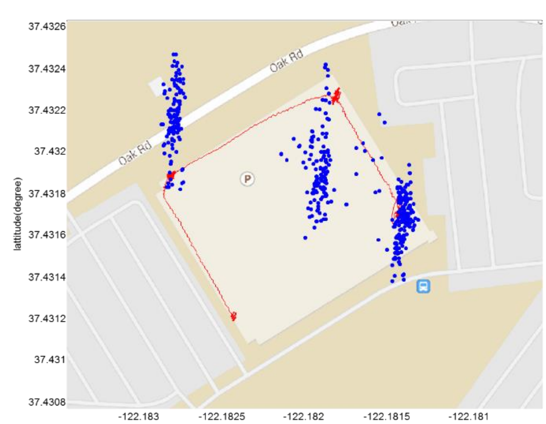

Figure 17. Positioning results in the static case

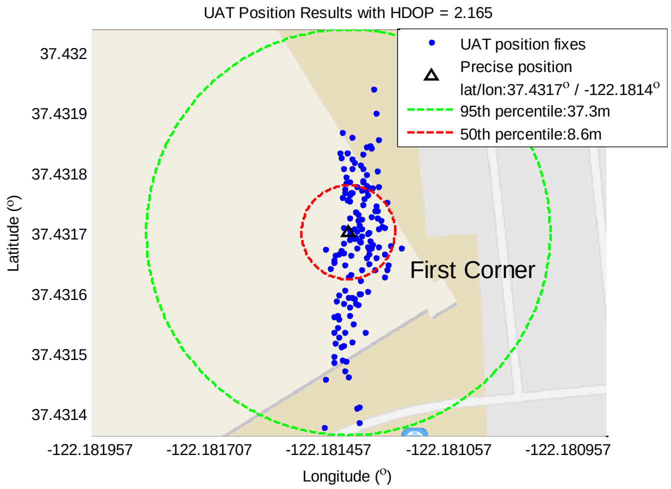

Figure 18. Corner I: Position fixes and quality

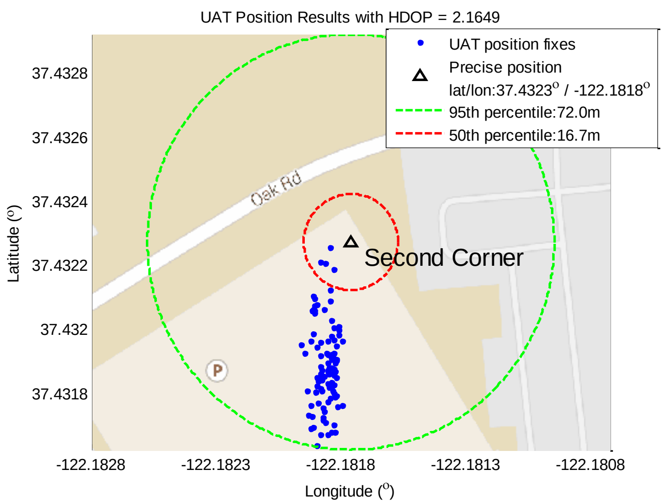

Figure 19. Corner II: Position fixes and quality

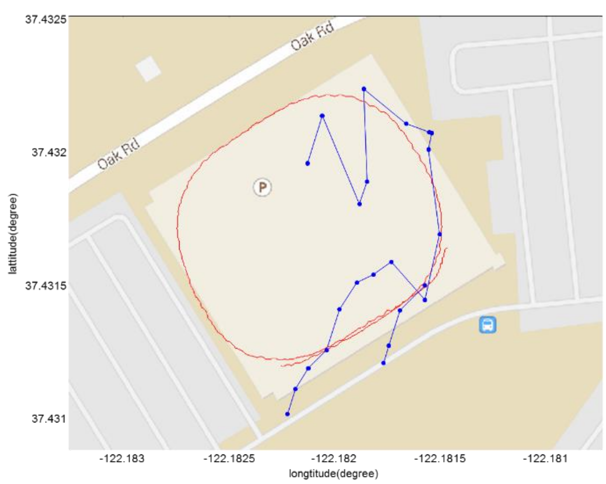

Figure 20. Positioning results in the dynamic case

CONCLUSIONS

This paper examines the use of UAT signal for passive ranging and provides an evaluation for ranging and positioning with on-air data. It discusses how to use UAT for ranging and introduces a means of using ADS-B segment transmissions, not designed for ranging, for ranging. This enables higher range update rates. The results of the paper indicate that UAT signals have good nominal ranging accuracy comparable or better than pseudoranging using DME pseudolite (PL) [18]. Hence, as ADS-B and DME ground stations are geographically separated, combining ADS-B based pseudolite and DME PL can greatly improve the area of pseudolite service. The ranging and positioning performance using UAT initially indicate that it can support RNP 0.3. Future works includes conducting an authorized unmanned aerial vehicle (UAV) flight test and adding the DME ranging for support hybrid APNT.

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