DME/DME NAVIGATION USING A SINGLE LOW-COST SDR AND SEQUENTIAL OPERATION

Taher Jalloul and Wessam Ajib, Université du Québec à Montréal, Montreal, Canada

Omar A. Yeste-Ojeda and René Landry, Jr., Laboratory of Specialized Embedded System, Navigation and Avionics (LASSENA), École de Technologie Supérieure, Montreal, Canada

Claude Thibeault, Department of Electrical Engineering, École de Technologie Supérieure, Montreal, Canada

Abstract

Federal Aviation Administration is initiating an Alternative Position, Navigation, and Timing (APNT) program to insure continuous services in the event of GNSS failure. One of the promising solutions is an Optimized Distance Measuring Equipment (DME) Network based on DME/DME navigation. In comparison to other proposed APNT architectures, such as DME pseudolite network and passive Wide-Area Multilateration, airline operators find DME/DME more attractive for backup, as this solution requires no change to avionics used by commercial aircraft. This paper presents the implementation of the DME/DME system on the low-cost, Software Defined Radio (SDR) Nutaq ZeptoSDR platform. The SDR technology was chosen for its flexibility and reconfiguration. In fact, the success of implementing the DME avionic in a SDR platform will provide opportunities to implement other technologies. With such a versatile platform many problems can be avoided in an aircraft like the excessive wiring. To enable DME/DME in a single radio SDR, a new concept: "Sequential DME/DME" is introduced. This paper describes the principle of operation of the system and its implementation. To evaluate the Sequential DME/DME in a laboratory environment, a test bench platform is developed using avionics certification equipment. In lab tests using this platform are conducted to evaluate the system performances and results are presented. The accuracy of the system is studied by examining distance and position measurement precision.

I. Introduction

The Federal Aviation Administration (FAA) is developing Next-Generation Air Transportation System (NextGen) to support the predicted increase in operations in the aircraft transportation by 2025. NextGen is as an overhaul of the current US air traffic control system [1]. Global Navigation Satellite Systems (GNSS) such as GPS is predicted to play a central role in providing Position Navigation and Timing (PNT) services for NextGen. However, GNSS is susceptible to unavailability that can be caused by RF interference, adverse solar activity, or constellation failures. A significant GNSS outage will severely disrupt air traffic management. To avoid such problems, the FAA is developing an alternative position, navigation, and timing (APNT) system that will continuously provide service. FAA's studies on APNT systems [2] proposed three architectures, namely DME pseudolite network, passive Wide- Area Multilateration and optimized DME network. The last architecture uses the DME/DME positioning. The DME/DME architecture is attractive for many reasons. In fact, this solution will use existing systems and technologies and will not require a system redesign. This interest in the DME shows its success in current and future aircraft navigation.

With the proposition of DME/DME as an APNT candidate, the research interest in the DME has arisen again. Recently, researchers have started to study DME from different perspectives. In [3], the author analyzed the DME/DME accuracy in 2D. The author showed the relationship between the DME/DME accuracy, the accuracy of the DME ranging signals and the inclusion angle between the DME transponders used for the position determination. Furthermore, the author studied the accuracy of DME/DME in 3D for several specific cases. For these scenarios, the author investigates the horizontal accuracy. In [4], the author investigated the feasibility of DME/DME proposed APNT solution. The author studied the optimal DME/DME ground station network that enables required performances for navigation and surveillance by using coverage analysis method. Furthermore, a DME capacity analysis was

978-1-4799-5001-0/14/$31.00 ©2014 IEEE

done to investigate whether the DME in the optimal networks can process the expected load. The paper assumes higher range accuracy of the existing DMEs than the DME standard. This assumption is from recent flights inspection data. In [5], the authors investigated the optimal methods of DME stations distribution for DME/DME positioning. Matlab simulations were conducted for the study. This paper provides theoretical guidance for implementation of DME/DME in China. In [6] [6], the authors worked on performance enhancement techniques for the DME to meet APNT requirements. The concept of enhanced DME (eDME) was introduced. Theory, application and performances of processing techniques were discussed. For performances evaluation, a measurement system for eDME was presented. Also flight test results were shown to demonstrate the performances. As far as we know, the subject of implementation of the DME/DME system on a SDR has not yet been discussed in the literature. SDR technology is gaining popularity because of the capability of reprogramming it to work under different standards with minimum hardware change. The implementation of DME avionic can be a first step to implement other technologies like transponder mode S and ADS-B in the same SDR platform. A multi-standard platform can be a solution to existing problems like the excessive cost, size and weight of aircraft avionic systems. To develop the DME/DME system in a single radio platform a new concept: "sequential DME/DME" is introduced.

The remainder of this paper is organized as follows: A DME overview is presented in Section II. Section III details the implementation of the system. The hardware and software used are presented and principle of operation is detailed. Section IV presents test results and performance analysis.

II. DME overview

The DME system is a pulse-ranging navigation system composed by an airborne interrogator and a ground station transponder for slant range distance measurements. The DME operation frequencies are in the range of 960 -1215 MHz. The frequencies are divided into 252 channels with 1 MHz separation [7]. Each ground station is assigned to a fixed channel, with aircraft DME interrogators able to transmit in transponder DME frequencies. The interrogator starts communication with the ground transponder (search mode) by sending randomly jittered interrogations of a maximum of 150 pulse pairs per second (ppps) to one transponder frequency. The goal of jittering is to differentiate valid own replies from DME replies to other aircraft interrogators. Once the interrogator establishes proper communication with a ground transponder, it goes to tracking mode. In this mode, the interrogator sends interrogations (also randomly jittered) at a lower rate with a maximum of 16 ppps [7]. The DME interrogator coupled with a VOR is used for rho-theta navigation because the navigation method only needs one transponder at a time.

Multichannel or scanning DME avionics use interrogator architectures able to obtain multiple DME distance measurements simultaneously. In a scanning DME, available channels are typically between two and six. In a six channel interrogator, five of the channels are used in the foreground mode to provide slant range distance measurements for position computation. The sixth channel is assigned to the background mode which is used for an acquisition of new transponder stations. The average interrogation rate of a scanning DME should not exceed 48 ppps for all frequencies [7].

The DME interrogation signal shape consists of a Gaussian pulse pair with a separation time depending on the Mode. Existing modes are X, Y, W, Z. Mode W and Z are rarely used in today's systems. The pulse pair is separated 12 µs in X mode for both interrogation and reply, and 36 µs and 30 µs in Y for the interrogation and reply respectively. When the ground transponder receives a valid interrogation, it replies with the same type pulse pair after adding a time delay of 50 µs (considering the leading edge of the second pulses). In addition to reply pulses, the ground transponder transmits squitter and code identification signals. For these two signals the same type of pulse pair is used. The squitter signal consists of random transmissions to maintain a minimum pulse repetition frequency (PRF) of about 800 Hz whenever the number of decoded interrogations is lower than this range. The identity signal consists of the transmission of a Morse coded three letter identification for the transponder and is transmitted at least once every 30 seconds [8].

III. Implementation

Hardware and Software

The selected hardware platform for the implementation is Nutaq's ZeptoSDR [9]. This platform, which offers cost and performance trade-off, is composed of Zynq-based Zedboard and Nutaq's Radio420S FMC card. This SDR provides both external and embedded host APIs. The Zedboard offers a coupled dual core ARM Cortex-A9 and the Artix-7 series FPGA. The FMC card enables the RF interface to tune the frequency from 300 MHz to 3.8 GHz and to select the bandwidth from 1.5 to 28 MHz with 14 selectable RF band pass filters to avoid interference.

ZeptoSDR supports GNU Radio software suite to create complex SDR systems [10]. GNU Radio is a free and open source software development toolkit that provides signal processing blocks to implement SDRs using off-the-shelf RF hardware. The Python programming language is used for writing GNU Radio applications. For the performance-critical signal processing tasks, C++ is used. A variety of operating systems are compatible with GNU Radio, mainly Linux based ones. For running GNU Radio in this project, a Linux based operating system, Ubuntu 10.04, was used.

Principle of Operation

Compared to the scanning DME, the ZeptoSDR platform is equipped with only one transceiver. This feature does not allow the ZeptoSDR to get multiple signals at the same time for processing whenever their frequency separation exceeds the maximum bandwidth of Radio420S (i.e., 28 MHz). Hence, acquiring multiple distance measurements simultaneously is not always possible. To overcome this limitation, a new concept is introduced: "sequential DME/DME". Sequential DME/DME will get signals successively from each station. The principle of operation of this system is shown in Figure 1. For example, in the presence of four stations, the DME will start by tuning in its frequency to one station. After getting the distance, the DME will be tuned in to another station frequency. The same step is repeated for the other stations. Since the airplane is moving, at the time of acquiring the last distance, the three first distances are not exact anymore. Therefore, we propose an algorithm to determine the three first distances at the last distance measurement instant. With these four distances, the position of the aircraft is computed.

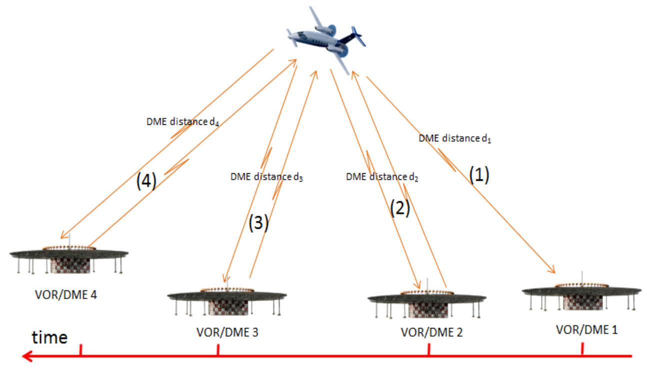

Figure 1. Sequential DME/DME Principle of Operation

Analytical Model for Position Computation

For positioning calculation purposes, let us consider the Earth Centered Earth Fixed (ECEF) coordinate reference system. Let us consider four ground stations. To compute the position, the system to be solved is composed by the four distances d_i to each station i given below:

$$\begin{cases} \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} = d_1 \\ \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} = d_2 \\ \sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} = d_3 \\ \sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2} = d_4 \end{cases}, \quad (1)$$

where (x, y, z) is the position of the aircraft (the unknown in the system) and (x_i, y_i, z_i) is the position of station i (which is known). As for GPS, this nonlinear system can be solved for the unknowns by employing iterative techniques based on linearization. Through Taylor series expansion we get:

$$d_i = \hat{d}_i - \frac{x_i - \hat{x}}{\hat{d}_i}\Delta x - \frac{y_i - \hat{y}}{\hat{d}_i}\Delta y - \frac{z_i - \hat{z}}{\hat{d}_i}\Delta z, \quad (2)$$

where $\left(\hat{x}, \hat{y}, \hat{z}\right)$ is the approximate position location and $(\Delta x, \Delta y, \Delta z)$ refers to the estimation error. We define:

$$\Delta d_i = d_i - \hat{d}_i$$

$$a_{xi} = \frac{x_i - \hat{x}}{\hat{d}_i}$$

$$a_{yi} = \frac{y_i - \hat{y}}{\hat{d}_i} \quad , \tag{3}$$

$$a_{zi} = \frac{z_i - \hat{z}}{\hat{d}_i}$$

Hence the equations can be put in matrix form as:

$$\Delta d = H.\Delta x \, , \tag{4}$$

where:

$$\Delta d = \begin{bmatrix} d_1 \\ \vdots \\ d_4 \end{bmatrix} \quad \Delta x = \begin{bmatrix} \Delta x \\ \vdots \\ \Delta z \end{bmatrix} \quad H = \begin{bmatrix} a_{x1} & a_{y1} & a_{z1} \\ \vdots & \vdots & \vdots \\ a_{x4} & a_{y4} & a_{z4} \end{bmatrix}$$

Algorithm for Distance Calculation

Let us define i as the iteration to compute the position and j the index of the station. Since the aircraft is moving and distances are acquired sequentially, the three first distances are not correct to compute the position. These three distances measured respectively at t_{i1}, t_{i2} and t_{i3} should be extrapolated to a common time, t_{i4}, the measuring time of the fourth distance. In order to do that, let us assume that the speed of the aircraft can be approximated as constant between two consecutive positions computations. Hence, the distance to station j can be defined as a linear equation as:

$$d_{ij} = a_{ij}.t_{ij} + b_{ij} \quad , \tag{5}$$

where d_{ij} is the measured distance to station j at the instant t_{ij}, a_{ij} and b_{ij} are the gradient and the constant term respectively. The algorithm to compute the three distances at the instant of measuring the fourth one is given in Algorithm 1.

Algorithm 1. Distance Determination Algorithm

for i *from* 2 *to* ∞ **do**

  for j *from* 1 *to* 3 **do**

  $a_{ij} \leftarrow \frac{d_{ij} - d_{i-1j}}{t_{ij} - t_{i-1j}}$;

  $b_{ij} \leftarrow d_{ij} - a_{ij}.t_{ij}$;

  $d_{ij} \leftarrow a_{ij}.t_{i4}$;

  end

end

OUTPUT: Distances calculation at the instant of acquiring the fourth distance

IV. Tests and Performances

Test Platform

To test and measure the performances of the system described in Section III, a laboratory test bench setup was created as shown in Figure 2.

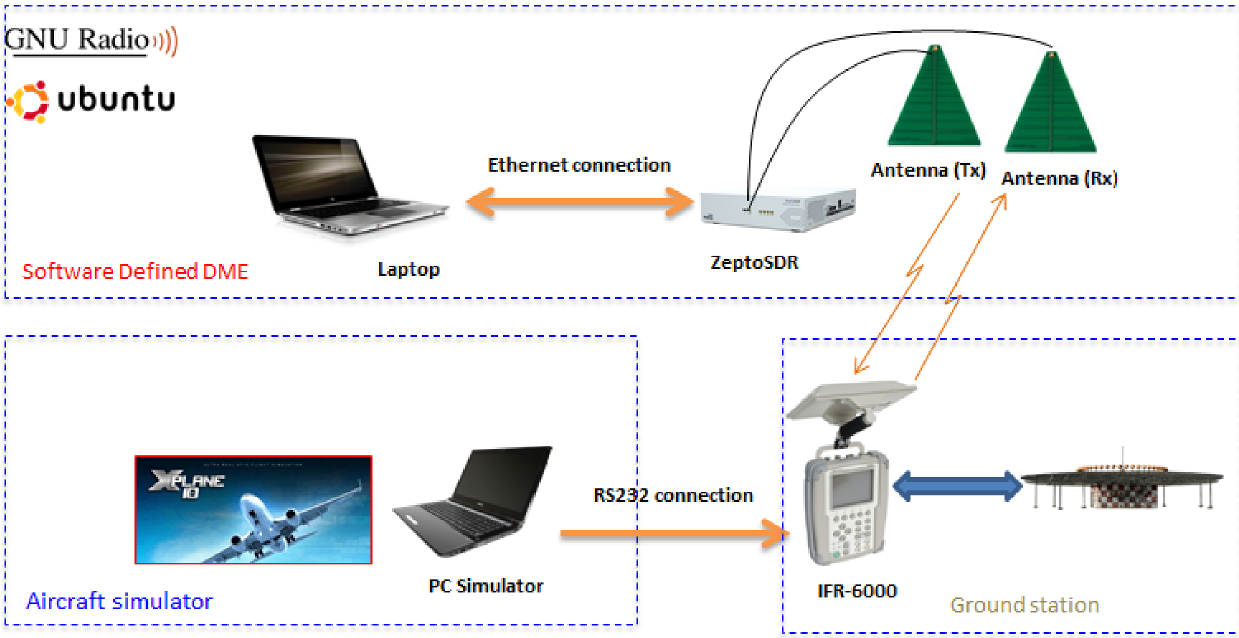

Figure 2. Lab Test Bench Platform

This test bench is composed of three parts:

- A flight simulator running on a laptop generates realistic flight data for the test bench. A simulator plugin is used to display information such as aircraft position, ground stations frequencies, and distances to each ground station as shown in Figure 3. This part of the test bench gives the distance to each station and the aircraft position to be compared with the ones calculated by the developed system.

- The IFR6000 avionics ramp test set [11] represents the ground stations in the DME/DME positioning system. This equipment is designed for testing transponder modes A/C/S, TCAS I and II as well as DME. In this paper only the DME features are used. The IFR6000 supports all DME/TACAN channels selectable in VOR paired channels. The laptop running the flight simulator is connected to the IFR6000 via an RS232 connection. A second program running in the background on the laptop is updating the range information at the IFR6000 at a rate of 10 Hz. This information is extracted from the flight simulator. In addition, the program sequentially switches from one ground station to another following a predefined list, while programming the IFR accordingly. Sequential ground station simulation is required as the IFR6000 cannot simultaneously emulate replies from several ground stations. The dwell time of every ground station must be set such that the SDR implementation of sequential DME is able to track the corresponding ground station and get a valid distance measurement. After measuring the distance, the DME interrogator switches to the frequency channel corresponding to the next ground station, following the same order as the IFR6000. If the ground station is not tracked within the dwell time, the DME interrogator remains in the same channel until a distance measurement can be obtained. That means to wait for the IFR6000 to sweep the complete list of ground stations at least once. Test results reveal that a dwell time of about 1.2 seconds minimizes the average time required to fix a position.

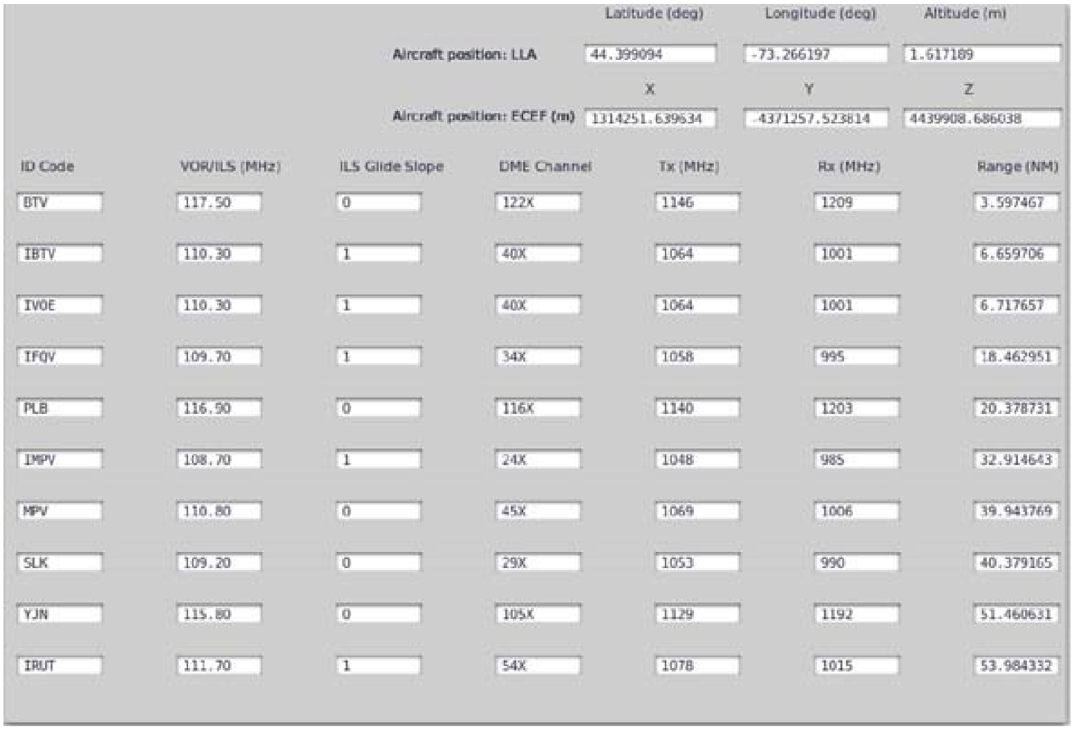

Figure 3. Plugin for the Aircraft Simulator

- The airborne DME interrogator consists of the ZeptoSDR connected to a laptop. Note that ZeptoSDR allows embedded operation as well, after proper optimization to run GNU Radio code on the Zedboard's ARM processor [12]. The positions, frequencies and switching order for the ground stations are configured in the interrogator. After computing the distance to a virtual station, the interrogator moves to another station frequency. When acquiring four distances, the position of the aircraft is computed. Aircraft position is calculated each 5s ($\approx 4 \times 1.2$ s). The frequency switching time for the ZeptoSDR is of the order hundreds of microseconds. This would allow in future decreasing the dwelling time of each ground station down to the time required to process a single reply (instead of waiting for tracking). Using this approach, the positioning rate of the system could increase up to about 16 Hz[1], and the constant velocity assumption will become much more realistic. However, it has been checked that the IFR6000 cannot switch between different frequencies at such a rate, and hence, a testing equipment with a higher frequency switching time (or as many of them as ground stations) would be required for testing the new approach.

System Performance

In this section, we provide some test results to illustrate the performance of the proposed system. The performance of sequential DME/DME is analyzed in terms of accuracy of the aircraft position. As for GPS navigation system, the relationship between the errors of distance measurements and aircraft position accuracy is described by the Geometric Dilution of Precision (GDOP). The position estimate is dependent upon the geometry of the ground stations used in the position calculation and the corresponding quality of

[1] For DME equipment which interrogates more than one frequency, the average interrogation rate cannot exceed either 48 ppps for all frequencies, or 16 ppps per frequency [7]. Therefore, the positioning rate depends on the number of stations interrogated and is limited by [7], but not the hardware used.

the distance measurements. The accuracy of sequential DME/DME position can be expressed as:

$$\sigma_{Position} = GDOP.\sigma_{Distance}, \qquad (6)$$

where $\sigma_{Position}$ is the standard deviation of the position accuracy, $\sigma_{Distance}$ is the standard deviation of the distance error and GDOP is the geometric dilution of precision in the position solution. Making the common assumption of unbiased position estimation and Gaussian errors, the GDOP is a dimensionless number defined as:

$$GDOP = \sqrt{trace\left(H^T H\right)^{-1}} = \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}}{\sigma_{Distance}} \qquad (7)$$

where H is the direction cosine matrix, and σ_x, σ_y and σ_z are the RMS errors in the estimated user position coordinates (x, y, z). In order to examine horizontal and vertical positioning errors independently, GDOP can be decomposed into:

- Horizontal Dilution of Precision (HDOP): It is a measure of uncertainty in horizontal position (Longitude and Latitude) of the navigation solution.
- Vertical Dilution of Precision (VDOP): It is a measure of uncertainty in vertical position (altitude) of the navigation solution.

To calculate HDOP and VDOP, the ECEF coordinates must be transformed to local tangent plane defined as east, north, up at the estimated location [13]. This results in a new matrix H_{enu}:

$$H_{enu} = \begin{bmatrix} \cos(EL_1)\cdot\cos(AZ_1) & \cos(EL_1)\cdot\sin(AZ_1) & \sin(EL_1) \\ \vdots & \vdots & \vdots \\ \cos(EL_4)\cdot\cos(AZ_4) & \cos(EL_4)\cdot\sin(AZ_4) & \sin(EL_4) \end{bmatrix} \qquad (8)$$

where EL_i and AL_i are the elevation and azimuth angles from the plane to the station i. HDOP and VDOP are defined as:

$$HDOP = \sqrt{C_{11} + C_{22}} \qquad (9)$$

$$VDOP = \sqrt{C_{33}} \qquad (10)$$

where

$$C = \left(H_{enu}^T . H_{enu}\right)^{-1} \qquad (11)$$

The first performance criterion investigated is the accuracy of the measured distance. Figure 4 presents the standard deviation of the measured distance as a function of the SNR [12]. In this figure, the distance in the IFR6000 is set to 3 m (short delay). We notice that the RMSE is low for the used SNR values. The figure illustrates the high accuracy of the measured distance by the system. The error in the distance is less than 20 m, which is the IFR6000 accuracy specification. Furthermore, Fig.4 shows that the RMSE increases slightly when the SNR decreases. The DME system loses track of ground station when SNR had lower values.

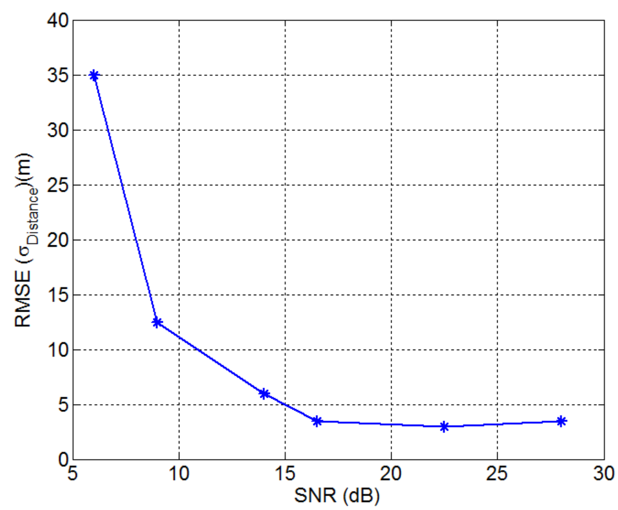

Figure 4. Distance RMSE vs SNR

In [4], the author gave the required HDOP values for navigation for some specific Flight Technical Error (FTE) [14]. Depending on the Required Navigation Performance (RNP), these values are HDOP = 2.38 for RNP 0.3, or HDOP = 13.87 for RNP 1.0. The analysis of these requirements is beyond the scope of this document, and only one scenario is considered regardless of its appropriateness for different RNP.

Figure 5 illustrates the 4 DME ground stations' positions relative to the aircraft for the considered scenario. This scenario is the one simulated in the flight simulator in order to program the IFR6000 and assess the position accuracy of the sequential DME/DME system. The figure shows the impact of the stations geometry by calculating the GDOP:

GDOP = 14.75, HDOP = 4.47 and VDOP = 13.97. The high value of the VDOP is due to the fact that the ground stations are located at similar altitudes. As a consequence, it is not possible to determine reliably the altitude of the aircraft only from the measured ranges, and altitude errors in the order of few kilometers have been observed even though the distance measurements are highly accurate. In fact, such errors are 10 times greater than what predicted from the theoretical VDOP factor. Further investigation shows that the cause may be that the ranging error is different for every ground station, as will be explained next. Even if the theoretical performance were achieved, GDOP is negatively affected by this and hereinafter only horizontal position errors shall be discussed. For 3D navigation, altitude information must necessarily be extracted from an additional sensor, such as an altimeter or GNSS.

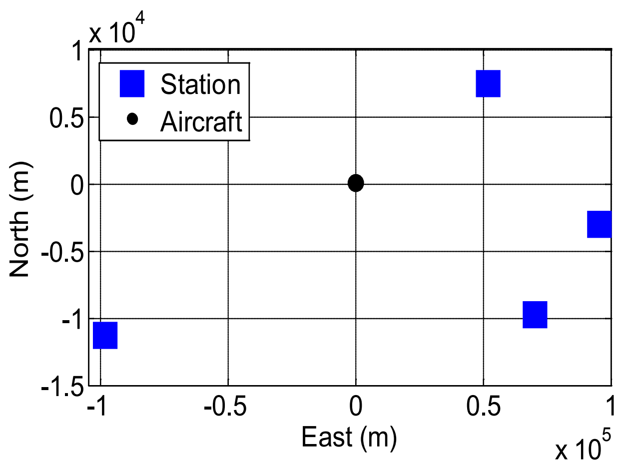

Figure 5. GDOP = 14.76, HDOP = 4.75, VDOP = 13.97

In the scenario represented in Figure 5, the four DME stations are located at distances 53 Km, 96 Km, 71 Km and 99 Km. As mentioned before, the range accuracy obtained during the in lab experiment is different for every ground station. The observed standard deviations were 10.2 m, 5.4 m, 5.6 m and 18.0 m, respectively. The accuracy seems not to be related to the distance. Further investigation of this phenomenon needs to be carried out, and our initial guess is a frequency related issue.

Figure 6 represents the horizontal position of the aircraft computed by the sequential DME/DME system relative to the true one, for the scenario represented in Figure 5. The results show different accuracies for the east and north coordinates, whose respective standard deviations are $\sigma_E = 9.23$ m and $\sigma_N = 56.05$ m. This difference can be explained by decomposing the HDOP into the east and north components, which will be denoted the East DOP (EDOP) and the North DOP (NDOP), respectively. For the scenario represented in Fig.5 they result EDOP = 0.66 and NDOP = 4.70 (note the different scales of the x and the y axes). Although the assumption made for DOP computation of equal ranging error for all the ground stations is not satisfied, the positioning accuracy is much closer to the value predicted from the DOP and the average range accuracy. The latter can be obtained as the square root of the mean variance of range measurements to every station, which yields $\overline{\sigma_r} = 11.1$ m. Therefore, the predicted error in the East component would be 7.3 m, while it would be 52.2 m for the North component.

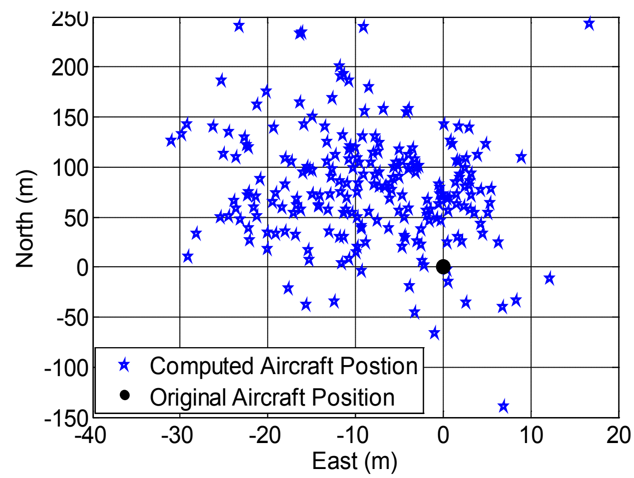

Figure 6. Distribution of the Computed Position

Figure 6 also shows the existence of a bias in the position estimates, being 8.6 m towards West and 79.0 m towards North. This bias is the result of biased range measurements, which in turn are due to the conjunction of two effects: 1) A frequency independent bias due to residuals during DME calibration step at the beginning of operation [12]; 2) a frequency dependent bias caused by the group delay of the different hardware involved. This bias can be removed, or at least highly compensated, by integration of the DME/DME navigator with a GNSS sensor, which will be aimed in further investigation.

V. Conclusion

In this paper we developed a DME/DME positioning system in the ZeptoSDR platform. The development of a scanning DME is not possible on this single radio platform. To overcome this limitation, the new sequential DME/DME concept was introduced. Currently, the interrogator performs the complete search/tracking procedure before switching to the next ground station channel which results in a positioning rate of about 0.2 Hz. It is planned, however, to accelerate the process by decreasing the interrogator dwell time at each frequency to the minimum allowed (about 20 ms). This time is long enough to process a single pair of pulses from its transmission up to measuring the distance. The new approach is expected to increase the positioning rate up to 16 Hz and to improve the positioning accuracy by reducing the error due to the constant velocity assumption. To test the system performance we developed a test bench platform in which we use avionic certification equipment. We studied the performance of the system and we showed that the position accuracy is dependent on the stations geometry and the distance measurement errors, which is highly accurate. To get the best performance from the system, station geometry should be controlled. Selection of stations for optimal geometry based on availability can be investigated in the future. Integration of DME/DME navigation with other navigation systems, such as GNSS, is also an interesting future research and would help to reduce the position bias.

References

[1] M. FAA, "NextGen Implementation Plan," Washington, DC, March 2011.

[2] M. Narins, "The Benefits of Alternative Positioning, Navigation, and Timing (APNT) to Aviation and Other Users - the Need for Robust Radio Navigation," in Integrated Communications, Navigation and Surveillance Conference (ICNS), 2012, 2012, pp. 1-37.

[3] M. Tran, "DME/DME Accuracy," in Proceedings of the 2008 National Technical Meeting of The Institute of Navigation, 2001, pp. 443-451.

[4] E. Kim, "Investigation of APNT Optimized DME/DME Network Using Current State-of-the-Art DMEs: Ground Station Network, Accuracy, and Capacity," in Position Location and Navigation Symposium (PLANS), 2012 IEEE/ION, 2012, pp. 146-157.

[5] L. Shuyu, N. Yude, and C. Na, "Optimal Strategy of DME Beacon Distrbution for DME/DME Area Navigation," in Signal Processing (ICSP), 2012 IEEE 11th International Conference on, 2012, pp. 2036-2039.

[6] W. Pelgrum, Li, Kuangmin, Smearcheck, Matt, van Graas, Frank,, "eDME Architecture Development and Flight-Test Evaluation," Proceedings of the 25th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2012), pp. 812-825, September 2012, .

[7] RTCA, "Minimum Operational Performance Standards for Airborne Distance Measuring Equipment (DME) Operating Within the Radio Frequency Range of 960-1215 Megahertz," DO-189, Sep. 1985.

[8] Federal Aviation Administration, "Performance Specification Distance Measuring Equipment (DME)," FAA-E-2996, pp. 7–16, April 2008.

[9] Nutaq, "ZeptoSDR,". Available: http://nutaq.com/en/products/zeptosdr.

[10] GNU Radio - WikiStart [Online]. Available: http://www.gnuradio.org

[11]"IFR 6000", Available: http://www.aeroflex.com/ats/products/product/Avionics/XPDR,_INTER,_DME,_TACAN,_TCAS/IFR_6000~190.html.

[12] O. A. Yeste-Ojeda and R. Landry, "Software Defined Radio Approach to Distance Measuring Equipment," in Position, Location and Navigation Symposium - PLANS 2014, 2014 IEEE/ION, 2014, pp. 680-685.

[13] M. Kayton and W. R. Fried, Avionics Navigation Systems: John Wiley & Sons, 1997.

[14] FAA, "APNT DMEIDME TSE Calculator V. I", unpublished, Nov, 2011.