Emitter Geolocation from Near-Space Platform Using 3D TDOA

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Abstract

The space between the maximum altitude at which a modern plane can fly and the minimum altitude at which a satellite can operate is known to as near space. A free balloon, an airship, and an unmanned aerial (UAV) vehicle are some of the aircraft in the near space. The near-space platform has the ability to identify far-off emitters in a large area due to its unique feature of having a large coverage area, full-time, and large-scaled. Near-space has drawn a lot of attention recently since it is below the ionosphere and doesn't experience ionospheric scintillations, which can significantly degrade RF communications and navigation performance. The focus of this paper is to compute geolocation in various scenarios. Geolocation is computed in two dimension (2D) using hybrid AOA/TDOA/FDOA measurements from ground/ship-based sensors at varying emitter distances and geolocation accuracy is calculated using Root Mean Square Error (RMSE) and Circular Error of Probability (CEP_{50}). Further, geolocation is computed in three dimension (3D) using TDOA measurements from ground/ship-based sensors at varying emitter altitudes and geolocation accuracy is computed in terms of total joint covariance matrix (Standard Deviation) from all receivers. The results of above geolocation accuracy are compared with geolocation from near-space based sensors placed at varying altitudes while the emitter is placed on ground/ship-based platform using 3D TDOA measurements. TDOA measurements are obtained by cross-correlating the signal received at all the sensors. The performance for all the scenarios are demonstrated through modeling and simulations. Experimental results in varied scenarios and specifically near-space platforms will help in designing of systems as per the required accuracy and in future visualizing the accuracies from space-based platforms.

Keywords: *3D TDOA, Near-space platforms, root mean square error, CEP_{50}*

1. Introduction

In recent years, research has focused on the geolocation of an emitter from electromagnetic emissions, which is largely employed in reconnaissance, surveillance, and intelligence gathering. In the fields of aeronautics and astronautics [1] [2], near-space [3] [4] has emerged as a new research hotspot. Figure 1 shows the near space platform comprising of planes, ballons and UAVs.

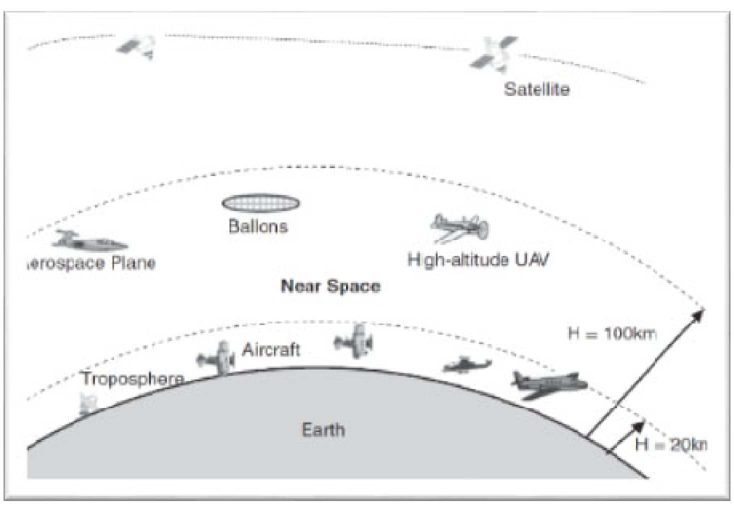

Figure 1: Near-Space Platforms

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The use of near-space for global high-speed hits, communication, alarming, battlefield observation, and other purposes is possible [5] [6]. A number of localization algorithms, including Angle-Of-Arrival (AOA), Frequency-Difference-Of-Arrival (FDOA), Time-Difference-Of-Arrival (TDOA), and Received Signal Strength Indication (RSSI) have been developed [7][8][9] in the past. Geolocation methods like TDOA, FDOA, AOA, or RSSI depend on the positioning scenario and each has its own benefits and drawbacks for a certain positioning application. The TDOA positioning technique offers great location accuracy, but it demands precise sensor synchronisation, and in 3D at least four receivers are needed to produce the intersection of hyperboloids. For geolocation on the plane, AOA measurement only needs two receiving sensors, and it operates without synchronisation between them. Nevertheless, the precision of the measurement degrades with distance. The RSSI technique of geolocation operates by gauging the signal strength received from emitters. Although RSSI has the advantage of being straightforward and easy to install, its location accuracy is poor because of the built-in exponential decrease of received power when the emitter is far from the sensor.

The TDOA geolocation method makes use of receivers placed on platforms that are ground-based, ship-based, or close to space. By analysing signal arrival time measurements at four or more stations, the TDOA approach locates a 3D target. A master station collects the measurements from the many stations and processes them. Radar and communication emitters can be geolocated via a network of receivers that have a GPS receiver and an advanced military support sensor. A receiver's position and time of arrival are transmitted to a fusion center when an electronic sensor on board detects the leading edge of an electromagnetic (EM) pulse coming from that receiver. Cross-correlation is used to determine the time difference of arrivals, which is used to deduce the position of the emitter, using the measurements that each receiver in the network has gathered.

In the past, a number of solution methods that address the TDOA problem have appeared in the literature. Li J et.al in [10] [11] have presented geolocation by space-air-ground integrated network using TDOA measurements but does not give qualitative results using the parameter root mean square error. The observations are limited by heights in [12], which offers an altitude constrained source localisation utilising Time Difference of Arrival, FDOA, and differential Doppler rate. The methods of joint TDOA and FDOA localization, passive DOA multiple sensor networks for mobile targets, and multiple sources are presented in [13], [14] and [15] respectively. However, they do not take into account receivers mounted on multiplatform devices, which can be stationary or mobile, and the method is computationally intensive.

Three scenarios for estimating the position of an emitter using TDOA are presented in this research. The first involves estimating 2-D source location for a ground-based source using hybrid AOA/TDOA/FDOA readings from ground-based and ship-based sensors at various emitter distances. The second is to locate an emitter using 3D TDOA measurements, placed on near-space platform, at varying altitudes from the receivers placed on ground/ship-based platforms. The third is to locate an emitter placed on ground/ship-based platform from receivers placed on near-space based platforms at varying altitudes using 3D TDOA measurements. Numerical results based on multiple receivers are presented depicting the geolocation accuracy in emitter-receiver geometry scenarios using both 2D and 3D technique of measurements. In the following paper, Section 2 covers signal characteristics measured by the receivers, followed by TDOA geolocation technique in Section 3. Section 4 gives mathematical description of Geolocation Principle. Section 5 gives performance metrics. Section 6 and Section 7 covers Simulation Scenarios and Simulation Results respectively followed by Conclusions in Section 8.

2. Emitting Signal Characteristics Measured by Receivers

The key parameters of any emitting source signal that is mostly received by a receiver are its time of arrival (TOA), pulse amplitude, pulse width, radio frequency (RF), and angle of arrival (AOA). Moreover, frequency modulation is a metric that can be utilised to pinpoint a specific emitter and to ascertain the chirp rate or phase coding of a signal. Signals with pulse lengths longer than a few hundred microseconds are known as Continuous Wave (CW) signals. The leading edge of the pulse's internal clock is used to reference TDOA measurements. Pulse descriptor words are the name given to variables measured on a single intercept (PDW). In the parameter space, the PDW are a collection of vectors. For achieving de-interleaving mostly RF and AOA as parameters are used. To estimate the pulse repetition interval, considerations include PW and difference in time of arrival (TOA) (PRI). The carrier frequency and chirp rate are both important parameters if the signal is phase coded. Thus the characteristics of the emitting signal can be represented as

$$S_{i=}\left[AOA_i \quad f_i \quad PW_i \quad TOA_i \quad PA_i\right], \qquad \text{.....(1)}$$

for $i = 1,....,n$ where n pulses are present.

3. TDOA Geolocation Technique

For the purpose of weapon targeting and situational awareness, geolocation of emitters from ground-based, ship-based, aerial, or space-based platforms is a crucial function. AOA measurements taken from several different sites are triangulated to establish the location of an emitter using this simple geolocation approach. Both the frequency difference of arrival (FDOA) and time difference of arrival (TDOA) provides accurate estimates of source location. One TDOA measurement from two aerial platforms can be used to determine the emitter position, which is known as the location where a cone contacts the earth's surface. A second measurement between a third aerial platform and one of the initial two aerial platforms can be used to pinpoint the position of the emitter. This technique needs a precise knowledge of the distance between the flying platforms in order to synchronise the TDOA measurements. While a cesium clock typically provides great time precision, GPS can be utilised to position the platforms accurately. The TDOA calculates the difference between the signal's arrival times at two different places. Several TDOA measurements are available when there are more than two receivers. There are only a few receivers or platforms that can be used to solve the emitter geolocation problem utilising UAVs. When the source is on the earth's surface minimum of three UAVs are required for geolocation and the fourth one is required in case the source altitude is not known.

4. Geolocation Principle

Let the emitter position be denoted by $X(x, y, z)$ and that of the receivers by $X(x_0, y_0, z_0)$ and $X(x_0, y_0, z_0), i = 1, 2, 3.$ Taking first station with associated receivers as S_1, range equation for TDOA can be written as

$$\begin{cases} r_0 = \left((x-x_0)^2+(y-y_0)^2+(z-z_0)^2\right)^{1/2} \\ r_i = \left((x-x_0)^2+(y-y_0)^2+(z-z_0)^2\right)^{1/2}, i=1,2,4 \\ r_{i0} = r_i - r_0 = ct_{io} \end{cases} \quad \text{.....(2)}$$

where r_i is the range between emitter and receiver X_i, r_{io} is the range difference between the receiver X_i and the associated master station X_0. t_{io} Indicates the corresponding time difference of r_{io}. c is the speed of the light.

Equation (2) can be transformed into

$$\begin{aligned}&(x_0-x_i)x+(y_0-y_i)y+(z_0-z_i)z \\ &=(c^2t_{i0}^2+x_0^2+y_0^2+z_0^2-x_i^2-y_i^2-z_i^2)/2+ct_{i0}r_0\end{aligned}, \; i=1,2,4 \quad \text{.....(3)}$$

Equation (3) can be written in the matrix form as

$$AX = b \quad \text{.....(4)}$$

where

$$A=\begin{bmatrix} x-x_1 & y-y_1 & z-z_1 \\ x-x_2 & y-y_2 & z-z_2 \\ x-x_4 & y-y_4 & z-z_4 \end{bmatrix}, X=\begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$b=\begin{bmatrix} (c^2t_{10}^2+x_0^2+y_0^2+z_0^2-x_1^2-y_1^2-z_1^2)/2+ct_{10}r_0 \\ (c^2t_{20}^2+x_0^2+y_0^2+z_0^2-x_2^2-y_2^2-z_2^2)/2+ct_{20}r_0 \\ (c^2t_{30}^2+x_0^2+y_0^2+z_0^2-x_4^2-y_4^2-z_4^2)/2+ct_{40}r_0 \end{bmatrix}$$

If matrix A is full rank, regard r_0 as a constant value, we can get the intermediate value of emitter location with r_0 as below:

$$X = A^{-1}b \quad \text{.....(5)}$$

Substitute (5) in (2), we get a monadic quadratic equation with r_0 as below:

$$m_1r_0^2 + m_2r_0 + m_3 = 0 \quad \text{.....(6)}$$

Form (6) we can get

$$r_0 = \frac{-m_2 \pm \sqrt{m_2^2 - 4m_1m_3}}{2m_1} \quad \text{.....(7)}$$

when $m_1 > 0, m_2 < 0$, and $m_2 - 4m_1m_3 > 0$, (7) gives two positive value. Eliminating location ambiguity is necessary since only one of them is true and the other is untrue. The estimated position of the emitter can be derived by changing (5) with the right one. Location principle of subsystems S_2, S_3 works the same as S_1.

5. Performance Metrics

Qualitative analysis is done using standard deviation measured between the estimated and true emitter location. Generally, covariance matrix $\text{cov}(A)$ for any variable can be expressed as

$$\text{cov}(A) = E\left[\left(A-\hat{A}\right)\left(A-\hat{A}\right)^T\right] \quad \text{.....(8)}$$

In matrix form it can be expressed in form of variances $\sigma_x, \sigma_y, \sigma_z$ along x, y, z axis and correlation coefficient $\rho_{xy}, \rho_{yz}, \rho_{zx}$ between the respective receivers

$$\text{cov}(A) = C_{UU} = \begin{bmatrix} \sigma_x^2 & \rho_{xy}\sigma_x\sigma_y & \rho_{xz}\sigma_x\sigma_z \\ \rho_{xy}\sigma_x\sigma_y & \sigma_y^2 & \rho_{yz}\sigma_y\sigma_z \\ \rho_{xz}\sigma_x\sigma_z & \rho_{yz}\sigma_y\sigma_z & \sigma_z^2 \end{bmatrix} \quad \text{.....(9)}$$

If x, y, z are uncorrelated, then $\rho_{xy} = \rho_{yz} = \rho_{zx} = 0$. Equation (9) reduces to

$$\text{cov}(A) = C_{UU} = \begin{bmatrix} \sigma_x^2 & 0 & 0 \\ 0 & \sigma_y^2 & 0 \\ 0 & 0 & \sigma_z^2 \end{bmatrix} \quad \text{.....(10)}$$

Total standard deviation can be expressed as

$$\sigma_{total} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \quad \text{.....(11)}$$

Physically this is interpreted as confidence ellipsoid along the orthogonal position axis.

6. Simulation Scenarios

Simulations are carried out using MATLAB tool kit and the various scenarios are descrided in detail. In scenario 1, geolocation is computed in two dimension (2D) using hybrid AOA/TDOA/FDOA measurements from ground/ship-based sensors at varying emitter distances. Data is received from emitters placed at locations (10,10) km, (15,15) km and (20,20) km by a pair of receivers placed at (2.5,0.5) km and (0.5,0) km. Geolocation accuracy is computed in terms of Root Mean Square Error (RMSE) and Circular Error of Probability (CEP_{50}). It is assumed that environmental errors and non-line-of-sight errors follow Gaussian distribution and the signal propagates with the speed of light.

In scenario 2, 3D TDOA geolocation is computed using measurements from n sensors, n=1,2,3,4,5 placed on ground/ship based, emitter is varied in altitudes i.e at (10,10,10) km, (15,15,15) km and (20,20,20) km. For each emitter positions, geolocation accuracy is computed in terms of total joint covariance matrix (Standard Deviation) from all receivers. In scenario 3, geolocation is computed using 3D TDOA measurements from near-space based n sensors, n=1,2,3,4,5 in form of, for example unmanned aerial vehicle and placed at an altitude of 10 km, 15 km and 20 km while the emitter is placed on ground/ship-based platform at (1,1,1) km. During simulations it is assumed that the error in the noise is having normal distribution with zero mean and in independent. Code is run for 700 times following

Monte Carlo simulations as the total standard deviations reaches stable value after 700 iterations. and results are presented validate the effectiveness of the proposed method.

7. Simulation Results

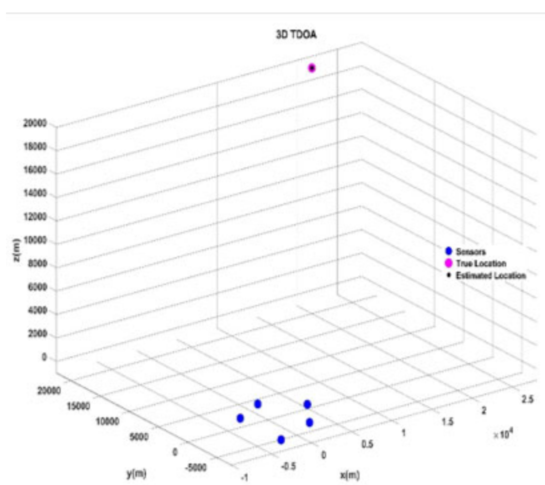
Table 1. shows the results for scenario 1 with geolocation accuracy computed using 2D hybrid methods. Table 2 shows the results for scenario 2 and 3 with geolocation accuracy computed using 3D TDOA method. It can be seen that RMSE of 1800 m, and CEP_{50} of 1220 m is obtained using 2D hybrid measurements at 20 km distance of emitter from receiver. In 3D scenario, measurements are taken using 3D TDOA, geolocation accuracy of 6 m is obtained when emitter is placed at an altitude of 20 km from the receiver, an d an accuracy of 16 m is obtained when data is collected from receivers placed at an altitude of 20 km (near-space platform) from the emitter placed on ground/ship based platforms. Geolocation accuracy using 3D TDOA three scenarios at 20 km is shown in Figure 1(a) and 1(b).

Table 1: Geolocation using 2D TDOA

Emitter on ground/ship-based platforms at varying distances from the receiver (placed on ground/ship-based platforms)			
Scenario 1	10 km	15 km	20 km
RMSE (m)	390	960	1800
CEP_{50} (m)	270	660	1220

Table 2: Geolocation using 3D TDOA measurements

Emitter on near-space platforms at varying altitudes from the receivers (placed on ground/ship-based platforms)			
Scenario 2	10 km	15 km	20 km
Geolocation accuracy Standard Deviation (m)	4.3565	5.2424	6.2061
Receivers placed on near-space platforms at varying altitudes from the emitter (placed on ground/ship-based platforms)			
Scenario 3	10 km	15 km	20 km
Geolocation accuracy Standard Deviation (m)	7.0626	11.4617	16.8820



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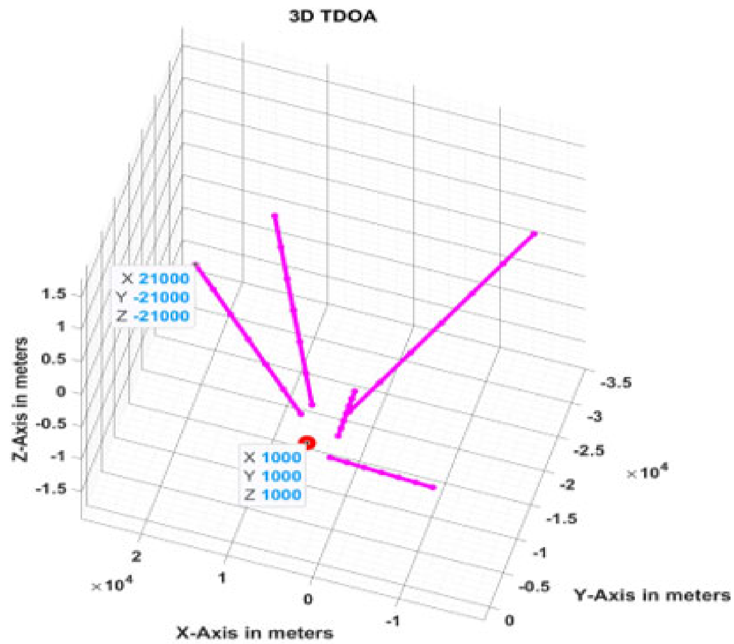

Figure 2(a) and 1(b) for geolocation accuracy for scenario 2 and 3

8. Conclusion

Geolocation from near-space platform using 3D TDOA technique have gained significance in past several years as it paves way for understanding geolocation accuracies from space-based platforms. In this paper, geolocation using 2D hybrid methods and geolocation using 3D TDOA is presented in all combinations of varying both emitter and receiver positions and altitudes and comparative measurements are tabulated. In 2D methods, simulation results have been presented using RMSE and CEP50, whereas for 3D TDOA, simulation results have been presented using measured Standard Deviation. In due course of time, simulation results from space-based platforms will be presented using 3D TDOA. Results are in accordance with the theoretical developments and they validate the effectiveness of the proposed method.

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