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Location Estimation of Beacon in MEOSAR System

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Abstract: This paper describes the satellite aided search and rescue system that provides services to save the lives at the distress or emergency regions. COSPAS - SARSAT is a satellite-based system designed to provide distress alert and location data to facilitate SAR operations. The ground receiver named as Local User Terminals (LUTs) is in charge of processing the incoming signal and determining the beacon position via Frequency Difference of Arrival (FDOA) and Time Difference of Arrival (TDOA) technique. A common method of calculating TDOA and FDOA is the Cross Ambiguity Function (CAF). This paper proposes the implementation of CAF map method, which is a simple method that reduces the processing complexity over CAF method and also as the ability to locate several beacons that eliminates the false location of beacons.

Keywords: Beacons, COSPAS - SARSAT, Cross ambiguity function (CAF), Frequency difference of arrival (FDOA), Geostationary earth orbit (GEO), Low earth orbit (LEO), medium earth orbit (MEO), Search and rescue (SAR) System, Time difference of arrival (TDOA).

I. Introduction

Search and rescue (SAR) system provides services to save the lives at the distress or emergency regions. Location of such regions is the important on the surface of earth. There are many applications where it is necessary to determine the location such applications includes Global Positioning System (GPS), location of beacon emitting emergency signals and in radar system.

COSPAS-SARSAT (means space system for search of vessels in distress - search and rescue satellite) is a satellite-based system designed to provide distress alert and location data to facilitate search and rescue operations. The system consists of both a ground segment and a space segment (see Figure 1). The space segment consists of geostationary satellite system for search and rescue (GEOSAR) and low-earth polar orbit satellite system for search and rescue (LEOSAR) and currently proposed medium-altitude earth orbiting satellite system for search and rescue (MEOSAR). The ground segment consists of local user terminals (LUTs), mission control centers (MCCs), rescue control centers (RCCs) and distress units with beacons. When an emergency beacon is activated, it emits distress signals which are relayed by satellites to LUTs which are in charge of processing the incoming signal and determining the beacon position via Frequency Difference of Arrival (FDOA) and Time Difference of Arrival (TDOA) technique. Then MCCs receives the data from LUTs verifies it and forwards them to RCCs which sends the alert message to the nearest SAR units that goes to the site and take care of the victims [1].

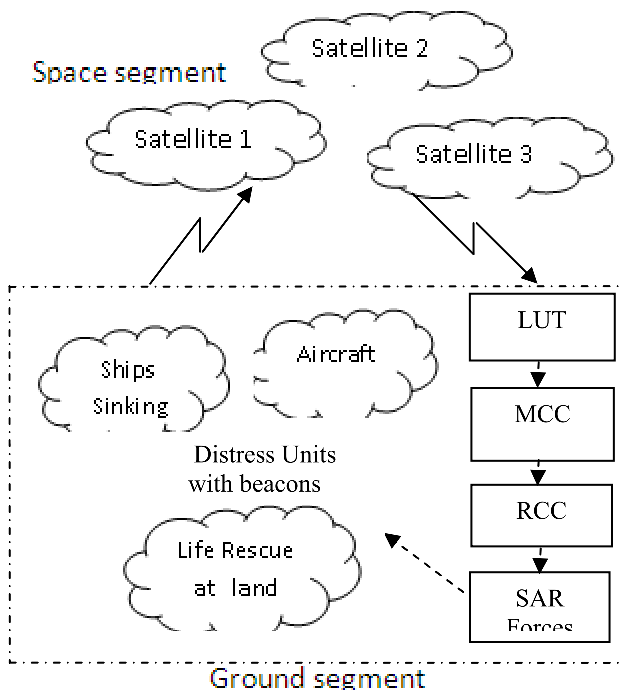

Figure 1: Satellite aided search and rescue system

Beacons

Beacon is a radio transmitter emitting signals also known as emergency beacons, are tracking transmitters which aid in the detection and location of boats, aircraft, and people in distress. The device is operating in 121.5MHz or 234MHz or 406MHz. The 406 MHz beacons transmit digital signals that are uniquely identified almost instantly via MEOSAR and furthermore, a GPS position encodes, that provides both instantaneous identification and position in the signal. Beacons are classified into three types such as Emergency Position Indicating Radio Beacons (EPIRBs) for signal maritime distress, Emergency Locator Transmitters (ELTs) for signal aircraft distress and Personal Locator Beacons (PLBs) to indicate a person in distress [1, 2]. Existing beacons uses only short message format and the proposed beacons uses both short and long message format. In the Figure 2(a) and 2(b) shows short message and long message format respectively. The short message of the transmitted signal contains 112-bit message at a bit rate of 400 bps. The long message of the transmitted signal contains 144-bit message at a bit rate of 400 bps. The preamble consists of bit synchronization, frame synchronization, format flag and data bits respectively as indicated in the Figure 2 (a) and 2(b). The Figure 3(a) and 3(b) shows the description of data bits shown in the Figure 2(a) and 2(b) respectively. The digital message data bits contains information regarding country to which it belongs to, user protocol, type f message obtained, type of distress and requirement of help message[2]. The proposed beacon modulates a 406MHz carrier at 400bps, the Tone is 160ms, the known Preamble takes 24 bits and the data field is 87 or 120 bits.

Local user terminal (LUT) Receiver System

The LUT in the MEOSAR system (MEOLUT) receiver system is essentially a ground receiving station that detects, characterizes and locates 406 MHz beacons, sends signal to MCCs and sends alert message to RCCs. Figure 4 shows the overall system level block diagram of the receiver involving the Digitization, Signal and Data Processing.

The MEOLUT receiver system is divided four major subsystems such as Front-end subsystem that includes antenna, RF receiver, beam forming system, IF digitizer, analog to digital converter (ADC) and double digital converter (DDC); Signal processing subsystem that includes demodulation & decoding, TDOA, FDOA and other parameter estimation; Data processing subsystem that verifies that data received and generates the alert messages; Back-end subsystem includes designing of the system [3]. The received signal to the ADC is of 70MHz IF signal, (where IFi, i = 1, 2… represents that each IF signal is received from different receivers as shown in figure 4). The ADC performs the initial processing of the digitizing the 70MHz IF. The DDC down converts the ADC output to the base band signal. Then the digitized beacon signals are demodulated using the Costas Loop and decoded using Biphase-L (Manchester) that converts data in a single-bit stream [1, 3].

160 ms Carrier	15 Bits	9 Bits	1 Bit	87 Bits

(a)

160 ms Carrier	15 Bits	9 Bits	1 Bit	119 Bits
Tone	Preamble			data

(b)

Figure 2: Digital message format, (a) Short message format, (b) Long message format.

Protocol flag 1 Bit	Country code 10 Bit	Identif- -ication /position 49 Bits	21 Bits BCH code	Emergency code/ national use

(a)

Proto- -col flag 1 Bit	Coun- -try code 10 Bit	Identif- -ication /position 49 Bits	21 Bits BCH code	Emerge- -ncy / national data code	12 Bit BCH code

(b)

Figure 3: Data bits (a) short message contains country code, identification and position information along with 21 bits BCH code, (b) long message contains same as short message with additional 12 bits BCH code.

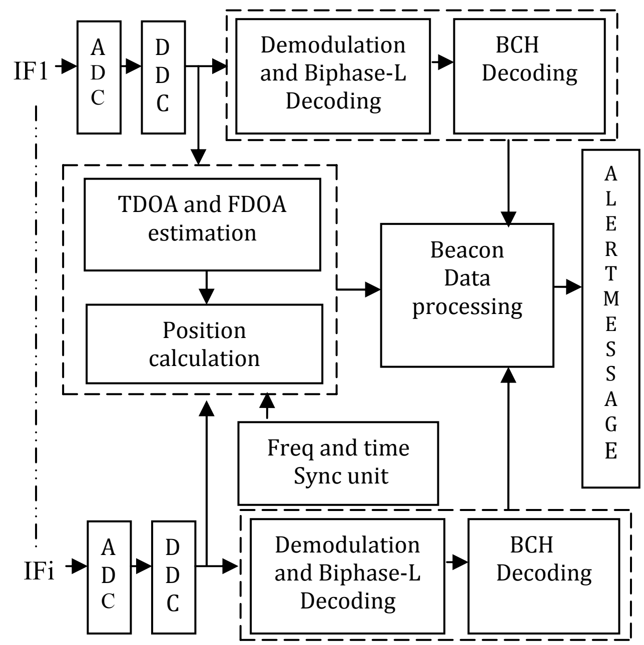

Figure 4: Meolut receiver system consists of two blocks (dashed) that performs the signal processing of received signal and position is estimated using some algorithm or method. The other blocks perform the data processing and alert message is generated.

II. Position Technique

A common way to locate beacon is to use the TDOA and FDOA information from receivers at geographically separated locations. There are other methods that can be used to locate the beacon but the TDOA and FDOA is the efficient way. Estimations, precisely in the real time may require at least three receivers and a wide band data link.

There are three main ways to estimate the TDOA and FDOA values such as Coherent method (estimates the TDOA and FDOA values by cross-correlating signals received at different receivers); Non-Coherent method (estimates the time of arrival (TOA) and frequency of arrival (FOA) at each of the receivers and then computes the TDOA and FDOA) and Semi-Coherent method (extracts a prototype pulse at one of the receivers and transmits this pulse to the other receivers. This pulse is correlated with each of the signals collected at the respective receivers to extract the TOA values and phase values that indirectly give the FOA values. The TDOA and FDOA values are extracted from the above information).

The TDOA is defined as the difference in the arrival times of the beacons signals between two satellites. Multilateration, also known as hyperbolic positioning is used. A main drawback for systems using TDOA technique only is that when the transmitter has a narrow bandwidth, the separations between satellites are restricted to be small. Consequently, the angle of intersection of the two hyperbolic curves on the earth is so small that it gives large geometric errors. The TDOAs must be very accurate in order to obtain an acceptable solution [5, 6]. FDOA also frequently called Differential Doppler (DD) is a technique analogous to TDOA for estimating the location based on observations from different points. FDOA differs from TDOA in that the observation points must be in relative motion with respect to each other and the emitter. This relative motion results in different Doppler shifts observations of the emitter at each location in general. For example the emitter location can then be estimated with knowledge of the observation points' location and vector velocities and the observed relative Doppler shifts between pairs of locations. A disadvantage of FDOA Technique only is that large amounts of data must be moved between observation points to a central location to do the cross-correlation that is necessary to estimate the Doppler shift.

Ambiguity function is a two dimensional function that is a functional of the waveform, It is a tool used to estimate the TDOA and FDOA between two signals. CAF concept is derived from the ambiguity function and is used extensively in TDOA and FDOA estimation [5].

TDOA and FDOA Mathematical Model

Real-world collection systems often employ a pair of separate collectors. The signals received by the individual collectors (i.e. satellites are considered as collectors) are from the same transmitter, but shifts in time and frequency are inherent due to the different paths traveled by the two signals. In these configurations, the two received signals can be processed to determine the TDOA and FDOA between the two collectors. With exact knowledge of the collectors' positions, successive TDOA and FDOA measurements can be plotted to determine the location of the associated emitter. This simulator creates geometry-specific signals that capture the time-varying quality of the TDOA and FDOA [7].

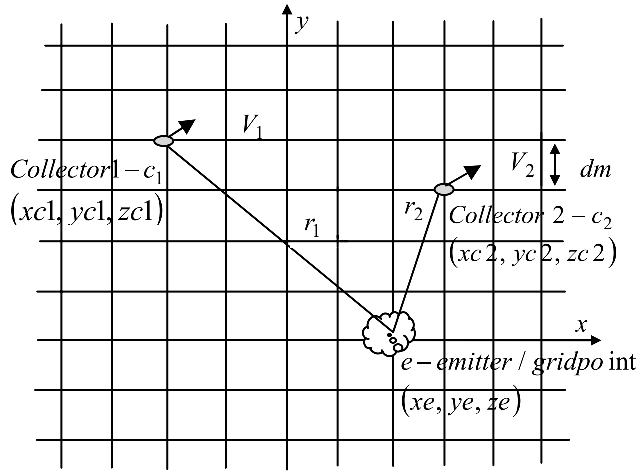

Figure 5: Emitter – Collector geometry

In the Figure 5, c_1, c_2 represents collector1 and collector2, e is emitter (grid point), $r1, r2$ are the position vectors from collector to the emitter, V_1, V_2 are the velocity vectors for each collector and dm is the resolution. The TDOA is the difference in time for the signal to propagate to c_1 with respect to c_2 of a two-collector system.

$$TDOA(\tau) = \frac{|r_2| - |r_1|}{c} \quad (1)$$

where, the vectors r_1 and r_2 are the difference between the x and y coordinates of the emitter and the collectors as shown in equation (2), and c is speed of light.

$$\vec{r}_1 = \begin{bmatrix} x_e - x_{c_1} \\ y_e - y_{c_1} \\ z_e - z_{c_1} \end{bmatrix} \text{ and } \vec{r}_2 = \begin{bmatrix} x_e - x_{c_2} \\ y_e - y_{c_2} \\ z_e - z_{c_2} \end{bmatrix} \quad (2)$$

The theoretical calculation for the FDOA involves finding the difference in Doppler shifts that each collector intercepts.

$$fd = \frac{f0}{c}\vec{v} \quad (3)$$

where, fd is the doppler frequency, $f0$ is the carrier frequency, c is the speed of light, and $\vec{v}$ is the velocity between collector and the emitter.

$$\vec{v} = \frac{\vec{V} \bullet \vec{r}}{|r|} \quad (4)$$

The vector $\vec{V}$ describes the relative velocity components in the x, y, z directions as shown in the equation (5).

$$\vec{V} = \begin{bmatrix} v_{e_x} - v_{c_x} \\ v_{e_y} - v_{c_y} \\ v_{e_z} - v_{c_z} \end{bmatrix} \quad (5)$$

$$fd = \frac{f0}{c}\left\{\frac{(v_{c_x}(x_e - x_c) + v_{c_y}(y_e - y_c) + v_{c_z}(z_e - z_c))}{\sqrt{(x_e - x_c)^2 + (y_e - y_c)^2 + (z_e - z_c)^2}}\right\} \quad (6)$$

Cross Ambiguity Function

Accurate Geolocation of radio frequency transmitters is critical to MEOLUT application. Simple process of correlation can be used to estimate the time delay between replicas of arbitrary continuous waveform signals arriving at two receivers. If there is no FDOA between two receivers (i.e. the difference in the two Doppler is zero), then simple cross-correlation computations can uncover the resulting TDOA [5, 6, 7].

$$CAF(\tau, f) = \frac{1}{T}\int_0^T s_1(t) s_2^*(t+\tau) e^{-j2\pi ft} dt \quad (7)$$

In this expression, $s_1(t)$ and $s_2(t)$ are complex envelopes of two waveforms that contain a common component, while τ and f the time lag and frequency offset parameters to be searched simultaneously for the values that cause magnitude of $CAF(\tau, f)$ to peak. For $f = 0$, the CAF reduces to the traditional complex correlation function (CCF) as shown by equation (9).

$$CCF(\tau) = \frac{1}{T}\int_0^T s_1(t) s_2^*(t+\tau) dt \quad (8)$$

This equation which will give a peak at $A(\tau, 0)$, where τ is the time lag or TDOA and A is amplitude. In the presence of frequency shifts simple correlation gives erroneous results during computation of TDOA. Hence to accommodate for the frequency shifts the factor $e^{-j2\pi ft}$ is added to equation (8) which gives equation (7). Some additional peaks appear but the maximum peak will always be at $t = \tau$ represents TDOA and $f = \Delta f$ represents FDOA of the signals. In order to get the above into the discrete time domain, let

$$f = \frac{kfs}{N} \text{ and } fs = \frac{1}{Ts} \quad (9)$$

where, Ts is the sample period, $fs = 1/Ts$ is the sampling frequency, n represents individual sample numbers, and N is the total number of samples. By inserting above values into CAF equation and simplifying yields the discrete form of the CAF.

$$CAF(\tau.k) = \sum_{n=O}^{N-1} s_1(n) s_2(n+\tau) e^{-j2\pi\frac{kn}{N}} \quad (10)$$

where, s_1 and s_2 are sampled signals in analytical form, N is the total number of samples in s_1 and s_2, τ is time delay in samples, and k/N is the frequency difference in digital frequency. Each point in the CAF plane represents the magnitude of the correlation at a specific time and frequency offset. The magnitude of the CAF will peak when τ and k/N are equal to the embedded TDOA and FDOA respectively between s_1 and s_2 signals Hence, the CAF is a three dimensional surface with the coordinates of TDOA, FDOA and magnitude as shown in Figure 6.

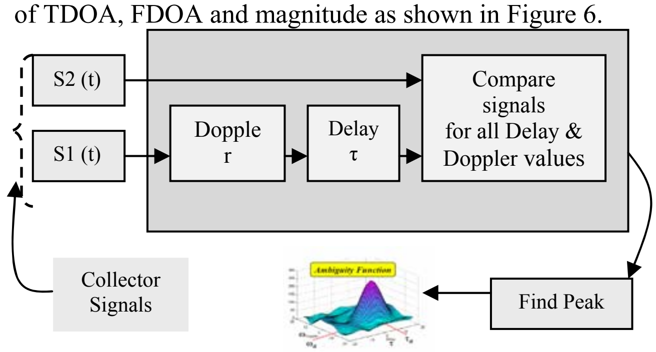

Figure 6: Typical Cross Ambiguity Function

The performance for the standard CAF algorithm can be known by the standard deviation of the TDOA and FDOA measurements [6]. The standard deviation of the TDOA and FDOA measurements are given by,

$$\sigma TDOA = \frac{1}{\beta s}\frac{1}{\sqrt{BnT\gamma}} \quad (11)$$

$$\sigma FDOA = \frac{0.55}{T}\frac{1}{\sqrt{BnT\gamma}} \quad (12)$$

where, Bn is the noise bandwidth(BW) common to the two receivers, T integration time of the signal, βs is rms BW in the received signal spectrum, γ signal-to-noise ratio (SNR) given by equation (14).

$$\beta s = 2\pi\left[\frac{\int_{-\infty}^{\infty} f^2 W_s(f) df}{\int_{-\infty}^{\infty} W_s(f) df}\right]^{1/2} \quad (14)$$

$$\frac{1}{\gamma}=\frac{1}{2}\left[\frac{1}{\gamma 1}+\frac{1}{\gamma 2}+\frac{1}{\gamma 1\gamma 2}\right] \tag{16}$$

Ws is the signal's power spectral density and γ_i is the SNR of the *i*th receiver in the receiver's noise bandwidth. For a signal with a constant envelope, such as a BPSK signal, a good rule of thumb according to Stein [6] is $\beta s \approx 1.8\, Bs$ as shown below

$$\beta s = \frac{\pi}{\sqrt{3}} Bs \tag{17}$$

where *Bs* is the signal RF bandwidth.

III. Methodology

Common CAF Method

The CAF method is performed on each successive snapshot pair and the TDOA and FDOA values are estimated by determining the peak or peaks in the CAF plane. To determine the location estimate in n dimensions, n measurements are required. Once estimates are made of the FDOA and TDOA for a number of independent snapshots, the location can be determined. One of the most common methods used as the geolocation engine to get the linear equation of the obtained nonlinear equation is by Newton-Raphson method [8]. The Newton-Raphson method is based on the Taylor Series expansion and for the case of three variable functions such Taylor Series can be written in the form:

$$f(x_0,y_0,z_0)=f(x_1,y_1,z_1)+\frac{\delta f(x_1,y_1,z_1)}{\delta x}(x_0-x_1)+\frac{\delta f(x_1,y_1,z_1)}{\delta y}(y_0-y_1)+\frac{\delta f(x_1,y_1,z_1)}{\delta z}(z_0-z_1) \tag{18}$$

where (x_0,y_0,z_0) are the roots of $f(x_0,y_0,z_0)=0$ and $(x_1,y_1,z1)$ are the guesses at the root. These (x_0-x_1) (y_0-y_1) and (z_0-z_1) are essentially three variables $(\delta x,\delta y,\delta z)$ in order to solve we need three independent equations.

$$f(x_0,y_0,z_0)=f(x_1,y_1,z_1)+\frac{\delta f_1(x_1,y_1,z_1)}{\delta x}\delta x+\frac{\delta f_2(x_1,y_1,z_1)}{\delta y}\delta y+\frac{\delta f_3(x_1,y_1,z_1)}{\delta z}\delta z \tag{19}$$

$$f(x_0,y_0,z_0)=f(x_1,y_1,z_1)+\frac{\delta f_2(x_1,y_1,z_1)}{\delta x}\delta x+\frac{\delta f_2(x_1,y_1,z_1)}{\delta y}\delta y+\frac{\delta f_2(x_1,y_1,z_1)}{\delta z}\delta z \tag{20}$$

$$f(x_0,y_0,z_0)=f(x_1,y_1,z_1)+\frac{\delta f_3(x_1,y_1,z_1)}{\delta x}\delta x+\frac{\delta f_3(x_1,y_1,z_1)}{\delta y}\delta y+\frac{\delta f_3(x_1,y_1,z_1)}{\delta z}\delta z \tag{21}$$

The hardest part theoretically is, finding the independent equations since after that the problem can be solved with some basic linear algebra. Then we can rewrite our system of equations in the form $f + A\delta = 0$ which has the solution $\delta = A^{-1}(-f)$. All the above equations are implemented in the form of matrices and used to solve for the location. Here (x_1, y_1, z_1), (x_2, y_2, z_2) and (x_3, y_3, z_3) are the positions of the three collectors used to determine (x, y, z) position of emitter. The main drawback of using Newton-Raphson method is the complexity involved in the implementation of the mathematical equations. The number of known variables required and the order in which they must be input into the matrix to estimate the location of the emitter must also be done very carefully. These complexities can be reduced in the CAF map method described in next section.

CAF Map Method : CAF map method eliminates the use of numerical approximation methods to locate step and directly maps the CAF peak surface onto the X-Y co-ordinate system using the TDOA-FDOA look-up tables. The geolocation of a beacon using CAF-map method consists of identifying and associating the primary correlation peaks across multiple CAF surfaces and multiple independent collections. This technique relies on the fundamental principle that primary-correlation peaks for an emitter will be perfectly consistent for all CAF surfaces. In actuality, the maps from different collector geometries are combined using a simple summation technique in a common geographical frame. Three assumptions are considered, firstly BPSK random generation of signals is received from satellites for processing at ground receiving station (LUT). Secondly, the communication between the satellites and ground station is synchronized. Thirdly, implementation depends on the satellite system

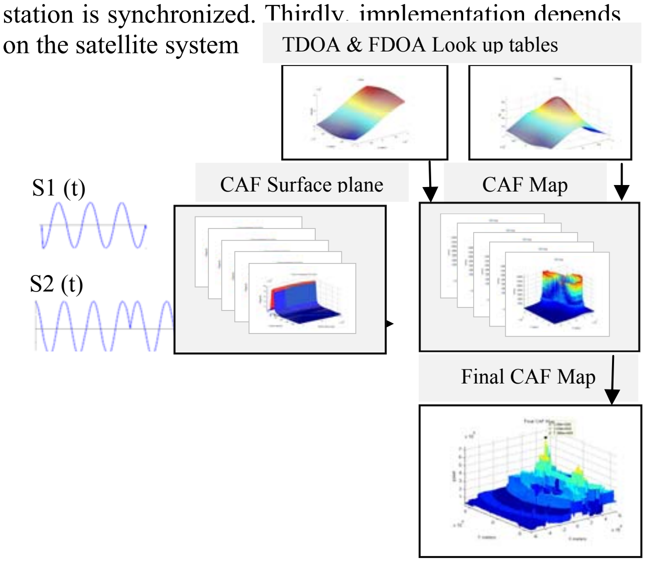

Figure 7: Steps involved in CAF map method

The Figure 7 shows the steps involved in the CAF-map method. The Approach in this method is divided into three steps as indicated in see Figure 7. Firstly creation of the TDOA and FDOA look-up Tables and dividing into number of grid points. TDOA and FDOA are computed at each of these intermediate grid points and stored as a look-up table. Secondly calculation of the normal CAF surface for current snapshot i.e. the range of TDOA and FDOA values are determined through these look-up tables by finding the maximum and minimum possible TDOA and FDOA values. This range is used to calculate all the possible CAF peak surfaces. Then mapping the amplitude of the CAF surfaces to the look-up tables, i.e. after the CAFs are computed for each snapshot, a geographic map can be formed using the look-up tables to map the CAF to the ground. The above 3 steps are performed and map for one emitter-collector geometry is formed. Multiple maps from different collector geometries are summed over common geographical area to provide an RF energy map.

IV. Simulation Results

In Figure 8, the peak value indicates the maximum TDOA and FDOA value for the particular scenario. In the Figure 9 location of the beacon is mapped with respect to the collector positions to get the location of the beacon. The Figure 10 shows the peak value, that indicates the location of the beacon. This scenario utilizes two collectors to estimate the correct emitter position. In the Figure 10 position are at a greater height of 9000km from the surface of the earth. Hence they can be considered as satellites being present in the MEOSAR range in space. This gives the demonstration for the utilization of CAF map method by satellites in the MEOSAR system.

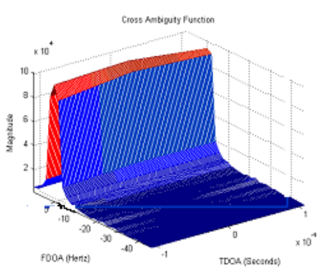

Figure 8: CAF Plane generated by mapping function

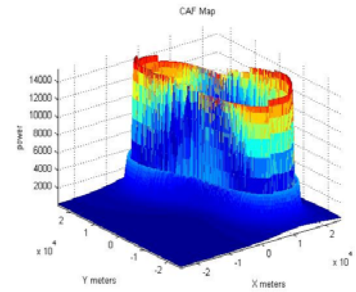

Figure 9: CAF Surface generated by mapping function

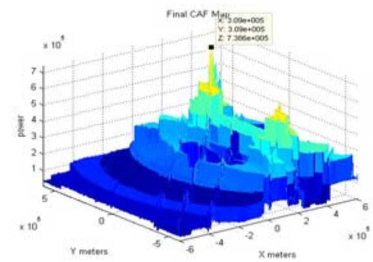

Figure 10: 3D view of final CAF map

V. Conclusions

The implementation of the CAF map method and its ability to locate a beacon by extracting TDOAs and FDOAs from CAF function has been demonstrated. The position is at a greater height of 9000km from the surface of the earth. Hence they can be considered as satellites present in the MEOSAR range in space. This gives the solution for the utilization of CAF map method by the satellites in the MEOSAR range. The CAF Map method computation process is less compared to traditional method. This method eliminates the false location of beacon. In this method, the use of Digital Terrain Elevation Data (DTED) technique to improve the results and to get better images and position of the beacons is demonstrated.

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