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A Research on Signal Processing Technique of Passive Radar Based on GPS

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Abstract: This paper has firstly introduced signal characteristics of GPS external illuminators, then focused on the basic principle of passive location, studied a T^n-R multi-static positioning system utilizing Time Difference of Arrival (TDOA), given a specific method solving target location, implemented detailed analysis of positioning accuracy of the positioning system, and lastly introduced a target tracking algorithm based on impacts of Extended Kalman Filter. The paper has carried out simulation of influences of factors including distance measurement errors and station location errors on passive location accuracy, and launched simulation comparison of factors influencing tracking accuracy. The results have indicated that the algorithm in this paper not only boasts a fast convergence speed, stable performance and a high locating and tracking accuracy, but can also be able to meet practical needs.

Keywords: *Signal processing technique, passive radar, GPS*

1. Introduction

It is not easy to trace back into the history of passive radar, for people performed experiments of radar principle through transmit-receive separation in the initial stage of radar development, and it was then widely used in the 1930s. However, with later invention of transmit-receive switch, homeostatic radar has become a major development direction of radar, achieved remarkable development in the following decades, and constituted the main system of current radars. Moreover, at the very beginning of radar system establishment, people have also utilized civil electromagnetic wave signal which may be the prototype of passive radar.

Contents of this paper include using GPS satellite signals for passive location and tracking, which differ from terrestrial TV signals and FM broadcast signals adopted by currently common passive radars in spite of its collective advantages and difficulties in many aspects with the latter one. However, as a branch of passive radar, satellite-based passive radar possesses its own special technology. Therefore, this paper has summarized advantages of passive location utilizing GPS satellite signals, explained the reason why satellite signal is used for passive location, and put forward a detailed discussion upon adopted satellite signals, including the form, bandwidth, coding, modulation type and correlation of the signal.

Next, according to specific target positioning scheme, this paper has discussed how the system carries out target location, displayed detailed mathematical derivation process, and obtained the method to solve target position in terms of range difference information. On the basis of positioning scheme, positioning accuracy is discussed while GDOP (geometric dilution of precision) is used for characterization. It also has simulated and analyzed a series of factors affecting positioning accuracy; put forward some solutions to improving the positioning accuracy[1-3]. Through simulation analysis in the following chapters, GDOP distribution of passive radar system has varied distinctive features compared with passive radar based on terrestrial station.

On the basis of positioning, this paper has also discussed about target tracking issues, realized target tracking in three-dimensional space through Extended Kalman Filter, and launched simulation comparison influencing tracking accuracy.

2. Analysis of GPS Signal Performance

With development of modern communication technology, electromagnetic wave signal existing in space is highly rich such as broadcast signal, television signal, mobile communication signal and satellite signal, which can serve as the radiation source of passive radar and constituted bi-static (multi-static) passive radar system with an independent receiver[4-5]. In particular, satellite signal boasts features including all-weather capacity, no-blind zone and absolute security, which are incomparable to electromagnetic signal in other spaces.

As shown in Figure 1, GPS system is composed of 24 polar-orbiting satellites at 20200 km above the Earth's surface (21 working satellites and 3 spare satellites), which are uniformly distributed in 6 different orbital planes with an inclination angle of 55 in comparison with the equatorial plane and an orbital planar spacing of 60[6]. As a result, theoretically, any time at any location on the earth can be covered by 4-11 satellite beams.

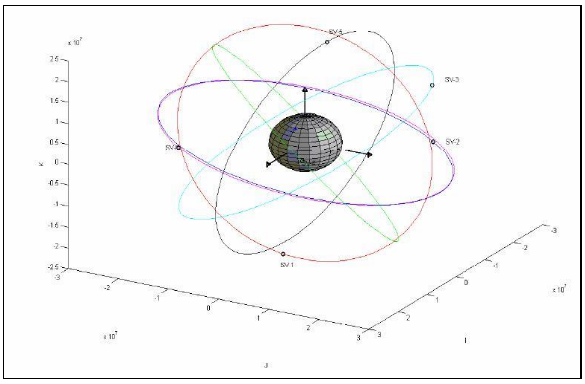

Figure 1: *GPS satellite orbital diagram*

GPS system uses the concept of unidirectional Time of Arrival (TOA) ranging, and satellite will be launched with a benchmark of high-precision space-borne atomic frequency standard[7-8]; while space-borne atomic frequency standard is synchronized with the benchmark of internal GPS system. The satellite is used for measuring code and navigation data at two frequencies with a technology called Code Division Multiple Access (CDMA)[9].

The signal sent by GPS satellite to the majority of users for navigation and positioning is a modulated wave and a phase-modulated signal utilizing Pseudo-Random Noise Code (referred to as PRN Code, or Pseudo Noise Code) for delivering navigation message, which differs from common frequency and amplitude modulation signal sent by radio broadcasting station. Currently, GPS satellite signal is one of two common satellite navigation and positioning signals, including carrier signal (L1 and L2), ranging code (C/A code and P code) and data code (D code, also known as baseband signal or navigation message) [10-13].

GPS satellite signals sent by GPS satellite have adopted two L-band carrier frequencies as carrier waves which are respectively called dominant frequency of L1 and secondary frequency of L2. These carrier frequencies are modulated by spreading spectrum codes (each satellite has its specific pseudo-random sequence) and navigation messages[14]. All satellites are launched at two identical carrier frequencies, but there is no evident mutual interference due to different modulation of pseudo-random codes. Since each satellite is equipped with specific pseudo-random codes and all pseudo-random sequences are mutually uncorrelated, each satellite signal can be divided and detected by Code Division Multiple Access (CDMA) technology [15-16].

3. EKF Algorithm of Target Tracking

3.1. EKF Algorithm

EKF algorithm is based on following concepts: if the nonlinear function is smooth enough, they are expanded into Taylor series and low-order term is selected to approximate them [17]. Nonlinear filtering is closely related to radar tracking algorithm, for the relationship between measured data and dynamic target parameters is non-linear in many cases. Extended Kalman Filter is a quasi-perfect nonlinear filter[18]. Without any control input, state equation and measurement equation of the nonlinear system are as follows:

$$x(n+1) = F(n, x(n)) + v_1(n) \quad (1)$$

$$Y(n) = H(n, x(n)) + v_2(n) \quad (2)$$

$V_1(n)$ and $V_2(n)$ are irrelevant zero-mean white-noise processes with respectively correlation matrices of $Q_1(n)$ and $Q_2(n)$. And $F(n, x(n))$ can represent a nonlinear time-varying transfer matrix function. Likewise, $H(n, x(n))$ can represent a nonlinear time-varying measurement matrix.

The basic idea of Extended Kalman Filter is to launch linear zed processing of nonlinear transfer matrix and measurement matrix function at every moment of last state estimation. Once the linear model is obtained, the standard Extended Kalman Filter can be applied[19].

3.2 Algorithm Procedures

Procedure 1: Establish Following Two Matrices

$$F(n+1, n) = \frac{\partial F(n,x)}{\partial x}\Big| x = x(n|y_n) \quad (3)$$

$$H(n) = \frac{\partial H(n,x)}{\partial x}\Big| x = x(n|y_{n-1}) \quad (4)$$

Procedure 2: Once matrices $F(n+1, n)$ and $H(n)$ are solved, they can be used in the first-order Taylor expanded formula of nonlinear functions including $F(n, x(n))$ and $H(n, x(n))$. Expand $F(n, x(n))$ and $H(n, x(n))$ respectively close to $\bar{x}(n|y_n)$ and $\bar{x}(n|y_{n\text{-}1})$, and the results can be approximated as:

$$F(n, x(n)) \approx F(n, \bar{x}(n|y_n)) + F(n+1, n)\left[x(n) - \bar{x}(n|y_n)\right] \quad (5)$$

$$H(n, x(n)) \approx H(n, \bar{x}(n|y_{n-1})) + H(n)\left[x(n) - \bar{x}(n|y_{n-1})\right] \quad (6)$$

Through above approximate expressions, the original nonlinear state space model can be approximated as a linear model. Apply the standard Kalman equation into aforementioned linear zed model and thus the Extended Kalman Filter equation is obtained. This leads to the following group of equations:

$$\bar{x}(n|y_{n-1})=F(n+1,n)\bar{x}(n|y_n)+d_n$$
$$=F(n+1,n)\bar{x}(n|y_n)$$
$$+\left[F\left(n,\bar{x}(n|y_n)\right)-F(n+1,n)\bar{x}(n|y_n)\right]$$
$$=F(n+1,n)\bar{x}(n|y_n) \quad (7)$$
$$\bar{x}(n|y_n)=\bar{x}(n|y_n)+G_f(n)\alpha(n) \quad (8)$$
$$\alpha(n)=y(n)-H\left(n,\bar{x}(n|y_{n-1})\right)$$
$$=y(n)-H\left(n,\bar{x}(n|y_{n-1})\right)$$
$$+H(n)\bar{x}(n|y_{n-1})-H(n)\bar{x}(n|y_{n-1})$$
$$=y(n)-H\left(n,\bar{x}(n|y_{n-1})\right) \quad (9)$$

In terms of equation (7) - (9), updated signal-flow graph of one-step prediction in the Extended Kalman Filter can be drawn as follow:

(1) Build Models

$$x(n+1)=F\left(n,x(n)\right)+v_1(n) \quad (10)$$
$$y(n)=H\left(n,x(n)\right)+v_2(n) \quad (11)$$

$V_1(n)$ and $V_2(n)$ are white-noise vectors with following qualities:

$$E\left[v_1(n)\right]=0;$$
$$E\left[v_2(n)\right]=0;$$
$$E\left[v_1(n)v_2^T(k)\right]=0 \quad (12)$$
$$E\left[v_1(n)v_2^T(k)\right]=\begin{cases}Q_1, n=k\\ 0, n\neq k\end{cases} \quad (13)$$
$$E\left[v_2(n)v_2^T(k)\right]=\begin{cases}Q_2, n=k\\ 0, n\neq k\end{cases} \quad (14)$$

(2) Set Initial Value

$$x(1|0)=E\left(x(1)\right) \quad (15)$$
$$K(1|0)$$
$$=E\left[x(1)-E\left[x(1)\right]\left(x(1)-E\left[x(1)\right]\right)^H\right] \quad (16)$$

(3) Input the Vector Process

Observed Value $=\left\{y(1), y(2), \cdots, y(n)\right\}$

Given Parameters: Nonlinear State Transfer Matrix $=F\left(n,x(n)\right)$

Nonlinear Measurement Matrix $=\mathrm{H}\left(n,x(n)\right)$

Correlation Matrix of Process Noise Vector $=\mathrm{Q}_1(n)$

Correlation Matrix of Measurement Noise Vector $=\mathrm{Q}_2(n)$

(4) Make recursive calculation: $n=1,2,3,\cdots$

$$G_f=K(n,n-1)H^H(n)$$
$$\left[H(n)K(n,n-1)H^H(n)+Q_2(n)\right]^{-1} \quad (17)$$
$$\alpha(n)=y(n)-H\left(n,x(n|y_{n-1})\right) \quad (18)$$
$$\bar{x}(n|y_n)=\bar{x}(n|y_{n-1})+Gf(n)\alpha(n) \quad (19)$$
$$\bar{x}(n+1|y_n)=F\left(n,\bar{x}(n|y_n)\right) \quad (20)$$
$$K(n+1,n)=F(n+1,n)K(n)$$
$$F^H(n+1,n)+Q_1(n) \quad (21)$$

4. Simulation Experiments

Parameters Setting: satellites are respectively located at

T1= (18649.810, 8953.511, 16672.850) km;
T2=(15304.570,3508.505,21434.210)km;
T3=(13285.000,-13189.160, 18848.930) km;

T0= (26570.000, 0, 0.1) km, range differences and measurement errors are object to Gaussian distribution of zero mean, and range differences, measurement errors and standard deviations among three secondary emission stations corresponding to the main emission station are all 200m; suppose that the position of initial point is (6380,10,10)km, its flying speed is x=0m/s,y=-360m/s,z =-360m/s,initial estimation of its position is(6450,70,20)km. Suppose that the target is affected by random perturbation with zero mean value and variances of 21m/s2, 21m/s2 and 21m/s2 in x, y, z directions. Basic EKF method and EKF method with initialization can respectively be used for target tracking, and the results are as follow figure2-4

Figure 2-4 can illustrate that: basic EKF algorithm requires 80s for convergence; EKF with initial algorithm can achieve relatively accurate estimation of initial target position in only 10s. With initial position, EKF can soon converge to required precision range in 20s. We have also noticed that, EKF algorithm with initialization has acquired rather high tracking accuracy.

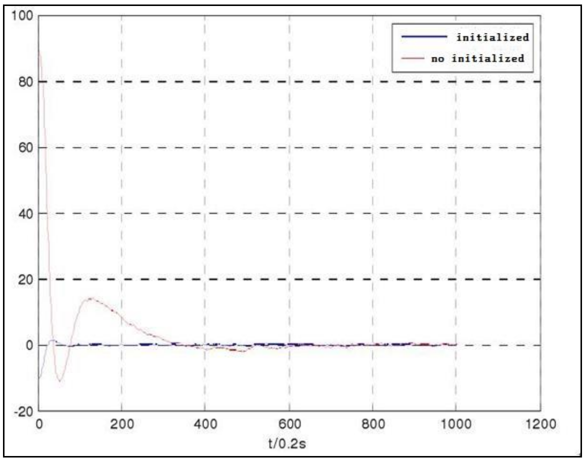

***Figure 2** The X axis error*

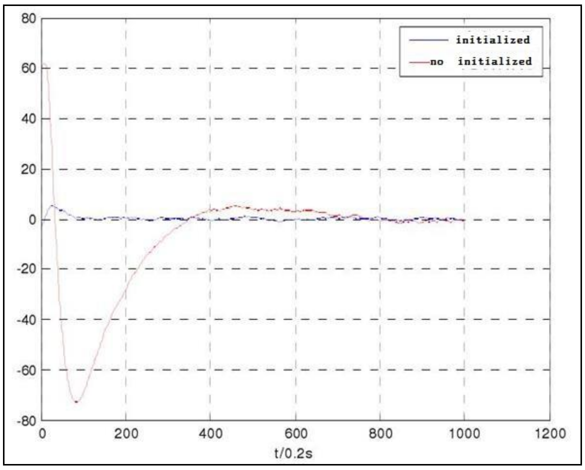

***Figure 3** The Y axis error*

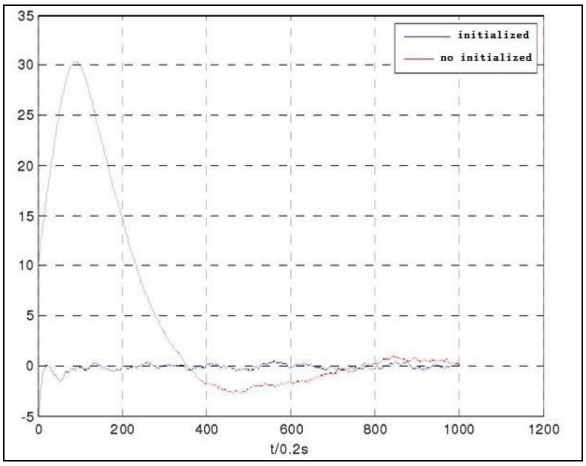

***Figure 4** The Z axis error*

5. Conclusions

This paper has firstly carried out all-dimensional analysis and discussion of the GPS satellite signals as external illuminators, launched detailed analysis and discussion from aspects including signal form, generation mechanism of C/A codes and radar detection range, and simply simulated ambiguity function graphs and detection range of radars. The results show that, as external illuminators of passive radars, GPS signals boast many special advantages such as moderate signal bandwidth and fine concealment. From known characteristics of GPS signal, it can conveniently achieve signal detection and thus promote signal recognition and parameter estimating accuracy. Therefore, GPS satellite is a relatively ideal “transmitter” based on passive radar system of satellite signals.

Finally, in view of EKF algorithm, this paper has built target model, elaborated on the basic principle and algorithm process of EKF algorithm, and lastly carried out simulation of the algorithm respectively in EKF’s effects on target tracking and influences of ranging errors on tracking accuracy with or without initial algorithm.

Passive radars based on external GPS illuminators boast many practical application values:

(1) Sorting of Satellite Signals

Reflected GPS satellite signals can be acquired through utilizing GPS receiver as the receiving device of passive system. GPS satellite signals contain satellite broadcast navigation messages which include time information of satellite transmitting signals. In terms of these messages, emission time of satellite signals can be inferred to divide received satellite signals into different batches. Finally, arrival time difference of the same batch of signals can be used for target detection and location.

(2) Multi-Station Networking

Single-station work and multi-station joint work can be accomplished through GPS satellite signals. Relatively weak GPS signals may influence detection distance of the system. For close-in defense, except that high-precision target positioning can be realized at a close range, it is also essential to provide early warning of penetration targets. In the direction of invading enemies, according to detection distance of the system, stations should be successively built on the basis of guaranteeing continuity of networking system on target detection. Of course, fine communication among systems shall be maintained in order to render each system motion parameters of targets, so that all-the-way tracking of invading targets can be achieved by multi-station system. Multi-station positioning can be employed in certain reconnaissance or defensive zone, so as to improve accuracy of the system.

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