A TRACKING ALGORITHM FOR GNSS REFLECTED SIGNALS ON SEA SURFACE

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ABSTRACT

The observation of the ocean surface using electromagnetic sources of opportunity (GNSS signals for instance) has been a green research topic for several years. The Global Navigation Satellite System (GNSS) presents a powerful and useful technology for remote sensing, ocean surface monitoring and oceanography. Many experi*ments* have been *conducted* to show the efficiency of the Global Positioning System (GPS) in applications such as ocean surface altimetry, wave height, surface current measurements, and current direction estimation [1].

Considering the GPS link as a passive sensor for ocean monitoring, we study in this paper the possibility of tracking GPS signal reflection footprints on the sea surface to improve the acquisition and the extraction of this signal.

As an analogy to the classical problem of moving targets Radar tracking, we develop a tracking algorithm based on Kalman filtering.

***Index Terms*—** GPS Signals, Moving Targets Tracking, Kalman Filtering, Doppler Delay Map

1. INTRODUCTION

Recent years have been seen an increase in the deployment of Global Navigation Satellite System (GNSS) in oceanographic applications such as ocean surface monitoring and remote sensing, ocean surface kinematics measurements and determination of oceanographic parameters such as wave height and current speed due to technological progress in space studies. The use of GNSS reflections such as the Global Positioning System (GPS) for oceanographic observation has already been discussed in [1], [2], [3].

In order to study the feasibility of passive systems in the vicinity of sea surface for oceanographers and to develop our platform measure which is the aim of the MOPS (Marine Opportunity Passive Systems) project [4], we have already presented a new approach in using the GPS signals for near-surface applications and coastal observations or monitoring [5].

Concretely, we defined an experiment that deals with interaction between an electromagnetic wave and a given mobile target. The target being detected, we will extend the problem of interaction to track the trajectory of some mobile target in a defined environment. Since we are dealing with long term GPS signals, weak targets and non-stationary media, adaptive filtering is required.

2. PROBLEM FORMULATION

In this paper, we study the possibility of extracting the GPS scattered signal reflected by the sea surface. Actually, the received signals include the direct signal and the scattered one. The direct signal, which is supposed to have the highest power, is already weak. To detect this signal, correlation is needed. On the other hand the scattered signal is so weak that a long term correlation is not sufficient; these signals have noise corrupted positions and depend mainly on sea state, which is moving over time. This displacement of the sea surface generates a frequency shift (Doppler effect) and time delay of the signal.

To start with, a suitable approach would be to consider the scattered signal reflection point footprint on the sea surface as a target, then to track the “target” on the Doppler Delay Map from one observation or correlation to another. This operation is principally affected by the SNR level. Thus, for a decreasing SNR, the filtering processing goes from the Linear Kalman filter to the Extended Kalman Filter and finally the Track-Before-Detect method.

The problem dimensions are perfectly determined by the position of the emitter which is a GPS satellite, the receiver which is an antenna, operating in a passive mode, located at the top of a light house at 22m and the target which is defined by its motion equations, as it is shown in Fig. 1.

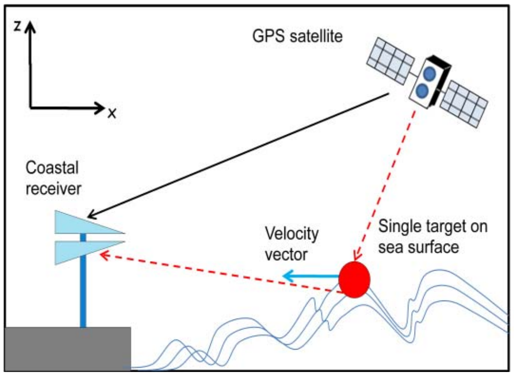

Fig. 1. Moving target representing the scattered GPS signal by sea surface in our simulation

The modeling and the initialization of parameters are possible with a simple and realistic hypothesis on sea surface. We consider that the signal is reflected by the sea wave near the coast. In this case, the moving target is supposed to be the crest of a wave approaching the coast.

In order to achieve this work, we suppose an analogy with the classical problem of moving targets tracking and we develop a tracking algorithm based on Kalman filtering.

3. KALMAN FILTERING

Usually in a classical target tracking, the process is performed on the basis of pre-processed measurements that are constructed from the original measurements data every time set up. In this case, the common approach is to submit all data to a threshold then to treat those that exceed the threshold as point measurements. This is acceptable if the Signal to Noise Ratio (SNR) is high [6]. A linear Kalman filtering is appreciated in this case.

For low SNR targets, the threshold must be low to allow sufficient probability of target detection. However, a low threshold also gives a high rate of false detections which may cause false tracks [7].

In this case, we need to perform Extended Kalman Filtering or we can perform simultaneous detection and tracking using unthresholded data, a process that is known in the literature as "Track-Before-Detect" [8]. This same reference clearly explains the use of this method for several applications such as ballistic object, bistatic radar, and stealthy targets tracking.

The role of tracking filter is to carry out recursive target state estimation given: the target dynamic equation, the sensor measurement equation, and the target originated measurements. The tracking filter considered here is the Kalman filter which is presented in [9].

3.1. Maritime environment

As an illustration, let us consider the mobile target (wave crest). It has a constant velocity depending on gravity acceleration g, water depth h and the length λ_{water} of the sea wave itself. The velocity v can be calculated as shown in this equation:

$$v = \sqrt{\frac{g\lambda_{water}}{2\pi}\tanh\left(\frac{2\pi h}{\lambda_{water}}\right)} = 1.7661\ m/s \qquad (1)$$

with g = 9.8 m/s^2, $\lambda_{water} = 2m$, and h = 10 m. The target is moving according to its motion equations: x = 1500 + vt and z = -22 m.

In our tracking approach, we consider estimating the values of the Doppler frequency shift δ due to the target motion and time delay τ.

3.2. System Dynamics

To perform this filtering, let us define our system parameters.

The state vector can be defined as: $s = [\delta \quad \tau]^T$. The dynamic evolution of the system is defined by the following recursive equation:

$$s_{k+1} = f(s_k) + v_k \qquad (2)$$

where f is a known linear function of s_k, represented by the matrix $F = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}$, $v_k \sim N(0, \sigma_n^2)$. T is the revisit time of the GPS signal, it is equal to 1 ms.

$$\delta = -\frac{f_c}{c} \cdot \frac{x_k\dot{x}_k + z_k\dot{z}_k}{\sqrt{{x_k}^2 + {z_k}^2}}\ (Hz) \qquad (3)$$

$$\tau = \frac{\sqrt{{x_k}^2 + {z_k}^2}}{c}\ (s) \qquad (4)$$

where $f_c = 1.5742\ GHz$, is the carrier frequency of the GPS signal, and $c = 3 \cdot 10^8 m.s^{-1}$is the wave speed.

This state model is adopted in our study. The measurement model changes depending on problem conditions.

3.3. Measurement model for linear KF

The measurements are related to the target state via the following equation:

$$z_k = g(s_k) + w_k \qquad (5)$$

where g is a known linear function of s_k and $w_k \sim N(0, \sigma_w^2)$. The values of s_k are extracted from an independent experiment presented in [5] designed to measure the Doppler frequency shift and the time delay of the GPS reflected signal for different instants.

3.4. Measurement model for EKF

In the preceding paragraph, it was possible to track the target trajectory in the DDM with a low noise level.

On the other side, when measurements are highly corrupted by noise, it will not be possible to detect the peak representing the Power Spectral Density PSD of the moving target, neither to extract the Doppler nor time delay values. That is why we should use a method that allows us to track our target without detecting it.

Thus we consider the whole DDM as an observation. Since the target moves slowly and the noise is randomly distributed, we will notice that while all the map points are moving from one observation to another, one point will remain fairly constant: this is the moving target. Extended Kalman Filtering presents a suitable solution for this kind of tracking.

For our observation model, we have measurements of the reflected power. The power measurements on a Doppler – Delay cell is defined by $z_k^{ij} = g^{ij}(s_k) + w_k$.

The function g^{ij} is defined by:

$$g^{ij}(s_k) = \left\{ \frac{I}{2\pi \cdot \sigma_\delta \cdot \sigma_\delta} \exp\left(-\frac{(\delta_i - \delta_k)^2}{2\sigma_\delta} - \frac{(\tau_i - \tau_k)^2}{2\sigma_\tau} \right) \right\}^2 \quad (6)$$

The parameters I, σ_δ and σ_τ represent respectively the intensity of pixel in the DDM, the standard deviation of the Doppler and the time delay.

δ_i and τ_j define the transition of the DD cell inside the DDM, with $\delta i = i\Delta\delta + \delta_0$ and $\tau_j = j\Delta\tau + \tau_0$, δ_0 and τ_0 are the measurements originated values.

In this case, for every value on the state vector, a map of observations is generated (Fig. 2).

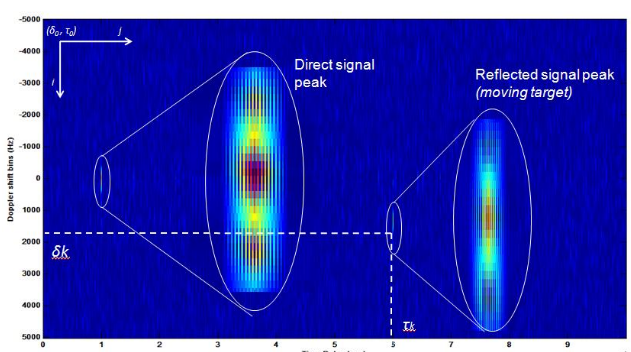

Fig. 2. The direct and reflected signals peaks on the DDM at *k*

4. FILTERING RESULTS

In this section, we are going to present our simulations results allowing us to track the position of the moving target at every instant *t* of 100 ms period.

The following figures show the computation of the Doppler and the time delay through the different steps to have a smoothed Doppler/Delay Map (DDM). In Fig. 3, we have the theoretical trajectory of the target in the DDM, while we have the observed trajectory in Fig. 4. This trajectory is used as an input for the Kalman filter. On the output of the filter, we found the filtered trajectory shown in Fig. 5.

Finally, the result is subjected to a smoothing operation using the KF parameters in Fig. 6. The Doppler value shown on the y-axis is Δ_{Doppler} which is equal to the difference between the estimated value of the Doppler δ (after filtering) and the mean of all the Doppler readings during 100 ms.

$$\delta = \Delta_{Doppler} + \mu_\delta \quad (7)$$

where $\mu_\delta \approx -9.27Hz$.

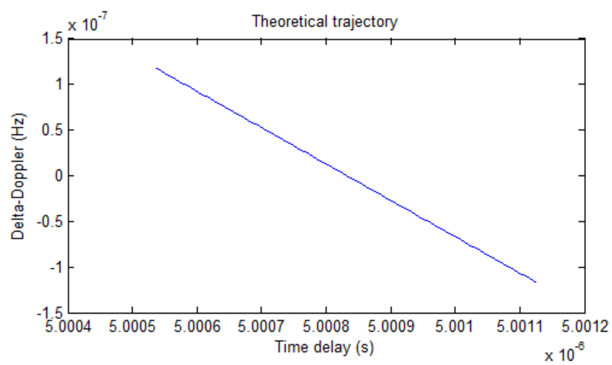

Fig. 3. Theoretical trajectory in the Doppler Delay Map

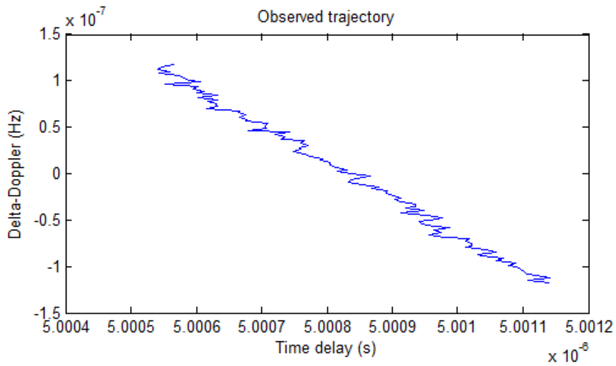

Fig. 4. Trajectory resulting from noise corrupted observations

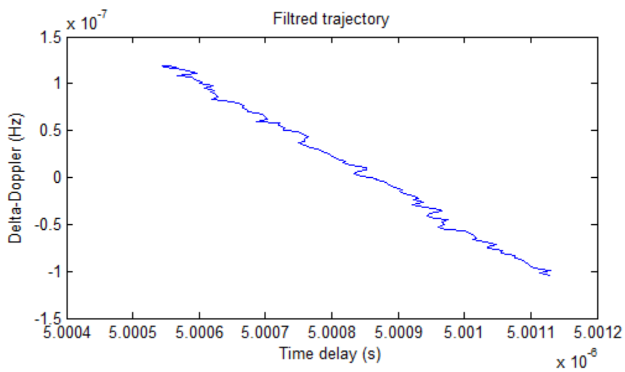

Fig. 5. Trajectory after the Kalman filtering itself

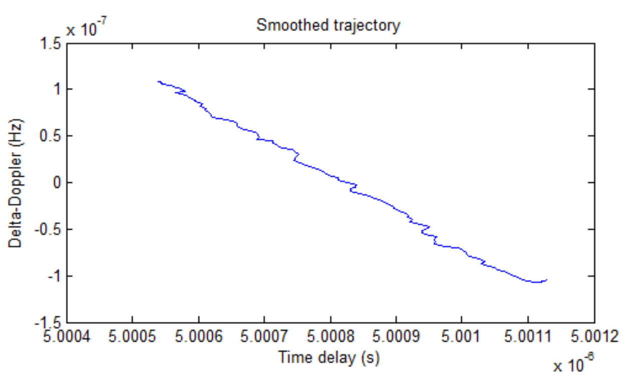

Fig. 6. Trajectory after the smoothing phase

We notice that with a sufficiently low noise level (variance of $\sigma_\tau^2 = 5 \cdot 10^{-11} s$) and for a linear motion of the moving target, we can find a trajectory very close to the theoretical one and thus track the target over time.

5. CONCLUSION AND PROSPECTS

In this paper, we have presented a tracking method based on Kalman filtering for target tracking.

Since the aim of our work is to develop a measuring and processing platform for the scattered GPS signals, we always underline the noise effect on processing. Thus, for various noise levels, we use a suitable filter adapted to the conditions.

We started the linear Kalman filter to see if it is possible to track a reflected GPS signal on the sea surface. The results obtained by our simulations are promising. For the EKF, we believe it will be also possible to perform tracking.

A next step would be to consider more constraints such as noise distribution and multiple targets to permits the using of our algorithms in measurements campaigns.

6. REFERENCES

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