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A sequential converted measurement Kalman filter in the ECEF coordinate system for airborne Doppler radar

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ABSTRACT

For an airborne Doppler radar, the carrying platform is moving and has time-varying attitudes. The filtering algorithms applicable to local coordinate system are not suitable anymore. In this paper, we propose a sequential converted measurement Kalman filter (SCMKF) with Doppler, which is based on the earth-centered earth-fixed (ECEF) coordinate system. First, to effectively utilize Doppler measurement with probable correlation with slant range, the correlated Doppler and range are decorrelated by the Cholesky factorization. The range component remains unchanged while the Doppler component is changed. Second, by a series of coordinate transformations with unchanged range component and other observations, the converted position measurement is obtained. Meanwhile, the corresponding error covariance is derived by using Taylor series expansion. With the resulting converted measurement and covariance, the target state is filtered by the converted measurement Kalman filter (CMKF), which is extended to the ECEF system. Finally, the filtered state is updated sequentially with the changed Doppler. Compared with the posterior Cramer–Rao lower bound as well as the CMKF, the proposed SCMKF is shown to be an efficient solution, and is superior to the CMKF. Although the gain brought from low-accuracy Doppler is limited, the introduction of high-accuracy Doppler can improve tracking performance significantly.

1. Introduction

The Doppler measurement plays an important role in radar target tracking. It was approved that the Doppler (or range rate, radial velocity) could improve track accuracy and enhance convergence speed of track initiation [1] and track confirmation [2], correction rate of data association [3], etc. In order to deal with the incorporated Doppler, which is a nonlinear function of unknown target state, nonlinear filters are usually adopted, such as the extended Kalman filter (EKF) [1,4], second-order EKF [5,6], unscented Kalman filter (UKF) [7–9], particle filter (PF) [10], etc. Many nonlinear filters were compared in [11] and it was shown that all filters had nearly the similar performance. In addition, the Doppler can be processed approximately as a linear measurement using the measured angles [12] or estimated direction cosine [13].

In general, it is assumed that measurement errors in range and Doppler are statistically uncorrelated [1–3,5,14]. However, there may be a correlation for some waveforms [15]. For 1-dimensional coordinate and linear measurement function, the performance improvement was quantified in [15]. For more practical 3-dimensional coordinate, the sequential filtering was introduced, namely, the converted measurement Kalman filter (CMKF) was implemented based on decorrelation for the converted position measurement, and then the Doppler was filtered sequentially. If the CMKF is used, it is needed to derive the error covariance for a nonlinear coordinate transformation. For error analysis of spherical-to-Cartesian (S2C) transformation, there are many methods, such as Taylor expansion method, debiasing method [16,17], unbiased method [18], modified unbiased method [19], etc. It was proved that the last three methods were more consistent and robust than Taylor expansion method only in the presence of large azimuth error [18]. In fact, Taylor expansion method is still effective in most practical radar systems [16].

The aforementioned algorithms are based on the local coordinate system of the ground fixed radar. Obviously, they cannot be directly used target tracking for airborne radar, as the carrying platform is moving and has time-varying attitudes. In this paper, we establish the target dynamic model and measurement model based on the general earth-centered earth-fixed (ECEF) coordinate system. A sequential converted measurement Kalman filter (SCMKF) with Doppler, which is based on the ECEF system, is pro-

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Nomenclature

Acronyms

ECEF	Earth-centered earth-fixed
NED	North-east-down
HRD	Head-right-down
S2C	Spherical-to-Cartesian
CMKF	Converted measurement Kalman filter
SCMKF	Sequential converted measurement Kalman filter
PCRLB	Posterior Cramer–Rao lower bound
RMSE	Root mean-square error

Main notations

$\boldsymbol{r}_E^p$	Target relative position in the ECEF system
$\boldsymbol{r}_N^p$	Target relative position in the NED system
$\boldsymbol{r}_H^p$	Target relative position in the HRD system
$\boldsymbol{\varpi}$	Position vector including longitude, latitude, and altitude
$\boldsymbol{T}_E^N(\boldsymbol{\varpi})$	Rotation matrix from the ECEF system to the NED system
$\boldsymbol{T}_N^E(\boldsymbol{\varpi})$	Rotation matrix from the NED system to the ECEF system
$\boldsymbol{\omega}$	Attitude vector including yaw, pitch, and roll
$\boldsymbol{T}_N^H(\boldsymbol{\omega})$	Rotation matrix from the NED system to the HRD system
$\boldsymbol{T}_H^N(\boldsymbol{\omega})$	Rotation matrix from the HRD system to the NED system
$\boldsymbol{h}(\cdot)$	Transformation from the Cartesian coordinate to spherical coordinate
$\boldsymbol{h}^{-1}(\cdot)$	inverse function of $\boldsymbol{h}(\cdot)$
ρ	Correlation coefficient
$\boldsymbol{z}$	Spherical measurement vector including range, azimuth, and elevation
z_d	Doppler measurement
$\boldsymbol{z}^c$	Converted position measurement vector
$z_{d''}$	Pseudo-Doppler measurement
$\boldsymbol{H}^c$	Converted position observation matrix
$\boldsymbol{\Psi}'_{k\|k}$	Pseudo-Doppler observation matrix
$\boldsymbol{R}_E^c$	Covariance of the converted measurement error
$\sigma_{d''}^2$	Variance of the pseudo-Doppler error
$\boldsymbol{G}^c$	Gain matrix for the converted position measurement
$\boldsymbol{G}^d$	Gain matrix for the pseudo-Doppler measurement
$\boldsymbol{X}(k)$	True target state
$\hat{\boldsymbol{X}}(k\|k)$	Filtered target state using the converted position measurement
$\hat{\boldsymbol{X}}^d(k\|k)$	Filtered target state sequentially using the pseudo-Doppler

posed. First, the correlated Doppler and range are decorrelated by the Cholesky factorization. After the factorization, the range component remains unchanged while the Doppler is changed. Second, the CMKF is extended to the ECEF system. The spherical measurement, including unchanged range component, is transformed to obtain the converted position measurement. Meanwhile, using the Taylor expansion method, the corresponding error covariances for related coordinate transformations are derived. These transformations not only involve the S2C transformation, but also include transformation between body coordinate system and airborne-carried north-east-down (NED) system, and transformation between the NED system and the ECEF system. Finally, the changed Doppler measurement is filtered sequentially using estimated direction cosine, which is drawn from [13]. It is shown that the proposed SCMKF approaches the posterior Cramer–Rao lower bound. Furthermore, it outperforms the CMKF, and the gain brought from low-accuracy Doppler is limited while the introduction of high-accuracy Doppler can improve tracking performance significantly.

This paper is organized as follows. Section 2 describes the measurement model based on the ECEF coordinate system. In Section 3, the SCMKF with Doppler is addressed. Numerical studies are provided to illustrate the effectiveness of the proposed method in Section 4. Finally, the conclusions are given in Section 5.

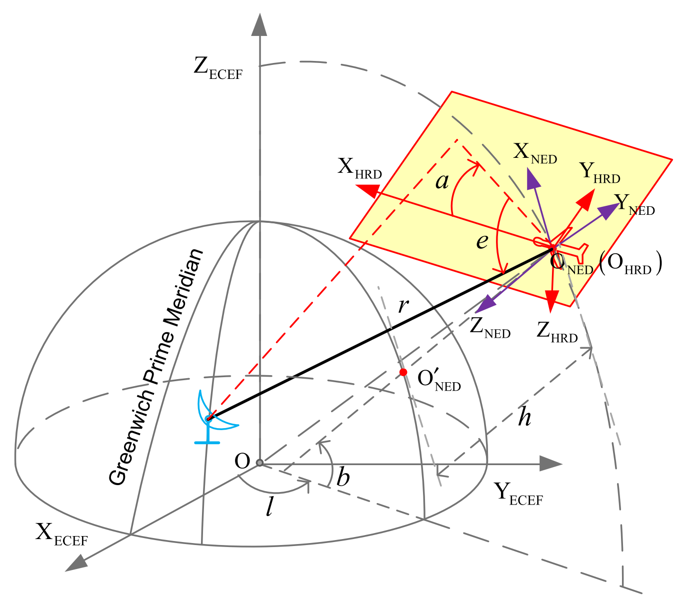

Fig. 1. Coordinate systems involved for airborne platforms.

2. The measurement model based on the ECEF coordinate system

For airborne platforms, there are several coordinate systems involved [20], as shown in Fig. 1. For ease of reference, we summarize the coordinate systems adopted in our work.

The origin of the ECEF coordinate system is located at the center of the earth. The X-axis extends from the origin to the intersection of the prime meridian (0° longitude) and the equator (0° latitude), and the Z-axis is along the spin axis of the earth, pointing to the north pole, and the Y-axis is orthogonal to the X- and Z-axes with the usual right-handed rule. The NED system is associated with the flying vehicle. Its origin is at the center of gravity of airborne platform, the X-, Y- and Z-axes point toward the geodetic north, toward the geodetic east, and downward along the ellipsoid earth normal, respectively. The body coordinate system is directly defined on the body of airborne platform. Its origin is also located at the center of gravity. The X-, Y- and Z-axes point forward head, toward right side, and downward to comply with the right-handed rule, respectively. Thus, the body coordinate system is called the head-right-down (HRD) system.

The target state in the ECEF coordinate system is defined as

$$\boldsymbol{X}(k) = \begin{bmatrix} x & y & z & \dot{x} & \dot{y} & \dot{z} & \ddot{x} & \ddot{y} & \ddot{z} \end{bmatrix}_k^{\mathrm{T}} \tag{1}$$

The observation platform state is similar to the target, namely,

$$\boldsymbol{X}^o(k) = \begin{bmatrix} x^o & y^o & z^o & \dot{x}^o & \dot{y}^o & \dot{z}^o & \ddot{x}^o & \ddot{y}^o & \ddot{z}^o \end{bmatrix}_k^{\mathrm{T}} \tag{2}$$