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Multi-Slots Joint MLE Relative Navigation Algorithm Based on INS/JTIDS/BA for Datalink Network

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ABSTRACT High accuracy relative navigation (RELNAV) information is crucial for datalink network members in the situation of joint operations, especially the situations that some datalink network members may not be able to obtain their location with absolute navigation. In this paper, relative navigation algorithm based on JTIDS/INS/BA is proposed, in this system datalink joint units(JUs) are positioned in two-dimensional plane with multi-slots joint maximum likelihood estimation (MLE), and altitude is located by a height filter independently, which overcome the problem of poor positioning geometry of altitude. Multi-slots joint MLE convert TOA measurements in different slots to one moment with short-time inertial navigation system(INS) information, which lead to a higher localization accuracy in two-dimensional plane. We simulate a joint tactical information distribution system (JTIDS) network with multiple members, to verify the performance and analyze the influence factors of the proposed algorithm. The simulation results show that compared to EKF that process TOA measurements sequentially in each navigation slot and MLE without multi-slots joint processing, the multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA performs better in two-dimensional plane location, and the height filter based on barometric altimeter (BA) improves the relative height positioning accuracy greatly.

INDEX TERMS JTIDS, datalink, TDMA, relative navigation, MLE.

I. INTRODUCTION

Relative position is a very important tactical information in large-scale joint military operations. Network members estimate their relative positions by ranging, and form a unified battlefield collaboration in a relative coordinate system with relative positions, so relative navigation is critical to achieve tactical objectives. At present, GNSS and integrated navigation system based on GNSS are the most common way to get relative position, relative positions of network members can be obtained after absolute navigation [1]. However, GNSS is vulnerable to jamming and requires an extra link to share location information between network members. The joint tactical information distribution system (JTIDS) is a time division multiple access (TDMA) communication system, JTIDS provides substantial advantages including high transmission power, high anti jamming capability, JTIDS units can obtain the ranges to other JUs by time of arrival (TOA), these advantages make JTIDS a primary choice when GNSS information is unavailable.

In general relative navigation algorithm of JTIDS or other TDMA datalinks, JUs get the information of RELNAV sources and TOA measurements from PPLI messages and then process with Kalman Filter [2]–[5]. In the situations of large-scale JTIDS network, height difference is much smaller than distance between JUs and RELNAV sources, which lead to a poor localization geometry of height and reduce the accuracy of localization. At the same time, JTIDS is a TDMA based communication system [6], each RELNAV sources broadcast PPLI messages in different slots, JUs receive PPLI messages from different RELNAV sources at different moments and positions, high dynamic members

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such as aircraft users can't achieve a satisfactory localization accuracy. To improve positioning accuracy of RELNAV, an improved navigation time slots allocation method is proposed in [7], the slots for transmitting PPLI(Precise Participant Location and Identification) messages are consecutively assigned to improve positioning accuracy by updating TOA measurements frequently, but this method can't completely eliminate the negative impact of TDMA characteristics. The works in [8] presents a TDLS datalink relative navigation algorithm which uses TOA measurement to calculate innovation and filter with EKF in each navigation slot, but due to the limitation of TDMA characteristics the convergence speed of this algorithm is slow. In [9], a cooperative localization algorithm is proposed to locate the autonomous underwater vehicle agents, the agents convert TOA information at different moments into a same moment with dead reckoning and then calculate the locations of the agents, the algorithm solves the problem that agents can't calculate position when receive TOA at different moments. A centralized maximum likelihood estimation is proposed in [10], [11] to solve the two-dimensional cooperative location estimate problem in wireless sensor network (WNS) with TOA and velocity measurements. In [12], an improved linear optimization process based on first-order optimal condition of MLE is proposed to estimate two-dimension positions of sensor network agents to improve the efficiency of search. In order to ensure altitude accuracy of the aircraft with low-cost GNSS and radar, in [13] different altimeter sensors are fused to constrain the error of altitude direction. A way of two satellites positioning is proposed in [14], by combining pseudorange, Doppler information and external altitude information from a MEMS barometric altimeter in receiver. Finally, a method of low cost INS/GNSS system with barometer information is proposed in loosely-coupled and tightly-coupled scheme in [15], to improve location accuracy under harsh GNSS-degraded environment.

In this paper, multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA is proposed. The proposed algorithm converts TOA information received by the RELNAV user at different slots into the calculating slot with short-time INS information, and estimate two-dimensional relative position with MLE, to improve two-dimensional positioning accuracy in TDMA network. At the same time, an independent altitude EKF filter based on barometer measurements is used to correct altitude error of inertial device, which solves the problem that altitude accuracy is low in large-scale JTIDS network, caused by poor localization geometry of the altitude.

The rest of this paper is organized as follows: The second part, we review the basic principles of JTIDS relative navigation and establishment method of relative navigation coordinate system. The third part, the proposed multi-slots joint MLE relative navigation algorithm of two-dimensional plane and independent altitude filter are detailed. The fourth part, influence factors of positioning error is analyzed in theory. The fifth part, simulation study is conducted to analyze and

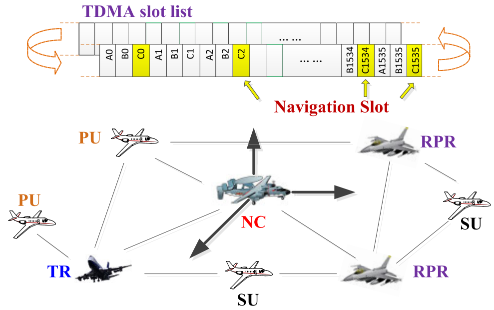

FIGURE 1. Relative navigation network architecture.

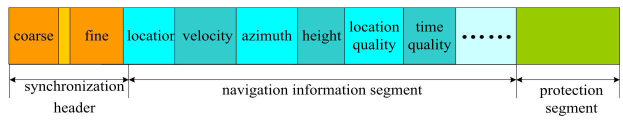

FIGURE 2. PPLI message structure.

evaluate the proposed algorithm. The sixth part, concludes the paper.

II. BASIC PRINCIPLES OF JTIDS RELATIVE NAVIGATION

Basic principles of JTIDS RENAV mainly include different roles of JTIDS members which set up the structure of network and relative navigation coordinate system. These two aspects is detailed in this part.

A. RELATIVE NAVIGATION NETWORK ARCHITECTURE

Members of JTIDS network are divided into different roles [17]. As shown in Fig. 1, high-level members include: ① Navigation controller(NC), NC is appointed as the origin of RELNAV coordinate system. ② Time reference(TR), clock of JTIDS, members synchronize with TR directly or indirectly. ③ Relative position reference(RPR), whose relative position and absolute position are exact enough. ④ Primary user (PU), PUs are permitted to synchronize clock with TR by exchanging RTT messages. ⑤ Secondary user (SU), passive synchronization is the main method for SUs, which often have to be radio silent.

Part of time slots are selected from the time slot list act as navigation slots to transmit PPLI messages periodically, as Fig. 2 shown, PPLI message transmit navigation information includes location, velocity, height, location quality and time quality. Members with exact positions and high clock accuracy can transmit PPLI messages as RELNAV sources. PPLI message contains coarse synchronization header and fine synchronization header, RELNAV users of network can extract TOA measurement with synchronization headers.

B. THE RELATIVE NAVIGATION COORDINATE SYSTEM

As shown in Fig. 3, the relative coordinate system is established by NC, the origin O of the relative coordinate system is the position of NC projected onto the standard ellipsoid of the earth, the axes ON and OE are located in the tangent

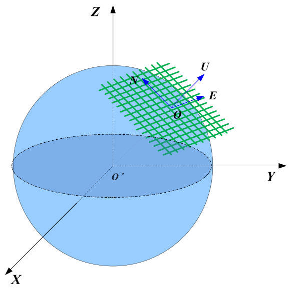

FIGURE 3. Relative coordinate system.

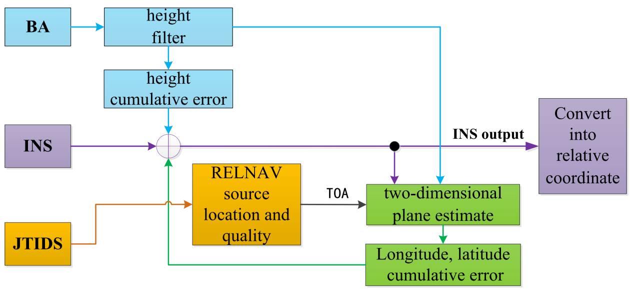

FIGURE 4. The multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA.

plane of the earth at the origin and point to north and east, OU axis is perpendicular to the NOE plane and points to the sky. All Members of JTIDS use this grid coordinate system to determine their relative positions.

ECEF coordinate (x, y, z) is converted to relative coordinate (x_p, y_p, z_p) with formula (1) and (2), the matrix for coordinate transform is

$$A = \begin{bmatrix} -\sin\lambda_0 & -\cos\lambda_0\sin\varphi_0 & \cos\lambda_0\cos\varphi_0 \\ \cos\lambda_0 & -\sin\lambda_0\sin\varphi_0 & \sin\lambda_0\cos\varphi_0 \\ 0 & \cos\varphi_0 & \sin\varphi_0 \end{bmatrix} \quad (1)$$

where λ_0, φ_0 are longitude and latitude of relative coordinate origin, and (x_0, y_0, z_0) is origin's ECEF coordinates, (x_p, y_p, z_p) is network member's relative coordinates, the transform formula is

$$\begin{bmatrix} x_P \\ y_P \\ z_P \end{bmatrix} = A^T \begin{bmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \end{bmatrix} \quad (2)$$

III. THE MULTI-SLOTS JOINT MLE RELATIVE NAVIGATION ALGORITHM BASED ON INS/JTIDS/BA

As presented in Fig. 4, considering independence of measurements and geometric distribution of network members. We decompose dimension of estimator, altitude is separate from other dimensions, altitude filter process measurements from barometer with EKF independently [19]. RELNAV sources broadcast their own geographic positions with PPLI messages, and RELNAV users estimate their positions with multi-slots joint MLE algorithm in two-dimensional plane. After revising the errors of INS in a close-loop method with cumulative errors, users transform coordinates from ECEF to relative navigation coordinate system.

A. HEIGHT FILTER

The states of height filter are INS altitude error Δh and height velocity error ΔV_h. According to INS system second-order damped error propagation equation of altitude and height velocity, continuous state equation of the height filter can be obtained, after discretization of state equation height filter is presented as (3).

$$X_h(k) = \Phi_h(k, k-1)\, X_h(k-1) + v_h(k-1) \quad (3)$$

where $X_h(k) = [\Delta h(k)\ \Delta V(k)]^T$ is state vector, $v_h(k-1)$ denotes process noise vector, covariance matrix Q_h is calculated by

$$Q_h(k-1) = \begin{bmatrix} \sigma_v^2\dfrac{T^3}{3} & \sigma_v^2\dfrac{T^3}{2} \\ \sigma_v^2\dfrac{T^3}{2} & \sigma_v^2 T^3 \end{bmatrix} \quad (4)$$

State transition matrix is written as

$$\Phi_h(k, k-1) = \begin{bmatrix} 1 - k_1 T & T \\ \left(\dfrac{2g_0}{R_e} - \dfrac{V_e^2}{R_1^2} - \dfrac{V_n^2}{R_2^2}\right)T & 1 \end{bmatrix} \quad (5)$$

The measurements of the height filter is the difference between the output of barometric altimeter h_{BA} and the height output of the INS h_{INS}.

And the matrix form of the measurement equation is given

$$Z_k = \begin{bmatrix} -1 & 0 \end{bmatrix}\begin{bmatrix} \Delta h \\ \Delta V_h \end{bmatrix} + w_h = H_h \begin{bmatrix} \Delta h \\ \Delta V_h \end{bmatrix} + w_h \quad (6)$$

where w_h denotes noise vector of barometric altimeter whose variance is $\mathrm{R_h}$ determined by barometric altimeter's precision [20].

B. MULTI-SLOTS JOINT MLE RELATIVE NAVIGATION ALGORITHM IN TWO-DIMENSIONAL PLANE

1) THE MEASUREMENTS OF MULTI-SLOTS JOINT MLE

RELNAV users are passive synchronized with PPLI messages. Position and clock error are estimated with multi-slots joint MLE algorithm, the four-dimensional state vector is $(x, y, z, \Delta t)$.

The measurement equation of TOA between RELNAV source s and RELNAV user u in slot n is given

$$TOA_u^n = \left\|(\mathrm{s}_s^n - \mathrm{s}_u^n)\right\| + \Delta t_u^n + w_{TOA}^n \quad (7)$$

where s_s^n is position of transmitter, that can be obtained form PPLI message, s_u^n is the position of user, Δt_u^n is time error with respect to RELNAV source, which is unknown. RELNAV sources are assigned some time slots to send RTT messages to synchronize with TR. w_{TOA}^n is TOA error modeled as a zero-mean white Gaussian process with variance σ_{TOA}^{n2}.The measurement vector after linearization is

$$h_{TOA-n-i} = [-(x_s^{n-i} - x)/R_c^{n-i}\ \ -(y_s^{n-i} - y)/R_c^{n-i}\ \ -(z_s^{n-i} - z)/R_c^{n-i}\ \ 1] \quad (8)$$

We use the following movement model to incorporate velocity measurements in the positioning estimate process of RELNAV user.

$$s_u^n = s_u^{(n-1)} + w_u^{n-1} + (v_u^n + w_v^{n-1})T \tag{9}$$

where T is period of localization. v_u^n is velocity of u obtained from INS in slot n which is modeled as a zero-mean white Gaussian process with covariance $\sigma_v^{n^2}$. w_u^{n-1} is position errors of last period of localization who's variance vector is $\sigma_p^{n-1^2}$. We assume that velocity of different coordinates is independent from each other, $w_{\mathrm{v-p}}^n$ is the error vector of position, covariance of $w_{\mathrm{v-p}}^n$ can be given by

$$\begin{aligned} &diag\left[\sigma_{v-px}^{n^2}\ \sigma_{v-py}^{n^2}\ \sigma_{v-pz}^{n^2}\right] \\ &= diag\left[\sigma_{px}^{n-1^2} + \sigma_{vx}^{n^2}T^2\ \ \sigma_{py}^{n-1^2} + \sigma_{vy}^{n^2}T^2\ \ \sigma_{pz}^{n-1^2} + \sigma_{vz}^{n^2}T^2\right] \end{aligned} \tag{10}$$

The measurement vector is

$$h_v = \left[I_3\ O_{3\times 1}\right] \tag{11}$$

With the result of altitude filter, we convert errors of x, y, z to altitude direction as constraint of height [16], constraint equation can be written as

$$B\left[s^n - s_u^n\right] = \Delta u = h_{KF}^n + w_h^n \tag{12}$$

$$B = \left[\cos\phi\cos\lambda \quad \cos\phi\sin\lambda \quad \sin\phi\right] \tag{13}$$

where h_{KF}^n is altitude error of INS in slot n which is obtained from height filter, w_h^n is noise of h_{KF}^n. λ, φ are the latitude and longitude obtained from user's INS device, corresponding measurement vector is

$$h_{BA} = \left[\cos\phi\cos\lambda \quad \cos\phi\sin\lambda\ \sin\phi \quad 0\right] \tag{14}$$

2) TOA MEASUREMENTS CONVERSION BASED ON SHORT-TIME INS INFORMATION

JTIDS is a TDMA system, navigation slots equally distributed in slot list. Owing to mobility during the intervals between navigation slots, RELNAV users receive PPLI messages at different locations, so navigation performance is degraded. To eliminate the effect of movement, the algorithm we proposed convert RELNAV information of different slots to one slot with short-time INS information, and estimate with multi-slots joint MLE.

The current slot is assumed to be slot n, and RELNAV user estimate location in this slot, RELNAV user's position is s_u^n and output of user's INS device is INS_u^n, position vector of RELNAV source is s_s^n. At slot *n-i*, the position vector of RELNAV source is s_s^{n-i}, and the position vector of RELNAV user is s_u^{n-i} output of INS device is INS_u^{n-i}, corresponding measurement equation is

$$\left\|(s_s^{n-i} - s_u^{n-i})\right\| = TOA^{n-i} - \Delta t_u^{n-i} + w_{TOA}^{n-i} \tag{15}$$

Variation of INS in this period can be approximated as real displacement. Variation of position Δs^i from slot *n-i* to n can be given

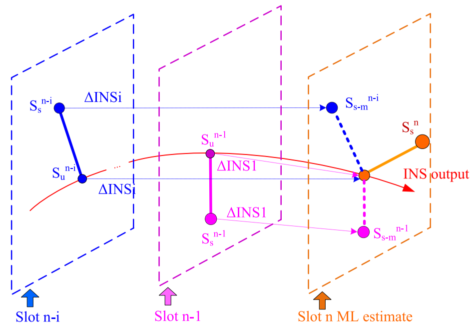

FIGURE 5. The method convert RELNAV information of previous slots to slot n in multi-slots joint MLE.

$$\Delta s^i = INS_u^n - INS_u^{n-i} + d_{d-ins}^{n-i} \tag{16}$$

We assume that INS drift d_{d-ins}^{n-i} is very small in a short period of time. Fig. 5 shows the method convert RELNAV information of previous slots to slot n. Position of RELNAV user in slot *n-i* is s_u^{n-i}, and the RELNAV source of slot *n-i* is s_{s}^{n-i}, $s_{u-\mathrm{m}}^{n-i}$ and $s_{\mathrm{s-m}}^{n-i}$ are the positions has been converted to slot n for ML estimate.

$$s_{s-m}^{n-i} = s_s^{n-i} + \Delta s^i \tag{17}$$

$$s_{u-m}^{n-i} = s_u^{n-i} + \Delta s^i \tag{18}$$

Measurement equation after conversion can be write as

$$\left\|s_{\mathrm{s-m}}^{n-i} - s_{\mathrm{u-m}}^{n-i}\right\| + \Delta t_{\mathrm{u}}^{n-i} = TOA^{n-i} + w_{TOA}^{n-i} \tag{19}$$

And s_u^n can be approximated as s_{u-m}^{n-i} we can get

$$\left\|s_{\mathrm{s-m}}^{n-i} - s_u^n\right\| + \Delta t_{\mathrm{u}}^{n-i} = TOA^{n-i} + w_{TOA}^{n-i} \tag{20}$$

3) LIKELIHOOD FUNCTION OF MULTI-SLOTS JOINT MLE

We assume that the period of maximum likelihood estimate is M navigation slots, the set of TOA measurements in M navigation slots is denoted by χ, the set of velocity measurement is ν, and height measurement is denoted by κ, conditional probability density function is

$$\begin{aligned} &f(\chi, \nu, \kappa / s_u^n) \\ &= f(\chi / s_u^n) f(\nu / s_u^n) f(\kappa / s_u^n) \\ &= \prod_{i=1}^{i=m} \frac{1}{\sqrt{2\pi\sigma_{TOA}^2}} \exp\left(-\frac{(\left\|s_{s-m}^{n-i} - s_u^n\right\| + \Delta t_u^{n-i} - TOA^{n-i})^2}{2\sigma_{TOA}^2}\right) \cdot \\ &\quad \frac{1}{\sqrt{2\pi\sigma_{v-p}^{n^2}}} \exp\left(-\frac{\left\|s_u^n - [s_u^{(n-1)} + v_u^n T]\right\|^2}{2\sigma_{v-p}^{n^2}}\right) \cdot \\ &\quad \frac{1}{\sqrt{2\pi\sigma_h^{n^2}}} \exp\left(-\frac{\left\|B(s_u^n - INS_u^n) - (h_{KF}^n - h^n)\right\|^2}{2\sigma_h^{n^2}}\right) \end{aligned} \tag{21}$$

ML estimate of s_u^n can be obtained by maximizing the conditional probability distribution function $f(\chi, \nu, \kappa / s_u^n)$, the problem translates into the following equation [12]. The problem is reduced to a weighted least squared problem after linearization.

$$\min \sum_{i=1,2\ldots,M} \frac{1}{\sigma_{TOA}^{n-i^2}}(\left\| s_{\mathrm{s-m}}^{n-i} - s_u^n \right\| + \Delta t_{\mathrm{u}}^{n-i} - TOA^{n-i})^2 + \frac{1}{\sigma_{\mathrm{v-px}}^{n2}} ||s_u^n - [s_u^{(n-1)} + v_u^n T]||^2 + \frac{1}{\sigma_h^{n2}} ||B(s_{MLE}^n - s_u^n) - (h_{KF}^n - h^n)||^2 \quad (22)$$

The INS device output is set as the initial position used to iterate, the obtained iteration step of the x, y and z, is revise value of INS error. According to the positions of NC transmitted in PPLI messages, relative coordinates can be obtained by coordinate conversion with equation (1), (2).

IV. ANALYSIS OF THE INFLUENCE ON RELATIVE NAVIGATION ACCURACY

We analyze several main influence factors of positioning errors in this part, include TOA measurement error, height error, relative position geometry, broadcast frequency of navigation slots.

A. POSITIONING ERROR AND GEOMETRIC ANALYZE IN TWO-DIMENSIONAL PLANE

Typically, we assume that measurement error is Gaussian distributed with zero mean, and mutual independence between measurements. ε_x, ε_y, ε_z are positioning errors of ECEF coordinates and ε_t is clock error.

The positioning equation of the likelihood function with weighted least squares is

$$H \begin{bmatrix} \Delta \mathrm{x} + \varepsilon_{\mathrm{x}} \\ \Delta \mathrm{y} + \varepsilon_{\mathrm{y}} \\ \Delta \mathrm{z} + \varepsilon_{\mathrm{z}} \\ \Delta \delta t_u + \varepsilon_{\Delta t} \end{bmatrix} = \mathrm{b} + \varepsilon_\rho \quad (23)$$

The corresponding weighted least squares solution is

$$\begin{bmatrix} \Delta x + \varepsilon_x \\ \Delta y + \varepsilon_y \\ \Delta z + \varepsilon_z \\ \Delta \delta t_{\mathrm{u}} + \varepsilon_{\Delta t} \end{bmatrix} = (H^T W H)^{-1} H^T W b + (H^T W H)^{-1} H^T W \varepsilon_\rho \quad (24)$$

W is diagonal matrix formed by covariance of measurement errors. N is number of measurements.

$$W = K_{\varepsilon_\rho}^{-1} = diag\left[w_{11}\ w_{22}\ \ldots\ w_{NN} \right] \quad (25)$$

$$K_{\varepsilon_\rho} = diag\left[\sigma_{TOA}^{12} \ldots \sigma_{TOA}^{i2}\ \sigma_{BA}^2\ \sigma_{v-px}^{n2}\ \sigma_{v-py}^{n2}\ \sigma_{v-pz}^{n2} \right] \quad (26)$$

Convert the errors in ECEF coordinate system to relative coordinate system with convert matrix A from equation (2).

$$\begin{bmatrix} \varepsilon_{xp} \\ \varepsilon_{yp} \\ \varepsilon_{zp} \\ \varepsilon_{\Delta t} \end{bmatrix} = \begin{bmatrix} A^T & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \varepsilon_{\Delta t} \end{bmatrix} = \begin{bmatrix} A^T & 0 \\ 0 & 1 \end{bmatrix} ((DH)^T DH)^{-1} (DH)^T (D\varepsilon_\rho) \quad (27)$$

$$= C^P (H^T W H)^{-1} H^T W \varepsilon_\rho$$

$$D = \mathrm{diag}\left[1/\sqrt{w_{11}}\ 1/\sqrt{w_{22}}\ \ldots\ 1/\sqrt{w_{NN}} \right] \quad (28)$$

The covariance matrix of corresponding relative positioning errors is

$$Cov\left(\begin{bmatrix} \varepsilon_{xp} \\ \varepsilon_{yp} \\ \varepsilon_{zp} \\ \varepsilon_{\Delta t} \end{bmatrix}\right) = E\left(\begin{bmatrix} \varepsilon_{xp} \\ \varepsilon_{yp} \\ \varepsilon_{zp} \\ \varepsilon_{\Delta t} \end{bmatrix} \left[\varepsilon_{xp}\ \varepsilon_{yp}\ \varepsilon_{zp}\ \varepsilon_{\Delta t} \right]\right)$$
$$= E\left(C^P (H^T W H)^{-1} H^T W \varepsilon_\rho \left(C^P (H^T W H)^{-1} H^T W \varepsilon_\rho \right)^T \right)$$
$$= C^P (H^T W H)^{-1} H^T W E\left(\varepsilon_\rho \varepsilon_\rho^T \right) W H (H^T W H)^{-1} \left(C^P \right)^T$$
$$= C^P (H^T W H)^{-1} H^T W H (H^T W H)^{-1} \left(C^P \right)^T$$
$$= C^P (H^T W H)^{-1} \left(C^P \right)^T \quad (29)$$

Weighted dilution of precision (WDOP) G^p of relative navigation coordinate system can be write as

$$G^P = C^P (H^T W H)^{-1} \left(C^P \right)^T \quad (30)$$

$$WDOP^p = \sqrt{{G^P}_{11}^2 + {G^P}_{22}^2 + {G^P}_{44}^2} \quad (31)$$

Multi-slots joint MLE estimate in two-dimensional plane, height is not considered, so there are 3 dimensions in $WDOP^p$.

B. INFLUENCE FACTORS OF RANGING ERROR

Uncertainty of TOA measurements is an important factor affect positioning accuracy. There are several important parts constitute the uncertainty of TOA measurement, including position errors and clock error of the RELNAV source, height filter errors projection, and random error of TOA measurement. w_{s-q}^n is uncertainty of RELNAV source's position in slot n with variance σ_{s-q}^{n2}, w_{s-t}^n is clock error of RELNAV source with variance σ_{s-t}^{n2}, w_h^n is the influence of height error on TOA with variance σ_h^{n2}.

1) INFLUENCE OF RELNAV SOURCE

σ_{s-q}^{n2} and σ_{s-t}^{n2} can be obtained from the covariance matrix information of RELNAV source, which is sent to RELNAV users with PPLI message.

$$\sigma_{s-q}^{n2} = \left(\left(P_{\ln g} + P_{1at} + \left[\left(P_{\ln g} - P_{1at} \right)^2 + 4P_{\mathrm{cov}}^2 \right]^{1/2} \right) /2 \right)^{1/2} \quad (32)$$

$$\sigma_{s-t}^{n2} = P_t \quad (33)$$

P_{lng}, P_{lat} is variance of longitude and latitude and P_{cov} is covariance, P_t is variance of clock error which is obtained from RELNAV source's RTT filter.

We assume that the random error due to hardware delay, atmospheric delay correction, thermal noise and signal interference is w_p^n with variance σ_p^{n2}, we can get

$$\sigma_{TOA}^{n2} = \sigma_{s-q}^{n2} + \sigma_p^{n2} + \sigma_{s-t}^{n2} + \sigma_h^{n2} \tag{34}$$

2) ANALYSIS OF THE INFLUENCE OF HEIGHT ERROR ON TOA

The linearized distance r between RELNAV source and user is

$$r = r_c - \frac{X_s^n - X_u^n}{r_c}(X_{uT}^n - X_u^n) - \frac{Y_s^n - Y_u^n}{r_c}(Y_{uT}^n - Y_u^n) - \frac{Z_s^n - Z_u^n}{r_c}(Z_{uT}^n - Z_u^n) \tag{35}$$

$\left(X_{uT}^n \ Y_{uT}^n \ Z_{uT}^n \right)$ is true position of RELNAV user in ECEF coordinate system, measurement equation can be written as

$$TOA^n = r_c + \frac{X_s^n - X_u^n}{r_c}\Delta X_u + \frac{Y_s^n - Y_u^n}{r_c}\Delta Y_u + \frac{Z_s^n - Z_u^n}{r_c}\Delta Z_u + \Delta t_u^n + w^n \tag{36}$$

Total differential of the formula convert from geographical coordinates to ECEF coordinates is

$$\begin{aligned}\Delta X_u = & \Delta L_u[2\mathrm{Re} f \sin L_u^n \cos^2 L_u^n \cos\lambda_u^n \\ & -(\mathrm{Re}(1+f\sin^2 L_u^n) + h_u^n)\cos\lambda_u^n \sin L_u^n] \\ & +\Delta\lambda_u[-(\mathrm{Re}(1+f\sin^2 L_u^n) + h_u^n)\cos L_u^n \sin\lambda_u^n] \\ & +\Delta h_u \cos L_u^n \cos\lambda_u^n \end{aligned} \tag{37}$$

$$\begin{aligned}\Delta Y_u = & \Delta L_u[2\mathrm{Re} f \sin L_u^n \cos^2 L_u^n \cos\lambda_u^n \\ & -(\mathrm{Re}(1+f\sin^2 L_u^n) + h_u^n)\sin\lambda_u^n \sin L_u^n] \\ & +\Delta\lambda_u[(\mathrm{Re}(1+f\sin^2 L_u^n) + h_u^n)\cos L_u^n \cos\lambda_u^n] \\ & +\Delta h_u \cos L_u^n \cos\lambda_u^n \end{aligned} \tag{38}$$

$$\begin{aligned}\Delta Z_u = & \Delta L_u[2\mathrm{Re} f (1-f)^2 \sin^2 L_u^n \cos L_u^n \\ & +(\mathrm{Re}(1+f\sin^2 L_u^n)(1-f)^2 + h_u^n)\cos L_u^n] \\ & +\Delta h_u \sin L_u^n \end{aligned} \tag{39}$$

Substitute (37)-(39) into (36) and simplify the equation

$$TOA^n = r_c + h_{\ln gs}\Delta\lambda_u + h_{lats}\Delta L_u + h_{hs}\Delta h_u + \Delta t_u^n + w^n \tag{40}$$

where $h_{\ln gs}$, h_{lats}, h_{hs} are coefficients after simplify. We assume that ε_{xu}, ε_{yu}, ε_{zu} are errors corresponding to ΔX_u, ΔY_u, ΔZ_u, and in geographical coordinate system $\varepsilon_{\lambda u}$, ε_{Lu}, ε_{hu} are errors corresponding $\Delta\lambda_u$, ΔL_u, Δh_u. substitute them into(40)

$$TOA^n = r_c + h_{\ln gs}(\Delta\lambda_u + \varepsilon_{\lambda u}) + h_{lats}(\Delta L_u + \varepsilon_{Lu}) + h_{hs}(\Delta h_u + \varepsilon_{hu}) + \Delta t_u^n + w^n \tag{41}$$

We can get the influence of height error w_h^n is

$$w_h^n = h_{hs}\varepsilon_{hu} \tag{42}$$

And the variance σ_h^{n2} is

$$\sigma_h^{n2} = E\left(w_h^n \cdot w_h^{nT}\right) = h_{hs}^2 P_h \tag{43}$$

where P_h is variance of height error which is obtained from the covariance matrix of height filter. The height conversion coefficient h_{hs} is

$$h_{hs} = \frac{X_s^n - X_u^n}{r_c}\cos L_u^n \cos\lambda_u^n + \frac{Y_s^n - Y_u^n}{r_c}\cos L_u^n \cos\lambda_u^n + \frac{Z_s^n - Z_u^n}{r_c}\sin L_u^n \tag{44}$$

where L_u, λ_u is output of INS device.

3) ANALYSIS OF THE EFFECT OF NAVIGATION SLOTS BROADCAST FREQUENCY

JTIDS is a TDMA system, if estimate time period is fixed, navigation slots broadcast frequency will influence the number of available RELNAV sources of each estimate period, the lower navigation slots broadcast frequency the fewer available RELNAV sources.

$D_m H_m$ is weighted measurement matrix of likelihood function with m measurements, we analyze the effect of one TOA measurement in H on location accuracy. Eliminating one TOA measurement vector which is received in slot i from H, the weighted measurement matrix without this measurement vector is $D_{m-1}^i H_{m-1}^i$.

$$\begin{aligned} H_m^T W_m H_m &= (D_m H_m)^T D_m H_m \\ &= (D_{m-1}^i H_{m-1}^i)^T D_{m-1}^i H_{m-1}^i + d_i h_i^T d_i h_i \end{aligned} \tag{45}$$

We assume that

$$\hat{H}_m = D_m H_m, \hat{H}_{m-1}^i = D_{m-1}^i H_{m-1}^i, \hat{h}_i = d_i h_i = h_i/\sqrt{w_{ii}} \tag{46}$$

where h_i is the eliminated vector in H.

$$h_i = \left[-(x_s^i - x)/R_c^i \ -(y_s^i - y)/R_c^i \ -(z_s^i - z)/R_c^i \ 1 \right] \tag{47}$$

We form a singular value decomposition (SVD) of the matrix $\hat{H}_{m-1}^i$.

$$\hat{H}_{m-1}^i = USV^T \tag{48}$$

According to the above equation, we apply orthogonal transformation to both sides of equation (45), and use the Sherman–Morrison formula [21].

$$\begin{aligned} & \left[V^T C^P \left(\hat{H}_m^T \hat{H}_m\right)\left(C^P\right)^T V\right]^{-1} \\ &= \left[V^T C^P \left(\hat{H}_{m-1}^i T \hat{H}_{m-1}^i\right)\left(C^P\right)^T V + V^T C^P \hat{h}_i^T \hat{h}_i \left(C^P\right)^T V\right]^{-1} \\ &= \left[V^T C^P \left(\hat{H}_{m-1}^i T \hat{H}_{m-1}^i\right)\left(C^P\right)^T V + V^T C^P \hat{h}_i^T \hat{h}_i \left(C^P\right)^T V\right]^{-1} \\ &= \left[Z + vv^T\right]^{-1} \\ &= Z^{-1} - Z^{-1}vv^T Z^{-1}/\left(1 + v^T Z^{-1} v\right) \end{aligned} \tag{49}$$

where

$$Z = V^T C^P \left(\hat{H}^i_{m-1} T \hat{H}^i_{m-1}\right) \left(C^P\right)^T V$$
$$= diag\,(z_{11}, z_{22}, z_{33}, z_{44}) \tag{50}$$
$$v = V^T C^P \hat{h}_i^T = [v_1, v_2, v_3, v_4] \tag{51}$$

The orthogonal transformation does not change the trace of the matrix, so we can get

$$WDOP^{i2}_{m-1} = trace\left(\left(C^P\left(\hat{H}^i_{m-1} T \hat{H}^i_{m-1}\right)\left(C^P\right)^T\right)^{-1}\right)^{1,2,4} = trace\left(Z^{-1}\right)^{1,2,4} \tag{52}$$

where

$$trace\,(M)_{1,2,4} = M_{11} + M_{22} + M_{44} \tag{53}$$

In relative coordinate system, after eliminating a TOA measurement of one slot, we get the relationship between $WDOP^i_{m-1}$ and $WDOP_m$. Two-dimensional plane location does not consider height direction therefore

$$WDOP^{i2}_{m-1} = trace\left(\left(V^T C^P \hat{H}^T_m \hat{H}_m \left(C^P\right)^T V\right)^{-1}\right)_{1,2,4} + trace\left(k v_z v_z^T\right)_{1,2,4} \tag{54}$$

$$WDOP^{i}_{m-1} = sqrt\left(WDOP^2_m + trace\left(k v_z v_z^T\right)_{1,2,4}\right) \tag{55}$$

where v_z and k are given by

$$v_z = Z^{-1} v, \quad k = 1/\left(1 + \sum_{i=1, i\neq 2}^{4} (v_i/z_{ii})^2\right) \tag{56}$$

$$q = trace\left(k v_z v_z^T\right)_{1,2,4} = k \sum_{i=1, i\neq 3}^{4} (v_i/z_{ii})^2 > 0 \tag{57}$$

And q is positive, so we can get the conclusion

$$WDOP^{i2}_{m-1} = WDOP^2_m + q > WDOP^2_m \tag{58}$$

We can draw the conclusion from (58) that if number of RENAV sources is sufficient, the more available navigation slots in each estimate period, the smaller $WDOP_m$ is. Therefore, a higher navigation slots transmission frequency can provide more available *TOA* measurements for estimate, and reach a higher location accuracy.

V. SIMULATION EXPERIMENTS AND ANALYSIS

Simulation experiments are carried out to evaluate the performance of multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA. The simulation we present is a complete accomplishment of GPS, BA, INS, and JTIDS data processing and conducted using a personal computer with Core i7 2.7GHz. We simulate a JTIDS network with multi-access mode of TDMA, and the observed members operate the multi-slots joint MLE relative navigation algorithm.

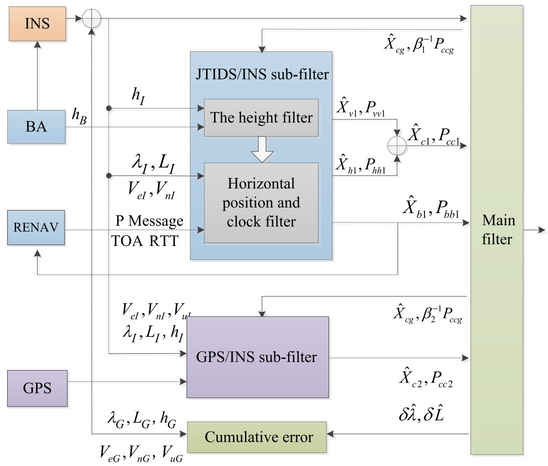

FIGURE 6. Federated Kalman filter of RENAV sources.

The real navigation data of JTIDS members, such as location, speed and attitude of the members are generated by the preset real trajectories. The real navigation information adds errors that include position and velocity errors, using error propagation equation to simulate the INS data. On the basis of real distance between network members, Gaussian white noise error and clock error are added to the real distance between two JTIDS members to simulate TOA pseudorange measurements, and clock error modeled as Markov model. The RENAV sources broadcast PPLI messages to other members in navigation slots. The computer codes were developed by the authors using the Microsoft Visual C++ 6.0 software.

A. SIMULATION CONDITIONS

We consider a JTIDS network with 12 members within an area about 100km^2, members are assumed to be on the planes, and these planes members have different missions, so trajectories of different network members are different and not related. Member 1 is designated as NC and the time reference of network. Members 2-8 are assumed to be primary users, and member 9,10,11,12 are secondary users.

Primary users and NC positioning with federated Kalman filter that consists of two sub-filters and a main filter. As shown in Fig. 6, the two sub-filters are GPS/INS filter and JTIDS/INS filter which integrated by the main filter. Primary users and NC can reach a higher localization accuracy, so they broadcast PPLI messages as RENAV sources, and members 9-12 execute multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA.

The trajectories of the planes include level flight, wheel flight, curve flight, and so on. The two-dimensional plots of the trajectories for the all 12 members with 500s simulation time are shown in Fig. 7. The random error of the clock frequency at the JTIDS user terminals is 3×10^{-6}/h. The 1-sigma

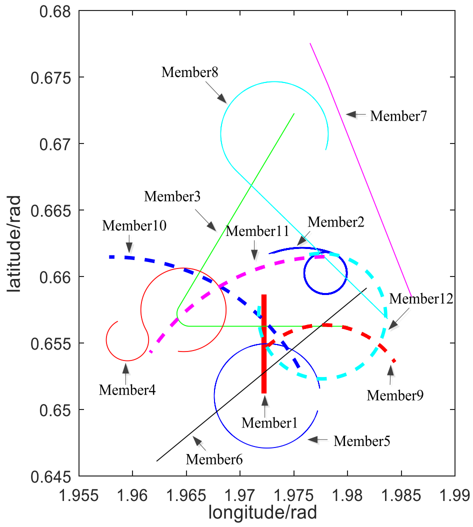

FIGURE 7. Two-dimensional vehicle trajectories of 12 members.

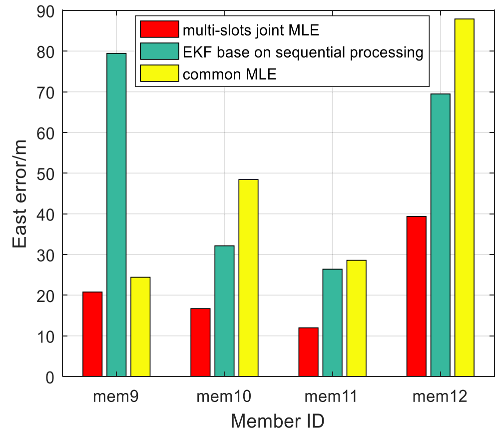

FIGURE 8. RMS east errors comparison between multi-slots joint MLE, EKF based on sequential processing and common MLE.

gyro bias error of INS is 0.1° per hour, and the 1-sigma accelerometer bias error is 0.0001g.

The length of basic slot is 7.8125ms, and every 8 basic slots allocate one navigation slot. The proposed algorithm is carried out every 500ms which corresponding 8 navigation slots.

First, we set members 9-12 as observed members, and compare the performance of multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA, EKF based on sequential processing and common MLE under the same condition.

Second, the performance of member 10 in different conditions is used for analyze under scene shown in Fig. 7. Finally a separate scene is given to evaluate effect of RENAV user's velocity on localization accuracy, which is detailed in part I.

The starting position of member 10 is (E113.2, N37.4, U4500), initial velocity of north is -100.0m/s, and initial velocity of east is 200m/s, flying at a radius of 100km. Starting position 1-sigma error of east and north is 1000m, 1-sigma error of height is 200m, and they all follow the Gaussian distribution.

B. PERFORMANCE COMPARISON OF ALGORITHMS

Performance of Multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA, EKF based on sequential processing and common MLE algorithm are compared in this part. In order not to be disturbed by the error of height direction, the three algorithms are positioned with the same algorithms in height. The 1-sigma error of BA is 50m, and the 1-sigma random noise of pseudorange measurement is 3m.

Compared with the algorithm we proposed, common MLE algorithm dose not use the multi-slots joint method that convert the TOA measurements into one slot before estimate.

The state vector of EKF has 7 dimensions

$$X = [\phi_e, \phi_n, \phi_u, \Delta\lambda, \Delta L, \Delta V_e, \Delta V_n]^T \tag{59}$$

where ϕ_e, ϕ_n, ϕ_u denote the east, north, and height directional angle errors, $\Delta\lambda$, ΔL denote the longitude, latitude position errors, ΔV_e, ΔV_n denote the east and north directional velocity errors. The state equation of the EKF is

$$X(k) = \Phi(k, k-1)X(k-1) + W(k-1) \tag{60}$$

where $\Phi(k, k-1)$ is state-transition matrix, $W(k-1)$ denotes process noise vector. The measurement is the difference between TOA and calculate pseudorange ρ_c.

$$\Delta\rho = \rho_{TOA} - \rho_c \tag{61}$$

The measurement equation is obtained by

$$Z_k = HX(k) + h_h\Delta h + \Delta b_u - \Delta\hat{b}_u - \Delta b_s + v \tag{62}$$

$H = [0\ 0\ 0\ h_{\ln g}\ h_{lat}\ 0\ 0]$ denotes the measurement matrix.

EKF based on sequential processing algorithm select RENAV source and filter in every navigation slot, if the RENAV source's accuracy is higher than the RENAV user the source will be selected, and only one TOA measurement is used to filter in each navigation slot. Fig. 8 and Fig. 9 show east, north RMS errors of members 9-12 with the compared algorithms, and the corresponding 3D RMS errors of RENAV sources are given in Fig. 10.

Fig. 11 and Fig. 12 show east, north errors of members 9-12 with compared algorithms in every estimate moment of 500s.

It can be observed that multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA performs better for most of RENAV users. Multi-slots joint MLE convert TOA measurements of different slots to a same slot, decreases effect of user's movement in different slots, reduces loss of measurement information, improves positioning precision.

C. COMPARISON BETWEEN USE OF HEIGHT FILTER

Under the same condition, height positioning error compared between multi-slots joint MLE algorithm with height filter and without height filter. The 1-sigma error of BA is preset as 50m, and the 1-sigma random noise of pseudorange

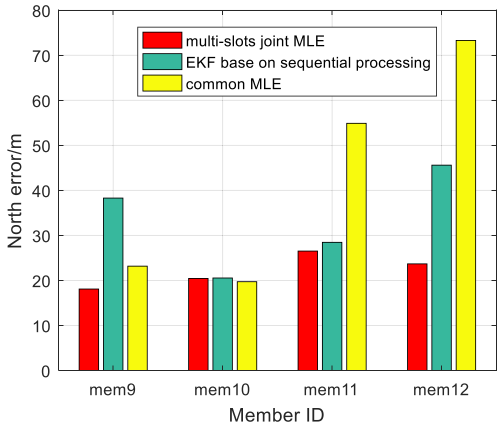

FIGURE 9. **RMS north errors comparison between multi-slots joint MLE, EKF based on sequential processing and common MLE.**

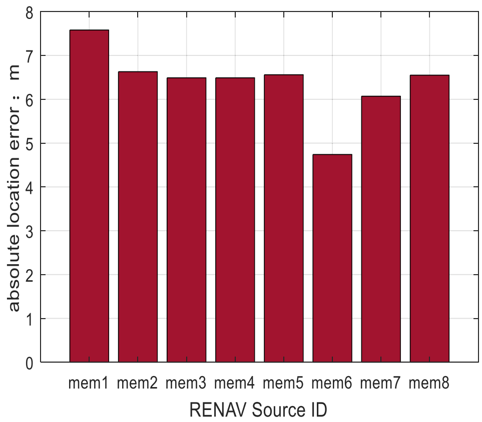

FIGURE 10. **RMS errors of RENAV sources.**

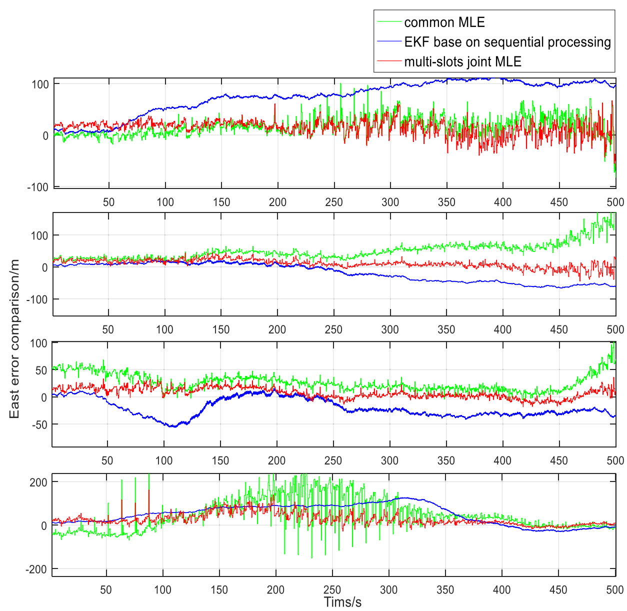

FIGURE 11. **East errors comparison between multi-slots joint MLE, EKF based on sequential processing and common MLE.**

measurement is 3m. Fig. 13 shows the comparison result of RMS altitude errors, and Fig. 14 shows the altitude errors of members 9-12 in every estimate moment.

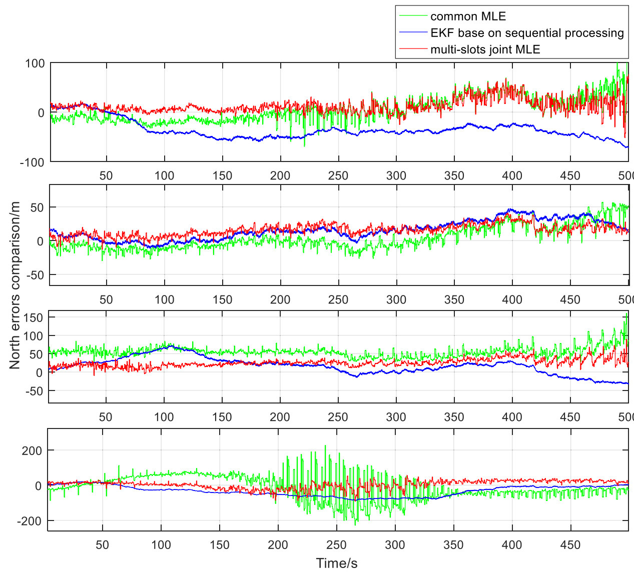

FIGURE 12. **North errors comparison between multi-slots joint MLE, EKF based on sequential processing and common MLE.**

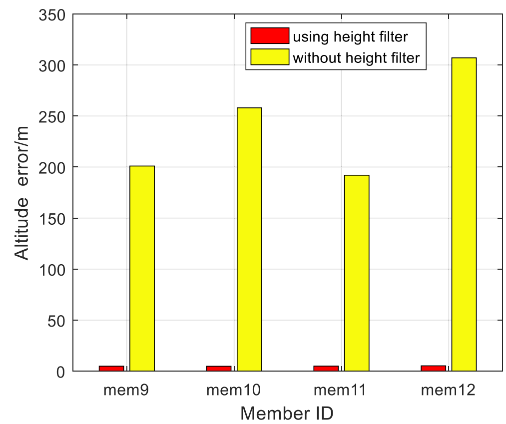

FIGURE 13. **Comparison of altitude RMS errors between use of height filter.**

As shown in Fig. 13 and Fig. 14, when using height filter the average height accuracy is about 5m, however height accuracy is about 200m without height filter. Height filter based on barometer revise altitude error of inertial device in a independent dimension, eliminates the effect of the poor localization geometry on altitude estimate, and improves the accuracy of altitude.

D. EFFECT OF HEIGHT ERROR ON LOCALIZATION ACCURACY

If RENAV source and user move are at different altitudes, the projection of height errors on TOA may influence the uncertainty of TOA measurement and affect localization accuracy of two-dimensional plane. Therefore, we compare effect of barometer with different accuracy on localization accuracy. The preset 1-sigma barometer errors is 50m for the first time and increase 50m at a time, to analyze the effect.

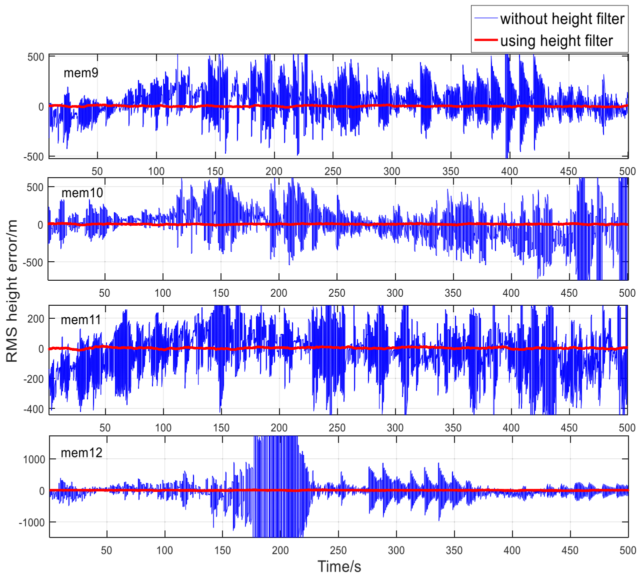

FIGURE 14. Comparison of altitude errors between use of height filter.

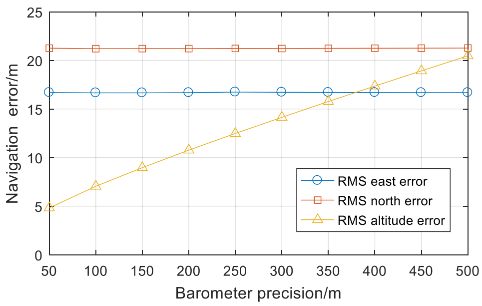

FIGURE 15. RMS errors comparison of member 10 between different barometer precisions.

The 1-sigma random noise of TOA measurement is 3m.We set member 10 as an object of observation. Fig. 15 shows the comparison of localization RMS errors.

As shown in Fig. 15, in large-scale network the range between RENAV source and user is much larger than height error, the projection of height errors on the TOA is very small, barometer errors mainly affect height accuracy, therefore if JTIDS members are working over a large area, the errors of height has a feeble influence on two-dimensional plane localization.

E. EFFECT OF TOA MEASUREMENT RANDOM ERROR ON LOCALIZATION ACCURACY

The 1-sigma random error of TOA measurements that member 10 received is set to 3m first time, and increase 3m at a time, 1-sigma barometer error is 50m. We also set member 10 as an object of observation to analyze the effect of random error.

The results of relative navigation RMS errors are shown in Fig. 16, height filter is estimate separately, so different random error of TOA measurement mainly affects the relative positioning results of two-dimensional plane.

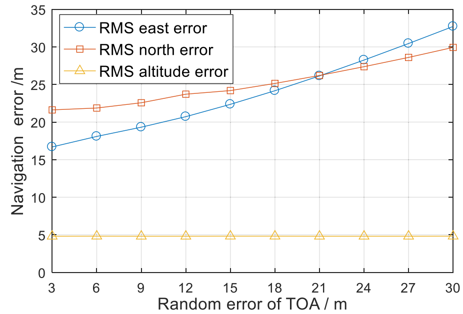

FIGURE 16. RMS errors comparison of member 10 between different random error of TOA.

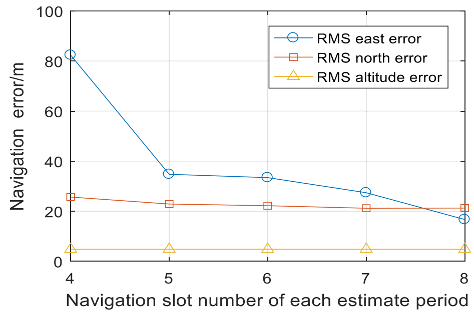

FIGURE 17. RMS errors comparison of member 10 between different broadcast frequencies.

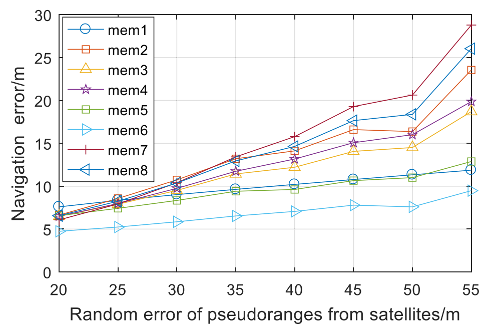

FIGURE 18. RMS errors of RENAV sources with different GPS pseudorange random error.

F. EFFECT OF DIFFERENT NAVIGATION SLOTS BROADCAST FREQUENCIES IN DYNAMIC SCENE

JTIDS based on the multi-access mode of TDMA, so broadcast frequencies of navigation slots will affect the positioning accuracy of RENAV users. We set 1-sigma barometer error as 50m and 1-sigma TOA measurement random error is 3m. Estimate period is 500ms which include 8 navigation slots, and height filter will estimate in every navigation slot. We allocate different numbers of navigation slots in each estimate period, and compare the RMS errors of relative positioning results.

As shown in Fig. 17, higher broadcast frequencies of navigation slots means more available RENAV sources, and leads to a higher accuracy when RENAV sources is sufficient.

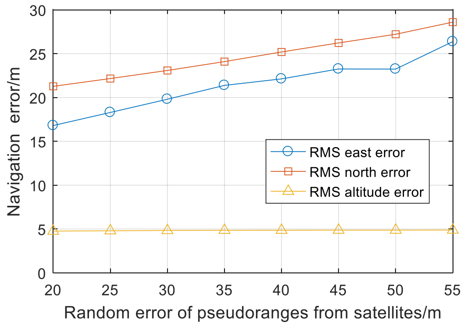

FIGURE 19. RMS errors comparison of member 10 between different sources accuracy with different GPS pseudorange random error.

G. EFFECT OF RENAV SOURCE'S POSITIONING PRECISION ON USER'S LOCALIZATION ACCURACY

By changing the uncertainty of pseudoranges from GPS satellites to RENAV sources, we change the localization precision of RENAV sources, and analyze the effect of RENAV source's localization precision on RENAV user's localization accuracy. We set 1-sigma barometer error as 50m, and 1-sigma TOA measurement random error is set as 3m. Fig. 18 shows 3D RMS errors of RENAV sources in different pseudorange random errors, and Fig. 19 shows the RMS errors of member 10 which is preset as object of observation.

As shown in Fig. 18 and Fig. 19, localization accuracy of RENAV user is reduced when localization precision of RENAV sources are decreased.

H. EFFECT OF SIGNAL INTERFERENCE ON USER'S LOCALIZATION ACCURACY

JTIDS is a TDMA system with incontinuous signal, so we assume that RENAV users extract TOA measurements with open-loop tracking approach, and the uncertainty of code correlation is given in formula (63) [22].

$$\sigma_{EML} = \sqrt{\frac{\tau_d}{2 \cdot C/N_0 \cdot T_{\text{coh}}} \left(1 + \frac{1}{T_{\text{coh}} \cdot C/N_0 \, (1 - \tau_d)}\right)} \tag{63}$$

where τ_d is sizes of code search grid, T_{coh} is coherent integration time, C/N_0 is carrier-to-noise density ratio. Coherent integration time is very short, so the influence of Doppler frequency is small when members are moving, we assume that Doppler frequency has been captured correctly.

Normal transmit power of JTIDS is from 30w to 200w, we assume that transmit power of RENAV sources is 30w, and transmit frequency is 969Mhz, the gain of transmitting and receiving antenna is 1dB. We can obtain the receiving power of RENAV users according to the spatial power attenuation. We increase the power of interference signal from -105.22dBw to -93.19dBw. The total length of fine synchronization header is 0.104ms, so we assume that T_{coh} is 0.104ms. We set τ_d as 0.1 times of code slice width. We take the interference signal as a white noise with large power, and convert C/N_0 to the uncertainty of TOA, to simulate the effect of interference signal on localization accuracy.

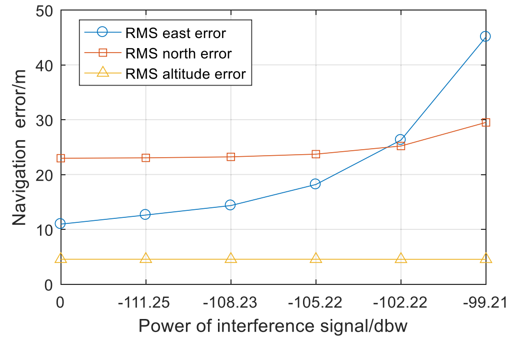

FIGURE 20. RMS errors comparison of member 10 between different powers of interference signal.

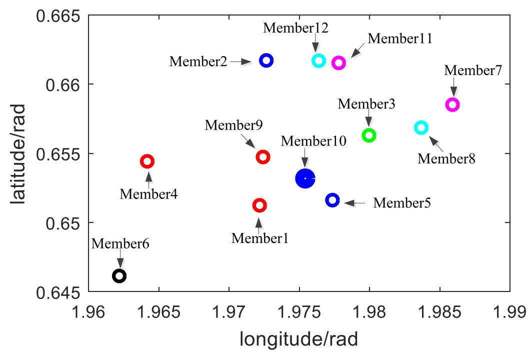

FIGURE 21. Relative position relation of network members.

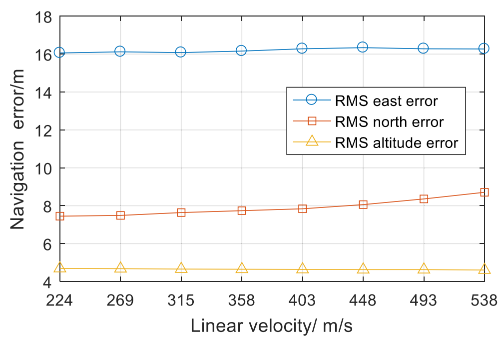

FIGURE 22. RMS errors comparison of member 10 between different velocity.

As shown in Fig. 20, when power of the interference signal is became larger, the accuracy of TOA is reduced, which lead to a lower accuracy of RENAV user's localization.

I. EFFECT OF RENAV USER'S VELOCITY ON LOCALIZATION ACCURACY

In order to evaluate effect of RENAV user's velocity on localization accuracy, we have to keep relative position relation between members unchangeably to avoid the influence of positioning geometry, analyze the effect of velocity independently. The relative position relation between network members are shown in Fig. 21, the members move with a same velocity to keep positioning geometric unchangeably. The initial velocity of north is -100.0m/s, initial velocity of east is 200m/s, the value of initial linear velocity is 224m/s, flying at a radius of 100km.We increase a velocity increment at a time, the velocity increment is 0.2 times of initial velocity, to analyze effect of RENAV user's velocity on localization accuracy.

As shown in Fig. 22, multi-slots joint MLE convert TOA measurements in different slots to one moment with short-time INS information, which reduce the effect of movement during the intervals between navigation slots, so effect of RENAV user's velocity on localization accuracy is not very obvious.

VI. CONCLUSION

The multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA is proposed in this paper. The multi-slots joint MLE relative navigation model of two-dimensional which use short-term INS device information to convert TOA measurements of different slots to a same slot and then estimate user's location and revise error of INS device in two-dimensional plane. At the same time, an independent altitude filter based on barometer measurements is used to revise altitude error of INS device, and then the relative position coordinates are obtained by transformation of coordinate system. In this paper, software simulation is carried out to analyze performance of the proposed algorithm. We compared the proposed algorithm with the sequentially processing EKF algorithm and common MLE algorithm. Simulation results show that, in TDMA network, the multi-slots joint MLE relative navigation algorithm based on INS/JTIDS/BA performs better in two-dimensional location, and the height filter based on BA measurements can eliminate the effect of the poor localization geometry. And we analyze the influence factors of location accuracy, including barometer error, TOA measurement random error, navigation slots broadcast frequencies and interference signal. It provides a theoretical basis for datalink location of TDMA system.

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