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(54) Title: A METHOD FOR CALIBRATING TEH CARRIER-PHASES OF RADIO SIGNALS FROM SATELLITES AND OTHER TRANSMITTERS BY USING FAST KALMAN FILTERING

(57) Abstract: Information on orbits like those of the Global Navigation Satellite Systems (GNSS) or other transmitters is collected in Near Real-Time (NRT) from global or local computing centres like those of the IGS. Carrier-phase reconstructions of the radio signals from these transmitters are received by a local reference network and forwarded operationally to a Fast Kalman Filter (FKF) processor for computing estimates of both the state and the calibration parameters accompanied with most reliable accuracy estimates. These state parameters typically include the Integrated Water Vapour (IWV) or the 3-dimensional distribution of Water Vapour (3WV) of the local troposphere and the Total Electron Content (TEC) of the local stratosphere. Precision adjustments of the carrier-phases accompanied with necessary accuracy information can then be operationally produced for the local needs of most reliable navigation, mobile positioning and warning of environmental hazards etc.

A METHOD FOR CALIBRATING TEH CARRIER-PHASES OF RADIO SIGNALS FROM SATELLITES AND OTHER TRANSMITTERS BY USING FAST KALMAN FILTERING

Technical Field

The invented method relates primarily to the technological convergence of Satellite Geodesy and Meteorology. The Helmert-Wolf Blocking (HWB) method known from Geodesy since 1880 is expanded to **Fast Kalman Filtering (FKF)** to cover all security-critical operational applications of Kalman Filtering (KF) such as Navigation, Remote Sensing and Computer Vision. Rapid fluctuations of the tropospheric water vapour and the ionospheric electron content are estimated operationally for adjusting the carrier-phases measured by a precision receiver for most reliable navigation, mobile positioning, detection of crustal movement and tsunami warning etc. Local alerts of those meteorological hazards that stem from unexpected concentrations of water vapour like tornados, thunderstorm, fog, ice formation and road slipperiness are included under the general context of Global Monitoring of Environment and Security (GMES).

Prior Art

The inventor of the Fast Kalman Filtering (FKF) reported to the scientific communities of both Satellite Geodesy and Meteorology by Lange (2001 and 2003) how his FKF formulas are closely related to the foundation-laying computations of the Helmert-Wolf Blocking (HWB) method. Single, Double and/or Triple Differences of the carrier-phases are used for sorting out Integer (lane) Ambiguities of the GNSS carrier-phase measurements in Real-Time Kinematic (RTK) and Virtual Reference Station (VRS) land surveying. A sub-decimetre level of accuracy has been achieved which is necessary for computing rough estimates of water vapour content of the atmosphere. The theory of optimal Kalman filtering (1960) is needed for building up fault-tolerance into a wide range of operational systems, including real-time imaging of atmospheric water vapour. The inventor knows no operational applications of the HWB method wherein the error covariance matrix is computed from its exact blockwise solution given by formula (3) of Lange (2001) and no licenses of his previous FKF patents were sold so far.

Summary of the Method

Large moving windows of locally linearized time-series of the carrier-phase and related data are analysed by the Fast Kalman Filter (FKF) processing instead of tediously sorting out the lane ambiguities in real-time. Those GNSS signal propagation effects that result from rapid variations of integrated water vapour (IWV) and total electron content (TEC) are either detected or estimated depending on configuration of the satellites, reference receivers and other geophysical observations. Abrupt increases in the TEC and IWV values create detectable losses in internal consistency between all observed and simulated carrier-phases. These different effects cannot always be separated from each other neither from clock errors of the satellites or reference receivers. Residual error variances of the carrier-phases are computed operationally using methods based on the Minimum Norm Quadratic Unbiased Estimation (MINQUE) theory for indicating the quality and usefulness of each GNSS signal. The blockwisely computed error covariance matrix (Lange, 2001) of the estimated state and calibration parameters gives accuracy information on each adjustment or indicates that Kalman's observability condition is not satisfied.

Best Modes of Carrying out the Method

Large moving windows of the carrier-phase and related data are used for maintaining Kalman's observability condition. Optimal physical and mathematical modelling is used for satisfying Kalman's controllability condition and it is monitored by estimating all error variances. Adding radio frequencies and selected combinations of the GNSS signals, increasing sampling-rates and using denser receiver and meteorological observing networks improve temporal and spatial resolution. However, this is made at the expense of even more rapidly increased requirements for both computing and data transmission power.

The **Observation Equation** for a moving data-window of length L is obtained for carrier-phase measurement $\varphi_{i,j,k,t}$ of a receiver as follows:

$$y_{i,j,k,t-l} = \varphi_{i,j,k,t} - \rho_{i,k,t} = \tau_{k,t} + \gamma_{j,t} + g_{i,j,k,t} w_{k,t} + h_{i,j,t} c_t + e_{i,j,k,t} \qquad (1)$$

for $i=1,2,\ldots,m$, $j=1,2,\ldots,n$, $k=1,2,\ldots,K$, $l=0,1,2,\ldots,L-1$ and $t=L, L+1, L+2,\ldots,\infty$

where y = of the total carrier-phases between the j^{th} satellite and the k^{th} receiver
i = index of the signals (L1, L2, L3,…, G1,…, E1,…, etc.)
j = index of the satellites (GPS, Glonass and Galileo, etc.)
k = index of the receivers (or receiver sites)
l = local index of epochs for a moving data window of length L at epoch t
t = index of the epoch times ($t=1, 2, 3,\ldots$)
φ = total phase of the reconstructed carrier of the i^{th} signal at epoch t
ρ = propagation distance [phase] in dry air from the j^{th} satellite to the k^{th} receiver at epoch t
τ = clock adjustment for the k^{th} receiver at epoch t
γ = clock adjustment for the j^{th} satellite at epoch t
g = slant-mapping of the IWV refractivity for the i^{th} signal from the j^{th} satellite to the k^{th} receiver at epoch t (see Slant-delay models on pages 39-49 of Kleijer (2004))
w = the IWV value for the k^{th} receiver at epoch t
h = slant-mapping of the TEC refractivity for the i^{th} signal from the j^{th} satellite to the receiver(s) at epoch t

c = the TEC value of the receiver(s) at epoch t
e = random measurement error at epoch t; and,
m, n and K = the number of signals, satellites and receivers, respectively.

There are four **System Equations** as follows:

$$\begin{aligned}
\tau_{k,t} &= \tau_{k,t-1} + \zeta_{k,t} \\
\gamma_{j,t} &= \gamma_{j,t-1} + \eta_{j,t} \\
\mathbf{w}_t &= (A_t + dA_t)\mathbf{w}_{t-1} + \mathbf{v}_t \\
c_t &= c_{t-1} + \xi_t
\end{aligned} \tag{2}$$

where

$\zeta_{k,t}$, $\eta_{j,t}$, ξ_t and $\mathbf{v}_t$ = the random walk terms; respectively
$\mathbf{w}_t$ = vector $[w_{1,t}, w_{2,t}, \ldots, w_{K,t}]'$
$\mathbf{v}_t$ = vector $[v_{1,t}, v_{2,t}, \ldots, v_{K,t}]'$
A_t = state transition matrix describing the speed and direction of IWV along mean air-flow
dA_t = matrix of those state transition errors that can be adjusted by adaptive Kalman Filter.

Adaptive Fast Kalman Filtering (FKF) is applied to dense receiver and observing networks that are operated with high sampling rates (see Equations (23) and (24) on pages 12-13 in PCT/FI96/00621 of WO 97/18442).

Using the FKF processor

The **Augmented Model** of the moving sample is written out in matrix form as follows (see Equation (18) on page 11 in PCT/FI90/00122 of WO 90/13794):

$$\left[\begin{array}{c}
y_t \\
\hat{s}_{t-1} + u_{t-1} \\
\hline
y_{t-1} \\
\hat{s}_{t-2} + u_{t-2} \\
\hline
\vdots \\
\hline
y_{t-L+1} \\
\hat{s}_{t-L} + u_{t-L} \\
\hline
\hat{C}_{t-1} + u_{c_{t-1}}
\end{array}\right]
=
\left[\begin{array}{cccc}
H_t & & & F_t \\
I & & & \\
\hline
& H_{t-1} & & F_{t-1} \\
& I & & \\
\hline
& & \ddots & \vdots \\
\hline
& & H_{t-L+1} & F_{t-L+1} \\
& & I & \\
\hline
& & & I
\end{array}\right]
\left[\begin{array}{c}
s_t \\
s_{t-1} \\
\vdots \\
s_{t-L+1} \\
C_t
\end{array}\right]
+
\left[\begin{array}{c}
e_t \\
(\hat{s}_{t-1} - s_{t-1}) - a_t \\
\hline
e_{t-1} \\
(\hat{s}_{t-2} - s_{t-2}) - a_{t-1} \\
\hline
\vdots \\
\hline
e_{t-L+1} \\
(\hat{s}_{t-L} - s_{t-L}) - a_{t-L+1} \\
\hline
(\hat{C}_{t-1} - C_{t-1}) - a_{c_t}
\end{array}\right] \tag{3}$$

where vectors $\mathbf{y}_t$ and $\mathbf{s}_t$ and matrix H_t represent the compositions of quantities to be **partitioned** as follows (see Equation (17) on page 10 in PCT/FI90/00122 of WO 90/13794):

(4)

$$s_t=\begin{bmatrix} b_{t,1}\\ \vdots \\ b_{t,K}\\ c_t\end{bmatrix}\quad y_t=\begin{bmatrix} y_{t,1}\\ y_{t,2}\\ \vdots\\ y_{t,K}\end{bmatrix}\quad H_t=\begin{bmatrix} X_{t,1} & & & G_{t,1}\\ & X_{t,2} & & G_{t,2}\\ & & \ddots & \vdots \\ & & X_{t,K} & G_{t,K}\end{bmatrix}$$

The following semi-analytical Fast Kalman Filtering (FKF) formulas are used for the processing (see Equation (20) on pages 11-12 in PCT/FI90/00122 of WO 90/13794):

(5)

$$\hat{s}_{t-l}=\left\{X'_{t-l}V^{-1}_{t-l}X_{t-l}\right\}^{-1}X'_{t-l}V^{-1}(y_{t-l}-G_{t-l}\hat{c}_t) \quad \text{for } l=0,1,2,\ldots,L-1$$

$$\hat{c}_t=\left\{\sum_{l=0}^{L}G'_{t-l}R_{t-l}G_{t-l}\right\}^{-1}\sum_{l=0}^{L}G'_{t-l}R_{t-l}y_{t-l}$$

where, for $l=0,1,2,\ldots,L-1$,

$$R_{t-l}=V^{-1}_{t-l}\left\{I-X_{t-l}\left\{X'_{t-l}V^{-1}_{t-l}X_{t-l}\right\}^{-1}X'_{t-l}V^{-1}_{t-l}\right\}$$

$$V_{t-l}=\begin{bmatrix}\mathrm{Cov}(e_{t-l}) & \\ & \mathrm{Cov}\left\{(\hat{s}_{t-l-1}-s_{t-l-1})-a_{t-l}\right\}\end{bmatrix}$$

$$y_{t-l}=\begin{bmatrix} y_{t-l}\\ \hat{s}_{t-l-1}+u_{t-l-1}\end{bmatrix}$$

$$X_{t-l}=\left[\begin{array}{c} H_{t-l}\\ \hline I\end{array}\right]$$

$$G_{t-l}=\left[\begin{array}{c} F_{t-l}\\ \hline \\ \end{array}\right]$$

and, i.e. for $l=L$,

$$R_{t-L}=V^{-1}_{t-L}$$

$$V_{t-L}=\mathrm{Cov}\left\{(\hat{c}_{t-1}-c_{t-1})-a_{c_t}\right\}$$

$$y_{t-L}=\hat{c}_{t-1}+u_{c_{t-1}}$$

$$G_{t-L}=I.$$

The Hybrid Windfinding Algorithm (HWA) reported in Paper 5 of Lange (1999) computes the Best Linear Unbiased Estimates (BLUE) recursively in real-time for the clock adjustments of the receivers (k=1, 2,..., K) and the satellites (j=1, 2,.., n), the values (k=1, 2,..., K) of integrated water vapour (IWV) and the total value of ionospheric electron content (TEC). Their accuracies depend on both information and the degree of over-determination that the **Augmented Model** (3) has at each epoch time t. The estimation accuracies for all calibration parameters and/or the adjusted carrier-phases:

$$y_{i,j,k,t} = \varphi_{i,j,k,t} - \rho_{i,k,t} = \tau_{k,t} + \gamma_{j,t} + g_{i,j,k,t} w_{k,t} + h_{i,j,t} c_t \qquad (6)$$

for $i = 1,2,\ldots,m$, $j=1,2,\ldots,n$, $k=1,2,\ldots,K$, and $t=L, L+1, L+2,\ldots,\infty$

are obtained in real-time (or NRT) from C. R. Rao's MINQUE theory (see e.g. Equation (23) on page 19 in Paper 5 of Lange (1999)).

Firstly, in order to specify vectors $\mathbf{y}_t$ and $\mathbf{s}_t$ and matrix $\mathbf{H}_t$ the following logical insertions are made in Equations (4):

$\mathbf{c}_t :=$ [empty]
and for all k=1,2,...,K:

$\mathbf{b}_{t,k} := \tau_{k,t}$
$\mathbf{y}_{t,k} := [y_{1,1,k,t}, y_{2,1,k,t},\ldots, y_{m,1,k,t}, \; y_{1,2,k,t}, y_{2,2,k,t},\ldots, y_{m,2,k,t}, \ldots, \; y_{1,n,k,t}, y_{2,n,k,t},\ldots, y_{m,n,k,t}, \tau_{k,t-1}]'$
$X_{t,k} := [1, 1, 1,\ldots,1, 1]'$ and $G_{t,k} :=$ [empty] ;

so that $\mathbf{y}_t = [\mathbf{y}'_{t,1}, \mathbf{y}'_{t,2},\ldots, \mathbf{y}'_{t,K}]'$, $\mathbf{s}_t = [\tau_{1,t}, \tau_{2,t},\ldots, \tau_{K,t}]$ and $\mathbf{H}_t = \mathrm{diag}(X_{t,1}, X_{t,2},\ldots, X_{t,K})$.

Thereafter, the following logical insertions are made in the **Augmented Model** of Equation (3):

$\mathbf{F}_t := [\mathrm{diag}(\mathbf{f}_{t,1}, \mathbf{f}_{t,2},\ldots, \mathbf{f}_{t,n}), \mathrm{diag}(\mathbf{g}_{t,1}, \mathbf{g}_{t,2},\ldots, \mathbf{g}_{t,K}), [\mathbf{h}'_{t,1}, \mathbf{h}'_{t,2},\ldots, \mathbf{h}'_{t,K}]']$

where
$\mathbf{f}_{t,j} = [1, 1, 1,\ldots, 1, 0]'$
$\mathbf{g}_{t,v} = [\mathbf{g}'_{t,v,1}, \mathbf{g}'_{t,v,2},\ldots, \mathbf{g}'_{t,v,K}]'$
$\mathbf{g}_{t,,k} = [g_{1,1,k,t}, g_{2,1,k,t},\ldots, g_{,m,1,k,t}, \; g_{1,2,k,t}, g_{2,2,k,t},\ldots, g_{m,2,k,t}, \ldots, \; g_{1,n,k,t}, g_{2,n,k,t},\ldots, g_{m,n,k,t}, 0]'$
where $g_{i,j,k,t}$ = slant-path refractivity of IWV for the ith signal from the jth satellite to the kth receiver
and
$\mathbf{h}_{t,k} = [h_{1,1,t}, h_{2,1,t}, \ldots, h_{m,1,t}, \; h_{1,2,t}, h_{2,2,t}, \ldots, h_{m,2,t}, \ldots, \; h_{1,n,t}, h_{2,n,t}, \ldots, h_{m,n,t}, 0]'$
where $h_{i,j,t}$ = slant-path refractivity of TEC for the ith signal from the jth satellite to the kth receiver;

and,

$\hat{\mathbf{s}}_t = \mathbf{u}_t :=$ [empty], $\mathbf{u}_c := 0$ and $\mathbf{c}_t := [\gamma_{1,t}, \gamma_{2,t},\ldots, \gamma_{n,t}, \; w_{1,t}, w_{2,t},\ldots, w_{K,t}, c_t]'$;
so that for Equations (5): $\mathbf{y}_{t-l} = \mathbf{y}_{t-l}$, $\mathbf{X}_{t-l} = [\mathbf{H}_{t-l}]$ and $\mathbf{G}_{t-l} = [\mathbf{F}_{t-l}]$
where vector $\hat{\mathbf{c}}_t$ with the hat (^) on top of it gives the BLUE estimates for tomography etc.

The processing method above can be extended to the 3- (or 4-) dimensional tomography where also vertical (and temporal) variations of all atmospheric constituents are explicitly taken into account. This is made at the expense of extra lapsed time that is required for collecting and properly processing much more data (see Equations (26-29) on pages 12-13 in PCT/FI93/00192 of WO 93/22625) as follows:

The **Observation Equation** for a moving data-window of length L is obtained for the carrier-phase measurement $\varphi_{i,j,k,t}$ of a receiver as follows:

$$y_{i,j,k,t-l} = \varphi_{i,j,k,t} - \rho_{i,k,t} = \tau_{k,t} + \gamma_{j,t} + \mathbf{g}'_{j,k,t}\mathbf{w}_t + h_{i,j,t}c_t + e_{i,j,k,t} \qquad (1t)$$

for $i=1,2,\ldots,m$, $j=1,2,\ldots,n$, $k=1,2,\ldots,K$, $l=0,1,2,\ldots,L-1$ and $t=L, L+1, L+2,\ldots,\infty$

where y = difference of the total carrier-phases between the j^{th} satellite and the k^{th} receiver
i = index of the signals (L1, L2, L3,... , G1,... , E1,... , etc.)
j = index of the satellites (GPS, Glonass and Galileo, etc.)
k = index of the receivers (or receiver sites)
l = local index of epochs for a moving data window of length L at epoch t
t = index of the epoch times (t=1, 2, 3,...)
φ = total phase of the reconstructed carrier of the i^{th} signal at epoch t
ρ = propagation distance [phase] in dry air from the j^{th} satellite to the k^{th} receiver at epoch t
τ = clock correction of the k^{th} receiver at epoch t
γ = clock correction of the j^{th} satellite at epoch t
$\mathbf{g}$ = vector of the slant-path 3WV refractivity values of pixel volumes from the j^{th} satellite to the k^{th} receiver at epoch t (see Slant-delay models on pages 39-49 of Kleijer (2004))
$\mathbf{w}$ = vector of the 3WV values of pixel volumes at epoch t
h = slant-mapping of the TEC refractivity for the i^{th} signal from the j^{th} satellite to the receiver network(s) at epoch t
c = the TEC value of the receiver network(s) at epoch t
e = random measurement error at epoch t; and,
m, n, K and V = the number of signals, satellites, receivers and pixel volumes, respectively.

There are four **System Equations** as follows:

$$\begin{aligned} \tau_{k,t} &= \tau_{k,t-1} + \zeta_{k,t} \\ \gamma_{j,t} &= \gamma_{j,t-1} + \eta_{j,t} \\ \mathbf{w}_t &= (A_t + dA_t)\mathbf{w}_{t-1} + \mathbf{v}_t \\ c_t &= c_{t-1} + \xi_t \end{aligned} \qquad (2t)$$

where

$\zeta_{k,t}$, $\eta_{j,t}$, $\mathbf{v}_t$ and ξ_t = the random walk terms; respectively
$\mathbf{w}_t$ = vector $[w_{1,t}, w_{2,t},\ldots, w_{V,t}]'$
$\mathbf{v}_t$ = vector $[v_{1,t}, v_{2,t},\ldots, v_{V,t}]'$
A_t = state transition matrix describing advection of the 3WV values in the air-mass
dA_t = matrix of the state transition errors to be adjusted by adaptive Kalman Filtering.

Matrix A_t is a tangent-linear approximation of the Numerical Weather Prediction (NWP) model that is applied in the data assimilation of the 3WV values at epoch t for obtaining them from their previous values at epoch t-1 (see Equations (26-29) on pages 12-13 in PCT/FI93/00192 of WO 93/22625). Matrix dA_t is approximated by a vector **r** that is estimated by adaptive Fast Kalman Filtering (FKF) (see Equations (22-24) on pages 12-13 in PCT/FI96/00621 of WO 97/18442).

Using the FKF processor

The **Augmented Model** of the moving sample is written out in matrix form as follows (see Equation (24) on page 13 in PCT/FI96/00621 of WO 97/18442):

(3t)

$$\begin{bmatrix} \mathbf{y}_t \\ A\hat{\mathbf{s}}_{t-1}+\mathbf{Bu}_{t-1} \\ \hline \mathbf{y}_{t-1} \\ A\hat{\mathbf{s}}_{t-2}+\mathbf{Bu}_{t-2} \\ \hline \vdots \\ \hline \mathbf{y}_{t-L+1} \\ A\hat{\mathbf{s}}_{t-L}+\mathbf{Bu}_{t-L} \\ \hline A\hat{\mathbf{C}}_{t-1}+B\mathbf{u}_{c\,t-1} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_t & & & \mathbf{F}^y_t & \\ \mathbf{I} & & & \mathbf{F}^s_t & \mathbf{M}_{t-1} \\ \hline & \mathbf{H}_{t-1} & & \mathbf{F}^y_{t-1} & \\ & \mathbf{I} & & \mathbf{F}^s_{t-1} & \mathbf{M}_{t-2} \\ \hline & & \ddots & \vdots & \vdots \\ \hline & & \mathbf{H}_{t-L+1} & \mathbf{F}^y_{t-L+1} & \\ & & \mathbf{I} & \mathbf{F}^s_{t-L+1} & \mathbf{M}_{t-L} \\ \hline & & & & \mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{s}_t \\ \mathbf{s}_{t-1} \\ \vdots \\ \mathbf{s}_{t-L+1} \\ \hline \mathbf{C}_t \end{bmatrix} + \begin{bmatrix} \mathbf{e}_t \\ A(\hat{\mathbf{s}}_{t-1}-\mathbf{s}_{t-1})-\mathbf{a}_t \\ \hline \mathbf{e}_{t-1} \\ A(\hat{\mathbf{s}}_{t-2}-\mathbf{s}_{t-2})-\mathbf{a}_{t-1} \\ \hline \vdots \\ \hline \mathbf{e}_{t-L+1} \\ A(\hat{\mathbf{s}}_{t-L}-\mathbf{s}_{t-L})-\mathbf{a}_{t-L+1} \\ \hline A(\hat{\mathbf{C}}_{t-1}-\mathbf{C}_{t-1})-\mathbf{a}_{c_t} \end{bmatrix}$$

where vectors $\mathbf{y}_t$ and $\mathbf{s}_t$ and matrix $\mathbf{H}_t$ represent the compositions of quantities to be **partitioned** as follows (see Equation (17) on page 8 in PCT/FI96/00621 of WO 97/18442):

(4t)

$$\mathbf{s}_t = \begin{bmatrix} \mathbf{b}_{t,1} \\ \vdots \\ \mathbf{b}_{t,K} \\ \mathbf{c}_t \end{bmatrix} \quad \mathbf{y}_t = \begin{bmatrix} \mathbf{y}_{t,1} \\ \mathbf{y}_{t,2} \\ \vdots \\ \mathbf{y}_{t,K} \end{bmatrix} \quad \mathbf{H}_t = \begin{bmatrix} \mathbf{X}_{t,1} & & & \mathbf{G}_{t,1} \\ & \mathbf{X}_{t,2} & & \mathbf{G}_{t,2} \\ & & \ddots & \vdots \\ & & \mathbf{X}_{t,K} & \mathbf{G}_{t,K} \end{bmatrix}$$

The following semi-analytical Fast Kalman Filtering (FKF) formulae are used for the processing (see Equations (25) on page 14 in PCT/FI96/00621 of WO 97/18442):

(5t)

$$\hat{\mathbf{s}}_{t-l} = \{\mathbf{X}'_{t-l}\mathbf{V}^{-1}_{t-l}\mathbf{X}_{t-l}\}^{-1}\mathbf{X}'_{t-l}\mathbf{V}^{-1}(\mathbf{y}_{t-l}-\mathbf{G}_{t-l}\hat{\mathbf{c}}_t) \quad \text{for } l=0,1,2,\ldots,L-1$$

$$\hat{\mathbf{c}}_t = \left\{\sum_{l=0}^{L}\mathbf{G}'_{t-l}\mathbf{R}_{t-l}\mathbf{G}_{t-l}\right\}^{-1}\sum_{l=0}^{L}\mathbf{G}'_{t-l}\mathbf{R}_{t-l}\mathbf{y}_{t-l}$$

where, for $l=0,1,2,\ldots,L-1$,

$$\mathbf{R}_{t-l}=\mathbf{V}_{t-l}^{-1}\left\{\mathbf{I}-\mathbf{X}_{t-l}\left\{\mathbf{X}'_{t-l}\mathbf{V}_{t-l}^{-1}\mathbf{X}_{t-l}\right\}^{-1}\mathbf{X}'_{t-l}\mathbf{V}_{t-l}^{-1}\right\}$$

$$\mathbf{V}_{t-l}=\begin{bmatrix}\mathrm{Cov}(\mathbf{e}_{t-l}) & \\ & \mathrm{Cov}\left\{\mathbf{A}_{t-l}(\hat{\mathbf{s}}_{t-l-1}-\mathbf{s}_{t-l-1})-\mathbf{a}_{t-l}\right\}\end{bmatrix}$$

$$\mathbf{y}_{t-l}=\begin{bmatrix}\mathbf{y}_{t-l}\\ \mathbf{A}_{t-l}\,\hat{\mathbf{s}}_{t-l-1}+\mathbf{B}_{t-l}\,\mathbf{u}_{t-l-1}\end{bmatrix}$$

$$\mathbf{X}_{t-l}=\left[\begin{array}{c}\mathbf{H}_{t-l}\\ \hline \mathbf{I}\end{array}\right]$$

$$\mathbf{G}_{t-l}=\left[\begin{array}{cc}\mathbf{F}_{t-l}^{y} & \\ \hline \mathbf{F}_{t-l}^{S} & \mathbf{M}_{t-l-1}\end{array}\right]$$

and, i.e. for $l=L$,

$$\mathbf{R}_{t-L}=\mathbf{V}_{t-L}^{-1}$$

$$\mathbf{V}_{t-L}=\mathrm{Cov}\left\{A_c(\hat{\mathbf{c}}_{t-1}-\mathbf{c}_{t-1})-\mathbf{a}_{c_t}\right\}$$

$$\mathbf{y}_{t-L}=A_c\hat{\mathbf{c}}_{t-1}+B_c\mathbf{u}_{c_{t-1}}$$

$$\mathbf{G}_{t-L}=\mathbf{I}.$$

The HWA algorithm in Paper 5 of Lange (1999) computes the Best Linear Unbiased Estimates (BLUE) recursively in real-time for the clock adjustments of the receivers (k=1, 2,…, K) and the satellites (j=1, 2,.., n), the voxels (pixel volume) (v=1, 2,…, V) of water vapour (3WV) and the total value of ionospheric electron content (TEC). Their accuracies depend on both the information and the degree of over-determination that the **Augmented Model** (3t) has at each epoch time t. The estimation accuracies of all calibration parameters and/or the adjusted carrier-phases:

$$y_{i,j,k,t-l}=\varphi_{i,j,k,t}-\rho_{i,k,t}=\tau_{k,t}+\gamma_{j,t}+\mathbf{g}'_{j,k,t}\mathbf{w}_t+h_{i,j,t}\,c_t \qquad (6t)$$

for $i=1,2,\ldots,m$, $j=1,2,\ldots,n$, $k=1,2,\ldots,K$, and $t=L, L+1, L+2,\ldots,\infty$

are obtained in NRT from C. R. Rao's MINQUE theory (see e.g. Equation (23) on page 19 in Paper 5 of Lange (1999)).

Firstly, in order to specify vectors $\mathbf{y}_t$ and $\mathbf{s}_t$ and matrix $\mathbf{H}_t$ the following logical insertions are made in Equations (4t):
$\mathbf{c}_t := [\text{empty}]$
and for all k=1,2,...,K:
$\mathbf{b}_{t,k} := \tau_{k,t}$
$\mathbf{y}_{t,k} := [y_{1,1,k,t}, y_{2,1,k,t}, \ldots, y_{m,1,k,t}, \quad y_{1,2,k,t}, y_{2,2,k,t}, \ldots, y_{m,2,k,t}, \ldots, \quad y_{1,n,k,t}, y_{2,n,k,t}, \ldots, y_{m,n,k,t}, \tau_{k,t-1}]'$
$X_{t,k} := [1, 1, 1, \ldots, 1, 1]'$ and $G_{t,k} := [\text{empty}]$;
so that $\mathbf{y}_t = [\mathbf{y}'_{t,1}, \mathbf{y}'_{t,2}, \ldots, \mathbf{y}'_{t,K}]'$, $\mathbf{s}_t = [\tau_{1,t}, \tau_{2,t}, \ldots, \tau_{K,t}]$ and $\mathbf{H}_t = \operatorname{diag}(X_{t,1}, X_{t,2}, \ldots, X_{t,K})$.

Thereafter, the following logical insertions are made in the **Augmented Model** of Equation (3t):

$\mathbf{F}_t := [\operatorname{diag}(\mathbf{f}_{t,1}, \mathbf{f}_{t,2}, \ldots, \mathbf{f}_{t,n}), [\mathbf{g}_{t,1}, \mathbf{g}_{t,2}, \ldots, \mathbf{g}_{t,V}], [\mathbf{h}'_{t,1}, \mathbf{h}'_{t,2}, \ldots, \mathbf{h}'_{t,K}]']$

where
$\mathbf{f}_{t,j} = [1, 1, 1, \ldots, 1, 0]'$
$\mathbf{g}_{t,v} = [\mathbf{g}'_{t,v,1}, \mathbf{g}'_{t,v,2}, \ldots, \mathbf{g}'_{t,v,K}]'$
$\mathbf{g}_{t,v,k} = [g_{1,1,k,v,t}, g_{2,1,k,v,t}, \ldots, g_{m,1,k,v,t}, \quad g_{1,2,k,v,t}, g_{2,2,k,v,t}, \ldots, g_{m,2,k,v,t}, \ldots, g_{1,n,k,v,t}, g_{2,n,k,v,t}, \ldots, g_{m,n,k,v,t}, 0]'$
where $g_{i,j,k,v,t}$ = slant-path refractivity of 3WV for voxel v if the ith signal from the jth satellite goes to the kth receiver through it at epoch time t else =0
and
$\mathbf{h}_{t,k} = [h_{1,1,t}, h_{2,1,t}, \ldots, h_{m,1,t}, \quad h_{1,2,t}, h_{2,2,t}, \ldots, h_{m,2,t}, \ldots, h_{1,n,t}, h_{2,n,t}, \ldots, h_{m,n,t}, \quad 0]'$
where $h_{i,j,t}$ = slant-path refractivity of TEC for the ith signal from the jth satellite to the kth receiver t;

and,

$\hat{\mathbf{s}}_t = \mathbf{B}\mathbf{u}_t := [\text{empty}]$, $\mathbf{u}_c := 0$ and $\mathbf{C}_t := [\gamma_{1,t}, \gamma_{2,t}, \ldots, \gamma_{n,t}, w_{1,t}, w_{2,t}, \ldots, w_{V,t}, c_t, \mathbf{r}'_t]'$ and $\mathbf{r}_t$ = a vector of selected elements of matrix dA_t of Equation (23) as specified on pages 12-13 of PCT/FI96/00192; so that for Equations (5t): $\mathbf{y}_{t-l} = \mathbf{y}_{t-l}$, $\mathbf{X}_{t-l} = [\mathbf{H}_{t-l}]$, $\mathbf{G}_{t-l} = [\mathbf{F}_{t-l}, \mathbf{0}]$ and $\mathbf{G}_{t-L} = \operatorname{diag}(\mathbf{I}, \mathbf{M}_{t-L})$

where vector $\hat{\mathbf{c}}_t$ with the hat (^) on top of it gives the BLUE estimates for tomography etc.

This method can be extended to 3- or 4-dimensional data-assimilation where the temporal variation of atmospheric constituents is taken more explicitly into account at the expense of extra lapsed time that is required for collecting and processing much more data by other methods (see Equations (26-29) on pages 12-13 in PCT/FI93/00192 of WO 93/22625). There are many variations how this invention can be applied. Therefore the scope of the invention should not be limited to the two embodiments described if the claims do not specifically say so.

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CLAIMS

1. A method for adjusting model and/or calibration parameters of a sensor system that is equipped with said model of external events where sensor output units of said system provide signals in response to said external events and said method makes use of Kalman Filtering that comprises the following steps of:

a) providing a data base unit for storing information on:

- a plurality of test point sensor output signal values for some of said sensors and a plurality of values for external events that correspond to said test point sensor output signal values and/or simultaneous time series of sensor output signal values from adjacent sensors for comparison;

- values of said sensor output signals, values of said model and/or calibration parameters and values of said external events that correspond to a situation; and,

- controls of said sensors and changes in said external events corresponding to a new situation;

b) providing a logic unit for accessing both said sensor signal output values and said model and/or calibration parameter values, where said logic unit has both a two-way communications link to said data base unit and the capability of computing good initial values for unknown model and/or calibration parameters;

c) providing said sensor output signal values from said sensors, as available, to said logic unit;

d) providing information on said controls and changes of said sensors to said data base unit;

e) accessing current values of both model and/or calibration parameters and state transition matrices, and computing updated values of said model and/or calibration parameters, in said logic unit, for said situation; and where the improvement comprises exploiting an FKF processing method for solving a locally linearized Augmented Model (3 or 3t) of the total carrier-phases of received signals from satellites and other transmitters and of related geophysical data;

f) controls stability of said FKF-filtering by monitoring accuracy estimates of said updated values of model and/or calibration parameters, in said logic unit, and indicates needs for sensor output signal values, test point data, sensor comparisons or a system reconfiguration;

g) adjusts said model and/or calibration parameter values if stable updates are available.

INTERNATIONAL SEARCH REPORT

International application No
PCT/FI2007/000052

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01S1/00 H03H21/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01S H03H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 97/18442 A (LANGE ANTTI AARNE ILMARI [FI]) 22 May 1997 (1997-05-22) claim 1 -----	1
X	US 5 506 794 A (LANGE ANTTI A I [FI]) 9 April 1996 (1996-04-09) claim 3 -----	1
X	WO 93/22625 A (LANGE ANTTI AARNE ILMARI [FI]) 11 November 1993 (1993-11-11) pages 6-7 - pages 12-23 ----- -/--	1

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search 18 May 2007	Date of mailing of the international search report 14/06/2007
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Dragomir, Adrian

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	RANNAT K ET AL: "Water vapour tomography for ultra-reliable tracking in air-space surveillance" COST716 FINAL WORKSHOP (KNMI, DE BILT, NL), [Online] 3 September 2004 (2004-09-03), XP002434048 Retrieved from the Internet: URL:http://web.archive.org/web/20040903133951/http://www.knmi.nl/samenw/cost716/final-workshop/posters/Rml.pdf> [retrieved on 2007-05-16] the whole document -----	1
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Information on patent family members

International application No

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