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HIGH-FREQUENCY GLOBAL NAVIGATION SATELLITE SYSTEM'S RECEIVERS FOR AIRBORNE GRAVIMETRY

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Abstract

The development of global navigation satellite systems (GNSS) provides a solution of many applied problems with increasingly higher quality and accuracy nowadays. Researches that are carried out by the Bavarian Academy of Sciences and Humanities in Munich (BAW) in the field of airborne gravimetry are based on sophisticated data processing from high frequency GNSS receiver for kinematic aircraft positioning. Applied algorithms for inertial acceleration determination are based on the high sampling rate (50Hz) and on reducing of such factors as ionosphere scintillation and multipath at aircraft /antenna near field effects.
The quality of the GNSS derived kinematic height are studied also by intercomparison with lift height variations collected by a precise high sampling rate vertical scale [1].
This work is aimed at the ways of more accurate determination of mini-aircraft altitude by means of high frequency GNSS receivers, in particular by considering their dynamic behaviour.

The Problem

Airborne gravimetry, i.e. the reconnaissance of gravity anomalies along surface of the Earth from an aircraft, relies on the data fusion from two different groups of sensors. The first group includes accelerometers (spring-mass systems), that sense the total acceleration **a** [m s^{-2}] of the aircraft. The second one is a GNSS receiver, that permits the determination of a time series of positions [m]; the second time derivative in inertial fixed frame provides the inertial acceleration **b** [m s^{-2}]. The difference between **a** and **b** provides e.g. the gravity vector. In order to ensure the identical metric, the systems that deliver **a**, **b** have to conform to the identical reference. In this treatise, we focus on the system characteristics for **b**, i.e. for the GNSS receiver hardware and the software for subsequent data processing including the proper settings. Our current focus is not the (3D) acceleration but the restriction to the vertical position.
The problem is to identify the dynamical characteristics of the GNSS system to provide the kinematic height estimation. We shall not be dealing with e.g. episodic multipath effects or antenna phase centre variations or phase centre variations, because from the point of view of acceleration determination, we are interested primarily in short term effects.

The Setting

In this case, the reference is realized by a lift of proprietary design, see fig.1, with a vertical scale and with an electro-optical reading device of high resolution (~0.001 mm) which provides instantaneous lift heights at high sampling rates; we use at least 200/sec; a GPS receiver provides time tagging to GPS time. The lift is driven manually over a height range of about 0.6 m. On top of the lift, there is an antenna of the GNSS receiver to be studied.
The GPS receiver to be investigated in this example is a NovAtel OEM4 L1L2 GPS receiver, capable of a sampling rate of 50 /sec. This receiver permits the selection of order and bandwidth of the control loop; these parameters are useful to adopt the receivers dynamic characteristics to the dynamics of the aircrafts motions.
In order to reduce a number of GNSS-positioning errors such as tropospheric delay T_r^s, ionospheric delay I_r^s and orbit errors, differential positioning was applied. The reference receiver of similar

performance as the kinematic receiver was located at a distance of only a few meters from the kinematic receiver; hence, it can be assumed that the above errors are eliminated completely.

Fig 1. Measurement equipment (measuring lift, receiver's antenna)

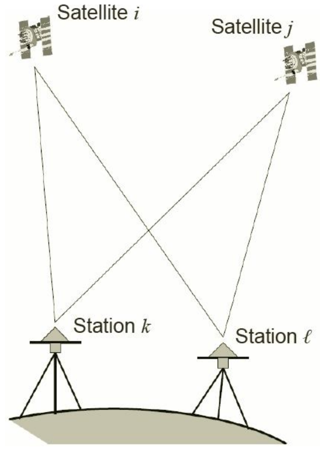

Fig 2. Double difference of observation scheme

The software GeoGenius® was used for processing the GPS observations, setting the 'Hopfield modified (fixed values)' mode for troposphere errors, the 'ionosphere free' observations for ionosphere errors and the broadcast ephemeris for orbit computations [2]; as was pointed out above, these precautions are nearly meaningless in view of the short distance to the reference station.

$$L_r^s = \rho_r^s + c\delta t_r - c\delta t^s + T_r^s - I_r^s + \lambda(N_r^s - \alpha^s + \alpha_r) + \varepsilon_r^s \qquad (1)$$

where:

$L_r^s, \rho_r^s, \varepsilon_r^s$ – observed carrier phase receiver – satellite, geometric range, noise

$\delta t_r, \delta t^s$ – receiver and satellite clock deviations

T_r^s, I_r^s – troposphere and ionosphere delays

λ, N_r^s – carrier wavelength, ambiguity

α^s, α_r – instrument biases in satellite, receiver, resp.

The GPS positions in this article were achieved using the double differencing method: The observation (1) are differenced w.r.t. receivers and satellites, thus elimination the errors (see figure 2):

$$\nabla\Delta L_{kl}^{ij} = \Delta L_{kl}^{i} - \Delta L_{kl}^{j} = \nabla\Delta\rho_{kl}^{ij} + \nabla\Delta T_{kl}^{ij} - \nabla\Delta I_{kl}^{ij} + \lambda\nabla\Delta N_{kl}^{ij} + \nabla\Delta\varepsilon_{kl}^{ij} \qquad (2)$$

where: i, j refer to the satellites, and k, l refer to the receivers.

Least-Squeres-Mapping the range differences to position differences, referred to reference receiver position, provides H_{GPS} – Height of antenna of GPS receiver, [m]. The data set also includes: H_L – position reading of the measuring lift, [m]; D – difference H_L–H_{GPS}, [m]; $H_{GPSFilt}$ – filtered GPS heights, which approximate real positions of measuring lift, [m].

The Experiments

Nine experiments were carried out in Munich, the duration of each of them was between 40 seconds and 2 minutes. Time synchronization procedure is described in BAW research report [3]. The motion of the reference lift is similar to harmonic oscillation with frequencies from 0,3 to 1,5 Hz, which simulates a short period motion of vehicle for airborne gravimetry (e.g. small airplane). It was used the second order of control loop and its bandwidth about 25 Hz.

Evaluation

As mentioned above, the aim was to characterize the dynamic behavior of the GNSS positioning system as presented above with reference to the lift system.

This may be approached e.g. by

– the receiver settings and software processing parameters set;

– input / output analysis either in the time domain or in the spectral domain.

We may address these activities as a contribution to system identification, ARMA-modelling, or filter design of FIR (finite-duration impulse response) or IIR-filters (infinite-duration impulse response) in time domain or spectral domain.

From the wide range of samples in this area, we present a few examples:

1. System characterization from receiver settings

Assume common models that are often used in process industry. Low-order continuous-time transfer functions are usually employed to describe process behavior. Our model must include the basic types: static gain, time constant filter, time delay. They may be represented as

$$P(s) = K \cdot e^{-T_d s} \frac{1 + T_z s}{(1 + T_{p1} s)(1 + T_{p2} s)} \tag{3}$$

where:

s – Laplace operator

K – static gain coefficient

T_{p1}, T_{p2} – time constants, which characterize the poles of filter with transfer function $P(s)$, [s]

T_z – time constant, which characterizes the zero of filter with transfer function $P(s)$, [s]

T_d – time constant, which characterizes delay, [s].

The time delay part e^{-Ts} is responsible for time synchronization between H_L and H_{GPS} measurements. Owing to Matlab function "pem", which estimates parameters of general linear models, it is possible to value parameters of desirable filter's structure [4]. Both time-domain and frequency-domain signals are supported.

Because of errors caused by inexact calculation of ambiguity the systematic trend of H_{GPS}-data is observed. The procedure of trend elimination consists of two steps:

– trend identification based on usage of MATLAB polynomial curve fitting function (polyfit);

– subtraction from H-data this polynomial description of trend.

The installation-specific settings of receiver (the second order of regulator, bandwidth of 25 Hz) determine the parameters of low-pass part of filter $P_{1(Tp=1/25\ s)}$ (4). By means of defined settings and function pem the second filter $P_{2\ (Tz=1/30\ s,\ Tp=1/25\ s)}$ (5) with pole was created.

$$P_{1(\mathrm{Tp}=1/25)}(s) = \frac{H_{GPSFilt}}{H_{GPS}} = \frac{1}{(0.0016 \cdot s^2 + 2 \cdot 0.707 \cdot 0.04 \cdot s + 1)} \tag{4}$$

$$P_{1(\mathrm{Tp}=1/25,\ \mathrm{Tz}=1/30)}(s) = \frac{H_{GPSFilt}}{H_{GPS}} = \frac{(0.333 \cdot s + 1)}{(0.0016 \cdot s^2 + 2 \cdot 0.707 \cdot 0.04 \cdot s + 1)} \tag{5}$$

Because of dynamical delay added by these filters for better precision in results of comparison H_L and $H_{GPSFilt}$ is necessary to use 0.1 s time delay in H_L signal.

2. *Discrete model ARX440 estimated by System Identification Tool using ARX method* with number of representative A and B polynomials $n_A = 4$, $n_B = 4$, resp. and the number of delays from input to output $n_k = 0$:

$$H_L(t) = q^{-n_k} \frac{B(q)}{A(q)} H_{GPS}(t) \tag{6}$$

where:

$A(q) = 1 - 1.535q^{-1} + 1.225q^{-2} - 0.7139q^{-3} + 0.08127q^{-4}$

$B(q) = 0.8812 - 1.146q^{-1} + 0.7341q^{-2} - 0.4155q^{-3}$

q^{-i} – delay operator on *i* measurements backwards.

3. *Discrete time model OE230 estimated by System Identification Tool using prediction error method* ($n_A = 2$, $n_B = 3$, $n_k = 0$):

$H_L(t) = \frac{B(q)}{F(q)} H_{GPS}(t)$ therefore filtering procedure:

$$H_{GPSFilt}(t) = \frac{B(q)}{F(q)} H_{GPS}(t) \tag{7}$$

where:

$$B(q) = 0.994 - 0.988q^{-1}$$

$$F(q) = 1 - 0.987q^{-1} - 0.01949q^{-2} + 0.014q^{-3}.$$

4. Time domain filter design based on experience of Bavarian Academia of Science and Humanities (Bavarian committee for international geodesy) scientists – BAW Solution.

The milestone is determination of vector **x** [1x10] (x_1 – offset, x_2 – trend, $x_3 \ldots x_{10}$ – filter coefficients):

$$\mathbf{x} = (\mathbf{A}^T \times \mathbf{A})^{-1} \times \mathbf{A} \times \mathbf{H_L}, \text{ where}$$

$$\mathbf{A} = \begin{bmatrix} 1 & t_{11} & H_{GPS}(t_8) & H_{GPS}(t_9) & \ldots & H_{GPS}(t_{15}) \\ 1 & t_{12} & H_{GPS}(t_9) & H_{GPS}(t_{10}) & \ldots & H_{GPS}(t_{16}) \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 1 & t_{n-10} & H_{GPS}(t_{n-13}) & H_{GPS}(t_{n-12}) & \ldots & H_{GPS}(t_{n-10-r+f}) \end{bmatrix}$$

t_i – time of i-th measurement $i \in [1 \ldots n]$ from amount of H_{GPS} data

$r = 4$ – regressive part of filter

f – length of filter.

Filtering procedure: $\mathbf{H}_{GPSFilt} = \mathbf{A} \times \mathbf{x}$. (8)

Discussion of Results

The results of filtering was compared by MATLAB function "compare", which computes the output $H_{GPSFilt}$ as a operation of synthesized filter with input H_{GPS}. The result is plotted together with the corresponding measured output H_L (see fig. 3, 4). Table 1 demonstrates the percentage of the outputs variations (3):

$$fit = \frac{1 - norm(H_{GPSFilt} - H_L)}{norm(H_L - mean(H_L))} \cdot 100\% \quad (9)$$

where norm (x) is the Euclidean length of a vector x: $norm(x) = \sqrt{x_0 + \sum_{i=1} (x_i + x_{i-1})}$).

Table 1

Parameter	Initial data	OE230	BAW solution	ARX440	P_2 (Tp=1/30 s, Tf=1/25 s)[1]	P_1(Tf=1/25 s)[1]
Best fit	91.5 %	95.08 %	94.74 %	94.34 %	93.19 %	93.14 %
Loss function	–	$5.523 \cdot 10^{-5}$	–	$4.901 \cdot 10^{-5}$	–	–
FPE	–	$5.669 \cdot 10^{-5}$	–	$5.097 \cdot 10^{-5}$	–	–

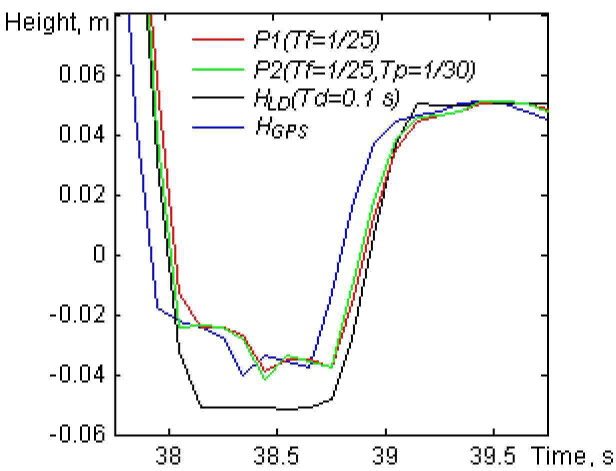

Fig. 3.

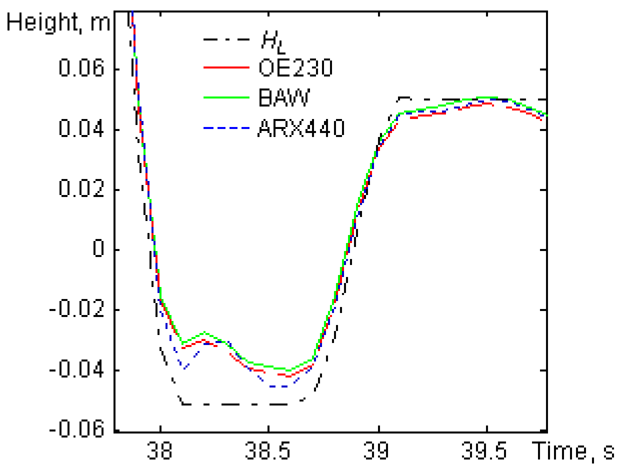

Fig. 4.

[1] With additional time delay of H_L on 0.1 s.

Conclusions

The key interest was to develop reconstruction filter between solution of GNSS height and direct position of receiver's antenna on measurement lift. This reconstruction filter can provide real position of measured carrier (foundation) or vehicle.

The best H_{GPS} filtering approaches in case of accuracy adequacy to H_L are OE230 (7), BAW (8) and ARX440 (6) filters, whose fit is about 95%. The GPS-solution filtered by "pem" linear model (4, 5) demonstrates middle accuracy conformity, but the computed P_1 and P_2 filters (4, 5), as well as OE230 (7) and ARX440 (6) filters, can use for real-time tasks. The advantage of these filters, as distinct from e.g. BAW approach, is possibility of real-time position determination. On the contrary, BAW approach (8) uses both past and future measured values for current real kinematical height reconstruction. This solution is in the most interesting and commonly used approach for geodesists, who as a rule deal with post-processing measurements. The possibility of real-time position determination has a great importance for the purpose of aircraft positioning e.g. for precise aircraft's height determination by means of GNSS including GBAS[2] method for aircraft approach and landing.

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[2] GBAS – Global Base Augmentation Systems