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GNSS Rapid Movement Detection

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ABSTRACT

In 2007, Guillaume and Geiger presented a new method for the detection of small and rapid movements of a single GPS receiver called G-MoDe (GPS movement detection). The method is based on the prediction of single differences of carrier phase measurements between pairs of satellites by using appropriate filter methodologies. By assuming that the effects which do have an impact on the measurements (orbit trajectory, atmosphere, clocks, etc.) vary slowly at a sub-second resolution, an antenna displacement can be detected, if the predicted phase differs significantly (95 %) from the measured phase. The results indicated that quick horizontal movements above the 5 [mm] level are detectable with a GPS L1 receiver.

In order to apply the G-MoDe algorithm it is necessary to have continuous measurements available for the purpose of system identification and filter initialization for a proper time interval even before an antenna displacement occurs. However, within the scope of X-Sense II such an algorithm should already be applicable at an event-driven (triggered) start-up of the sensor, in order to prove if there is happening something and if further measurements should be collected for a precise point positioning.
To achieve this, a possible solution could be not to track the phase, but its time derivative, the Doppler frequency, which is linear related to the radial velocity of a moving object.
In this case, this corresponds to the receiver-satellite line-of-sight (LOS) velocity, for which an analytical expression can be derived by a time derivation of the GPS phase observation equation (after conversion to [m]). By applying this time derivation, the various effects which affect the phase measurements enter the velocity observation equation only by their gradients, which vary very smoothly. Another benefit is, that effects like satellite velocity, tropospheric effects (dry part) or relativistic effects can very well be modeled. They can be used for an error model for a sequential least squares adjustment or they can serve as a deterministic servo control input in a filter for the tracking of satellite velocities, in order to estimate the velocity of a moving receiver.

Concept of G-MoDe

After an initialization and system identification process, all available pairs of satellite-to-satellite phase differences *k* are tracked in a function f_k in a Kalman Filter, which includes all effects on the GPS phase observation (receiver-satellite range, ambiguities, satellite clocks, atmospheric effects, …) and enters the G-Mode observation equation (1).

$$\nabla\Phi^{ij}(t)+\nabla\epsilon^{ij}(t)=-\vec{d}(t)[\vec{e}_i(t)-\vec{e}_j(t)]+f_k(t) \quad (1)$$

$\nabla\Phi^{ij}$ = single phase differences of the incoming observations [m] of satellite I and j
f_k = single phase differences estimated with the Kalman Filter [m]
$\nabla\epsilon^{ij}$ = correlated noise [m]
$\vec{d}$ = unknown displacement vector [m]
$\vec{e}_i, \vec{e}_j$ = receiver – satellite unit vector

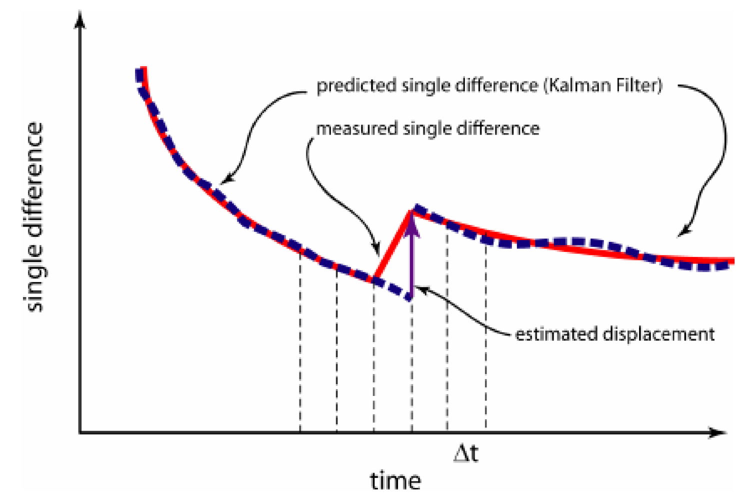

Figure 1: Concept of G-MoDe displacement detection

By step-wise tracking and predicting the function f_k for the next epochs, it becomes possible to detect a movement w.r.t. the incoming observations (figure 1). In a next step, the differences 'observed – predicted' can be formed and the equation can be solved for the displacement in a least-squares sense.

The Idea of G-MoDe+

An expanded version of the phase observation equation (with the displacement $\vec{d}$ added) forms the observation equation for the receiver-to-satellite LOS velocity. After derivation w.r.t. time it reads

$$\dot{\Phi}^i(t)+\dot{\epsilon}^i(t)=-\vec{v}_r(t)\vec{e}_i(t)+\vec{v}_s(t-\tau^i)\vec{e}_i(t-\tau^i)+c\,\dot{d}T(t)-c\,\dot{d}t^i(t-\tau^i)-\dot{d}\,Ion^i(t)+\dot{d}\,Trop^i(t)+\dot{d}\,Mult^i(t)+\dot{d}\,Rel^i(t) \quad (2)$$

The terms on the right-hand-side correspond to receiver velocity, satellite velocity and the time gradients of receiver clock, satellite clock, ionospheric effects, tropospheric delay, multipath and relativistic effects. τ is the time between the emission of the signal at the satellite to the reception at the receiver. As for eq. (1), single differences can be formed (eliminates receiver clock effects) and the G-MoDe concept can be adapted. (Serrano et al, 2004) developed an algorithm for the solution of eq. (2) in an sequential least squares adjustment for $\vec{v}_r$. They accounted for satellite orbits and various errors by-using a priori models. For a GPS L1 low-cost receiver in a static case they arrived at an accuracy of better than 1 cm/s (figure 2).

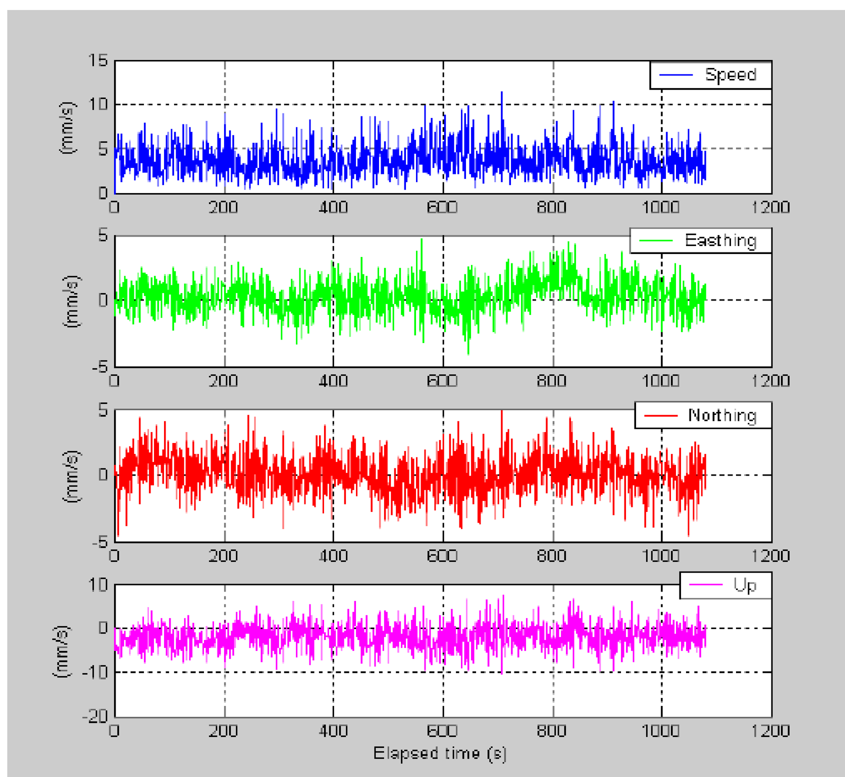

Figure 2: Results of (Serrano et al, 2004) for the velocity estimation of a static, low-cost GPS L1 receiver

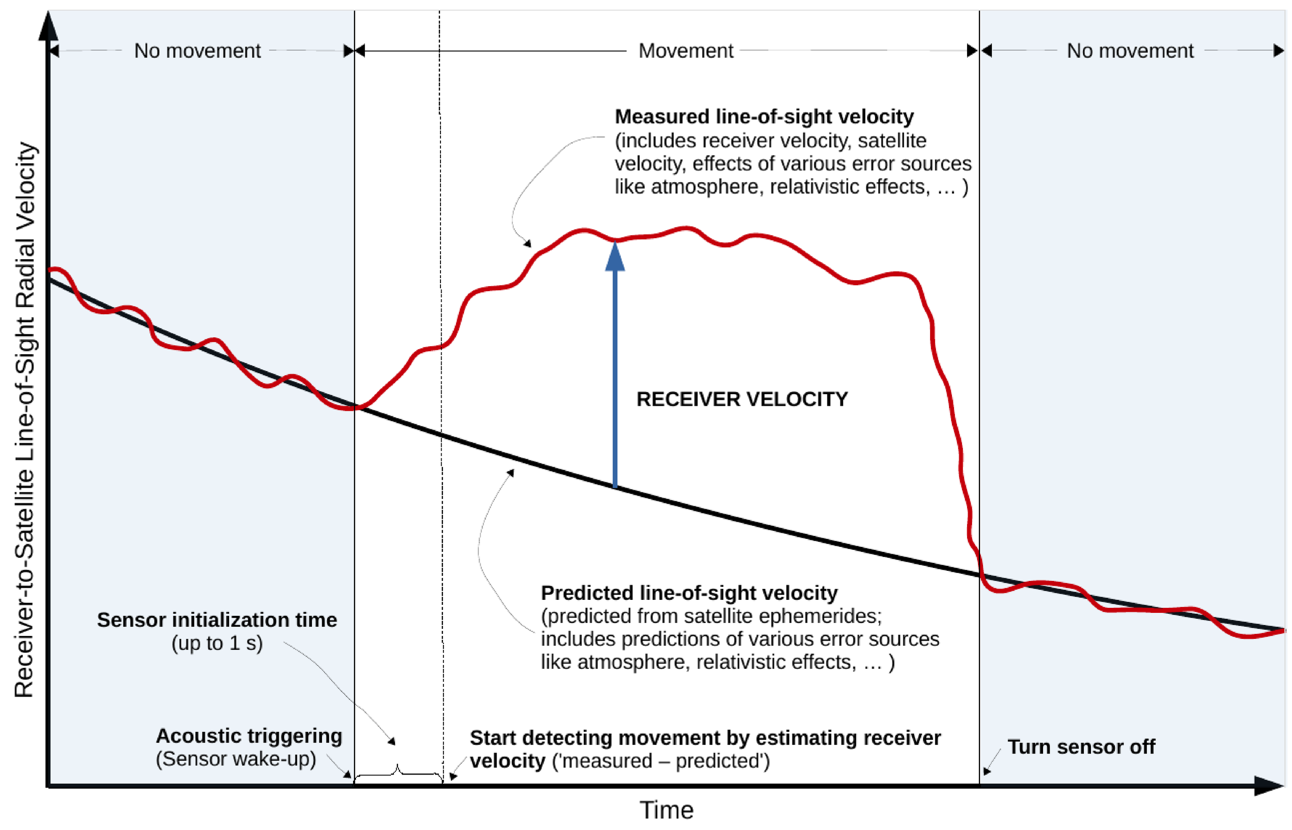

Figure 3: Idea of G-Mode+ to detect a movement on sensor wake-up by estimating the receiver velocity

The idea of G-Mode+ is to use deterministic servo control inputs for the contributing terms to f_k to predict the line-of-sight velocity right from sensor start-up and to check for a movement via estimating the receiver velocity (figure 3).

(Zhang et al, 2008) investigated the terms contributing to the receiver-satellite LOS velocity (figure 4). Most of the effects can be modeled with an adequate accuracy by information obtained from the navigation message. In case of G-MoDe, receiver related effects cancel out because of the formation of single differences. It was concluded, that, if all error sources are properly accounted for, the predicted receiver-satellite LOS velocity can be reconstructed with a mm/s accuracy.

	Error Terms	Modelling in Doppler Measurements	Magnitude Estimated
Satellite Orbit	Broadcast Ephemeris	Yes	±1mm/s per axis
Satellite Clock	Satellite Clock Correction	Yes	Negligible
	L_1-L_2 Correction	No	Negligible
Relativity	Orbit Eccentricity	Yes	Several cm/s
	Sagnac	Yes/No**	Several mm/s
	Second-order Doppler Effect	Yes	Over 2.0 cm/s
	Secondary Relativistic Effects	No	Negligible
Atmosphere	Ionospheric Correction	Yes	mm/s to cm/s
	Tropospheric Correction	Yes	mm/s to cm/s
Receiver	Receiver Site Displacement	No	Negligible
	Receiver Clock	As an unknown to be estimated	

(**: whether or not to apply the Sagnac correction depends on different treatments of the propagation delay)

Figure 4: Main error sources and their estimated magnitudes on Dopper measurements (Zhang et al, 2008)

Conclusions

Based on the concept of G-MoDe and on the work of (Zhang et al, 2008) and (Serrano et al, 2004), the goal is to expand the G-MoDe algorithm towards a near real-time monitoring tool to detect hazardous events almost instantaneously on a triggered startup with a low-cost GPS equipment

The results stated in previous works already indicate promising results to reach an accuracy at the sub-centimeter per second level. To reach such an accuracy it is necessary to account for the various error sources affecting the velocity measurement. The most unpredictable part is assumed to come from the atmosphere. Multipath effects are also assumed to have a small influence; however, in a non or slowly changing antenna environment they can possible be accounted for with a multipath mask.

Preliminary tests with a shake table together with a geodetic two-frequency receiver already indicate that very small movements at the cm/s level can be detected in the GPS velocity data. In a next step, such measurements have to be collected for single frequency low-cost GNSS receivers to assess the quality of the Doppler measurements and their predictability by modeling the contributing effects.

References

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