A GPS/Galileo Software Snap-Shot Receiver for Mobile Phones

Dominik Dötterböck and Bernd Eissfeller
Institute of Geodesy and Navigation
University FAF Munich

BIOGRAPHY

Dominik Dötterböck is a Research Associate of the Institute of Geodesy and Navigation at the University FAF Munich. He received his diploma in Electrical Engineering and Information Technology from the Technical University Munich. His current research interests include signal processing and positioning algorithms for GNSS receivers and software receiver development.

Prof. Bernd Eissfeller is Full Professor and Director of the Institute of Geodesy and Navigation at the University FAF Munich. He is responsible for teaching and research in the field of geodesy, navigation and signal processing. Till the end of 1993 he worked in industry as a project manager on the development of GPS/INS navigation systems. From 1994 - 2000 he was head of the GNSS Laboratory and since 2000 full professor of Navigation at University FAF. Since 2008 he is director of the institute.

ABSTRACT

Snap-shot positioning is an efficient method for a quick position fix, especially when the necessary assistance can be easily provided from one of the mobile phones communication links. State of the art mobile phones provide enough processing power and resources usually used for multimedia applications. This paper describes a software based snap-shot receiver implementation for mobile phones, which reduces the additional hardware effort to the signal conditioning and digitizing RF front end.

INTRODUCTION

In the recent years personal navigation using GPS receivers experienced a boom, making navigation equipment affordable for everybody. Snap-shot positioning is an effective solution for consumer applications where there is no need for a continuous navigation solution, e.g. location based services (LBS) or the E-112 and E-911 respectively. It reduces the power consumption of the handheld device and leads to a reduced time to first fix with the aid of cellular communication network assistance like ephemeris, approximate time, coarse Doppler frequency and position. In synchronized communication networks also fine Doppler and code phase assistance is possible. Within this paper a practical implementation of a snap-shot software receiver for mobile devices is presented. The software architecture is very flexible such that it can process arbitrary signals from multiple systems just by defining the reference codes. The platform used for the snap-shot receiver implementation is a current smart phone with a legacy XScale processor with ARMv5 instruction set and a MMX2 coprocessor. Using assistance data, the snap shot receiver can reduce the Doppler search space for acquiring the signals. For the acquisition a circular FFT with coherent or additional non-coherent correlation is used. The implementation uses a fixed point FFT with optimized assembler code. This ensures fast processing utilizing integer instructions with reasonable accuracy losses. As the measurements for snap shot positioning are approximated code phases from the acquisition instead of pseudoranges from a steady state tracking loop, it is necessary to refine the code phase measurements. From calculated correlation values an improved code phase estimate with a reduced multipath bias is obtained through the combination of correlation values at distinct code phase offsets around the assumed correlation peak.

For the validation of the proposed mobile snap-shot receiver it has been assessed using simulated IF samples from GPS C/A and Galileo E1-B/C signals. Performance measures of the acquisition module will be discussed, e.g. accuracy and processing time, depending on front-end bandwidth and sampling rate. Moreover the position accuracy from the snap-shot positioning will be investigated in different scenarios for GPS C/A, Galileo E1-B/C and combined for both signals.

The next section discusses the theoretical background of a snap-shot receiver, e.g. signal detection, code phase estimation and snap-shot positioning including GPS/Galileo combined processing. Then the specific implementation of the receiver will be presented. Before the final conclusion results from snap-shot positioning and the practical implementation will be demonstrated and discussed.
THEORY

Signal Detection
The signals of GPS L1 C/A and Galileo E1 B from a particular satellite received at the receiver antenna can be modeled as:

\[ s(t) = \sqrt{2C}d(t-\tau)c(t-\tau)e^{j\omega t}, \]  

(1)

where \( t \) is time, \( \tau \) is group delay, \( C \) is signal power \( C = A^2/2 \), where \( A \) is the signal amplitude, \( d \) is sign of the navigation data symbol, \( c \) is PRN code, and \( \omega \) is angular carrier frequency.

Assuming that the change in code delay and phase delay is small during the integration time \( T_i \) and that the correlation process is realized within one data bit, the lowpass-equivalent I and Q values after RF down conversion, de-spreading, and coherent integration can be approximated by:

\[ I = \frac{C}{2} R(\epsilon_x) \sin (\pi \Delta f T_i) \cos (\phi) + n_i, \]  

(2)

\[ Q = \frac{C}{2} R(\epsilon_x) \sin (\pi \Delta f T_i) \sin (\phi) + n_q, \]  

(3)

\[ R(\tau) = \sum_{\mu=1}^{M} c_\mu c_{\mu+\tau}, \]  

(4)

where \( \epsilon_x \) is group delay error \( (\epsilon_x = \tau - \xi) \), \( \phi \) is carrier phase error \( (\phi = \Phi - \Phi_0) \), \( \Delta f \) is frequency deviation after Doppler removal, \( n_i, n_q \) are i.i.d. WGN, and \( T_i \) is coherent integration time.

The covariance between two correlation values \( I_m \) and \( I_n \) at correlation points \( m \) and \( n \) can be calculated by:

\[ \text{Cov}(I_m,I_n) = R(m-n)\sigma^2. \]  

(5)

This means correlation values correlate depending on the correlation function and their distance from each other.

An important performance issue for a navigation receiver is the bandwidth which is used in the front-end. As this paper concentrates on a consumer application, the effects of band limiting have to be taken into account. Figure 1 shows autocorrelation functions around the peak for GPS L1 C/A and Galileo E1 MBOC correlated with BOC(1,1) for different RF bandwidths. The rounding effect which can be seen at the peak for lower bandwidth implies a correlation loss. Together with a lower sampling rate the selection of correlator spacing and FFT resolution is limited and thus the accuracy.

For signals with random phase \( \epsilon_x \) in additive Gaussian noise the envelope detector resembles the optimum detector.

The hypothesis \( H_1 \) for acquisition is given by the following threshold condition, where this hypothesis represents the fact that the signal was received:

\[ l = \frac{1}{M} \sum_{j=1}^{K} \left( \sum_{i=1}^{M} l_i \right)^2 + \left( \sum_{i=1}^{M} Q_i \right)^2 \geq TH \]  

(6)

Where \( l \) refers to the test statistic, \( TH \) is the threshold, \( M \) is the number of in-phase and quadrature-phase samples summed prior to squaring and \( K \) represents the number of samples summed after squaring or non-coherent integration. This means that if the threshold level of \( l \) is reached, the acquisition was achieved. On the contrary, if no signal is received, hypothesis \( H_0 \) applies, and the statistic \( l \) gives:

\[ l = \frac{1}{M} \sum_{j=1}^{K} \left( \sum_{i=1}^{M} l_i \right)^2 + \left( \sum_{i=1}^{M} Q_i \right)^2 \leq TH \]  

(7)

When the signal is present, the estimator \( l \) under hypothesis \( H_1 \) can be expressed as:

\[ l = \sum_{i=1}^{K} \left[ R^2(\epsilon_x) \sin^2 (\pi \Delta f T_i) + n_i \right] \]  

(8)

On the other hand, under hypothesis \( H_0 \), the output of the statistic estimator \( l \) will be:

\[ l = \sum_{i=1}^{K} \left( n_{i,1}^2 + n_{i,2}^2 \right) \]  

(9)

In both cases, \( n_i \) and \( n_0 \) are \( 2M \) independent Gaussian variables. It follows that \( l \) normalized by \( \sigma_n \) is the sum
of $2M$ independent Gaussian variables squared, that result in a non-centred Chi-Square distribution with $2M$ degrees of freedom and a non-centrality parameter $\lambda$ defined as:

$$\lambda = \sum_{i=1}^{k} \frac{1}{\sigma_{\xi_i}^2} (E[I_{i}^2] + E[Q_{i}^2])$$

$$\lambda = 2K\frac{C}{N_0}T_iR^2(\tau)\sin^2(\pi\Delta f T_i)$$

$$\sigma_{\xi_i}^2 = E[n^2] = \frac{N_0}{T_i}$$

$\lambda$: Boltzmann constant
$T_0$: noise temperature

The general probability density function of $l$ under hypothesis $H_1$, $l \geq TH$, as a function of $K$ is given by:

$$p(s|H_1) = \frac{1}{(2\lambda)^{K-1/2}} \frac{1}{\Gamma(K)} e^{-\lambda} I_{K-1}(\sqrt{2s})$$

(9)

Where $I_{K-1}(X)$ is the modified Bessel function of the first kind. Using the Neyman-Pearson criterion, the probability of detection $p_d$ is maximized for a given fixed false alarm rate $p_{fa}$. The corresponding probability of detection for a threshold $TH$ is given by:

$$p_d = \int_{TH}^{\infty} p(s|H_1) \, ds$$

(10)

The general probability density of $l$ under hypothesis $H_0$ is given by:

$$p(s|H_0) = \frac{1}{2^{K(K-1)/2}} \frac{1}{\Gamma(K-1/2)} e^{-\lambda s}$$

(11)

Here it is assumed that only interference due to the thermal noise is considered.

The probability of false alarm for a threshold $TH$ is given by:

$$p_{fa} = \int_{TH}^{\infty} p(s|H_0) \, ds$$

(12)

Considering thermal noise as the only nuisance parameter and no interference from multipath or other strong satellites, the theoretical detection probability bounds for a given false alarm rate are depicted in Figure 2 and Figure 3 for GPS C/A and Galileo E1 B case, respectively. Black curves stand for the ideal bound, whereas red curves stand for more realistic bounds, which include a loss due to a mean Doppler frequency mismatch between real Doppler and nearest Doppler search grid frequency.

Assuming a Ricean multipath fading channel with a strong line-of-sight signal path and multiple non-direct signal paths, the pre-detection samples can be described as:

$$l + jQ = \sqrt{2CR}(\epsilon_c) \sin(\pi\Delta f T_i) \exp(j\phi)\nu_c + n_c$$

(13)

$n_c$: complex Gaussian zero mean random variable
$\nu_c$: complex Gaussian non-zero mean random variable

Normalizing this non-zero mean Gaussian random variable by its standard deviation, gives again a non-centred Chi-Square distribution, where we obtain:

$$\lambda = FK\left(\frac{F + 1}{C T_i R^2(\tau)\sin^2(\pi\Delta f T_i)}\right)^{-1}$$

$$\sigma_{\nu_c}^2 = \frac{C R^2(\tau)\sin^2(\pi\Delta f T_i)}{F + 1} + \frac{N_0}{T_i}$$

the Ricean fading factor $F$ is defined by:

$$F = \frac{\sigma_{\xi_i}^2}{\sigma_{\nu_c}^2}$$

with $\sigma_{\nu_c}$ Amplitude and variance of $\nu$
Analog to the noise only case Figure 4 and Figure 5 give the ideal and realistic detection bounds for a Ricean fading channel, both with a Ricean fading factor $F$ of 5. From the figures one can see that the loss due to fading is higher for fewer non-coherent integrations.

From the figures one can see that the loss due to fading is higher for fewer non-coherent integrations.

**Figure 4:** Theoretical minimal bounds for GPS C/A signal after Rice channel with Rice factor 5, $P_{fa}=10^{-3}$ and $T_{coh}=1\text{ms}$

**Figure 5:** Theoretical minimal bounds for Galileo E1B after Rice channel with Rice factor 5, $P_{fa}=10^{-3}$ and $T_{coh}=4\text{ms}$

### FFT Correlation

For signal detection without previous knowledge about the code phase, the Fast Fourier Transformation is an efficient tool to calculate the complex correlation array $X$ for the whole code phase range in parallel for one Doppler bin by:

$$X(\tau) = \text{IFFT} \left\{ \text{FFT} \{s(t)\} \text{FFT}^*\{c(t)e^{j\delta t}\} \right\}$$  \hspace{1cm} (15)

In order to get a real-valued result which is independent of the unknown carrier phase, standard techniques calculate the final result as an envelope or squared envelope with:

$$\hat{R}(\tau) = |X(\tau)|^2 \text{ or } \tilde{R}(\tau) = |X(\tau)|$$  \hspace{1cm} (16)

### Interpolation

In order to estimate the code phase of the true correlation peak, it has to be interpolated between the correlation values around the detected peak, because these have an arbitrary offset in the range of half the code phase step size. The easiest method to estimate the correlation peak can be described as follows. From the highest correlation value and its surrounding nearest early and late values the peak point is calculated from the slope between the peak and the lower point out of early and late neighboring samples. This method minimizes the variance and the effect of multipath, as analyzed in [2].

### Snap-Shot Positioning

Since the single shot acquisition derives only code phase measurements instead of pseudorange measurements in tracking mode, one gets a code ambiguity comparable to carrier ambiguities in carrier phase measurements. Since no bit and frame synchronization is achieved in the acquisition phase, the exact send time of the signal is not known and clock synchronization between the receiver clock and GNSS system time cannot be achieved. Only synchronized communication networks can give sub-ms assistance or code phase estimates. Without knowing the exact signal send time, the receiver coordinates and the receiver’s clock bias, the navigation algorithm has to solve for an additional coarse time, which might make positioning impossible in environments with only 4 visible satellites, but the combination of GPS and Galileo observations compensates the increased number of unknowns.

As mentioned before, in the single shot mode it is not possible to receive/decode the navigation message, since the receiver does not track the satellites. Altogether the receiver needs at least assistance in form of navigation data, coarse position and time, which could be received via GSM/UMTS or WLAN. The snap-shot positioning can be done by following [9]: The observations are converted into the fractional domain by:

$$\text{frac}_A(\tau) = A \text{ frac}\left(\frac{\tau}{A}\right) = \tau - A \text{ round}\left(\frac{\tau}{A}\right)$$  \hspace{1cm} (17)

$A$ code period

From the known approximate position and time the satellite positions can be calculated and thus the range and the number of full code cycles, the code ambiguity. The position can be estimated by the standard iterative Newton Raphson method:

$$\delta x = (A^TWA)^{-1}A^TW\delta p$$  \hspace{1cm} (18)

$[t, x, y, z, b, o]^T$

$t$ receiver time
$x, y, z$ receiver position
$b$ fractional clock bias
$o$ system time offset
$W$ weighting matrix
$A$ design matrix

As time is not known exactly, it is divided into a coarse receiver time and a clock bias which is in the range of the fractional code phases from Equation 17. The design matrix in this case is given by:
The Galileo GPS time offset (GGTO) will be included in the Galileo navigation message in form of model parameters. Even if the offset will be in the range of a few meters and the broadcast parameters are quite accurate [7], it is no problem to spend an observation for the estimation of the time offset in case of enough satellites, which will be the case in a combined solution [8]. The pseudorange residual can be calculated from:

\[
\delta p_i = p_{\text{meas}} - p_{\text{model}}
\]

\[
p_{\text{meas}} = N_i \tau_i + \tau_i
\]

\[
p_{\text{model}} = ||s_i(t-t_i) - r|| - b + \epsilon_i
\]

The area of convergence for the snap-shot positioning is given by:

\[
\nu_{\text{LOS}} |\Delta t| + |\Delta r| + |\Delta b| + |\Delta \epsilon| < \frac{\Lambda}{2}
\]

\[
\nu_{\text{LOS}} \text{ line of sight velocity}
\]

\[
\Delta \text{ indicating errors from time, position, fractional clock bias, correction parameters}
\]

The line of sight velocity \( \nu_{\text{LOS}} \) should be set to the maximum possible velocity. The clock bias search range and density can then be chosen to fulfill Equation 22, where the assumed scenario defines the maximum absolute error in time \(|\Delta t|\) and position \(|\Delta r|\). Assuming as a reasonable example a position accuracy of 10km and a time accuracy of 2 seconds, then two bias starting values are sufficient in order to let the algorithm converge.

**IMPLEMENTATION**

In this section the implementation and design of the software based snap-shot receiver will be presented. Figure 6 shows the view of the signal/data path for signal detection in one single channel. The analog signal is down converted, sampled, quantized packet wise and stored in memory. For signal detection the samples are coherently integrated and the envelopes further integrated non-coherently. Figure 7 gives a first overview of the platform architecture with the data flow of the snap-shot receiver. Any processing of the samples is done on the host processor on the mobile phone.
The microprocessor on the implementation platform is a current smart phone with a legacy XScale processor using ARMv5 instruction set and a MMX2 coprocessor [11, 13,14]. The detailed specification of the platform is summarized in Table 1. The multimedia extensions include SIMD instructions, which allow for example a parallel multiply-and-accumulate of four 16 Bit values; this is very helpful for time domain correlation [12].

Table 1: Platform specifications

| Processor | Marvell PXA 312, 624 MHz |
| Processor Core | Intel XScale |
| Coprocessor | Multimedia Coprocessor with Intel Wireless MMX 2 Technology |
| Instruction Set | ARMv5TE |
| Cache Size L1 | 32 KB Data/32 KB Instructions |
| Cache Size L2 | 256 KB SRAM |
| RAM | 128 MB |

Compared to standard PC Software there are special requirements of existing resources in an embedded system. The major constraints are:

- limited memory
- low processor speed
- reduced instruction set (no SSE)
- floating point calculations only with software libraries
- limited number of registers

Following constraints for an implementation for an embedded processor include economical deployment of:

- dynamically allocated memory
- templates
- multiple inheritance

The block diagram depicted in Figure 8 illustrates the architecture of the snap-shot receiver from the software point of view.

![Block diagram of snap-shot receiver](image)

Figure 8: Overall snap-shot software receiver architecture.

The receiver is implemented as a set of C++ classes, grouped into modules, with well defined input and output data interfaces.

After receiving IF-samples from the extern, the whole signal processing is controlled by the Main Receiver. According to the attached configuration for all signals of interest the acquisition module processes the samples of each incoming packet. Assistance Data collected in a message container and in the receiver state allow after successful acquisition the position solution via snap-shot positioning. The assistance data can also be used to reduce the acquisition search space in terms of PRNs, Doppler and code phases.

The flexibility of the software allows the support of any kind of CDMA Signal, just by providing the suitable reference codes and a proper configuration for the signal.

### Acquisition

Different acquisition modules have been implemented:

- a time domain Matched Filter approach for assisted acquisition and a FFT based acquisition with varying data word length, where signal parameters are estimated from the likelihood cost function.
- The receiver performs acquisition in one common step for all different GNSS signals successively. Signal acquisition can be done on different levels according to the required sensitivity. To acquire strong signal components, the receiver uses a conventional coherent acquisition algorithm. For weak signal detection, a combination of coherent and non-coherent integrations can be used.

### FFT

For a first implementation the algorithms were optimized for the available processor resources. One step was to adapt the most time consuming calculations to the L1 cache size, which is correlation in time or frequency domain (FFT correlation). In our case this means for FFT, that a FFT size of $2^{12}$ with 16 bit fixed point implementation would be best in terms of efficiency. Longer FFT sizes have the disadvantage of longer read and store latencies.

Fixed point FFT's have a slight performance loss in terms of accuracy compared to floating point implementations, as shown in [6]. The fact that floating point is seldom supported by current processor architectures for mobile phones makes it unfeasible, as floating point emulations are slow.

As an example the comparison of floating point and fixed point acquisition (each 32bit, $2^{14}$ point, 4ms coherent) in the snap-shot receiver gave a degradation in the position domain from 16.5699m to 16.5862m RMSE.

Including all overheads for loading, storing and loops assuming zero wait state memory or cache hits, the number of cycles and the resulting processing time for different FFT sizes is summarized in Table 2.

<table>
<thead>
<tr>
<th>FFT Order (radix-4)</th>
<th>Cycles</th>
<th>Processing time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>66,196</td>
<td>1.0608e-004</td>
</tr>
<tr>
<td>12</td>
<td>318,878</td>
<td>5.1102e-004</td>
</tr>
</tbody>
</table>
Assisted Acquisition

Another acquisition module was implemented in order to support assistance data like Doppler and code phase. This module is designed straightforward as a Matched Filter correlation module, which searches the Doppler and code phase space only partially according to the assistance information, which saves a lot of computations and therefore gives place for longer dwell times. The search space is computed in compliance with the user configuration for position accuracy, user velocity, time accuracy, coherent integration time and oscillator stability/synchronization accuracy. The coherent integration time $T_c$ can be chosen as long as the carrier offset $\Delta f$ and the phase offset $\Delta \phi$ remain approximately constant.

In case of only coarse time information, a first signal can be acquired from full code phase search. From the range between receiver and satellite the clock bias modulo code period can be estimated and therefore code phases for other signals of the same system [10]. The search space then is increased due to range imprecision from user position and satellite position (line of sight velocity multiplied by time error).

Optimizations

Apart from algorithmic optimizations there are a few points, which make computations more efficient, especially in a software implementation.

In case of a binary reference code, calculations can be reduced from a multiply-and-accumulate to a pure accumulate instruction [5]. Also the loop size in samples for correlation can be optimized to available cache sizes [4]. Here cache misses encounter loop overhead, a trade off can be found by testing on the specific platform.

In order to speed up the IF- and Doppler frequency wipe off, it is implemented as a look-up-table. For this a full cycle of the sin/cos function is stored sampled with a fixed resolution and integer amplitude. For the frequency wipe off the table index is increased by the carrier phase increment per sample step after each processed sample.

RESULTS

For validation of the algorithms of a combined positioning with satellite signals from GPS and Galileo a static scenario was generated from the NavX constellation Simulator from IfEN GmbH (NavX ®-NCS RF NAVIGATIONAL CONSTELLATION SIMULATOR) and recorded with the NavPort RF front end. The core specification of the used front end are a bandwidth of 10 MHz, a noise figure of 1.5 dB and a sampling rate of 23.1 MHz at a ADC resolution of 1.5 Bit. Figure 9 shows constellation geometry of the simulation in the sky-plot with azimuth and elevation for all simulated GPS and Galileo satellites, labeled by “G” and “E”, respectively.

In the following results for different acquisition configurations in combination with various signal collections are examined and compared.

![Figure 9: Sky plot for simulated scenario with six Galileo signals (E) and eight GPS signals (G)](image)

Figure 10 and Figure 11 depict exemplary acquisition results from FFT acquisition with full search space in the code phase and Doppler range. The single correlation peaks can be detected easily in this constellation.

![Figure 10: 3D FFT acquisition plot for GPS C/A, 4ms coherent, 5 times non-coherent processing, 43 dBHz](image)

Figure 12 and Figure 13 show the 3D acquisition plot for the implemented assisted acquisition module, the correlation peak of the acquired satellite is clearly visible. The limited search space allows the use of a higher code phase resolution, this leads to a higher post-correlation $C/N_0$ due to a lower code phase.
mismatch loss. In Figure 13 the side peaks from the BOC(1,1) autocorrelation function can be seen.

Figure 12: 3D assisted acquisition plot for GPS C/A, 4ms coherent, 5 times non-coherent processing, 43 dBHz

Figure 13: 3D assisted acquisition plot for Galileo E1 B, 4ms coherent, 5 times non-coherent processing, 41 dBHz

As a first example for snap-shot positioning from acquisition stage results, a constellation consisting of eight GPS signals is considered, as presented in the sky plot from Figure 9. In Figure 14 the positioning results are depicted in the east-north plane for all configurations of Table 3. In the figure one can see the true error and the deviation from the true position. Applying ionospheric and tropospheric corrections, the position exhibits no apparent bias in this plane. Figure 15 shows the errors for the best configuration in north-, east- and up-directions as well as the computed estimated accuracy. On the whole 1200 epochs have been processed with an epoch length of 0.08s.

The second example provides snap-shot positioning results from a combined GPS/Galileo positioning with 14 satellites in total (8 GPS and 6 Galileo). The configuration and accuracy for this approach is listed in Table 5. Analog to the previous example, Figure 16 and Figure 17 give the observed position errors. Additionally, Figure 18 shows the estimated system time offset between GPS and Galileo for all epochs of this simulation. With a mean of 0.87m and a standard deviation of 3.14m the system offset is in a reasonable range.
Figure 17: Position accuracies in east-, north- and up-direction for Snap-Shot positioning with 8 GPS C/A-code signals and 6 Galileo E1 B signals.

Figure 18: Estimated Galileo-GPS time offset for snap-shot positioning with 8 GPS C/A-code signals and 6 Galileo E1 B signals.

Table 3: Position accuracies (RMSE) for GPS processing (eight satellites) at a C/N0 of about 43 dBHz

<table>
<thead>
<tr>
<th>FFT Order</th>
<th>Coherent integration [ms]</th>
<th>Non-coherent integrations</th>
<th>3D RMS Error [m]</th>
<th>2D RMS Error [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>4</td>
<td>1</td>
<td>24.3182</td>
<td>15.2402</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>1</td>
<td>16.5699</td>
<td>10.6093</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>5</td>
<td>7.7743</td>
<td>5.1168</td>
</tr>
<tr>
<td>13</td>
<td>4</td>
<td>5</td>
<td>5.4208</td>
<td>3.5436</td>
</tr>
</tbody>
</table>

Table 4: Position accuracies (RMSE) for Galileo Processing (six satellites)

<table>
<thead>
<tr>
<th>FFT Order</th>
<th>Coherent integration [ms]</th>
<th>Non-coherent integration</th>
<th>3D RMS Error [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>4</td>
<td>1</td>
<td>29.3294</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>1</td>
<td>25.7663</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>5</td>
<td>17.552</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>5</td>
<td>11.1238</td>
</tr>
</tbody>
</table>

Table 5: Position accuracies (RMSE) for GPS/Galileo Processing (six satellites Galileo, eight satellites GPS)

<table>
<thead>
<tr>
<th>FFT Order</th>
<th>Coherent integration [ms]</th>
<th>Non-coherent integration</th>
<th>3D RMS Error [m]</th>
<th>2D RMS Error [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/15</td>
<td>1/4</td>
<td>10/3</td>
<td>6.4593</td>
<td>3.7092</td>
</tr>
<tr>
<td>12/15</td>
<td>1/4</td>
<td>4/1</td>
<td>13.9998</td>
<td>8.2808</td>
</tr>
</tbody>
</table>

Major advantage of processing both GPS and Galileo is a higher accuracy due to better GDOP in environments where one system alone as has to low availability. Table 3 and Table 4 summarize accuracies for FFT based snap-shot positioning with varying configurations for the GPS- and Galileo-constellations, respectively. In case of GPS a coherent correlation over four code periods was used. Here an ideal correlation gain of 6dB is reduced by an average bit alignment loss of less than 0.5dB.

As previously discussed, for this specific implementation a FFT order smaller than 13 is most efficient. Under this assumption Table 6 states position accuracies for FFT based GPS processing. Table 7 gives a first hint for the processing load for relevant configurations on the current target platform. Here, the average processing time per snap-shot position fix is listed.

Table 6: Processing times for FFT acquisition for GPS Processing (eight satellites)

<table>
<thead>
<tr>
<th>FFT Order</th>
<th>Coherent integration [ms]</th>
<th>Non-coherent integration</th>
<th>Processing time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1</td>
<td>1</td>
<td>0.643</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>1</td>
<td>0.686</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>5</td>
<td>1.618</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>5</td>
<td>1.824</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>5</td>
<td>3.046</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>10</td>
<td>3.358</td>
</tr>
</tbody>
</table>
CONCLUSION

In this paper theory and implementation of a software based snap-shot receiver for mobile phones has been presented. Results for different acquisition configurations and constellations with signals from GPS, Galileo, and both have been compared in the position domain. The results show that this approach delivers good performance in reasonable computation time, where there is still some space left for optimizations on algorithm and implementation level in form of the reduction of redundant calculations.

ACKNOWLEDGEMENTS

The investigations and developments of this work are supported within the scope of the research project “HIGAPS II (Highly Integrated Galileo/GPS Receiver Chipset)” (FKZ: 50 NA 0610), successor of HIGAPS I [10], in contract with the Bavarian State Ministry for Economy, Infrastructure, Traffic and Transport and DLR (German Aerospace Center).

REFERENCES