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Single Shot Positioning

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ABSTRACT

Aiding satellite navigation with assistance data can improve the reception sensitivity substantially. Reference receivers continuously track all satellite signals and maintain a database of relevant signal parameters. Assisted satellite navigation enables single shot positioning by providing the navigation message via a communications link. Single shot positioning as opposed to conventional positioning works with just signal acquisition and no signal tracking. The time consuming signal tracking, until the ephemeris data are received, can be skipped to reduce power consumption and positioning latency. The receiver only needs to estimate the spreading code phases so that its location can be calculated with the help of assistance data. Strongly attenuated signals also do not permit navigation message extraction, since the observation period has to be increased beyond the data bit boundaries. Assisted satellite navigation combined with single shot positioning hence allows positioning with increased observation times, which yields enhanced reception sensitivity. This paper illustrates a single shot positioning algorithm. It shows how the position solution can be derived by combining the code phase measurements with assistance data as defined by 3GPP. It also shows which requirements have to be imposed on the aiding information and how these requirements differ for various Galileo and GPS signals.

KEYWORDS: Single Shot, Snap Shot, Positioning Algorithm, Assistance Data, Assisted Navigation.

1. INTRODUCTION

Several new requirements and challenges are introduced with the transition from traditional navigation applications to location based services (LBS) and emergency caller location such as the E-911 legislation in the USA. Unlike the military, nautical, aviation and vehicular navigation applications of the past, LBS and E-911 require robust positioning determination in deep urban and indoor environments (Schmid *et al.* 2004). High availability is a very important prerequisite for the positioning services. However, urban settings, indoor areas, and reception inside vehicles introduce severe attenuation, making positioning with conventional GPS receivers nearly impossible (Collin *et al.* 2003), (Pérez-Fontán *et al.* 2004). Urban canyons cause severe shadowing and multipath fading effects. This severely limits the positioning availability and accuracy of conventional receivers. It is reportedly necessary to cope with a signal attenuation of around 30 dB to achieve a 90 % availability in deep urban settings (Collin *et al.* 2003), (MacGougan *et al.* 2002). The US E-911 legislation requires all wireless carriers to locate 95 % of all emergency calls with an accuracy of 150 m for handset based solutions such as GPS and Galileo receivers. Furthermore, 67 % of all distress calls have to be located with a precision of 50 m for handset based methods. A similar European E-112 legislation is currently in preparation. A large number of these emergency calls originate from inside buildings and deep urban areas. Traditional GPS tracking receivers have large start-up times and do not permit positioning with highly attenuated satellite signals. Aiding the satellite navigation receiver is the key for improving the availability and accuracy of location based services.

2. ASSISTED SATELLITE NAVIGATION

Most mobile communication standards have specified assistance protocols (3GPP 2006), (3GPP 2007), (3GPP2 2004). Reference receivers continuously track all available satellite signals and maintain databases of relevant signal parameters (Bryant 2005). These databases can then be readily supplied to mobile telephones. The closer the reference receivers are to the users, the more accurate are their aiding parameters. Depending on the mode of operation, the assistance may include (3GPP 2006), (3GPP 2007), (3GPP2 2004):

- Approximate time
- Approximate location
- Visibility of the satellites
- Ephemeris information
- Satellite clock corrections
- Ionosphere parameters
- Differential corrections
- Almanac data
- Integrity information
- Navigation data aiding

The merit of the assistance data is threefold (Bryant 2005), (Syrjärinne 2001). Firstly, it reduces the positioning latency by substantially limiting the acquisition search space. The information on satellite visibility limits the number of spreading codes to be searched for acquisition. The approximate DOPPLER frequency shift can be derived from the Ephemeris information. A certain DOPPLER uncertainty remains due to the user motion and local oscillator tolerances. In some modes of operation where high timing synchronization accuracy can be achieved, the assistance data may also limit the code phase search window. This becomes more important for the long spreading codes of modernized GPS and Galileo signals. The code phase of the secondary spreading code in some future Galileo/GPS pilot signals may also be transmitted via assistance data, since the secondary codes have quite long chip periods of 1–4 ms. The positioning latency is further reduced since the assistance data includes all the information about the navigation message. The receiver hence does not need to decode the satellite signal for up to 30 s in order to receiver the ephemeris information and satellite clock corrections. This allows significantly faster positioning, which in turn conserves mobile phone batteries and user patience.

Secondly, the assistance data allows for enhanced reception sensitivity. As the signals become weaker the bit error rate for the data demodulation increases to a point where navigation data recovery fails. However, code phase measurements are still feasible for much weaker signals. The reduction of the acquisition search space furthermore allows for extended dwell times, which facilitate synchronization with weaker satellite signals. Doubling the noncoherent integration time improves the acquisition sensitivity by around 1.5 dB, while doubling the coherent integration time may lead to around 3 dB increased sensitivity. Aiding is necessary because the size of each frequency search bin is thereby reduced. Predefining a correct range of frequency search bins decreases the required time for a position fix to an acceptable level. Since the navigation data has a quite low bit rate, the assistance data may indicate the data bit boundaries to align and maximize the coherent integration intervals. Aiding information may also be used for data modulation wipe-off to enable coherent processing beyond data bit boundaries.

Thirdly, the assistance data can also improve the positioning accuracy. Most importantly, differential corrections can effectively compensate for a large portion of the errors in modelling the satellite clocks, satellite trajectory, ionospheric delays and tropospheric delays. If the differential corrections are sufficiently localized, they can substantially improve the positioning accuracy. Assistance data may also enable the reception of more satellite signals, since their acquisition search can be narrowed down. This would improve the positioning geometry and accuracy. Real-time integrity information improves the reliability of the navigation solution.

3. SINGLE SHOT POSITIONING

Conventional positioning algorithms require signal tracking and synchronization with the time-of-the-week word at the beginning of each subframe. Single shot positioning as opposed to conventional positioning works with pure signal acquisition and no signal tracking (Sirola and Syrjärinne 2002), (Kaniuth *et al.* 2005). Strongly attenuated signals do not permit navigation message extraction, since the observation period has to be increased beyond the data bit boundaries. Single shot positioning allows positioning with increased observation times thus yielding enhanced reception sensitivity. The single shot positioning outlined subsequently allows the calculation of the position solution without synchronizing to any time stamp of the navigation message.

Without loss of generality, it shall be assumed that all signals are received simultaneously at time t. When the receiver only estimates the code phase without tracking the signal, the transmission time $t_0^{(\kappa)}$ of the received signal remains unknown. The index $\kappa \in \{1, \dots K\}$ represents the different visible satellites and K the number of visible satellites. Figure 1 illustrates time lines at a satellite and the receiver. The transmission time can be expressed as an integer multiple $\varsigma^{(\kappa)} \in \mathbb{Z}$ of the spreading code period LT_c plus the code phase $\tau^{(\kappa)}$ and the clock difference

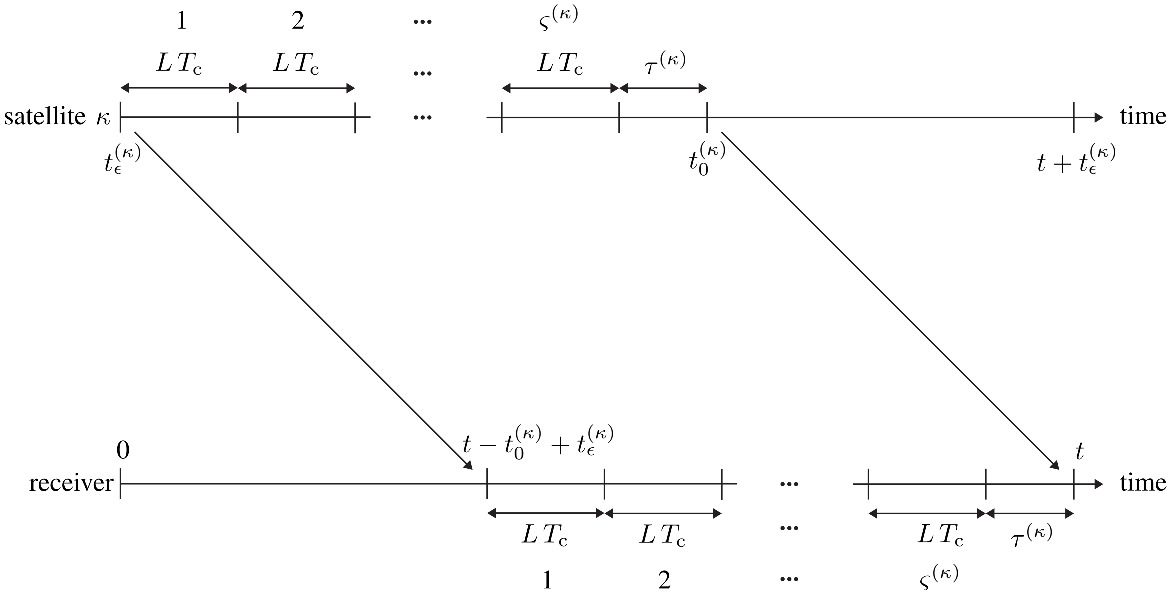

Figure 1. Satellite and receiver time lines for single shot positioning.

between satellite and system time $t_\epsilon^{(\kappa)}$

$$t_0^{(\kappa)} = \varsigma^{(\kappa)}\,L\,T_\mathrm{c} + \tau^{(\kappa)} + t_\epsilon^{(\kappa)} \,. \tag{1}$$

The spreading code length is denoted by L and the spreading chip period by T_c. When the signal is transmitted from the satellite at time $t_0^{(\kappa)}$, the code phase $\tau^{(\kappa)}$ has an arbitrary value. However, when the signal is received later at time t, the code phase still has the same value $\tau^{(\kappa)}$. Each satellite clock difference $t_\epsilon^{(\kappa)}$ relative to the system time t is supplied as assistance data. The distance between the receiver location $\mathbf{p}_\mathrm{r} \in \mathbb{R}^3$ and each satellite location $\mathbf{p}_\mathrm{s}^{(\kappa)} \in \mathbb{R}^3$ can be expressed as

$$\rho^{(\kappa)} = \left\|\mathbf{p}_\mathrm{s}^{(\kappa)} - \mathbf{p}_\mathrm{r}\right\|_2 = \mathrm{c}\left(t - t_0^{(\kappa)}\right) \ , \tag{2}$$

where c is the speed of light and $\|\cdot\|_2$ the EUCLIDIAN norm.

An approximate location $\mathbf{p}_\mathrm{a} \in \mathbb{R}^3$ and time t_a can be supplied by the assistance data and utilized to calculate the integer multiple $\varsigma^{(\kappa)}$. Solving (2) and (1) for $\varsigma^{(\kappa)}$ yields

$$\varsigma^{(\kappa)} = \frac{1}{L\,T_\mathrm{c}}\left(t_0^{(\kappa)} - \tau^{(\kappa)} - t_\epsilon^{(\kappa)}\right) = \frac{1}{L\,T_\mathrm{c}}\left(t - \frac{\rho^{(\kappa)}}{\mathrm{c}} - \tau^{(\kappa)} - t_\epsilon^{(\kappa)}\right). \tag{3}$$

Inserting the approximate distance between each satellite and the receiver

$$\rho^{(\kappa)} \simeq \left\|\mathbf{p}_\mathrm{s}^{(\kappa)} - \mathbf{p}_\mathrm{a}\right\|_2 \,, \tag{4}$$

as well as the approximate time

$$t \simeq t_\mathrm{a} \tag{5}$$

into (3) and rounding to the nearest integer, denoted by $\langle\cdot\rangle$, resolves the ambiguity

$$\varsigma^{(\kappa)} = \left\langle \frac{1}{L\,T_\mathrm{c}}\left(t_\mathrm{a} - \frac{\left\|\mathbf{p}_\mathrm{s}^{(\kappa)} - \mathbf{p}_\mathrm{a}\right\|_2}{\mathrm{c}} - \tau^{(\kappa)} - t_\epsilon^{(\kappa)}\right)\right\rangle \ . \tag{6}$$

Component name	Modulation scheme	Carrier frequency f_c [MHz]	Spreading chip period T_c [μs]	Primary code length L [chips]	Secondary code length U [chips]	Data bit period T_d [ms]	Combined code duration $U\,L\,T_\mathrm{c}$ [ms]
Galileo E1-B	BOC(1, 1)	1575.42	1/1.023	4092	none	4	4
Galileo E1-C	BOC(1, 1)	1575.42	1/1.023	4092	25	pilot	100
Galileo E5a-I	BPSK(10)	1176.45	1/10.23	10230	20	20	20
Galileo E5a-Q	BPSK(10)	1176.45	1/10.23	10230	100	pilot	100
Galileo E5b-I	BPSK(10)	1207.14	1/10.23	10230	4	4	4
Galileo E5b-Q	BPSK(10)	1207.14	1/10.23	10230	100	pilot	100
Galileo E6-B	BPSK(5)	1278.75	1/5.115	5115	none	1	1
Galileo E6-C	BPSK(5)	1278.75	1/5.115	5115	100	pilot	100
GPS L1-C/A	BPSK(1)	1575.42	1/1.023	1023	none	20	1
GPS L2-CM	BPSK(1)	1227.60	1/0.5115	10230	none	20	10
GPS L2-CL	BPSK(1)	1227.60	1/0.5115	767250	none	pilot	1500
GPS L5-I	BPSK(10)	1176.45	1/10.23	10230	10	10	10
GPS L5-Q	BPSK(10)	1176.45	1/10.23	10230	20	pilot	20

Table 1. Galileo and GPS civilian code lengthes (GPS JPO 2005), (Galileo JU 2006), (GPS JPO 2006).

The tolerable errors for the approximate location and time are

$$\left| t_\mathrm{a} - \frac{\left\| \mathbf{p}_\mathrm{s}^{(\kappa)} - \mathbf{p}_\mathrm{a} \right\|_2}{\mathrm{c}} - t + \frac{\rho^{(\kappa)}}{\mathrm{c}} \right| < \frac{L\,T_\mathrm{c}}{2}\,. \tag{7}$$

Since $\mathrm{c}\,L\,T_\mathrm{c}$ equals 300 km for the GPS L1-C/A code, the cell location of the mobile phone and an approximate time with some 100 μs accuracy is already sufficient. This timing accuracy can be provided by most cellular communication networks (Syrjärinne 2001).

The longer Galileo spreading codes yield further relaxed requirements on the approximate location and time. The maximum radius for a GSM/EDGE cell is 35 km, which however only occurs in sparsely populated rural areas. Furthermore, the term $\rho^{(\kappa)} - \left\| \mathbf{p}_\mathrm{s}^{(\kappa)} - \mathbf{p}_\mathrm{a} \right\|_2$ in (7) calculates the geometric difference in path length. It decreases with rising satellite elevation angle, assuming that there is little difference in altitude between the approximate location and the actual location. For the case of a rather large 10 km difference in path length, there is a 33 μs difference in propagation time. Hence, this factor has to be subtracted from the code duration when determining the timing accuracy requirements. The maximum distance to a GSM/EDGE base station for the case of a satellite with a very low elevation angle yields up to 100 μs timing error. A sufficiently accurate approximate time t_a can also be obtained if just one satellite signal is strong enough to align the navigation message from the assistance data with the navigation message from the satellite signal (Schmid 2007).

Table 1 provides an overview of the Galieo and modernized GPS code lengthes. It can be seen that the new pilot signals offer very long combined spreading codes durations. All Galileo pilot signals provide code periods of 100 ms, while the GPS L2-CL code even extends to 1.5 s. This relaxes the accuracy requirements for the approximate time t_a substantially. Up to a maximum of 100 μs might have to be subtracted for the distance to a cellular base station which serves as approximate location. A timing accuracy of 49.9 ms is hence required for all

Galileo bands, while this requirement varies from 0.49 ms for GPS L1-C/A to 749.9 ms for GPS L2-CL. The secondary spreading codes of the pilot signals also increase the acquisition search space substantially. However, since the chipping rate of the secondary codes is rather low with 1–4 ms its acquisition can effectively be aided by assistance data as well.

4. POSITION SOLUTION

The precise system time t is typically unknown. If $K \geq 4$ satellites are visible, the receiver position $\mathbf{p}_\mathrm{r}$ and time t can be estimated with the nonlinear Weighted Least Square Error (WLSE) estimation

$$\begin{aligned}
\left(\widehat{\mathbf{p}}_\mathrm{r},\, \widehat{t}\,\right) &= \underset{\substack{\widehat{\mathbf{p}}_\mathrm{r} \in \mathbb{R}^3 \\ \widehat{t} \in \mathbb{R}}}{\operatorname{argmin}} \sum_{\kappa=1}^{K} \frac{1}{\sigma^2_{\widehat{\rho}^{(\kappa)}}} \left(\widehat{\rho}^{(\kappa)} - \left\|\mathbf{p}_\mathrm{s}^{(\kappa)} - \widehat{\mathbf{p}}_\mathrm{r}\right\|_2\right)^2 \\
&= \underset{\substack{\widehat{\mathbf{p}}_\mathrm{r} \in \mathbb{R}^3 \\ \widehat{t} \in \mathbb{R}}}{\operatorname{argmin}} \sum_{\kappa=1}^{K} \frac{1}{\sigma^2_{\widehat{\rho}^{(\kappa)}}} \left(\mathrm{c}\left(\widehat{t} - t_0^{(\kappa)}\right) - \left\|\mathbf{p}_\mathrm{s}^{(\kappa)} - \widehat{\mathbf{p}}_\mathrm{r}\right\|_2\right)^2 \qquad (8) \\
\left(\widehat{\mathbf{p}}_\mathrm{r},\, \widehat{t}\,\right) &= \underset{\substack{\widehat{\mathbf{p}}_\mathrm{r} \in \mathbb{R}^3 \\ \widehat{t} \in \mathbb{R}}}{\operatorname{argmin}} \sum_{\kappa=1}^{K} \frac{1}{\sigma^2_{\widehat{\rho}^{(\kappa)}}} \left(\mathrm{c}\left(\widehat{t} - \varsigma^{(\kappa)}\, L\, T_\mathrm{c} - \tau^{(\kappa)} - t_\epsilon^{(\kappa)}\right) - \left\|\mathbf{p}_\mathrm{s}^{(\kappa)} - \widehat{\mathbf{p}}_\mathrm{r}\right\|_2\right)^2 .
\end{aligned}$$

The variance of the estimated satellite to receiver distance is denoted by $\sigma^2_{\widehat{\rho}^{(\kappa)}}$ and can be estimated by the receiver, e.g. with signal-to-noise ratio measurements (Axelrad and Brown 1996). The receiver time $\widehat{t}$ and location $\widehat{\mathbf{p}}_\mathrm{r}$ are calculated with (8). The integer multiples $\varsigma^{(\kappa)}$ are calculated with (3). The satellite clock differences $t_\epsilon^{(\kappa)}$ and the satellite locations $\mathbf{p}_\mathrm{s}^{(\kappa)}$ are derived from the assistance data. The only task left for the Assisted-Galileo/GPS receiver is hence to estimate the code delays $\tau^{(\kappa)}$ (Sirola and Syrjärinne 2002), (Kaniuth *et al.* 2005). In order to provide high availability for emerging applications in urban environments, code phase estimations have to be performed for low signal-to-noise ratios (Schmid *et al.* 2005), (Schmid 2007). The more code delays that can be estimated, the more accurate the position fix.

5. CONCLUSION

Location based services and emergency caller location mandates like E-911 and E-112 require a high level of positioning availability in deep urban and moderate indoor environments. Enhancing the reception sensitivity is a prerequisite for Galileo/GPS receivers in these environments. At the same time, low positioning latency is also required. Aiding the satellite receiver is key to improving the sensitivity and reducing the latency. Assistance data delivers the ephemeris parameters to enable fast spreading code acquisition. Single shot positioning furthermore relieves the receiver from the requirement to synchronize with the navigation message. The task of the Galileo/GPS receiver can then be reduced to the measurement of the spreading code phases. This not only further reduces the latency and power consumption of the receiver, it also permits the reception of substantially weaker signals. Sensitivity increases when the noncoherent integration time is extended beyond the data bit periods, but the navigation message can no longer be received. The combination of assistance data and single shot positioning yields the navigation solution in this situation. This paper elaborates on such a single shot positioning algorithm. The position solution is thereby derived from an approximate location and time in combination with at least four code phase measurements. The resulting accuracy requirements for the approximate time and location are derived for the civilian Galileo and modernized GPS signals.

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