Improving Position Accuracy by Combined Processing of Galileo and GPS Satellite Signals

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Abstract—In the future, the American GPS and the European Galileo Satellite Systems together will offer around 60 satellites for positioning and navigation. Despite technical differences between these two systems, the commonality of the center frequencies they use creates the potential to develop an interoperable navigation satellite receiver. Firstly, we evaluate the performance of both systems separately in terms of position accuracy. In order to assess the position accuracy, we describe the influence of the main error sources on the position solution. Furthermore, we will investigate the impact of the geometry of the satellite constellation relative to the user position. Finally, we will show the accuracy capability for a combined processing of Galileo and GPS signals.

I. INTRODUCTION

The analysis concentrates on the theoretical potential performance of the baseline signals of Galileo and the modernised signals of GPS in terms of positioning accuracy. The absolute positioning accuracy is evaluated on the basis of the overall error budget. Consequently, its main error contributions will be analysed in detail. These error sources are e.g. code-tracking, atmosphere and multipath effects. The atmospheric error is caused by the ionosphere and the troposphere. The influence of the ionosphere will be assessed using the Klobuchar model in order to estimate the propagation delay of the satellite signals passing the ionosphere. These results will be compared with the ionospheric data of the International GPS Service (IGS). Similarly, the IGS data centers have precise information about the tropospheric delay, which will be compared with the results of the MOPS model (Minimum Operational Performance Standard). If the ionospheric effect is eliminated, the main source of error that remains is due to multipath. Its performance is studied in detail, comparing the Narrow Correlator and the Double-Delta Correlator. In addition, we will apply a multipath model that considers statistical distributions of multipath geometric path delays and relative amplitudes. Another source of error is the thermal noise at the receiver. The code-tracking error due to thermal noise will be estimated by calculating the Cramer-Rao lower bound for the tracking error variance. Finally, the results of our investigations show the potential accuracy of the GPS and Galileo services alone and of a combined Galileo/GPS system. Two examples are considered for the combination of both systems: the Galileo Public Regulated Service (PRS) together with the GPS M-Code and the L1 Open Service (OS) signal combined with the modernized GPS L1C signal.

II. GNSS SIGNALS

The modernized GPS and Galileo system transmit various signals that make it possible for military and civilian users to determine their position on Earth. The signals are broadcast using the binary phase shift keying (BPSK)\(^1\) and the binary offset carrier (BOC)\(^2\) modulation. The normalized (unit power) power spectral density of a baseband signal with BPSK modulation can be expressed as:

\[
G_{\text{BPSK}(f)}(f) = f_c \cdot \left( \frac{\sin(f T_s)}{\pi f} \right)^2 ,
\]

with \(f_c\) = spreading code rate. The BOC signals can be described by a BPSK signal multiplied with a square wave subcarrier. The form of the power spectral density depends on both the ratio \(k\) and the phase angle \(\phi\) [1]:

\[
k = \frac{T_c}{T_s} \quad (2)
\]

with \(T_c\) = chip period and \(T_s = 1/2f_s\) half-period of a square wave generated with frequency \(f_s\).

\[
g_{\text{BOC}}(t) = g_{\text{BPSK}}(t) \cdot \text{sgn} [\sin(\pi t/T_s + \phi)]
\]

with \(g(t)\) = spreading symbol and \(\phi\) = phase angle. For \(\phi = 0^\circ\) and \(90^\circ\) the BOC signals are called sine-phased and cosine-phased, respectively.

\[
G_{\text{BOC}_{\text{sine}}(f_c,f_s)}(f) = \begin{cases} f_c \cdot \left( \frac{\sin(\pi f)}{\pi f} \right)^2, & \text{k even} \\ f_c \cdot \left( \frac{\cos(\pi f)}{\pi f} \right)^2, & \text{k odd} \end{cases} \quad (3)
\]

\[
G_{\text{BOC}_{\text{cosine}}(f_c,f_s)}(f) = \begin{cases} 4f_c \cdot \left( \frac{\sin(\pi f)}{\pi f} \right)^2, & \text{k even} \\ 4f_c \cdot \left( \frac{\cos(\pi f)}{\pi f} \right)^2, & \text{k odd} \end{cases} \quad (4)
\]

The GPS M-code utilizes a BOC(10.5)\(^3\) sine modulation for both signals on L1 (\(f_{\text{carrier}} = 1575.42\) MHz) and L2 (\(f_{\text{carrier}} = 1227.6\) MHz) [2].

\(^1\)BPSK(n) describes a signal with binary phase shift keying modulation and spreading code rate \(n \times 1.023\) MHz.

\(^2\)BOC(m,n) describes a signal using binary offset carrier modulation with subcarrier frequency \(m \times 0.5105\) MHz and spreading code rate \(n \times 1.023\) MHz.
The Galileo PRS consists of a BOC(15,2.5)cosine signal on L1 and a BOC(10,5)cosine signal on E6 \((f_{\text{carrier}} = 1278.75 \text{ MHz})\). The new L1C and the L1 Open Service signal were optimized and recommended by the GPS-Galileo Working Group A (WG A) [3], [4], [5]. The signal uses a multiplexed binary offset carrier modulation technique (MBOC), whose normalized (unit power) power spectral density, without the effect of bandlimiting filters and payload imperfections, is given by:

\[
G_{\text{MBOC}(6,1,1/11)}(f) = \frac{10}{\pi} \text{BOC}(1,1) + \frac{1}{\pi} \text{BOC}(6,1)
\]  

Most of the energy is contained in the BOC(1,1) signal part, as can be seen from equation (6). The spectra of the signals are shown in Figure 1.

**III. ERROR BUDGET**

The receiver measures the pseudoranges \(\rho\) to all satellites in view. With the observations of at least four satellites the user can calculate its own position \(\vec{x}_{\text{user}} = (x, y, z, t)^T\). However, the pseudorange measurements are affected by systematic and non-systematic errors. In order to estimate the positioning accuracy, the influence of the different error sources has to be considered. The error sources can be classified into the following groups.

1) Clock bias
2) Orbit error
3) Tropospheric refraction
4) Ionospheric refraction
5) Multipath effects
6) Code-Tracking error

In the following, the error sources are explained in more detail and estimates of the contribution to the overall error budget are given. Considering all error sources above-mentioned the fundamental error equation is given by [6]:

\[
G \cdot \Delta \vec{x} = c \cdot (-\Delta \vec{B} + \Delta \vec{I} + \Delta \vec{T} - \vec{v}) + \Delta \vec{R} \equiv \Delta \vec{\rho} \quad (7)
\]

with \(G = \) geometry matrix, \(\Delta \vec{x} = \) positioning error, \(\Delta \vec{B} = \) satellite clock error, \(\Delta \vec{I} = \) tropospheric delay, \(\Delta \vec{T} = \) ionospheric delay, \(\vec{v} = \) multipath and noise errors, \(\Delta \vec{R} = \) orbit error and \(\Delta \vec{\rho} = \) pseudorange error.

Equation (7) describes the general relation between pseudorange errors and positioning errors. From equation (7) the positioning error is given by \(\Delta \vec{x}\):

\[
\Delta \vec{x} = G^{-1} \Delta \vec{\rho} \quad \text{for } k = 4
\]

\[
\Delta \vec{x} = (G^T G)^{-1} G^T \Delta \vec{\rho} \quad \text{for } k > 4
\]

with \(k = \) number of satellites.

Equation (9) utilizes the pseudoinverse of matrix \(G\) to describe the relation between pseudorange errors and positioning errors. Thus, the positioning error depends on both the satellite constellation relative to the user position \((G^T G)^{-1} G^T\) and on the pseudorange errors \(\Delta \vec{\rho}\). The error covariance matrix \(\Sigma_{\text{ecef}}\) for the user position is given by:

\[
\Sigma_{\text{ecef}} = \sigma_R^2 \cdot (G^T G)^{-1} \quad (10)
\]

with the covariance of pseudorange errors \(\Sigma(\Delta \vec{\rho}) = I \cdot \sigma_R^2\).

According to the law of covariance propagation [7] the covariance matrix in a local system East, North and Up (ENU) can be expressed as:

\[
\Sigma_{\text{enu}} = F \cdot \Sigma_{\text{ecef}} \cdot F^T
\]

The matrix \(F\) connects the cartesian coordinates in the local system (ENU) at latitude \(\phi\) and longitude \(\lambda\) and the ECEF coordinates:

\[
F = \begin{bmatrix}
-\sin(\lambda) & \cos(\lambda) & 0 \\
-\sin(\phi) \cos(\lambda) & -\sin(\phi) \sin(\lambda) & \cos(\phi) \\
\cos(\phi) \cos(\lambda) & \cos(\phi) \sin(\lambda) & \sin(\phi)
\end{bmatrix}.
\]

\section{A. Clock and Orbit Errors}

The clock and orbit errors are often described together as Signal-in-Space Ranging Error (SISRE). The magnitude of the clock and orbit errors is effected by the number of monitoring stations around the world. For the present GPS constellation we will consider a value of 0.5 m in our analysis [8]. The contribution of clock and ephemeris errors to the error budget of the Galileo system is predicted to be less than 0.65 m [9].
B. Tropospheric Error

The troposphere is nondispersive for frequencies up to 15 GHz and produces delay effects which are in general on the range of $2 - 25$ m. The effect varies with the elevation angle because lower elevation angles produce a longer path length through the troposphere. The troposphere consists of dry gases and water vapor and is often modeled as a dry and wet component. Whereas the dry component can be predicted very accurately, the water vapor density varies widely with position and time. Due to the nature of the water vapor content, the delay of the wet component is more difficult to predict. Fortunately, the water vapor effect represents only about 10% of the total. In our simulations, we applied the MOPS model to estimate the tropospheric delay for a specific day and place. The MOPS algorithm does not require any input data from meteorological sensors but utilizes statistic meteorological data dependent on latitude and takes seasonal variations into account. The dry and wet components are computed using five parameters: pressure, temperature, water vapor pressure, temperature lapse rate and water vapor lapse rate [1]. For reference data, we used the tropospheric delay values from several IGS data centers around the earth. Table I shows the residual tropospheric errors (bias, standard deviation and maximum error) for different elevation angles.

I the average tropospheric deviation is $\sigma_{\text{tropo}} = 118$ mm for an elevation angle of $\zeta = 30^\circ$, which is used in the analysis for the tropospheric error.

C. Ionospheric Error

The ionospheric delay is one of the biggest contributors in the single-frequency receiver error budget. The free electrons in the ionosphere influence the electromagnetic wave propagation of the broadcasted satellite signals. The resulting ionospheric group delay shows a dispersive character and can be expressed in meters as:

$$e_{\text{iono}} = \frac{40.28}{f^2} \int N_e dl$$  \hspace{1cm} (13)

with $\int N_e dl$ referred to as Total Electron Content (TEC), expressed in [el/m²] and integrated along the path between user and satellite. In order to estimate the ionospheric error, we used data provided by the International GPS Service (IGS) for the years 2003 to 2007 as reference. The data contains the precise vertical TEC values (VTEC) with a sampling interval of two hours. The ionospheric group delay is calculated for the Earth surface on an interpolated grid $1^\circ \times 1^\circ$ and is compared with the results of the Klobuchar-Model, which is the broadcast model of GPS [10], [11]. The simulation results for the residual ionospheric error are shown in Figures 2-6.

<table>
<thead>
<tr>
<th>Station</th>
<th>$\zeta = 90^\circ$</th>
<th>$\zeta = 30^\circ$</th>
<th>$\zeta = 10^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOGT</td>
<td>-30 / 23 / 134</td>
<td>-60 / 46 / 268</td>
<td>-169 / 127 / 750</td>
</tr>
<tr>
<td>PTBB</td>
<td>12 / 35 / 168</td>
<td>25 / 70 / 335</td>
<td>70 / 195 / 938</td>
</tr>
<tr>
<td>DARW</td>
<td>-11 / 90 / 210</td>
<td>-21 / 180 / 420</td>
<td>-60 / 504 / 1176</td>
</tr>
<tr>
<td>HYDE</td>
<td>-61 / 82 / 208</td>
<td>-123 / 163 / 415</td>
<td>-345 / 458 / 1164</td>
</tr>
<tr>
<td>KSMV</td>
<td>-42 / 82 / 135</td>
<td>-83 / 163 / 270</td>
<td>-232 / 456 / 756</td>
</tr>
<tr>
<td>NRIL</td>
<td>-30 / 36 / 119</td>
<td>-60 / 71 / 237</td>
<td>-169 / 197 / 663</td>
</tr>
<tr>
<td>RBAY</td>
<td>-6 / 59 / 143</td>
<td>-13 / 118 / 285</td>
<td>-35 / 332 / 798</td>
</tr>
<tr>
<td>THTI</td>
<td>-9 / 58 / 168</td>
<td>-18 / 115 / 334</td>
<td>-51 / 321 / 935</td>
</tr>
</tbody>
</table>
The variation in time of the ionospheric error results from the sunspot activity. The remaining residual error after correction with the Klobuchar model is used to calculate the contribution of the ionospheric error to the error budget (see Table II).

<table>
<thead>
<tr>
<th>Year</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation $\zeta = 90^\circ$</td>
<td>1.72 m</td>
<td>1.22 m</td>
<td>1.03 m</td>
<td>0.84 m</td>
<td>0.72 m</td>
</tr>
<tr>
<td>Elevation $\zeta \approx 30^\circ$</td>
<td>2.77 m</td>
<td>1.97 m</td>
<td>1.66 m</td>
<td>1.34 m</td>
<td>1.15 m</td>
</tr>
<tr>
<td>Elevation $\zeta = 10^\circ$</td>
<td>4.38 m</td>
<td>3.10 m</td>
<td>2.61 m</td>
<td>2.14 m</td>
<td>1.87 m</td>
</tr>
</tbody>
</table>

A double-frequency receiver can eliminate the ionospheric error by combining pseudorange measurements $PR_1, PR_2$ from two different carrier frequencies. The ionosphere-free pseudorange $PR$ is obtained according to:

$$PR = \frac{\gamma}{\gamma - 1} \cdot PR_1 - \frac{1}{\gamma - 1} \cdot PR_2$$  \hspace{1cm} (14)

with $\gamma = (f_1/f_2)^2 > 1$ and $f_i =$ carrier frequency.

### D. Code-Tracking Error

The ability of the code-tracking loop to mitigate thermal noise can be described by the Cramer-Rao Lower Bound (CRLB). The CRLB specifies the lower bound for the code-tracking variance, given by [1]:

$$\sigma_{\text{crlb}}^2 = \frac{B_n}{(2\pi)^2 \cdot C/N_0 \cdot f^2 \cdot S(f) df}$$ \hspace{1cm} (15)

with $B_n =$ noise bandwidth , $C/N_0 =$ carrier power to noise density ratio , $B =$ signal bandwidth, $f =$ frequency and $S(f) =$ frequency spectrum.

As mentioned in section III-C, the ionospheric error can be eliminated by linear combination of two frequencies. The ionosphere-free pseudorange is given in equation (14). Due to the combination of two uncorrelated measurements the code-tracking error propagates according to:

$$\sigma_{\text{dual}}^2 = \frac{\gamma^2}{(\gamma - 1)^2} \cdot \sigma_{PR_1}^2 + \frac{1}{(\gamma - 1)^2} \cdot \sigma_{PR_2}^2$$ \hspace{1cm} (16)

with $\gamma = (f_1/f_2)^2 > 1$. In Table III the contributions of the code-tracking error to the single-frequency and double-frequency receiver error budget are given.

### Table III

<table>
<thead>
<tr>
<th>Signal</th>
<th>Modulation</th>
<th>Bandwidth</th>
<th>$C/N_0 = 45$ dBHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1C, L1(OS)</td>
<td>MBOC(6,1,1/11)</td>
<td>8 MHz</td>
<td>0.246 m</td>
</tr>
<tr>
<td>L1C, L1(OS)</td>
<td>MBOC(6,1,1/11)</td>
<td>16 MHz</td>
<td>0.112 m</td>
</tr>
<tr>
<td>M-Code</td>
<td>BOC(10,5)$_{\text{cosec}}$</td>
<td>30 MHz</td>
<td>0.031 m</td>
</tr>
<tr>
<td>PRS E1A</td>
<td>BOC(15,2.5)</td>
<td>40 MHz</td>
<td>0.021 m</td>
</tr>
<tr>
<td>PRS E6A</td>
<td>BOC(10,5)$_{\text{cosec}}$</td>
<td>40 MHz</td>
<td>0.031 m</td>
</tr>
<tr>
<td>M-Code</td>
<td>BOC(10,5)$_{\text{cosec}}$</td>
<td>30 MHz</td>
<td>0.092 m</td>
</tr>
<tr>
<td>PRS E1A</td>
<td>BOC(15,2.5)</td>
<td>40 MHz</td>
<td>0.085 m</td>
</tr>
<tr>
<td>PRS E6A</td>
<td>BOC(10,5)$_{\text{cosec}}$</td>
<td>40 MHz</td>
<td>0.085 m</td>
</tr>
</tbody>
</table>
E. Multipath Error

The GPS and Galileo system are both CDMA based. Due to spreading, a CDMA based system is capable of reducing the multipath influence on the positioning error. Virtually all echoes whose delays are greater than the chip duration can be canceled completely. We use the model depicted in Figure 8 to investigate the influence of delayed signal reflections.

The model consist of the line-of-sight signal (LOS) and one specular reflection. The reflected signal experiences a delay $\Delta \tau$, an attenuation $\alpha$ and a phase shift $\Delta \phi$. At the receiver, the incoming signal is correlated with an early ($E$) and late ($L$) copy of the code sequence. Due to the influence of the reflected signal the S-curve will be distorted. Thus the DLL of the receiver will usually detect a wrong propagation delay which leads to an inaccurate pseudorange. We simulated the DLL offset for two different discriminator functions. The discriminator function of the Narrow-Correlator is given by:

$$D_{\text{Narrow}} = E_1 - L_1$$  \hspace{1cm} (17)

The distance between early and late correlator is $d_{E_1L_1} = 0.05$ and $d_{E_2L_2} = 0.1$ chips. The discriminator function of the $\Delta\Delta$-Correlator consists of two pairs of correlators and is defined as:

$$D_{\Delta\Delta} = (E_1 - L_1) - \frac{1}{2} \cdot (E_2 - L_2)$$  \hspace{1cm} (18)

The distances between the early and late correlators are $d_{E_1L_1} = 0.1$ chips and $d_{E_2L_2} = 0.2$ chips. Considering an attenuation of 3 dB and a phase shift of 0° and 180° for the reflected signal, we obtain the error envelopes $E(\tau)$ shown in Figure 9 - 12.

For all other phases, the multipath error is smaller (bounded by the envelopes). In order to represent a more realistic multipath szenario we consider the distributions of path delays and relative amplitudes for a rural environment. The typical path delay for the rural channel is $\tau_0 = 90$ m. The normalized multipath probability density function $D(\tau)$ is described by:

$$D(\tau) = \frac{3 \cdot e^{-\frac{3\tau}{\tau_0}}}{2\tau_0}$$  \hspace{1cm} (19)
We calculate the multipath error $e_{mp}$ according to:

$$ e_{mp} = \frac{1}{2} \int_0^\infty \left[ E_{\text{max}}(\tau) + E_{\text{min}}(\tau) \right] \cdot D(\tau) d\tau $$

(20)

with $E_{\text{max}}, E_{\text{min}}$ = maximum and minimum multipath envelopes. The estimates of the multipath error are summarized in Table IV for single-frequency and double-frequency receivers (refer to equation (16)).

Table IV
MULTIPATH ERRORS FOR SINGLE- AND DOUBLE-FREQUENCY RECEIVERS IN A RURAL ENVIRONMENT

<table>
<thead>
<tr>
<th>Signal</th>
<th>Modulation</th>
<th>Bandwidth</th>
<th>Narrow</th>
<th>$\Delta \Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1C(OS)</td>
<td>MBOC(6,1/11)</td>
<td>8 MHz</td>
<td>0.77 m</td>
<td>0.434 m</td>
</tr>
<tr>
<td>L1C(OS)</td>
<td>MBOC(6,1/11)</td>
<td>16 MHz</td>
<td>0.225 m</td>
<td>0.159 m</td>
</tr>
<tr>
<td>M-Code</td>
<td>BOC(10.5)$_{siss}$</td>
<td>30 MHz</td>
<td>0.0625 m</td>
<td>0.06 m</td>
</tr>
<tr>
<td>E1,E4</td>
<td>BOC(15.2,5)</td>
<td>40 MHz</td>
<td>0.0579 m</td>
<td>0.0585 m</td>
</tr>
<tr>
<td>E6,A</td>
<td>BOC(10.5)$_{cosine}$</td>
<td>40 MHz</td>
<td>0.0519 m</td>
<td>0.0468 m</td>
</tr>
<tr>
<td>M-Code</td>
<td>BOC(10.5)</td>
<td>30 MHz</td>
<td>0.185 m</td>
<td>0.178 m</td>
</tr>
<tr>
<td>E1,E4</td>
<td>BOC(15.2,5)</td>
<td>40 MHz</td>
<td>0.197 m</td>
<td>0.193 m</td>
</tr>
</tbody>
</table>

IV. DILUTION OF PRECISION

Before we can give estimations of positioning accuracy the Dilution of Precision (DOP) parameters have to be known. The DOP parameters describe the influence of the satellite constellation on positioning accuracy. The DOP values can be obtained from the matrix $(G^T G)^{-1}$ which depends on the satellite geometry relative to the user position. For the GPS constellation, real satellite positions were used whereas the Galileo constellation was simulated using nominal constellation parameters. Based on the data, we calculated the matrix $(G^T G)^{-1}$ for every point on earth ($1^\circ \times 1^\circ$ grid). The Figures 13 - 18 show the Vertical and Horizontal Dilution of Precision (VDOP, HDOP) values for GPS, Galileo and the combination of both systems. The elevation masking angle was varied from $\zeta_{\text{min}} = 5^\circ$ to $15^\circ$ and the results are summarized in Table V.

Table V
GLOBAL MEAN VERTICAL (VDOP) AND HORIZONTAL (HDOP) DILUTION OF PRECISION VALUES

<table>
<thead>
<tr>
<th>Year</th>
<th>VPE 95%</th>
<th>HPE 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBOC(6,1,1/11), GPS only</td>
<td>10.91 m</td>
<td>5.75 m</td>
</tr>
<tr>
<td>MBOC(6,1,1/11), GPS + Galileo</td>
<td>14.54 m</td>
<td>14.54 m</td>
</tr>
</tbody>
</table>

An interesting aspect of the MBOC(6,1,1/11) signal is the cooperation of the GPS and Galileo system. The signal defined by equation (6) will be transmitted by GPS and Galileo satellites, i.e. approx. 60 satellite vehicles. Although the power spectral density can be realised using different time waveforms, the signal can still be acquired and tracked utilising only the BOC(1,1) part. By combining GPS and Galileo the positioning error can be reduced - see Table VII.

Table VII
VERTICAL AND HORIZONTAL POSITIONING ACCURACIES $[m]$ FOR THE JOINTLY OPTIMIZED MBOC(6,1,1/11) SIGNAL WITH NARROW-CORRELATOR $(d = 0.05$ CHIPS $)$

<table>
<thead>
<tr>
<th>Signal</th>
<th>VPE 95%</th>
<th>HPE 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 2003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBOC(6,1,1/11), GPS only</td>
<td>10.91 m</td>
<td>5.98 m</td>
</tr>
<tr>
<td>MBOC(6,1,1/11), GPS + Galileo</td>
<td>8.26 m</td>
<td>4.86 m</td>
</tr>
<tr>
<td>Year 2007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBOC(6,1,1/11), GPS only</td>
<td>4.69 m</td>
<td>2.57 m</td>
</tr>
<tr>
<td>MBOC(6,1,1/11), GPS + Galileo</td>
<td>2.85 m</td>
<td>1.59 m</td>
</tr>
</tbody>
</table>

A double-frequency receiver can use the ionosphere-free pseudorange equation (14) and therefore eliminates the ionospheric error. By combining GPS and Galileo signals it is possible to reduce the positioning error even further - see Table VIII.

V. POSITIONING ACCURACY

Based on the values obtained from the analyses, we can calculate the error budget. In combination with the DOP values we are able to give estimates of the positioning accuracy - horizontal (HPE) and vertical (VPE). The pseudorange error $\sigma_R$ is considered to be:

$$ \sigma_R^2 = \sigma_{\text{siss}}^2 + \sigma_{\text{tropo}}^2 + \sigma_{\text{iono}}^2 + \sigma_{\text{crlb}}^2 + \sigma_{\text{mp}}^2 $$

(21)

For the ionospheric error the result from 2003 is used. The positioning accuracy is given in Table VI for a single-frequency receiver with masking angle $\zeta_{\text{min}} = 10^\circ$.
Figure 13. Mean horizontal DOP values for elevation angle $\zeta_{\text{min}} = 5^\circ$

Figure 14. Mean horizontal DOP values for elevation angle $\zeta_{\text{min}} = 10^\circ$

Figure 15. Mean horizontal DOP values for elevation angle $\zeta_{\text{min}} = 15^\circ$

Figure 16. Mean vertical DOP values for elevation angle $\zeta_{\text{min}} = 5^\circ$
VI. CONCLUSIONS

We have described the fundamental error sources of satellite navigation systems and their impact on positioning accuracy. We have shown the potential improvement in performance by combining the GPS and Galileo navigation systems. The main reason for the improvement is the better satellite constellation compared to each system alone. The combined satellite constellation results in a lower dilution of precision value which leads to a better position estimate.

REFERENCES


BIOGRAPHY

Ulrich Engel received the Dipl.-Ing. degree in Electrical Engineering from Aachen University of Technology (RWTH), Germany in 2006. During 2004 he was with the University of Surrey in Guildford, United Kingdom. Since 2006, he has been a research associate at the Research Establishment for Applied Science (FGAN) in Wachtberg. His work is on positioning and navigation and further research interests are in the field of global navigation satellite systems.