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Impact of the GNSS Time Offsets on Positioning Reliability

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Abstract

With the development of GPS, GLONASS, Galileo, Compass, QZSS and the IRNSS, there has been growing interest in the development of system independent receivers. However, one of the problems encountered in system independent receivers is in the different time systems employed by each of the satellite navigation systems.

To overcome this problem it has become a standard practice to solve for the time differences within the receiver's navigation solution via a combination of receiver clock corrections and/or time offsets. While this technique overcomes the problem of the different time systems, it is at the cost of a satellite from each additional time system. Despite this, the numerous studies that combine multiple satellite navigation systems this way have still found that there are significant benefits in improved accuracy, integrity, continuity and availability.

To enhance interoperability though satellite navigation system providers are intending to measure and transmit the time offsets to other time systems. The subsequent use of these time offsets will provide a more accurate navigation solution than without them. However, the problem with using the time offsets is that they pose an additional integrity risk because they are also potential sources of faults. However, with the use of the time offsets for multiple constellation solution, a proper Receiver Autonomous Integrity Monitoring method has not been developed.

Thus, mathematical models to account for the time differences with and without the time offsets are presented in this paper. Furthermore, the model that incorporates the time offset allows the application of Receiver Autonomous Integrity Monitoring to detect the presence of any faults within the time offsets. The reliability of the linear models is then compared using GPS and GLONASS geometry in terms of the Minimal Detectable Biases, Protection Levels and the correlation coefficients. The results of this analysis indicate that a more reliable solution can be obtained with the time offsets because they are additional measurements.

Keywords: GPS/GNSS, Time offset, Fault Detection, Reliability

1. Introduction

With the development of numerous satellite navigation systems, there has been growing interest in the development of system independent receivers. This is due to the significant benefits that the additional ranging sources can provide in improved satellite geometry, accuracy, integrity, continuity and availability (Rizos et al. 2005; Parkinson 2006; Hewitson and Wang 2006; Hofmann-Wellenhof et al. 2008).

However, one of the problems encountered in system independent receivers is in the different time systems employed by each of the satellite navigation systems. For instance, GPS is based on GPS Time, GLONASS on GLONASS Time (RSA 2008), Galileo on Galileo System Time (Hahn and Powers 2005), Compass on Compass Time (Lu 2008), QZSS on QZSS Time (JAXA 2011), and the IRNSS on IRNSS Network Time (Neelakantan 2010).

To overcome this problem it has become a standard practice to solve for the time differences within the receiver's navigation solution (Moudrak et al. 2005; EC 2011). Computationally, this has been carried out by either solving for an additional receiver clock correction for each additional time system (Feng, 2005; Hewitson and Wang 2006; Hofmann-Wellenhof et al. 2008; Wang and Kubo 2010), or by solving for a receiver clock correction and the offsets to the other time systems (Vanschoenbeek et al. 2007; Cai and Gao 2009).

It is based on this strategy, that the impact of multiple constellations on the performance of Receiver Autonomous Integrity Monitoring (RAIM) has been assessed (Hewitson and Wang 2006; Ji 2008). Nevertheless, it has been found that the use of multiple constellations results in smaller Minimal Detectable Biases (MDBs), smaller Protection Levels, and a reduction in the maximum correlation coefficient between the outlier statistics.

While solving for the time differences overcomes the problem of the different time systems, it is at the cost of a satellite from each additional time system (Hahn and Powers 2005). Hence, the minimum number of satellites is now four plus the number of additional time systems encountered.

To avoid the loss of a satellite from each additional time system and to enhance interoperability though the satellite navigation system providers are planning to measure and transmit the time offsets to other time systems (IS-GPS-200 2006; RSA 2008; Hahn and Powers 2005; Lu 2008; JAXA 2011). To use the broadcast time offsets though the receiver's inter system biases must also be taken into account. However, due to the long-term stability of the receivers' inter system biases (Cai and Gao 2009; Defraigne and Baire 2011) the broadcast time offsets, and their standard deviations, can simply be adjusted accordingly (Moudrak 2004a).

It should also be noted that if a user does not wish to use the broadcast time offsets then they could also use their own time offsets. This can be achieved by solving for the time offsets when there are a sufficient number of satellites and then employing these offsets at a later point in time (Moudrak et al. 2005; Vanschoenbeek et al. 2007).

Regardless of the source of the time offsets, it is desired to have the most precise time offsets possible since full interoperability is achieved when they are highly precise. In this case, the time offsets can be applied as errorless corrections to correct all of the pseudoranges to a common time system, and the navigation solution can be obtained by solving for a single receiver clock correction. The resulting positioning solution is then more precise, and has smaller DOPs, than if the time differences were solved for (Moudrak et al. 2004b; Yang et al. 2011). In addition, the positioning solution is also more reliable with smaller Minimal Detectable Biases and smaller Protection Levels (Hewitson and Wang 2006).

However, it appears that the time offsets cannot be obtained to a high enough precision to consider that they are errorless corrections (Hewitson and Wang 2006). For example, the broadcast time offset to GPS Time by GLONASS has a standard deviation of 9m (RSA 2008) which is comparable to the standard deviation of GPS and GLONASS pseudoranges. The broadcast time offsets to GPS Time by Galileo and QZSS have standard deviations of 0.75m and 1m respectively (Hahn and Powers 2005; JAXA 2011) which are comparable to the precision of dual frequency GPS, Galileo and QZSS pseudoranges (Martineau et al. 2009). In addition, it is also unlikely that a receiver could simply solve for the time offsets to a high enough precision.

Acknowledging the imprecision of the time offsets Vanschoenbeek et al. (2007) and Cai and Gao (2009) persist with solving for the time differences. Although rather than disregarding the time offsets, they include them as measurements within the navigation solution. Thus, enabling a position to be obtained with any four, or more, satellites that is more precise than without the time offsets. Although due to the imprecision of the time offsets, the position is not as precise as when the time systems are precisely synchronised.

The problem with using the time offsets though is that they are another potential source of faults that can pose an integrity risk to the navigation solution. It is due to this reason that Wang and Kubo (2010) advises against using the time offsets, to correct the pseudoranges to a common time system, since any fault within a time offset can potentially cause a systemic failure. What is not considered though is the case where the time offsets are treated as measurements within the navigation solution. Since this allows the application of RAIM, to detect and mitigate the presence of any faults within the time offsets.

Hence, it is the intention of this paper to present some methods of modelling the time differences, with and without the time offset, that allow the application of RAIM. Then, the reliability of these models is compared in terms of the MDBs, Protection Levels and the correlation coefficients. In addition, the comparison is carried out for the case where multiple biases are considered.

2. Modelling the Time Differences

The time differences between each of the satellite navigation systems can be accounted for by either solving for the time differences or employing the time offsets.

2.1 Solving for the time differences

The time differences between the satellite navigation systems can be solved via the addition of extra receiver clock corrections. Hence, observing GPS and GLONASS pseudoranges, ℓ_G and ℓ_R respectively, which have the variance covariance matrix

$$\mathbf{\Sigma} = \begin{bmatrix} \sigma_G^2 & 0 & \cdots & & \cdots & 0 \\ 0 & \ddots & \ddots & & & \vdots \\ \vdots & \ddots & \sigma_G^2 & & & \\ & & & \sigma_R^2 & \ddots & \vdots \\ \vdots & & & \ddots & \ddots & 0 \\ 0 & \cdots & & \cdots & 0 & \sigma_R^2 \end{bmatrix} \quad (1)$$

where σ_G and σ_R are the standard deviations of the GPS and GLONASS pseudoranges. The Gauss-Markov model can be expressed as (Hewitson and Wang 2006; Hofmann-Wellenhof et al. 2008; Wang and Kubo 2010)

$$\mathbf{v} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ & & & 1 & 0 \\ & & & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ t_G \\ t_R \end{bmatrix} - \begin{bmatrix} \ell_{G1} \\ \vdots \\ \ell_{Gm} \\ \ell_{Rm+1} \\ \vdots \\ \ell_{Rn} \end{bmatrix} \quad (2)$$

where $\mathbf{v}$ is the vector of residuals, a_{ij} is the i^{th} row and j^{th} column of the design matrix, x, y and z are the coordinate parameters, and t_G and t_R are the GPS and GLONASS receiver clock correction parameters.

2.2 Employing the time offsets

When employing the broadcast time offsets, they can be treated as additional measurements within the navigation solution. Hence, expanding the linear model in Eq. (2) with the broadcast time offset, ℓ_T, gives (Vanschoenbeek et al. 2007)

$$\mathbf{v} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ & & & 1 & 0 \\ & & & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & 0 & 1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ t_G \\ t_R \end{bmatrix} - \begin{bmatrix} \ell_{G1} \\ \vdots \\ \ell_{Gm} \\ \ell_{Rm+1} \\ \vdots \\ \ell_{Rn} \\ \ell_T \end{bmatrix} \quad (3)$$

where the variance covariance matrix of the measurements is

$$\mathbf{\Sigma} = \begin{bmatrix} \sigma_G^2 & 0 & \cdots & & & \cdots & 0 \\ 0 & \ddots & \ddots & & & & \vdots \\ \vdots & \ddots & \sigma_G^2 & & & & \\ & & & \sigma_R^2 & & & \\ & & & & \ddots & \ddots & \vdots \\ \vdots & & & & \ddots & \sigma_R^2 & 0 \\ 0 & \cdots & & & \cdots & 0 & \sigma_T^2 \end{bmatrix} \quad (4)$$

assuming that the time offset and the pseudoranges are uncorrelated, and that σ_T denotes the standard deviation of the time offset.

3. Comparing the Reliability

To compare the reliability of the linear models, with and without the broadcast time offset, consider the GPS and GLONASS geometry displayed in Fig. 1 where a large part of the sky is obscured. In addition, for the purposes of the simulated comparison it was assumed that the pseudoranges are weighted according to their satellite's elevation angle and that the GPS pseudoranges are 1.5 times more precise than the GLONASS pseudoranges. Furthermore, it was also assumed in this study that the standard deviation of the time offset is, 4.5m, which is similar to the pseudoranges at the elevation of 45 degree for the GPS satellites.

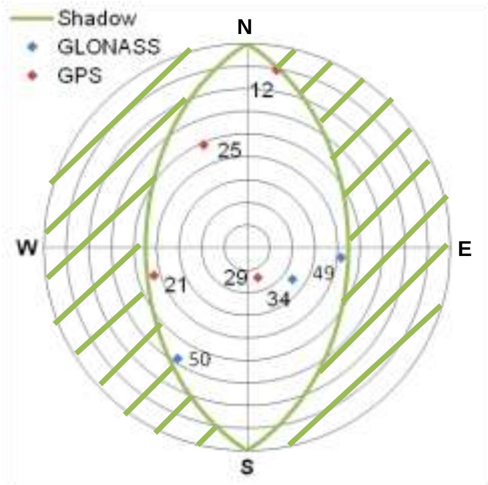

Figure 1: GPS and GLONASS Sky Plot

To detect the presence of one or more bias measurements it was considered that the chi-squared statistic,

$$T = \frac{\mathbf{v}^{\mathrm{T}} \mathbf{P}^{-1} \mathbf{v}}{\sigma_0^{\ 2}}, \quad (5)$$

was tested against the threshold $\chi^2_{1-\mathrm{P_{FA}},\, f}$, where f is the degrees of freedom, $\mathrm{P_{FA}}$ is the Probability of a False Alert, $\sigma_0^{\ 2}$ is the variance factor, and $\mathbf{P}$ is the weight matrix (Brown and Chin 1998; Knight et al. 2009; Wang and Kubo 2010). In this study, the Probability of a False Alert was set to 5% and the Probability of a Missed Detection, $\mathrm{P_{MD}}$, was set to 20%.

3.1 One bias measurement

If it is initially considered that there is at most a single bias measurement, then the MDBs are given by (e.g., Baarda 1967; Brown and Chin 1998)

$$\nabla_0 s_i = \sqrt{\frac{\lambda_0 \sigma_0^{\ 2}}{\mathbf{h}_i^{\ \mathrm{T}} \mathbf{PQ_v Ph}_i}} \tag{6}$$

where $\mathbf{h}_i$ is a vector of zeros with a one in the *i*th entry, $\mathbf{Q_v}$ is the cofactor matrix of the residuals, and λ_0 is the noncentral parameter that is given by (e.g., Brown and Chin 1998)

$$\chi^2_{1-\mathrm{P_{FA}},\, f} = \chi^2_{\mathrm{P_{MD}},\, f,\, \lambda_0} . \tag{7}$$

Therefore, calculating the MDBs for the geometry displayed in Fig. 1, with and without the time offset, gives the values displayed in Table 1. In addition, the MDBs for the situation where GPS Time is synchronised with GLONASS Time are also shown in Table 1.

Table 1: Minimal Detectable Bias (m)

SV	Solving	Offset	Sync.
12	79.60	68.70	65.28
21	23.80	25.30	25.29
25	43.60	40.02	38.51
29	39.92	22.20	20.03
34	33.07	22.96	21.14
49	31.05	32.97	32.95
50	44.04	46.67	46.62
ℓ_T		30.39	

From Table 1 it can be seen that the MDBs generally decrease with the use of the broadcast time offset. However, all of the MDBs decrease when the time systems are synchronised compared to when the time offset is employed. The synchronised MDBs though are not all smaller than the MDBs when the time differences are solved.

The reason for this can be explained from the equation for the MDB, which can be expressed as

$$\nabla_0 s_i = \sigma_{\nabla s_i} \sqrt{\lambda_0} \tag{8}$$

where $\sigma_{\nabla s_i}$ is the precision with which the bias can be solved. Calculating $\sigma_{\nabla s_i}$ yields the values displayed in Table 2 from which it can be seen that $\sigma_{\nabla s_i}$ improves with the time offset and further improves when the time systems are synchronised. However, the noncentral parameter increases with increasing degrees of freedom (Brown and Chin 1998; Wang and Kubo 2010). Thus, in this case the noncentral parameter increases from 9.63 to 10.90 when the time offset is employed and when the time systems are synchronised. It is due to this increase that any improvements within $\sigma_{\nabla s_i}$ can at times be cancelled out, causing the MDB to increase.

Table 2: Standard Deviation of the Bias (m)

SV	Solving	Offset	Sync.
12	25.64	20.81	19.77
21	7.67	7.66	7.66
25	14.05	12.12	11.66
29	12.86	6.72	6.07
34	10.65	6.95	6.40
49	10.00	9.98	9.98
50	14.19	14.14	14.12
ℓ_T		9.20	

The Horizontal and Vertical Protection Levels can be computed using (Brown and Chin 1998)

$$PL_i = \sqrt{\frac{\mathbf{h}_i^{\ \mathrm{T}} \mathbf{PA}(\mathbf{A}^{\mathrm{T}}\mathbf{PA})^{-1} \mathbf{CC}^{\mathrm{T}} (\mathbf{A}^{\mathrm{T}}\mathbf{PA})^{-1} \mathbf{A}^{\mathrm{T}} \mathbf{Ph}_i \lambda_0 \sigma_0^{\ 2}}{\mathbf{h}_i^{\ \mathrm{T}} \mathbf{PQ_v Ph}_i}} \tag{9}$$

where $\mathbf{C}$ is an appropriately constructed matrix of zeros and ones to select the parameters of interest. Thus, computing the Horizontal and Vertical Protection Levels for the three different situations yields the values displayed in Tables 3 and 4.

Table 3: Horizontal Protection Levels (m)

SV	Solving	Offset	Sync.
12	29.11	10.83	6.62
21	20.39	21.23	21.09
25	54.98	39.68	35.19
29	47.37	4.61	2.33
34	26.44	2.41	6.96
49	19.37	19.04	18.55
50	15.45	17.72	18.16
ℓ_T		25.61	
Max.	54.98	39.68	35.19

Table 4: Vertical Protection Levels (m)

SV	Solving	Offset	Sync.
12	77.05	38.83	28.64
21	4.53	6.47	6.98
25	44.24	16.69	8.83
29	5.74	43.53	50.71
34	66.65	10.45	0.75
49	35.51	34.72	33.77
50	38.41	44.76	45.98
ℓ_T		47.32	
Max.	77.05	47.32	50.71

From Tables 3 and 4 it can be seen that the Horizontal and Vertical Protection Levels generally decrease when the time offset is employed. Furthermore, the Protection Levels also tend to decrease when the time systems are synchronised. Despite this, the Protection Levels can increase due to larger MDBs and/or the mapping of the MDB onto the position. The maximum Horizontal and

Vertical Protection Levels though have a marked decrease when the time offset is employed. However, synchronisation of the time systems does not appear to result in a marked improvement and can actually increase the maximum Protection Level.

3.2 Two bias measurements

If two bias measurements are considered, then the Horizontal and Vertical Protection Levels can be obtained with (Angus 2006; Knight et al. 2009)

$$\boldsymbol{PL} = \sigma_0 \sqrt{\lambda_0 \lambda_{\mathbf{Max}}} \tag{10}$$

where λ_{Max} is the maximum eigenvalue of

$$\left(\mathbf{H}^{\mathrm{T}}\mathbf{PQ}_{\mathbf{v}}\mathbf{PH}\right)^{-1}\mathbf{H}^{\mathrm{T}}\mathbf{PA}(\mathbf{A}^{\mathrm{T}}\mathbf{PA})^{-1}\mathbf{C} \times \mathbf{C}^{\mathrm{T}}(\mathbf{A}^{\mathrm{T}}\mathbf{PA})^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{PHu} = \lambda\mathbf{u} \tag{11}$$

Thus, the Horizontal and Vertical Protection Levels when two biases are considered can be obtained as shown in Tables 5 and 6.

Table 5: Horizontal Protection Levels (m)

SV_i	SV_j	Solving	Offset	Sync.
12	21	35.46	24.16	22.65
12	25	59.86	58.55	58.03
12	29	58.89	10.84	8.45
12	34	6190.19	10.89	9.53
12	49	66.20	31.96	26.11
12	50	33.84	20.18	19.01
12	ℓ_T		39.99	
21	25	102.13	55.60	46.19
21	29	1571.15	23.69	24.62
21	34	27.26	21.80	22.41
21	49	40.02	40.32	39.64
21	50	201.17	166.58	157.42
21	ℓ_T		29.42	
25	29	158.78	39.68	36.21
25	34	101.13	39.68	35.99
25	49	56.68	40.86	36.12
25	50	154.55	94.74	84.00
25	ℓ_T		62.78	
29	34	51.78	8.25	8.63
29	49	74.52	21.37	18.70
29	50	235.95	18.86	20.57
29	ℓ_T		56.52	
34	49	26.63	23.64	26.35
34	50	26.63	17.77	18.86
34	ℓ_T		37.97	
49	50	26.63	28.66	28.81
49	ℓ_T		32.47	
50	ℓ_T		27.79	
Max.		6190.19	166.58	157.42

From Tables 5 and 6 it can be seen that the general trend continues with smaller Protection Levels when the time offset is employed and smaller still when the time systems are synchronised. However, there are still numerous situations where this trend is defied. In terms of the maximum Horizontal and Vertical Protection Levels, it is found that there is a significant improvement when the time offset is employed compared to the case of simply solving for the time differences. However, synchronisation of the time systems only results in a minor improvement upon the time offset values.

Table 6: Vertical Protection Levels (m)

SV_i	SV_j	Solving	Offset	Sync.
12	21	77.36	38.92	28.99
12	25	77.94	44.27	36.65
12	29	77.14	78.29	81.70
12	34	16210.97	41.24	28.72
12	49	155.13	78.04	63.53
12	50	100.14	70.16	63.48
12	ℓ_T		94.64	
21	25	71.29	18.10	8.96
21	29	47.72	48.36	55.15
21	34	68.11	13.01	6.98
21	49	40.21	38.14	36.73
21	50	287.27	267.67	261.32
21	ℓ_T		47.56	
25	29	67.36	47.76	53.82
25	34	138.93	19.69	8.99
25	49	56.85	38.12	34.61
25	50	182.89	102.11	88.08
25	ℓ_T		66.74	
29	34	68.00	70.35	74.26
29	49	40.10	49.97	55.91
29	50	252.69	83.43	86.59
29	ℓ_T		47.71	
34	49	69.64	35.94	39.42
34	50	69.64	45.04	46.25
34	ℓ_T		85.24	
49	50	69.64	75.28	75.70
49	ℓ_T		60.55	
50	ℓ_T		62.52	
Max.		16210.97	267.67	261.32

4. Correlation Coefficients between the Fault Detection Statistics

When one or more bias measurements are detected by Fault Detection, the aim of Exclusion is to identify and remove the offending measurements. However, the ease to which a bias measurement can be correctly identified is dependent on the correlation coefficients between the outlier detection statistics.

Table 7: Correlation Coefficients When Solving For the Time Difference

ρ	12	21	25	29	34	49	50
12	1.00000	0.14876	-0.68541	-0.12357	**0.99996**	-0.73122	-0.29477
21	0.14876	1.00000	**-0.82202**	**-0.99968**	0.13999	0.56577	**-0.98879**
25	-0.68541	-0.82202	1.00000	**0.80728**	-0.67893	0.00448	**0.89784**
29	-0.12357	-0.99968	0.80728	1.00000	-0.11477	-0.58655	**0.98467**
34	0.99996	0.13999	-0.67893	-0.11477	1.00000	-0.73724	-0.28629
49	-0.73122	0.56577	0.00448	-0.58655	-0.73724	1.00000	-0.43628
50	-0.29477	-0.98879	0.89784	0.98467	-0.28629	-0.43628	1.00000

Table 8: Correlation Coefficients When Employing the Time Offset

ρ	12	21	25	29	34	49	50	ℓ_T
12	1.00000	0.10027	**-0.77531**	0.44596	0.08686	-0.55535	-0.28825	0.58458
21	0.10027	1.00000	-0.69124	-0.55191	0.11771	0.56212	**-0.98159**	-0.03482
25	-0.77531	-0.69124	1.00000	-0.06682	0.00043	-0.02791	**0.81507**	-0.50547
29	0.44596	-0.55191	-0.06682	1.00000	-0.68493	-0.25240	0.43994	**0.85251**
34	0.08686	0.11771	0.00043	-0.68493	1.00000	-0.52798	-0.12147	**-0.75748**
49	-0.55535	0.56212	-0.02791	-0.25240	-0.52798	1.00000	-0.43920	0.06286
50	-0.28825	-0.98159	0.81507	0.43994	-0.12147	-0.43920	1.00000	-0.08548
ℓ_T	0.58458	-0.03482	-0.50547	0.85251	-0.75748	0.06286	-0.08548	1.00000

Table 9: Correlation Coefficients with Synchronised Time Systems

ρ	12	21	25	29	34	49	50
12	1.00000	0.08918	**-0.79375**	0.51664	-0.04575	-0.51644	-0.28851
21	0.08918	1.00000	-0.65961	-0.50628	0.11596	0.56098	**-0.97935**
25	-0.79375	-0.65961	1.00000	-0.17556	0.10694	-0.03644	**0.79635**
29	0.51664	-0.50628	-0.17556	1.00000	-0.73736	-0.21241	0.37584
34	-0.04575	0.11596	0.10694	-0.73736	1.00000	-0.49944	-0.09297
49	-0.51644	0.56098	-0.03644	-0.21241	-0.49944	1.00000	-0.44011
50	-0.28851	-0.97935	0.79635	0.37584	-0.09297	-0.44011	1.00000

To analyse the impact of the time offset, on the ability to identify an offending measurement, the correlation coefficients between the one-dimensional outlier detection statistics (called W-test) were computed with (Hewitson and Wang 2006; Knight et al., 2010)

$$\rho_{ij} = \frac{\mathbf{h}_i^{\mathrm{T}} \mathbf{P} \mathbf{Q}_{\mathrm{v}} \mathbf{P} \mathbf{h}_j}{\sqrt{\mathbf{h}_i^{\mathrm{T}} \mathbf{P} \mathbf{Q}_{\mathrm{v}} \mathbf{P} \mathbf{h}_i} \sqrt{\mathbf{h}_j^{\mathrm{T}} \mathbf{P} \mathbf{Q}_{\mathrm{v}} \mathbf{P} \mathbf{h}_j}} \quad (12)$$

and are displayed in Tables 7, 8 and 9.

From Tables 7, 8 and 9 it is noted that, in general, with the use of time offset or in the case of synchronized systems, the correlation coefficients are smaller than the case of solving the time-offset. Again, there are measurements, which have higher correlation. Thus, it is difficult to tell if there must a specific trend for all in the correlation coefficients between the three different models. However, the maximum correlation coefficient does reduce from 0.99996 to -0.98159 when the time offset is employed and reduces further to -0.97935 when the time systems are synchronised.

5. Concluding Remarks

A number of studies have analysed the impacts of multiple satellite navigation systems on the performance of integrated positioning and navigation solutions. The overall conclusions have been that the use of multiple satellite navigation systems results in significant improvements in reliability. However, these studies only consider that the time differences, between the satellite navigation systems, are solved within the receiver's navigation solution.

An alternate method of combining multiple satellite navigation systems is to employ the time offsets. Since satellite navigation system providers intend to measure and transmit the time offsets to other time systems. The problem with using the time offsets though is that they are another potential source of faults.

However, it has been shown that this risk can be safely mitigated by treating the time offsets as additional measurements within the navigation solution. Since this allows the application of RAIM, to detect the presence of any faults within the time offsets.

The more important finding was that the use of the time offsets results in a more reliable solution. This is because the time offsets are additional measurements that results in, overall, smaller MDBs, smaller Protection Levels, and a reduction in the maximum correlation coefficients between the outlier statistics. The usage of the time offsets has also been shown to be more reliable when multiple biases are considered.

Thus, it can be concluded that there is strong evidence that the time offsets should always be employed. Since they not only allow a more precise positioning solution to be obtained, with any four or more satellites, but also allow a more reliable solution to be obtained. The results also indicate that a more reliable solution could potentially be obtained if the time systems are synchronised.

The results presented here though are only initially results. Thus, future work includes a more complete analysis the benefits of the time offsets in terms of different satellite navigation systems and different operating environments. Besides integrity, this can also be carried out for accuracy, continuity and availability.

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References

Angus JE (2006) ***RAIM with Multiple Faults***. Nav. 53(4):249-257.

Baarda W (1967) ***Statistical Concepts in Geodesy. Netherlands Geodetic Commission, Publications on Geodesy***, New Series, Vol. 2, No. 4, Delft, Netherlands.

Brown RG, Chin GY (1998) ***GPS RAIM: Calculation of The Threshold and Protection Radius Using Chi-Square Methods - A Geometric Approach***. In: Global Positioning System, Vol. 5. The Institute of Navigation, Fairfax, Virginia, 155-178.

Cai C, Gao Y (2009) ***A Combined GPS/GLONASS Navigation Algorithm for use with Limited Satellite Visibility***. J. Nav. 62(4):671-685.

Defraigne P, Baire Q (2011) ***Combining GPS and GLONASS for Time and Frequency Transfer***. Adv. Space Res. 47(2):265-275.

EC (2011) ***EGNOS Safety of Life Service Definition Document,*** Version 1.0. European Commission, Directorate-General for Energy and Transport.

Feng Y (2005) **Future GNSS Performance, Predictions Using GPS with a Virtual Galileo Constellation.** GPS World, 16(3): 46-52.

Hahn JH, Powers ED (2005) ***Implementation of The GPS To Galileo Time Offset (GGTO).*** In: Frequency Control Symposium and Exposition, 29-31 August, Vancouver, Canada, 33-37.

Hewitson S, Wang J (2006) ***GNSS Receiver Autonomous Integrity Monitoring (RAIM) Performance Analysis***. GPS Solut. 10(3):155-170.

Hofmann-Wellenhof B, Lichtenegger H, Wasle E (2008) ***GNSS - Global Navigation Satellite Systems: GPS, GLONASS, Galileo, and More***. Springer, New York.

IS-GPS-200 (2006) ***Interface Specification-Global Positioning System-200, Revision*** D. Navstar GPS Joint Program Office, El Segundo, California.

JAXA (2011) ***Interface Specification for QZSS,*** Version 1.2. Japan Aerospace Exploration Agency.

Ji S (2008) ***Positioning Performance Improvements with European Multiple-Frequency Satellite Navigation System-Galileo***. Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hong Kong.

Knight NL, Wang J, Rizos C, Han S (2009) ***GNSS Integrity Monitoring for Two Satellite Faults.*** In: IGNSS Symposium 2009, 1-3 December, Surfers Paradise, Australia.

Knight N L, Wang J. & Rizos C. (2010) ***Generalised Measures of Reliability for Multiple Outliers***. Journal of Geodesy, 84(10): 625-635.

Lu J (2008) ***COMPASS/Beidou Navigation Satellite System Development***. In: 3rd Meeting of the International Committee on GNSS, 8-12 December, Pasadena, California.

Martineau A, Macabiau C, Mabilleau M (2009) ***GNSS RAIM Assumptions for Vertically Guided Approaches.*** In: ION GNSS 2009, 22-25 September, Savannah, Georgia, 2791-2803.

Moudrak A, Bauch A, Konovaltsev A, Schroth A, Hammesfahr J, Furthner J, Defraigne P, Bedrich S (2005) ***Interoperability on Time: GPS-Galileo Offset Will Bias Position***. GPS World 16(3):24-32.

Moudrak A, Konovaltsev A, Furthner J, Hammesfahr J, Bauch A, Defraingne P, Bedrich S (2004a) ***Timing Aspects of GPS-Galileo Interoperability: Challenges and Solutions***. In: 36th Annual Precise Time and Time Interval Meeting, 7-9 December, Washington, DC.

Moudrak A, Konovaltsev A, Furthner J, Hornbostel A, Hammesfahr J (2004b) ***GPS Galileo Time Offset: How It Affects Positioning Accuracy and How to Cope with It***. In: ION GNSS 2004, 21-24 September, Long Beach, California, 660-669.

Neelakantan N (2010) ***Overview of the Timing System Being Planned for India's IRNSS***. In: Fifth Meeting of the International Committee on Global Navigation Satellite Systems, 18-22 October, Turin, Italy.

Parkinson B (2006) ***Three Critical Issues***. GPS World 17(11):12-14.

Rizos C, Higgins MB, Hewitson S (2005) ***New GNSS Developments and Their Impact On Survey Service Providers and Surveyors***. In: Spatial Sciences Conference, 12-16 September, Melbourne, Australia, 1100-1113.

RSA (2008) ***GLONASS Interface Control Document***, Version 5.1. Russian Space Agency, Moscow, Russia.

Vanschoenbeek I, Bonhoure B, Boschetti M, Legenne J (2007) ***GNSS Time Offset: Effects on GPS-Galileo Interoperability Performance***. Inside GNSS 2(6):60-70.

Wang J, Kubo Y (2010) ***GNSS Receiver Autonomous Integrity Monitoring.*** In: Sugimoto S, Shibasaki R (Ed) GPS Handbook, Asakura, Tokyo.

Yang YX, Li JL, Xu JY, Tang J, Guo HR, He HB (2011) ***Contribution of the Compass Satellite Navigation System to Global PNT Users***. Chin. Sci. Bull. 56(26):2813-2819.

Biography

Jinling Wang is an Associate Professor in the School of Surveying & Spatial Information Systems, University of New South Wales (UNSW). His major research interests are in the areas of navigation and geospatial mapping with multi-sensors, such as GNSS, INS, cameras. He has published over 200 papers in journals and conference proceedings as well as two commercial software packages (**www.gmat.unsw.edu.au/wang**). He is a Fellow of the Royal Institute of Navigation (RIN), UK, a Fellow of the International Association of Geodesy (IAG), and is a member of the Editorial Board for the international journal GPS Solutions, International Journal of Navigation and Observations, and President of IAG Sub-Commission 4.2 (2011-2015) on Geodesy in Geospatial Mapping and Engineering. He was elected 2004 President of the International Association of Chinese Professionals in Global Positioning Systems (CPGPS), and the Founding Editor-in-Chief for the Journal of Global Positioning Systems (2002-2007).

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