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Combined Galileo and GPS: A Technical Perspective

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Abstract. Based on the analysis for Galileo unique features, this article attempts to outline the specific benefits that the Combined Galileo and GPSconstellations can bring to users, including some implications that can be expected when Galileo and a modernized GPS are fully operational. The article presents the author's personal observations and visions for Combined Galileo and GPStechniques, expecting comments from experts in the field, service providers and users.

Key words: Galileo, GPS, TCAR, Integrity, RAIM, Availability

1 Introduction

Galileo is the European contribution to the Global Navigation Satellite Systems (GNSS), which is independent of, but interoperable with the American Global Positioning System (GPS). However, from the professional and user prospective, Galileo is a better alternative space—based system, covering GPS shortfalls and offers several critical advantages (Commission ,2002).

A more dependable system. Galileo is under European civilian control, representing an effective solution to remove or reduce the ever-increasing dependence on the GPS system in a cost effective manner. In the USA, GPS is regarded as the new utility, alongside water, electricity, gas and telephone. US military and civilian users have developed a considerable dependence on the system. Similar dependencies have also been developed in other countries albeit it at a different degree. Instances of dependence on the GPS include the dependences of social and economic growth; government transport policy, regulation and safety applications; time reference and time synchronisation for digital communications networks, as well as political, technical and industry and scientific dependence. There are three major concerns for GPS users: 1) the US military controls the system infrastructure, operation, user access, current and future performance, 2) the service disruptions due to vulnerability of the navigation signals, signal blockages, satellite failure, signal denial and degradation by US authorities, unintentional and intentional interference etc, and 3) insufficient solution performance for safety-of-life services. As a complementary, independent and interoperable GNSS system, Galileo will neutralise these concerns. Galileo is dependable; because it not only remains under civilian control, but also provides service guarantees, signal integrity monitoring, improved service performance and signals globally. It also allows value-added services to be provided on a regional or local basis.

Services Guarantees. Use of GPS is free of charge, but no guarantee is provided whatsoever. Galileo provides **services guarantees** for certain types of civilian users in terms of accuracy, availability, continuity and integrity for certain types of services such as commercial and safety-of-life services. Technically, this service guarantee is provided in the first instance by the integrity information, which ensures to the users that the system is operating well in the normal status and provides alarms in case of failures. This service guarantee is achievable through a legal framework of service level agreements between the Galileo operator, the service providers and end-users. From a legal point of view, the notion of service guarantee is relying on mechanisms implemented to prevent, inform (off-line), alert (on-line) or compensate failure, disruption, or provision of service not meeting all of its specifications.

Global Integrity. Galileo allows users to be warned if the signal cannot be used. Integrity on global installation for safety-of-life services will also be in the service guarantee environment. This will increase the overall safety, particularly in civil aviation and railway control, because the time to alarm (TTA) of 6 seconds will help users of standard commercial services to react rapidly to malfunctions. It also provides transparent tools allowing assessment of performance in the light of the service guarantee. In addition, Galileo allows more critical integrity requirements to be satisfied through regional or local services. The Galileo global integrity information can be provided to the users through two types of data:

- Signal-in-Space accuracy (SISA): the uncertainty estimates of the Galileo ranges transmitted by Galileo;
- Integrity Flags for demanding operations, which warn users of failure within a very short time delay, for instances, 6s for CAT I precision approaches. For each satellite, the integrity flags (IF) will indicate whether SISA is OK in case the satellite can be used, or SISA is not OK in case the satellite is not monitored or is not to be used.

Improved service performance and signal. The Galileo signal in space is designed to bring significant improvements with a higher signal strength, which is important for use in the new applications such as GSM and UMTS networks, having needs for economic safety and guaranteed performance. These improvements are due to the following factors:

- Higher data rates than GPS will allow integrity, Search and Rescue Services (SAR) and limited commercial data to be broadcast;
- Wider bandwidth E5A+E5B versus L5 gives better accuracy;
- Slightly higher signal strength may improve operations indoors;
- Greatly improved ionosphere modelling techniques provides higher positioning accuracy for the single frequency users;
- Galileo will transmit at least three frequencies;
- Introduction of authentication mechanism is to protect the user and the operator in service guarantee environments.

Search and Rescue Service onboard the Galileo will also contribute to security operations. It will significantly improve the existing search and rescue system by detecting alerts in near real time and locating them with an accuracy of meters.

Supported Galileo regional and local value-added services (European Commission, 2002; Blomenhofer et al., 2003). The complete design of the Galileo baseline consists of global components, regional components and local components. Galileo's global components contain all the necessary infrastructure elements to provide five Galileo core services: open services (OS), safety-of-life services (SoL), commercial services (CS), publicly regulated services (PRS) and search and rescue services (SAR). The Galileo baseline already foresees to include a multi-regional integrity concept, where regions can install their own integrity determination architecture while Galileo will provides the interfaces from regions to the Galileo satellites for disseminating the regionally determined integrity. The concept suggests that a regional integrity determination network should be deployed, consisting of Galileo Sensor Stations (GSS), a regional Integrity Processing Facility (IPF) and possibly uplink (U/L) station on the regional territory. The regions are given the possibility to generate their own integrity flags in 1 second intervals and such assure warnings if the globally broadcast SISA does not bound the regionally determined estimate of the true SIS error SISE. Such regionally determined IF depends on a globally determined SISA. The advantage of this concept is that the Galileo satellites broadcast the regionally determined IF for Galileo satellites. It is planned that Galileo will provide a direct satellite uplink access to the regions to broadcast regional IF sets. Galileo regional services based on the regional component may only be available for up to 5 regions and be an optional or preferable component for regions such as Asia and Australasia. **Galileo Local Component** includes the entire fixed infrastructure required to support the provision of Galileo local services over the entire service area. It consists of a number of different types of local elements, each being capable of supporting a different class of service. The complete local component includes multiple instances of each type of local element to allow large geographic regions to be covered through multiple service providers. Galileo local services will be an important and necessary enhancement to the global services and possible regional services. These will deliver improvements in accuracy, availability and continuity in various combinations and levels, to meet specific requirements of different applications within the three major user communities:

- Professional positioning and timing services (surveying, deformation monitoring, GIS data acquisition, geodetic reference networks)
- Safety-of-life related services (aviation, maritime, road and rail)
- Mass market (location based services)
- These services are locally assisted value-added services.

2 Advantages of Combined Galileo and GPS Constellations

While Galileo is designed to be interoperable with GPS, Galileo signals may be combined with GPS signals at both regional/local component system level and user terminal levels. Enhancements resulting from combined use of GPS and Galileo are generally identified in the following two aspects:

Performance improvements. In an open space environment with no sky obstructions, either GPS or Galileo constellation would allow 6 or more satellites to be visible. This gives sufficient redundancy for mass-market, non-safety-critical applications. With a single constellation the autonomous receiver integrity computation capability is marginal and is not trusted for safety of life applications. Two interoperable constellations will allow the receiver to compute two non-dependent robust solutions, or a joint receiver to regard all GPS and Galileo satellites as a single GNSS constellation. As a result, the combined Galileo and GPS will increase the coverage of the service from 55% to 95% notably in the urban areas where most mass-market applications are developed. Tab. 1 summarises the results from the recent Galileo performance studies examining the potential of both constellations for urban operations over Europe (O'Donnell et al., 2002). The second and third columns compare the predicted availabilities of a 20m 95% horizontal accuracy between 28 GPS satellites only and 28 GPS + 27 Galileo constellations. The forth and fifth columns compare the predicted accuracy and availability for the same two cases.

Tab. 1 Performance improvements resulting from both GPS and Galileo constellations for urban operations (Blomenhofer et al., 2003)

Analysis scenario And Constella-tion	Availability of 20-m 95% 2D accuracy		Accuracy and Availability-satellites only		Accuracy availability differential
	28GPS only (%)	28GPS +27Gal (%)	28GPS only (m/%)	28GPS +27Gal (m/%)	28GPS +27 Gal (m/%)
Open sky	90%	100%	7 /95	4/95	1.5/95
Suburban	70%	100%	32/90	8/95	4/95
Low-rise	30%	90%	17/50	14/95	7/95
High-rise	15%	80%	-	42/90	25/90

Safety Critical Services. If Safety Critical Services are to use GNSS systems as their time or position providers, then the GNSS system must clearly meet safety critical levels of services with respect to accuracy, availability, continuity and integrity. Neither GPS nor Galileo alone reaches its full safety critical potential. Provision of both constellations allows greater penetration into the realm of safety critical services. Mathematically, the positioning solution will be massively over-determined and the ability for receivers to detect and exclude rogue satellites will be much more robust. Joint integrity potential could provide an extremely high degree of confidence to the user. The use of GPS together with Receiver Autonomous Integrity Monitoring (RAIM) fulfills requirements down to the Non-Precision flight phases. Without a dedicated Integrity Function in Galileo, it is expected that the RAIM techniques allow the use of Galileo for the less critical flight phase down to APV-I. The combination of GPS and Galileo will improve the RAIM performance significantly. But, whether APV-II can really be achieved is to be verified with the real future GPS III and Galileo constellations (Blomenhofer et al., 2003).

3 Combined Galileo and GPS: technical potential and implications

Partially because of the above Galileo unique features, and advantages of the combined Galileo and GPS constellations, several potential technological benefits and implications have been identified:

(a) *Accuracy and availability of the navigation solutions with code measurements would be further improved using the combined signals, due to the following factors*:

- Significantly reduced Galileo code noise level, compared to GPS code noise;
- Improved ionospheric modeling techniques for positioning with single frequency code receivers;
- Improved tropospheric propagation models allowing better low-elevation angle performance (Guo and Langley, 2003).
- More frequently updated Galileo orbits and clocks and more accurate clocks onboard Galileo satellites;
- An average of 16 satellites in view allows for detection and estimation of multiple gross errors in code measurements simultaneously, or allow for use of only accurate measurements for positioning. This was not the exact case for GPS navigation, where 6 to 8 visible satellites will leave no room for detection and rejection of multiple larger errors in the measurements;
- The quality of integrity information available for Receiver Autonomous Integrity Monitoring (RAIM) algorithms will increase dramatically due to the combined constellations and improved accuracy of the signals. As a result, new RAIM algorithms could be developed to replace the traditional weighted least squares residuals (LSR) method to promise much better RAIM availability (Loizou et al., 2002).

Most analysis for navigation and RAIM availabilities reported to date have been based on the assumptions of the existing GPS User Equivalent Range Error (UERE) performance and expected Galileo performance using the LSR RAIM algorithms. Improvement on both UERE performance and algorithms are expected to meet the availability requirements for more critical requirements, for instance, for Cat I precision approach applications.

(b) *Performance of local area Real Time Kinematic (RTK) positioning solutions with carrier phase measurements would be improved from a few centimeters with GPS only and to subcentimetre with Galileo and GPS signals*. This is because much more redundant double difference measurements allow for careful treatment of systematic errors such as multipath errors and outliers and small cycle slips.

(c) *Use of triple frequencies allows for the integer ambiguity resolutions from ionosphere-free phase measurements*. This is evident from the line-of-sight ionosphere-free phase measurements expressed as

$$\left.\begin{aligned} L_{12} &= \rho + a_{12}\lambda_1 N_1 - a_{22}\lambda_2 N_2 + \varepsilon_{12} \\ L_{13} &= \rho + a_{13}\lambda_1 N_1 - a_{23}\lambda_3 N_3 + \varepsilon_{13} \\ L_{23} &= \rho + a_{23}\lambda_2 N_2 - a_{33}\lambda_3 N_3 + \varepsilon_{23} \end{aligned}\right\} \quad (1)$$

where L_{ij} is the ionosphere-free phase measurements with frequencies f_i, f_j and f_j, for i=1,2, and j=2,3). $a_{ij} = \frac{f_i^2}{f_i^2 - f_j^2}$, N_i (i=1,2,3) is the integer phase ambiguity for each phase measurement; ρ represents the real range $\overline{\rho}$ lumped with clocks biases, tropospheric delay and orbit error:

$$\rho = \overline{\rho} + c(dt - dT) + d_{trop} + d_{orb} \quad (2)$$

These three equations are linearly independent. Double differencing these measurements eliminates clocks biases and reduces the effects of the tropospheric delay d_{trop} and orbit error d_{orb}, thus making the integer ambiguity resolutions from ionosphere-free DD phase measurements more tangible. Using precise orbit products and good tropospheric modeling techniques, integer ambiguity resolution over a long baseline, such as a few hundred kilometers, could still be valid. This compares to the current situation where the baseline for valid ambiguity resolution should be 20 kilometers or shorter, in case of single base station, and 70 kilometers for case of multiple base stations, using dual frequency GPS receivers.

(d) *Three Carrier Ambiguity Resolutions (TCAR) can be achieved without ambiguity search* (Foressell et al., 1997). We propose here a slightly different combination. We start with the following two independent combinations of phase measurements L_i (j=1,2,3),

$$\left.\begin{aligned} L_{1,2} &= (f_1 L_1 - f_2 L_2)/(f_1 - f_2) \\ &= \rho + K/f_1 f_2 + \lambda_{1,2} N_{1,2} + \varepsilon_{1,2} \\ L_{1,3} &= (f_1 L_1 - f_3 L_3)/(f_1 - f_3) \\ &= \rho + K/f_1 f_3 + \lambda_{1,3} N_{1,3} + \varepsilon_{1,3} \end{aligned}\right\} \quad (3)$$

And pseudorange measurements P_i (i=1,2,3)

$$\left.\begin{aligned} P_{1,2} &= (f_1 P_1 + f_2 P_2)/(f_1 + f_2) \\ &= \rho + K/f_1 f_2 + \varepsilon_{P1,2} \\ P_{1,3} &= (f_1 P_1 + f_3 L_3)/(f_1 + f_3) \\ &= \rho + K/f_1 f_3 + \varepsilon_{P1,3} \end{aligned}\right\} \quad (4)$$

Frequencies and wavelengths for the modernised GPS and Galileo are shown in Tab. 2 and Tab. 3. It can be seen that the virtual wavelengths for the two independent combined signals L_1-L_2, L_1-L_5 in the GPS case are 86.2cm, 75.1cm respectively. $N_{1,2}$, $N_{1,3}$ are integers. With the help of these combined psuedoranges, we can obtained the wide-lane biases $N_{1,2}$ and $N_{1,3}$ by subtracting (4) from (3) with no ambiguity search. The question is whether biases estimates are reliable depends on the quality of the observations. We observe that from Tab. 2 the combined code noises are 31cm and 25cm respectively, which are about one-third of their wavelengths. The situation would be improved in the Galileo case, where the combined wavelengths are 101cm and 75.1cm respectively while the combine code noises are reduced to 14.1cm and 11.9cm. Therefore, the direct estimates of the widelane phase biases should be theoretically much more reliable.

In the existing methods, the next step is to determine the integers for L1 phase measurements. In the proposed method, the next step is to form another phase combination:

$$\begin{aligned} L_{23,1} &= (2f_3 L_3 - f_1 L_1)/(2f_3 - f_1) \\ &= \rho + K\frac{(2f_1 - f_3)}{f_1 f_3 (2f_3 - f_1)} + \lambda_{23,1} N_{23,1} + \varepsilon_{23,1} \end{aligned} \quad (5)$$

which has the wavelength of 38.56 cm in both GPS and Galileo cases, nearly double of between the L1 carrier wavelength of 19cm and half of the combination $L_{1,3}$ (75cm). Theoretically, ambiguity resolution for the carrier phase $L_{23,1}$ instead of L_1 phase should be easier. This, however, is yet to be verified with real GPS L5 signals or Galileo three carrier signals. What is of most interest to us is the possibility of determining the phase bias $N_{23,1}$ for the line-of-slight phase measurements and without ambiguity search. We form the pseudorange combination

$$P_{23,1} \equiv (2f_3P_3 + f_1P_1)/(2f_3 + f_1) = \rho + K\frac{(2f_1 + f_3)}{f_1f_3(2f_3 + f_1)} + \varepsilon_{P23,1} \tag{6}$$

Due to the difference in the ionospheric terms in the above two equations, direct estimation of the $N_{23,1}$ is not achievable with the difference between (5) and (6). However, the expressions (5) and (6) indicate the possibility for estimation of $N_{23,1}$ if the ionosphere biases corrections are known, which could be the case when network based positioning techniques are used. In addition, as shown in Tab. 2 and 3, the combined code noises for the pseudorange combination (6) are 18.6cm and 9.8cm for GPS and Galileo cases respectively. At the very least, the initial values of the integers $N_{1,2}$, $N_{1,3}$, and $N_{23,1}$ could be estimated with high level of confidence using this procedure. Because of the following relationship,

$$\begin{bmatrix} L_1 - L_2 \\ L_1 - L_3 \\ 2L_3 - L_1 \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ -1 & 0 & 2 \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \\ L_3 \end{bmatrix}, \tag{7}$$

we can obtain the initial values of the ambiguities for all three carriers L_1, L_2, and L_3

$$\begin{bmatrix} L_1 \\ L_2 \\ L_3 \end{bmatrix} = \begin{bmatrix} 0 & 2 & 1 \\ -1 & 2 & 1 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} L_1 - L_2 \\ L_1 - L_3 \\ 2L_3 - L_1 \end{bmatrix} \tag{8}$$

With these initial integer values, we can proceed with ambiguity resolution with integer search techniques as developed for dual frequency cases. Alternatively, more efficient algorithms may be developed to the triple carrier ionospheric free measurements expressed by (1).

Tab. 2 GPS signal characteristics and virtual signal characteristics for combined GPS signals

Signals	frequency f_i (MHz)	Wave-length λ_i (m)	Code noise (m)	Carrier noise (mm)
L1	1575.42	0.1903	0.430	0.760
L2	1227.6	0.2442	0.430	0.970
L5	1176.45	0.2548	0.114	1.020
Combined signal	Virtual frequencies	Virtual wave-length	Combined Code noise(m)	Carrier Noise* (mm)
L1-L2	347.82	0.8619	0.306	3.621
L1-L5	398.97	0.7514	0.251	4.249
2L5-L1	777.48	0.3856	0.186	2.671
* without including multipath effects				

Tab. 3. Galileo signal characteristics and virtual signal characteristics for combined GPS signals

Signals	Carrier MHz	Wavelength (m)	Code noise (m)	Carrier Noise (mm)
L1	1575.42	0.1903	0.176	0.762
E6	1278.75	0.2344	0.229	0.94
E5a	1176.45	0.2548	0.114	1.02
Combined signal	Virtual Carrier MHz	Virtual Wavelength (m)	Combined code noise (m)	Carrier Noise* (mm)
L1-E6	296.67	1.0105	0.141	5.719
L1-E5A	398.97	0.7514	0.119	4.248
2E5A-L1	777.48	0.3856	0.098	2.671

(e) *Dual Carrier Ambiguity Resolution (DCAR) would be more reliable*. Currently, DCAR is achievable in real time with single-epoch measurements subject to the good or ideal observational environments. The reliability of the DCAR solutions has always been the question mark for users, although the GPS manufactures or researchers seem more confident about their RTK engines than users. With the average 16 satellites visible, DCAR algorithms will work more reliably, with high successful rate for integer ambiguity resolutions. DCAR relies on complicated mathematics and software approaches, while TCAR can use the simpler or simplified procedures to achieve the same purpose.

(f) *Single Carrier Ambiguity Resolution (SCAR) would be achieved with a much shorter observation period*. The advantage of single frequency techniques is the significant reduction of the hardware cost. This could be the case again in the future when Galileo becomes fully operational. The major problems for SCAR real time kinematics positioning are twofold: firstly, it takes the measurements collected between several and 30 minutes to resolve correct integers, and secondly, the baseline must be shorter then 20km for being able to cancel the distant dependent errors. Use of Combined Galileo and GPS receivers would improve both situations significantly, thanks to the more measurements available and advancement of ionospheric modeling techniques over a service network coverage area. In addition, recent development in mathematical methods has demonstrated the potential of successful SCAR with a few epochs (Wang, 2003).

(g) *Precise geodetic positioning accuracy could be improved from the level of a few millimeters using GPS alone, to the level of 1 millimeter using the combined signals*. This judgment may be intuitive, but is based on the following improvements:

- The number of measurements for geodetic solutions are doubled, but in turn the redundancy factor would be increased by three times or more;

- Orbits and clocks would be determined more accurately and updated more frequently;
- Systematic errors in phase measurements can be analyzed or corrected due to the high redundancy of measurements and use of more frequencies.

This improvement does not come alone. Other associated parameters, such as tropospheric delays, earth rotation parameters will also be improved correspondingly.

(h) *Use of three frequencies would eventually allow TCAR to be achieved with the line-of-sight measurements (un-differenced) instead of double difference measurements*. Ionospheric delays can be separated from other error components and biases. Network-based epoch-by-epoch positioning algorithms may be developed to allow the estimation of the line-of-slight tropospheric delays and clock biases with minimum constraints. As a result, GNSS meteorology studies would lead to practical applications for real time weather forecasting.

In general, Combined Galileo and GPStechnologies would introduce many fundamental changes in the existing GPS positioning theory and practice, leading to many new application areas. The most remarkable improvement lies in carrier phase based RTK positioning, which in future could be as fast (in time-to-fix ambiguity) and reliable as code based positioning. The algorithms behind this, however, could be amazingly simpler and robust. All these observations are yet to be verified via real GPS and Galileo data.

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Biography

Dr. Yanming Feng is senior research fellow with the Cooperative Research Centre for Satellite Systems (CRCSS) at Queensland University of Technology (QUT). He is currently the Project Leader for FedSat precise orbit determination (POD) and atmospheric occultation studies within CRCSS. He also provides project leadership for research programs such as ARC project "network-based GPS solutions for regional and local positioning services" and the international collaborative activities (with Japanese JAXA) "ETS-VIII Navigation Experiments and Monitor Station" within the Centre. He received PhD in Satellite Geodesy from Wuhan University and he has served at QUT since 1992