Potential Performance Levels of a Combined Galileo/GPS Navigation System

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This paper presents the results of a research project that investigated the potential benefits of a combined Galileo/GPS navigation system. The research addressed in detail the two key required navigation performance (RNP) parameters of accuracy and integrity. The project was supported by Alcatel Space and was a contribution to the Galileo definition studies (supported by the European Community under the GALA project). The results show significant improvements in both accuracy and integrity (achievable through RAIM) when a combined constellation is used rather than Galileo alone.

KEY WORDS

1. Galileo. 2. GPS. 3. Accuracy. 4. Integrity

1. INTRODUCTION. The Galileo system is the European contribution to the second generation of global navigation satellite systems (GNSS 2). It has been proposed as a European-controlled satellite-based navigation system offering global coverage, and will support *multi-modal* transport navigation requirements and many other applications requiring spatial and/or temporal information (plus derivatives) to users equipped with suitable Galileo receivers. It is intended that the system will be compatible with GPS/GLONASS and interoperable with space-based augmentation systems (SBAS) and ground-based augmentation systems (GBAS) currently under development. The issues of compatibility and interoperability, and their impact on the Galileo system, are still to be studied and consolidated. After an In-Orbit-Validation (IOV) phase involving satellite launches in 2004, further launches should allow an *initial operational capacity* (IOC), using 12 satellites, to be achieved by 2006. The system is expected to achieve *full operational capability* (FOC) by the year 2008.

As with any development aimed at providing services of this kind, a detailed analysis of the potential user needs is required. These needs are then translated into system requirements which form the basis for design, development, testing and eventual implementation. Part of the Galileo definition study carried out in 2000 was devoted to the identification and quantification of the user requirements within the domains of navigation and navigation-related communications. The parameters used to define the performance requirements for the different user needs include the standard required navigation performance (RNP) parameters of *accuracy*, *integrity*, *continuity* and *availability*. The others are *time to first fix*, *timing accuracy*, *navigation solution rate*, *timing*, *velocity accuracy*, *maximum outage time* and environmental constraints (*coverage*, *masking angle* and *multi-path levels*). Performance levels have been quantified for each of the user's needs.

Based on the user needs and the corresponding performance levels, several navigation service categories (levels) have been identified, only a sub-set of which can be supported by the Galileo system alone. A number of the other navigation services could be supported through the combined use of the Galileo system with other sensors (*the hybridisation concept*) and other satellite navigation systems such as GPS. From the user perspective, the use of Galileo together with other systems could lead to significant benefits due to enhanced navigation performance. A combined system could be realised by using Galileo together with current systems (GPS and GLONASS) and those under development (EGNOS, WAAS and MSAS). Potentially, a combined system could support more of the identified navigation service levels than the Galileo system alone.

The research described in this paper has quantified the potential improved performance levels, in terms of accuracy and integrity, which can be achieved when Galileo is used with GPS specifically. To do this, the probable status of the GPS and Galileo constellations in 2008 (±2 years) have been defined. Using this information, a number of simulations have then been undertaken to quantify accuracy and integrity levels.

2. THE GLOBAL POSITIONING SYSTEM IN 2008.

To predict the status of the global positioning system (GPS) in the year 2008 and beyond, information is required regarding the expected status of the system in May 2000, together with details of future launch schedules and modernisation plans. This section briefly describes the status of GPS (May 2000) and discusses some of the initiatives that have led to the performance levels enjoyed by users today. Following this status summary, details of the ongoing programme of GPS modernisation are given. Finally, the predicted configuration of the system in 2008 and the performance levels that GPS users can expect are described.

Since the system achieved full operational capability in 1995 with a 24-satellite constellation, there have been continued activities aimed at improving the navigation performance (OSTPNSC, 1996; OVP, 1998; OVP, 1999; OPS, 2000a, OPS, 2000b). These initiatives have resulted from operational shortcomings of the deployed system and pressure from the civilian community for access to improved performance levels. The significant developments since 1995 can be summarised as follows:

(a) Improvements within the ground segment resulting in better navigation data determination and prediction models. For example, the accuracy and quality of the satellite orbit and clock parameters have seen considerable improvement.
(b) The introduction of higher specification satellites (Blocks IIA and IIR) into the constellation.
(c) The removal of selective availability (*dither* and *epsilon*) with effect from 04:05 UTC on 2 May 2000 (Milbert, 2000; OPS, 2000).

Table 1. Estimated current SPS performance levels.

Navigation Parameter	Specification
Coverage	99·9% four satellite coverage with PDOP constraint of 6
Service availability	Intentionally no more than 3 satellites will be removed from the service and for no longer than 24 hours Availability 95·87% (Global Average) Availability 83·92% (Worst Regional Case)
Service reliability	99·97% (Global Daily Average) 99·79% (Worst Case Scenario)
Accuracy	UERE-Budget (at the zenith): 7·5 m Predicted horizontal error (95%) without SA: 22 m Measured horizontal error (95%) without SA: 8 m (Hill and Moore, 2000)

Table 2. Planned GPS satellite launches.

SV Types	Launch Schedule	Capabilities	Design mean life (years)
6 unmodified Block IIR	2000–2002	Current Capabilities	7·84
12 modified	2003–2006	C/A code on the L2 carrier frequency-new military M_E code on L1 and L2 carrier frequencies	7·84
2 Block IIF	2005–2006	IIR modified capabilities + 3rd civil frequency (L5)	12·7
22 Block IIF	2007–2015	IIR modified capabilities + 3rd civil frequency (L5)	12·7

These developments have significantly improved the system performance; for example, the mean UERE (User Equivalent Range Error) budget has improved from ~ 33 m (with SA) to ~ 7·25 m during the period 1993 to 2000 (Conley and Lavrakas, 1999). Table 1 gives the navigation performance levels, taken from the GPS Standard Positioning Service (SPS) Signal Specification (1995 version) and projected to May 2000 to recognise the effects of the removal of SA.

Due to the huge potential market for satellite navigation services, and the technological developments in security related areas, the US government has put in place new initiatives aimed at further enhancing the performance of the system whilst maintaining its crucial military role. Since 1996, several official announcements have been made in support of this. Notable examples have been the *Accuracy Improvement Initiative* (AII) and the decision to stop degrading GPS accuracy. The main objective of the AII is to carry out an analysis of the performance of the operational (ground) control system and to suggest possible improvements. This has already led to the upgrade of the operational control segment (OCS) to support the Block IIR autonav functionality for the precise positioning service (PPS) (Malys *et al.*, 1997). With the removal of SA, the AII is expected to benefit both PPS and SPS users.

Tables 2 and 3 show the planned modernisation activities for the GPS constellation and the planned changes of signal characteristics. According to the Federal Radionavigation Plan, '*the DOD will maintain a 24-satellite constellation. Replacement*

Table 3. Planned modernisation of the GPS signals.

Current Frequency Plan	Planned Frequency (additional)	Capabilities
Carrier frequencies	Additional civilian frequency	6 dB higher power relative to L1
L1: 1575·42 MHz	L5: 1176·45 MHz	20 MHz broadcast bandwidth
L2: 1227·60 MHz	(*Safety-of-life* service frequency protection (ARNS-Band))	Improved signal cross-correlation
Code frequencies (pseudo-random) P-Code: 10·23 MHz (on L1/L2)	M_E Code (L1/L2)	M-code designed to enhance system security and to improve anti-jamming
Code frequencies (gold code) C/A-Code: 1·023 MHz (on L1)	C/A Code on L2 (1127·60 MHz)	Dual frequency ionospheric correction (improved UERE and better accuracy)
Navigation message	Ephemeris, SV clock parameters, ionospheric parameters, SV health	On L1, L2 and L5

satellites will be launched on an expected failure strategy' (DoD, 1999). To implement the proposed changes, new generations of satellites are currently under development. These are the *modified Block IIR* satellites with the capability for a second C/A code on L2 frequency, and *Block IIF* satellites with the capability for the third civilian frequency L5 (for safety-critical applications). The launches of the first modified Block IIR and Block IIF satellites are expected during the years 2003 and 2005 respectively (Pappas, 2000). It should be noted that significant impact on the user cannot be expected before a critical number of modified Block IIR and Block IIF satellites have been launched.

To support the changes in the space segment, and to exploit the enhancement to a full extent, changes in the ground (control) segment are necessary. These are mainly aimed at better tracking and derivation of navigation data (high accuracy and integrity). The planned activities include the following (Malys *et al.*, 1997; DoD, 1999, Shaw *et al.*, 2000):

(a) Upgrade of Monitor Stations and ground antennas with new digital receivers,
(b) Replacement of existing Master Control Station mainframe computer with a distributed architecture,
(c) Addition of the so-called Air Force Satellite Control Network,
(d) Enlargement of the tracking network by incorporating the National Imagery and Mapping Agency (NIMA) tracking stations,
(e) Building of a full mission-capable Alternate Master Control Station (AMCS) at Vandenberg,
(f) Addition of full Block IIR and IIF command and control functionality,
(g) Refinement and improvement of the navigation data algorithms and models, including an update of the OCS Kalman filter estimation process,
(h) A new upload strategy to reduce the orbit prediction error.

Table 4 gives an estimate of the typical user range errors (m, 1σ) (Turner *et al.*, 2000) as a result of the planned modernisation activities. The introduction of a second civilian C/A code will significantly reduce the ionospheric error (from 7 to 0·01 m)

Table 4. Typical range errors (metres) after GPS modernisation.

Error Source	Without SA	Without SA + two C/A (L1/L2)	Without SA + two C/A (L1/L2) + OCS modernisation
Clock and ephemeris error (SS/CS)	2·3	2·3	1·25
Ionospheric error	7	0·01	0·01
Tropospheric error	0·2	0·2	0·2
Receiver measurement error	0·6	0·6	0·6
Multi-path	1·5	1·5	1·5
Total UERE error budget	7·5	2·8	2·0
Stand-alone horizontal accuracy, 95% (HDOP 1·5)	22·5	8·5	6·0

and modernisation of the operational control segment will reduce the clock and ephemeris error (from 2·3 to 1·25 m). The planned modernisation programme will therefore improve the expected system performance in terms of accuracy and integrity. Other significant benefits identified by Shaw *et al.* (2000) include:

(a) Increased robustness of the system (less vulnerable to interference),
(b) Better real-time integer ambiguity resolution (using tri-laning, three-carrier phase ambiguity resolution) will allow sub-centimetre accuracy for engineering and scientific applications with a higher reliability,
(c) Significantly reduced transmission rates for DGPS corrections because SA is set to zero,
(d) Increased feasibility of worldwide dual frequency aircraft navigation through the en-route to precision approach phases of flight, due to reduced infrastructure requirements for GBAS and SBAS.

Taking the current GPS constellation as a starting point, and using information about the proposed modernisation plans, a projected constellation for the period when Galileo achieves full operation capability was developed. The year 2010 for Galileo FOC has been assumed in this study so that a dual C/A code GPS constellation can be considered. If the Galileo constellation is complete before this date, then it may operate alongside a GPS constellation containing unmodified Block IIR satellites. A dual C/A code GPS constellation was chosen as it will be the general case during Galileo operation and, with some observers advocating an accelerated GPS modernisation programme, this may well be the GPS status in 2008.

The model used consists of 24 MEO (Medium Earth Orbit) satellites of which 12 will be of Block IIR (modified) and the rest Block IIF. The satellites are equally distributed in 6 orbital planes at a 55° inclination to the celestial equator. The satellites have a nominal altitude of 20 200 km. This GPS constellation, together with the corresponding UERE budgets, has been used for subsequent performance analyses. The UERE budgets are given in Table 5. A mapping function has been applied to relate the UERE values to satellite elevations. These values come from two sources; the first set is based on official DoT/DoD figures and the second set is based on results from the Galileo definition studies. Although both sets were considered during this study, the results shown later in this paper have all been derived using GALA estimates.

Table 5. Modernised GPS UERE budgets.

Elevation angle (degrees)	DoT/DoD estimates (m, 1σ)		GALA estimates (m, 1σ)	
	GPS L1/L2	GPS L1/L5	GPS L1/L2	GPS L1/L5
10	2·35	2·18	5·23	3·65
20	2·13	1·94	3·10	2·19
30	2·07	1·88	2·77	1·93
40	2·06	1·86	2·45	1·72
50	2·06	1·86	2·28	1·60
60	2·05	1·85	2·19	1·54
70	2·05	1·85	2·25	1·57
80	2·05	1·85	2·29	1·59
90	2·05	1·85	2·27	1·58

Table 6. Galileo baseline navigation performance requirements.

Galileo Segments	Galileo Global	Galileo Global + Regional	Galileo Global + Local
Coverage (TBC)	90 S to 90 N	75 S to 75 N	75 S to 75 N
Altitude (TBC)	3000 km	20 km	20 km
Accuracy (NSE, 95%)			
Position (H)	10 m	6 m	0.8 m
Position (V)	10 m	6 m	0·8 m
Velocity (3-D)	0·2 m/s	0·2 m/s	0·2 m/s
Integrity			
Risk	RAIM like	10^{-7}/hour	10^{-9}/hour
HAL		18 m	2·4 m
VAL		18 m	2·4 m
TTA		6 s	1 s (local)
Continuity			
Risk	N/A	10^{-5}/150 s	10^{-7}/150 s
Maximum Outage		TBD	TBD
Availability	99·9	99·9	99·999
Masking Angle	5	5	25

3. GALILEO IN 2008. Clearly the status of Galileo in 2008 must be based entirely on proposed activities, as there is no current system to consider. The Galileo definition phase was to be completed at the end of 2000, followed by a design and development stage. For the purposes of this study a baseline architecture using information available in May 2000 was used. The design of Galileo is being driven by the service requirements of a number of identified potential users. To meet these service requirements, performance targets for the system have been derived. Table 6 gives these baseline Galileo system requirements in terms of navigation performance parameters from May 2000. The system requirements are specified for three Galileo segments, or coverage areas: global, regional and local. The difference in the accuracy specification between the regional and global services is due to the differing coverage areas; the accuracy specification of 10 m in the global service applies to higher latitude areas (between 75° and 90° North and South).

The Galileo constellation used for the simulations described here, was the Walker model of 30 MEO satellites, evenly distributed in three orbital planes, each containing 10 active satellites. Each orbital plane was inclined at 57° to the celestial equator, and each satellite was assigned an altitude of 23000 km. The satellites were phased within each plane such that whenever a given satellite crosses the equator, there are another two from each of the other two planes crossing at the same time. The planes have been placed in between the GPS planes to maximise coverage.

The Galileo system will support the user navigation requirements through different access modes or service levels, reflecting the needs of different applications (mass market, professional, safety-of-life, security, etc.). For this research, the controlled access service (CAS), designed for professional market applications, has been considered. The UERE budgets for CAS, using satellite elevation dependent mapping, are given in Table 7.

Table 7. Predicted Galileo CAS UERE budget.

Elevation (°)	10	20	30	40	50	60	70	80	90
UERE	4·37	2·46	2·02	1·74	1·58	1·50	1·52	1·53	1·52

4. PERFORMANCE POTENTIAL OF A COMBINED SYSTEM.

This section briefly describes how data regarding Galileo and GPS have been used as inputs in a performance simulation. A selection of the results (accuracy and integrity levels) from these simulations is presented with some analyses that emphasise the improved performance levels that can be achieved using a combined Galileo/GPS constellation, rather than using Galileo only. To be able to identify the additional benefits offered by the combined system, initially it is necessary to quantify the performance levels that Galileo alone can provide. By comparing this to the performance of a Galileo/GPS configuration, it is then possible to identify the value-added features that may benefit potential users.

Two independent software packages, GCOST (GNSS Constellation Simulation Tool) and GDAP (GNSS Data Analysis Package), developed at University College London and Imperial College respectively, have been used to carry out the performance assessment. The GCOST software computes satellite availability, positioning accuracy and integrity data for a user-defined coverage area and time period, with a chosen spatial and temporal sampling rate. The results presented in this paper have been determined using a 5° ground separation and 5-minute time samples over a 24-hour period. The results can be presented either as a global distribution (showing variations in performance with location) or sampled data can be collated to produce appropriate summary statistics for the entire coverage area. GDAP is a satellite data processing engine with a system design capability and was used in this study as a quality assurance tool to validate the GCOST output. The key inputs for the simulations are the Galileo and GPS constellation characteristics, the UERE budgets and the required performance levels, details of which have been given in the previous two sections.

4.1. *Accuracy*.

To give a general view of the system performance, the accuracies (using the Galileo UERE budgets and expressed as a predicted positioning error at the 95% confidence level) from each ground point at each epoch have been combined and sorted into accuracy bands. This process has been carried out with a Galileo-only constellation and a combined Galileo/GPS constellation; all other parameters remained fixed. Table 8 shows the percentage of horizontal and vertical errors falling into each band. Results from the two alternative constellations are given in horizontal and vertical components for both regional (75°S to 75°N) and global coverage.

Table 8. Horizontal and Vertical Accuracy Estimates.

	Regional (75°S to 75°N)		Global	
Accuracy (NSE,95%)	Galileo Only (%)	Galileo + GPS (%)	Galileo Only (%)	Galileo + GPS (%)
Horizontal (m)				
2–4	4·30	73·53	15·27	76·57
4–6	96·70	26·4	84·73	23·43
6–8	–	–	–	–
8–10	–	–	–	–
Vertical (m)				
2–4	–	–	–	–
4–6	50·99	95·43	45·13	88·30
6–8	45·77	4·57	49·86	11·70
8–10	3·24	–	5·00	–

Some general and predictable trends can be readily identified. Firstly, horizontal performance is significantly better than vertical, and secondly, vertical accuracy degrades at high latitudes, apparent from the increase in the size of errors when global rather than regional coverage is considered. The reasons for these trends are related to the constellation geometry and are well understood and documented. It is worth noting however, that as Galileo performance targets are the same for horizontal and vertical components, the horizontal figures are of limited value as the system will always satisfy horizontal requirements if it is able to meet the vertical targets.

In the current context, the more interesting aspects of these results relate to the performance improvements achieved using a combined Galileo/GPS constellation. Using Galileo alone, less than 5% of the horizontal errors are below 4 m for the regional segment, the remainder being in the 4–6 m range. When a combined constellation is used, nearly three quarters of the errors (73·53%) are below 4 m, representing a significant improvement in horizontal accuracy. Although a combined constellation enhances performance, Galileo alone is capable of meeting the 6 m horizontal accuracy target (Table 8) so the improvement does not necessarily represent a significant benefit in terms of satisfying requirements. However, when the vertical component is considered, errors can exceed 8 m using Galileo alone and only around half (51%) of the errors are below 6 m (the accuracy target for the regional component). With a combined constellation around 95% of vertical errors are below the 6-m threshold; therefore, the improved performance has a significant impact on meeting system requirements. When global coverage is considered, the performance levels (horizontal and vertical) show a similar improvement when a combined system is used, but due to the less stringent accuracy requirement (10 m rather than 6 m) Galileo alone can also meet the requirements.

4.2. *Integrity*. Integrity relates to the trust that can be placed on the correctness of information supplied by a navigation system. It includes the ability of the navigation system to provide timely warnings to users when the system fails to meet its stated accuracy. Specifically, a navigation system is required to deliver a warning (*alarm*) when the error in the derived user position solution exceeds an allowable level (*alarm limit*). This warning must be issued to the user within a given period of time (*time-to-alarm*) and with a given probability (*integrity risk*). The two main approaches for monitoring the integrity of satellite navigation systems are Receiver Autonomous Integrity Monitoring (RAIM) and monitoring based on an independent network of integrity monitoring stations with a dedicated Ground Integrity Channel (GIC). As part of the overall Galileo definition study, the provision of integrity information using monitoring stations and a GIC has been investigated. One element of this study was an analysis of integrity using RAIM to assess whether in fact a GIC was needed to meet integrity requirements.

Receiver Autonomous Integrity Monitoring (RAIM) is a method applied in the user's receiver to check the consistency of the measurements made from different satellites to estimate the quality of the resulting position. RAIM methods therefore require redundant measurements and good constellation geometry. Range measurements must be available from a minimum of five satellites to allow an anomaly to be detected; a minimum of six satellites is required to identify and remove the faulty satellite observations from the solution. In order to carry out a RAIM capability analysis, the definition of integrity (as given above) has to be transformed into quantifiable requirements. Performance thresholds must be specified in terms of *alarm limits*, *integrity risk*, *time-to-alarm*, *false alarm rates* and *probability of missed detection*. The constellation configuration and the corresponding User Equivalent Range Error (UERE) budgets must also be known. Additionally, the coverage area and sampling interval (spatial and temporal) must also be defined.

The capability of Galileo and the combined Galileo/GPS system to perform RAIM was assessed using the Marginal Detectable Error (MDE) algorithm. If RAIM is available, then a receiver has enough information to be able to detect the presence of errors of a certain size at a certain probability. As the required probability levels will vary with the positioning application, scenarios have been tested using two alternative probability levels. These two values have been selected to try and cover a range of levels that may be required in practice. The minimum probability level has been set at a relatively relaxed level; i.e. a relatively high proportion of errors will remain undetected. The maximum probability level reflects more stringent requirements (for example in safety-of-life applications) for which the probability of detecting an error must be considerably higher. Details of the MDE algorithm and the process of defining probability levels are given in Ochieng *et al*. (2001).

Once values are set for the probability levels and alarm limits, it is possible to calculate the proportion of time for which RAIM is available. Table 9 shows the percentage of samples (at 5-minute time intervals and 5° ground resolution) at which the minimum size of position shift that could be detected was within the alarm limit (18 m in vertical and horizontal); i.e. RAIM availability. Availability figures are given on a regional and global scale using the two alternative probability levels and constellations. Figures 1 and 2 show the global distribution of RAIM availability using Galileo only and a combined Galileo/GPS constellation respectively (the minimum probability level has been used in each case).

Table 9. RAIM availability using alternative probability levels.

18 m threshold	Regional (75°S to 75°N) Galileo Only (%)	Regional (75°S to 75°N) Galileo + GPS (%)	Global Galileo Only (%)	Global Galileo + GPS (%)
Horizontal				
Minimum Probability	99·18	100	99·27	100
Maximum Probability	85·14	100	86·05	100
Vertical				
Minimum Probability	65·05	99·97	65·38	99·97
Maximum Probability	6·40	93·11	7·28	91·73

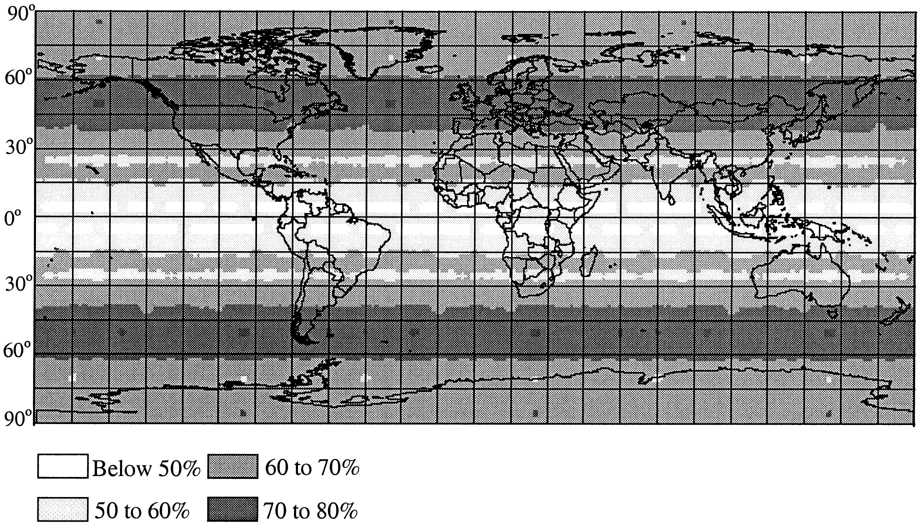

Figure 1. RAIM availability – Galileo only.

As with accuracy, Table 9 shows that horizontal performance is significantly better than vertical and that, if horizontal and vertical alarm limits are the same, then it is only the vertical component that will dictate whether or not RAIM is available. More importantly, Table 9 demonstrates that the increased redundancy resulting from a combined constellation improves RAIM availability significantly. Using a combined Galileo/GPS constellation, RAIM is available horizontally for all the sampled points at each sample epoch; i.e. if an error was present in an observed satellite range that would lead to a horizontal position error greater than 18 m, the user would be informed. RAIM availability using Galileo only falls well below 100% horizontally when the more stringent probability levels are applied. Using the vertical alarm limit as the threshold, RAIM availability is very poor (as low as 6% using the maximum probability levels) using Galileo alone. The availability improves substantially using a combined constellation although at the maximum probability level it is still some way short of 100%.

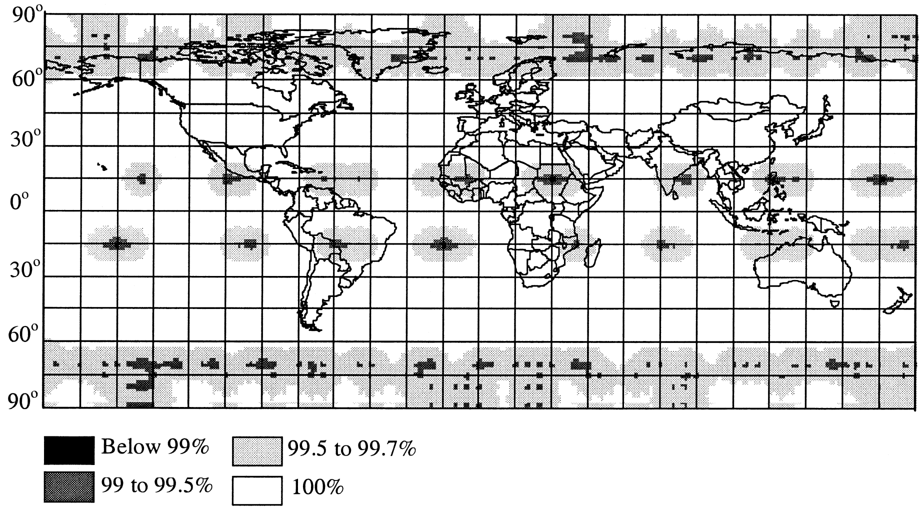

Figure 2. RAIM availability – Galileo + GPS.

The global distribution plots (Figures 1 and 2) show that using Galileo alone, RAIM is available for less than half the time in some equatorial areas, even using the minimum probability levels. Availability in mid-latitude areas is substantially higher, between 70 and 80 %, but this is still well below the near 100 % standards usually required. When GPS satellites are used in addition to the Galileo constellation the situation improves dramatically, with only a few isolated points having availability below 99 % and the majority of areas having between 99·7 and 100 % availability.

The probability levels at which errors must be detected to satisfy RAIM obviously affects its availability significantly. The *missed detection* and *false alarm* probabilities needed to carry out an analysis of RAIM availability will vary according to the application. These results show the importance of defining suitable values. The subject of defining probability levels in this context is discussed in more detail in Ochieng *et al.* (2001). Similarly, other parameters such as the constellation design and the UERE budgets must also be clearly defined to carry out meaningful analyses. The use of a combined system clearly improves RAIM performance, but to judge the significance of these improvements to a user requires more information regarding the needs of a particular application.

5. CONCLUSIONS.

This paper has presented results from a study assessing the performance potential, in terms of accuracy and RAIM, of a combined Galileo/GPS navigation system. In order to achieve this overall aim, a number of tasks were undertaken. Firstly, the probable characteristics of both the Galileo and GPS constellations in 2008 (±2 years) in terms of the constellation design and signal structure have been determined. In the case of GPS, this was based on the current system status and the proposed modernisation plans. For Galileo, a baseline architecture from May 2000 was adopted. Using this information, a number of simulations were undertaken to assess performance using Galileo alone and then using a combined Galileo/GPS constellation. The additional satellites available in a combined constellation clearly improve the accuracy and integrity performance, but to assess the *significance* of these improvements they must be related to the service requirements or system performance targets.

Using Galileo alone, the 6 m vertical accuracy requirement for the regional component can only be met for approximately 50% of the samples; using a combined constellation this improves to around 95% – a significant improvement. Although a combined constellation improves the horizontal accuracy, it is of limited significance as Galileo alone can meet the performance targets. Similarly, the global accuracy threshold of 10 m can be achieved using Galileo alone, so the improvements due to a combined solution are less significant.

A number of integrity parameters, including the false alarm rate, the probability of missed detection and the probability of unscheduled satellite failure are still either undefined or need to be set according to applications rather than the navigation system's performance. Assuming relatively stringent probability levels, of the kind required for safety-of-life applications, RAIM availability for Galileo alone is well below the levels normally specified (close to 100%). Even with more relaxed probability levels, performance – particularly in the vertical component – is well below this standard. The use of a combined constellation significantly improves RAIM availability, although to meet the current performance target of 18 m for the vertical alarm limit will still require some additional augmentation or system enhancement. The provision of a network of integrity monitoring stations and a GIC could help to meet the performance targets. Alternatively, the performance targets could be changed to reflect the potential system capabilities more closely (e.g. increase the vertical alarm limit to 25 to 30 m).

The use of GPS satellites with Galileo improves accuracy and integrity performance. These improvements can be shown to represent significant user benefits as the enhanced performance satisfies service levels that could not be met by Galileo alone.

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