Integrity Mechanisms for GPS Satellites within the Galileo Architecture

W. Y. OCHIENG [1], K. SAUER [1], P. A. CROSS [2], K. SHERIDAN [2], S. LANNELONGUE [3],
N. AMMOUR [3] and K. PETIT [3]

[1] Imperial College London
E-mail: "Ochieng, Washington Y" w.ochieng@ic.ac.uk

[2] University College London, [3] Alcatel Space Industries

Abstract

This paper presents the results of the study of a number of options for the provision of integrity data for GPS satellites within the Galileo architecture, and their corresponding impacts. 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), addressing in particular, the definition of strategies and mechanisms for the inclusion of GPS satellites within Galileo to realise a combined Galileo/GPS navigation system.

1 Introduction

The Galileo system currently under definition is the European contribution to the second-generation global navigation satellite systems (GNSS 2). It has been proposed as a global, European-controlled satellite based navigation system 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. It should be noted however, that the issues of compatibility and interoperability, and their impact on the Galileo system are still to be studied and consolidated. The system is expected to achieve *full operational capability* (FOC) by the year 2008.

Based on the user needs and the corresponding performance levels, several navigation service categories (levels) have been identified (Ochieng and Cross, 2000a; 2000b; Ochieng *et al*., 2001). Only a sub-set of these services are envisaged to be supported by the Galileo system. The other navigation services could be supported through the combined use of the Galileo system with other sensors (*the hybridisation concept*) and other systems such as GPS. Therefore, it is important to investigate the impact on the performance levels achievable and hence the potential user services that would benefit from such a combined approach. The aim of this study was to address the impact of the GPS constellation on performance (in terms of *accuracy* and *integrity*), were it to be used as part of the Galileo system. Three objectives were set to achieve this.

a) Carry out a detailed analysis of the technical and institutional evolution (modernisation) of GPS. Since the Galileo system is expected to achieve its *full operational capability* (FOC) by the year 2008, the GPS system has to be extrapolated to this period.
b) Taking into account the technical and institutional evolution (modernisation) of GPS, assess the impact of the GPS constellation on performance (in terms of *accuracy* and *integrity*).
c) Taking into account the modernisation of GPS, identify (and assess the impact of) the options for providing an integrity monitoring service for GPS satellites within the Galileo architecture.

The first two objectives were addressed in an earlier paper (Ochieng *et al*., 2001a, 2001b). This paper addresses the third objective involving the definition of options for providing an integrity monitoring service for GPS satellites within Galileo and their corresponding impacts on the Galileo architecture.

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2 Galileo Integrity Service Provision

Integrity relates to the trust that can be placed in the correctness of the information supplied by the navigation system. It includes the ability of the navigation system to provide timely warnings to users when the system must not be used for navigation. Specifically a navigation system is required to deliver a warning (i.e. an *alarm*) of any malfunction (as a result of a set *alarm limit* being exceeded) to users within a given period of time (i.e. *time-to-alarm*) and with a given probability (*integrity risk*). The main approaches to integrity monitoring are:

a) receiver autonomous integrity monitoring (possibly with aiding/hybridisation).
b) ground based integrity monitoring using an independent network of integrity monitoring stations and a dedicated integrity channel.

Note that for very strict (safety-of-life) integrity requirements both techniques will usually be required. In addition to the adoption of the two techniques above, the Galileo system designers propose also to investigate the possibility of the use of a third technique, referred to as the satellite autonomous integrity monitoring (SAIM) based on the monitoring of the performance of the frequency generation mechanism on board the satellite.

2.1 The GIC approach to Galileo Integrity Monitoring

This approach supports integrity monitoring using data from an independent network of tracking stations and a dedicated integrity channel - the Galileo Ground Integrity Channel (GIC). Within the Galileo system, satellite tracking data are captured with the network of Integrity Monitoring Stations (IMS) and transmitted via the Regional Integrity Network (RAN) to the Integrity Processing Facility (IPF). At the IPF the residual range errors for each satellite due mainly to control and space segment errors (largely as a result of imperfect modelling of the satellite orbits and clocks) are determined after the removal of the other navigation system errors. A *check process* then performs statistical analysis on the measured pseudorange residuals (for a given satellite and service region) to determine the probability that the broadcast *signal-in-space accuracy (SISA)* value actually bounds the residuals. An alarm is raised within a specified time-to-alarm if the probability parameter falls outside the specified value (i.e. the satellite is set to *don't use* and information transmitted to the user within the time-to-alarm). The SISA parameter for each satellite is computed at the OSPF (Orbitography and Synchronisation Processing Facility) as part of the determination of the satellite ephemeris and clock parameters using data from the Orbitography and Synchronisation Stations (OSS) within the global network. The SISA basically represents the quality of the ephemeris and clock data, and has a period of applicability of 45 minutes with an update rate of 30 minutes.

2.2 The Galileo integrity message

The Galileo navigation message will consist of two main parts.

a) Global navigation data consisting of satellite ephemeris and clock data, SISA parameter, alamanac, etc.
b) Integrity data based on data from the IMS network and the broadcast SISA parameters from the global network. The data includes a *region identifier, an authentication word, space vehicle identifier* and *space vehicle integrity flag (IF)* to be computed for each satellite.

The content of the Galileo integrity message will depend on several factors. These include the definition of the integrity parameter, the number of satellites monitored, the number of regions covered, navigation data rates, the Time-to-Alarm (TTA) budget and the Time-To-First Fix (TTFF). Note that the Galileo integrity service is to be offered at regional and global levels. The *regional service* is to be based on the use of tracking data from the regional IMS network to determine an integrity flag for each satellite at the regional IPF. Note also that according to the current specification of 6 service regions, it might be possible at times for a satellite to be visible from areas within all the six regions at higher and lower latitudes. Due to data transmission limitations, it has been proposed that a Galileo satellite broadcasts data for at most 4 regions. The global service will be based on the derivation of integrity flags at the European IPF using tracking data from a global IMS network. The integrity data would then be re-transmitted to the up-link station (ULS), inside and outside Europe. Only the regional service has been considered here. At least 4 dedicated Galileo satellites are to be used to transmit integrity data for each satellite. The criteria for selecting these satellites will depend on coverage.

Table 1 shows the proposed Galileo signal baseline for different services. Only satellites visible over a service coverage region will be monitored and integrity data generated and transmitted with an update rate of 1 second.

The regional time-to-alarm budget is given in Figure 1 showing both the data flow and the maximum allowable delay times for data throughput (Ochieng and Cross, 2000a; 2000b).

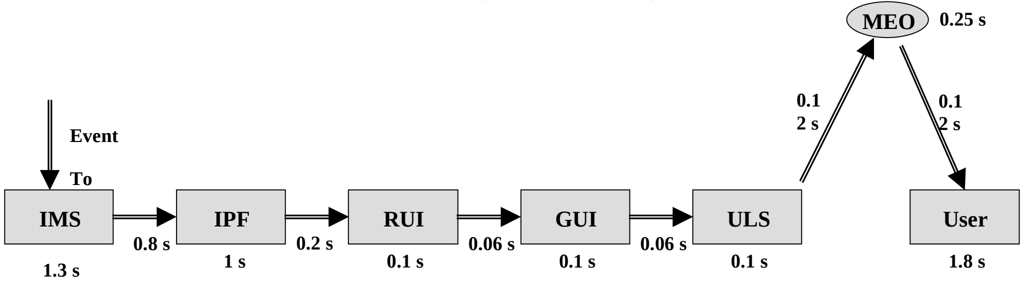

Figure 1: Time-to-alarm budget allocation

Where, RUI is the Regional Uplink Interface, GUI the Global Uplink Interface, ULS the Uplink Station and MEO represents a Galileo satellite in a Medium Earth Orbit.

Table 1: Proposed Galileo signal baseline

Frequency Band	**E5**	**E6**	**E2**	**E1**	**C**
Centre frequency (MHz)	1202.025	1278.75	1561.098	1589.742	5019.861
Code rate (Mcps)	10.23 / 1.023	20.46	2.046	2.046	8.814
Code Type	Gold	Gold	Gold	Gold	Gold

The time-to-first fix (TTFF) is the time interval between the start of the signal acquisition and the availability of an acceptable navigation solution. It depends on the time required by the receiver to lock on to each satellite signal and the time taken to acquire satellite ephemeris. The receiver could initiate the acquisition process either from *cold* (i.e. no data on satellite positions at the start) or *warm* (i.e. data on satellite position exists within the receiver at the start). Because of these temporal constraints, it is clear that the formulation of the navigation message will depend partly on the TTFF requirements. At the time of writing this paper no TTFF requirements have been defined for the Galileo system.

2.3 Definition of integrity data broadcast strategy

As indicated earlier, the definition of the integrity broadcast strategy will depend on several factors given in Section 2.2. One of the proposals under consideration for Galileo with respect to integrity data flow is based on the concept of the transmission of an integrity table containing integrity data (refreshed every 30 seconds) for all satellites visible over an area covered by 4 regions. This assumes that any one Galileo satellite could be selected by up to 4 regions for the dissemination of integrity data. When a failure occurs an integrity message containing the minimum necessary information to enable the table to be updated is sent within the time-to-alarm. The number of bits contained in the integrity table is given by:

$$IT\_bits = (r \times n \times IF) + r\,(AW + TS) \qquad (1)$$

Where n is the total number of satellites, IF is the number of bits for the integrity flag, r is the number of regions, AW is the number of bits for the authentication word and TS is the number of bits for the time stamp.

The integrity message to be transmitted when a failure occurs is determined by:

$$IA\_bits = \{RI + AW + (SI+IF)m\}r \qquad (2)$$

Where ***m*** is the number of failed satellites**,** ***SI*** is the number of bits for the satellite identifier and ***RI*** is the number of bits for the region identifier.

3 GPS Integrity Monitoring within Galileo

This section uses the approach to Galileo system integrity monitoring given in the previous section to define a pragmatic integrity mechanism for the provision of integrity data for GPS satellites within the Galileo architecture. The key inputs to this have been the following.

a) The GPS baseline for the period when Galileo achieves its full operation capability (Ochieng *et al*., 2001a, 2001b).
b) The Galileo system baseline and the service coverage regions (Section 2).

Using the above data, different approaches have been identified that could be adopted to provide integrity data for GPS satellites within the Galileo system. The potential impacts that each of these approaches could have on both the Galileo and GPS systems have been explored and used as inputs to the definition of potentially viable options for monitoring the integrity of GPS satellites within the Galileo system. The general methodology used is presented in Figure 2.

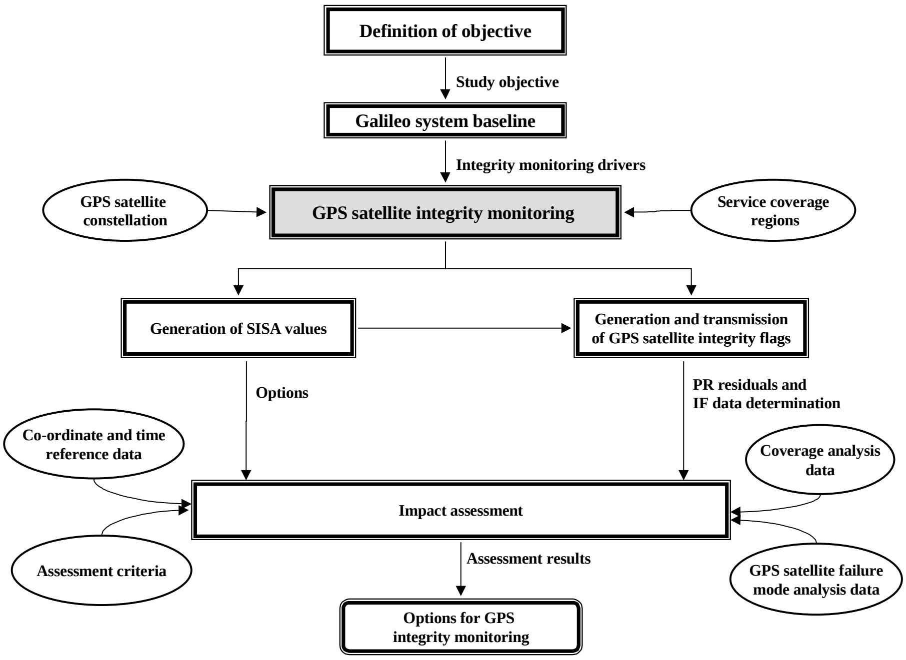

Figure 2: GPS satellite integrity analysis methodology

As shown in Figure 2, after the definition of the research objective, a review of the current approach to integrity monitoring within the Galileo system was carried out and the key driving parameters identified (Section 2). These parameters together with the projected GPS constellation for when Galileo achieves full operation capability (FOC) and the service coverage regions were then used for subsequent analysis.

Within the *GPS satellite integrity monitoring analysis* stage, the major activities required for the monitoring of GPS satellite integrity were identified, in this case *the generation of Signal-In-Space Accuracy (SISA) parameters (Section 3.2)* and *the generation and transmission of the integrity flags (Section 3.3)*. The potential impacts that each of these activities could have on both the GPS and the Galileo systems were then analysed taking into account *pre-defined assessment criteria*, *key system differences such as co-ordinate and time reference frames*, *satellite coverage analysis results* and *unscheduled instantaneous multiple satellite failure analysis results*. These impacts have been used as inputs to the definition of potentially viable options for the specification of an integrity mechanism for the monitoring of GPS satellites within the Galileo system (Section 3.4).

3.1 Options for GPS integrity monitoring within Galileo

Section 2 has reviewed the current approach to GIC-based satellite integrity monitoring within the Galileo system, identified the major constraining parameters and presented an approach (and simple algorithms) for the definition of a strategy for the broadcast of integrity data. Using this as a baseline reference, this section analyses the options for providing the integrity data for GPS satellites within the Galileo system and the corresponding impacts on both the GPS and Galileo systems. From Figure 2, it can be seen that this process requires two major activities.

a) The determination and dissemination of SISA values for all GPS satellites.
b) The derivation and dissemination of an integrity message for each GPS satellite in view of a given region.

For each of the above activities and the options identified thereof, an impact assessment has been carried out taking into account *pre-defined assessment criteria, key system differences such as co-ordinate and time reference frames*, *satellite coverage analysis results* and *unscheduled instantaneous multiple satellite failure analysis results.* These are dealt with briefly below before proceeding to the details on options and impact assessment.

Pre-defined assessment criteria

The credibility of an assessment of the impact that the provision of integrity data for GPS satellites could have on the Galileo system depends on the criteria used. The assessment criteria adopted are given below.

a) **Infrastructure:** the hardware requirements for GPS satellite tracking, data processing and transmission.
b) **Algorithms:** mathematical models and algorithms required to process the GPS data.
c) **Processing time:** the extra time required to process the data as a result of the inclusion of GPS data.
d) **Data size and throughput:** the extra size of data and throughput taking into account refresh rates.
e) **Institutional considerations:** the potential problems with respect to external guarantees of the navigation data generation processes.

Two stages can be identified for such an assessment, firstly determining the data and processes associated with the GPS satellites and secondly incorporating this information within the Galileo design to determine whether the design could cope with the extra resources required to accommodate GPS satellites.

Co-ordinate and time reference issues

The co-ordinate reference for the Galileo system has been given as the International Terrestrial Reference Frame 1996 (ITRF96) (Ochieng and Cross, 2000a; 2000b). The corresponding reference frame for GPS is the World Geodetic System 1984 (WGS84). Obviously significant differences between these two systems would have a major impact on the way that navigation products for GPS and Galileo satellites are determined and disseminated within the Galileo system. The ITRF is a global geocentric reference datum with station co-ordinates accurate to better than 10 cm. The original WGS84 reference frame realised from TRANSIT data was compatible with the ITRF at the 1m level.

There have now been two refinements carried out on the WGS84 reference frame, one in 1994 and the other in 1996. These resulted in the WGS84 (G730) and WGS84 (G873) reference frames respectively. Both refinements have adopted the *fiducial* processing approach whereby some of the IGS (International Geodynamics Service) stations have been held fixed to their ITRF co-ordinates. According to NIMA (1997), the agreement between WGS84 (G730) and the ITRF92 reference frames was at a level approaching 10 cm. The corresponding figure for WGS84 (G873) and

ITRF94 is at the level of 2 cm. This effective merger between the two reference frames is not surprising given that the processing approach adopted has used ITRF station co-ordinates as reference (fixed) points. It has therefore, been assumed that the two reference frames are effectively the same and hence no impact is to be expected on either the GPS or the Galileo systems. This is just as well given that the ICAO (International Civil Aviation Organisation) has adopted WGS84 as the reference frame for navigation globally.

The time reference for the global positioning system is the GPS system time. The corresponding reference for Galileo has been specified as the Galileo system time. The offset between the two time references will have to be determined to allow among other things, data from the GPS satellites to be referred to Galileo system time. This is in addition to the requirements of the timing community, which will partly be met by the fact that both the GPS and Galileo time scales will be steered to UTC with the required level of accuracy. The process of determining the offset between the GPS and Galileo time scales would be undertaken at the OSPF within the Galileo global ground segment, and could have a significant impact on the processing time depending on the approach taken. It has been assumed that a simple dynamic algorithm based on the single difference (at the satellite) carrier phase observable could be used for time transfer between the two systems. With the other navigation errors reduced to insignificance (i.e. satellite clock errors cancelled, orbit errors dealt with both by the use of high accuracy orbits and single differencing, tropospheric errors determined using state-of-the art models, multipath errors dealt with through internal receiver electronics and site calibration, receiver noise errors dealt with internally), the remaining errors will be to a high degree of accuracy due to non-synchronisation of the two time systems. This offset can be determined dynamically and transmitted as part of the Galileo global navigation message. Owing to the simplicity of this approach, it has been assumed that its effect on the OSPF processing time will be very small.

Satellite coverage analysis

Coverage has been defined to involve the determination of the statistics associated with satellite visibility over a given point, region or even globally under specified conditions such as elevation mask angle. The statistics generated cover both spatial and temporal aspects of satellite visibility. This type of analysis is a vital part of the identification of the options for the monitoring of integrity of GPS satellites and the assessment of their impact on the Galileo system. For example, the integrity monitoring stations (IMS) and for some options, the orbitography and synchronisation stations (OSS) will be required to track the GPS satellites, generating additional data to be transmitted from the IMS and OSS to the IPF and OSPF respectively for processing. In order to assess the impact that this will have on the Galileo system, the maximum number of GPS satellites visible from any location over the globe over a period of 24 hours is required. The result of the coverage analysis using the GDAP (GNSS Data Analysis Package) software is shown graphically in Figure 3. It can be seen that the maximum number of GPS satellites visible from any location globally over a period of 24 hours is 12. This figure has been determined based on a 5-degree elevation mask and has been used in the next sections for impact assessment.

Unscheduled satellite failure analysis

In general two types of satellite failures can be identified, *scheduled* (usually either as a result of routine maintenance or as a result of predictable anomalous events) and *unscheduled* (due to unpredictable events). For satellite integrity monitoring, it is the unscheduled failures that are of primary concern. Scheduled failures have a direct impact on service availability.

The requirements for the generation and transmission of integrity data for GPS satellites within Galileo will depend in part on the number of satellites failing (unscheduled) simultaneously. Hence satellite failure analysis is required to determine the data size and throughput of integrity data to be transmitted for GPS satellites when such failures occur. The results of the instantaneous unscheduled simultaneous multiple GPS satellite failure analysis are given in Table 2. The table shows the frequency for one, two, three, four and five multiple satellite failures over a period of ten years. It can be seen that multiple failures beyond 2 satellites are highly unlikely. Thus the main conclusion here is that the generation and transmission of integrity data for GPS satellites when failures occur should be based on 2 satellites. Beyond this, the source of satellite failure could be the main system in which case a constellation-wide *don't use* message should be transmitted to the users. This figure is used later for impact assessment.

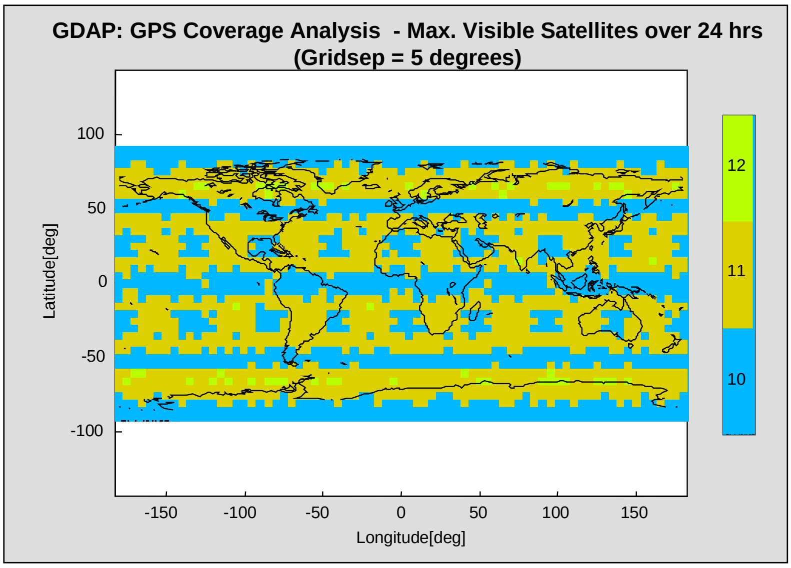

Figure 3: Maximum number of GPS satellites at any location over 24 hours

Table 2: Frequency of simultaneous unscheduled satellite failures over 10 years

Simultaneous Satellite Failures	Frequency
One	896.10
Two	1.22e-03
Three	1.06e-09
Four	6.59e-16
Five	3.12e-22

Having addressed the key considerations for the study, the following sub-sections present the details on their application to the identification of options and the corresponding impact assessment. Institutional issues have been considered also.

3.2 Generation of SISA values for GPS satellites

Three approaches can be envisaged to provide the SISA values for GPS satellite integrity monitoring within the Galileo system.

a) Based on the current GPS Operation Control Segment (OCS) derived User Range Accuracy (URA) data contained in the navigation message for each GPS satellite.
b) Based on the OCS derived URA values but disseminated by the Galileo global component.
c) Based on SISA values computed and disseminated by the Galileo global component.

3.2.1 Current GPS OCS derived URA data in the GPS navigation message

In this approach, the User Range Accuracy (URA) for each satellite computed by the GPS Operational Control Segment (OCS) and contained in the GPS navigation message is used as the signal-in-space accuracy parameter for GPS satellites. The URA is a statistical indicator of the ranging accuracies obtainable with a specific satellite and corresponds to the maximum value anticipated during the validity period of the transmitted data. It is determined as part of the satellite orbit and clock parameter determination and prediction process, and is essentially equal to the projection of the errors in this process onto to the user range. It does not include the errors due to atmospheric propagation effects and user equipment. According to the GPS SPS signal specification document, a four bit positive integer URA indicator with a range of 1 to 15 is transmitted within sub-frame 1 of the GPS navigation message. The indicators are converted into actual range errors, X metres, according to the following expressions:

$$\boldsymbol{N} \le 6, \quad \boldsymbol{X} = 2^{(2+\boldsymbol{N}/2)}$$

$$6 \le \boldsymbol{N} < 15, \quad \boldsymbol{X} = 2^{(\boldsymbol{N}-2)}$$

N=15, indicates the absence of an accuracy prediction, hence the SPS users use that satellite at their own risk.

The applicability of the URA for the monitoring of the integrity of GPS depends on the accuracy with which the URA is determined which, in turn depends on the following.

a) The GPS tracking data used in the estimation and prediction process.
b) The algorithms and the Kalman filtering process used for the estimation of the satellite parameters.
c) The navigation data upload strategy.

In the current system, data from five monitoring stations are used in a partitioned Kalman filtering process to determine satellite parameters (orbit and clock) at 15-minute intervals. Just before an upload scheduled to take place once per day per satellite (plus a few contingency uploads invoked only when an SV shows unusually high errors) a prediction process takes place to generate the navigation data to be transmitted to the satellite. This process also estimates the value of the URA for this satellite (i.e. the maximum value anticipated during the validity period of the transmitted data over the worst location). The contribution of the use of *old* navigation data (up to 24 hrs) to the user range error has been estimated at 2.4 m (RMS) (Brown *et al*., 1998).

During the period under study here (i.e. the Galileo FOC) the modifications to the control segment under the Accuracy Improvement Initiative (AII) should improve the signal-in-space error contribution of the GPS control segment. These improvements, which are expected to have the same effect for both the PPS and SPS users, will involve the following (Brown *et al*., 1998; Malys *et al*., 1997).

a) The incorporation of additional tracking data, including 6 National Imaging and Mapping (NIMA) monitoring stations. Data from the current 5 plus the NIMA stations will be transmitted in real time to the OCS MCS for processing to determine the satellite navigation data. The additional tracking stations should ensure that all GPS satellites are monitored continuously thereby improving the orbit and clock parameter estimation accuracy.
b) Improved OCS algorithms and the use of a single-partition Kalman filtering capability embracing the entire constellation as opposed to the previous multi-partitioned filtering process involving a subset of 6 satellites.
c) Improved navigation data uploading strategy to the GPS satellites.

Studies carried by Brown *et al.* (1998) have shown that only a 20 percent improvement will be achieved in the signal-in-space error as a result of the use of additional tracking data and improved Kalman filtering. The more significant improvement will arise from a different approach to the navigation data uploading strategy. Results show that as a result of an increase in scheduled uploads from the current once to twice, the signal-in-space error (RMS) will improve from 2.4m to 1.5m. Three uploads per satellite per day results in an RMS SIS error of 1.25 m. An ingenious approach to navigation data uploading, referred to as *dynamic uploading*, is capable of achieving the above improvement with approximately 1.4 uploads per satellite per day.

Another approach to the upload strategy is given by Ghassemi and Fisher (1997). The authors state that Block IIF satellites incorporate a new capability referred to as *crosslink navigation upload mode* which significantly increases the frequency of navigation data updates using the satellites UHF crosslink system without additional operator workloads. The UHF crosslink operates on a TDMA (Time Division Multiple Access) cyclical structure in which each of 24 satellites is assigned a 1.5 second transmission slot. This design allows for a full set of corrections to the clock and ephemeris parameters to be uploaded to all satellites in the constellation within 2 TDMA cycles (i.e. 72 seconds). This process would involve:

a) a scheduled uplink of the full navigation message for a specific satellite once per day.
b) the generation of correction parameters to the broadcast parameters every 15 minutes (note that the GPS OCS Kalman filter generates state estimates every 15 minutes).
c) a satellite in view of the Ground Antenna (GA) is used to upload the corrections to all 24 satellites.

The effect of this approach will be to keep the age of data broadcast in the navigation message between 1.5 and 2.5 hours resulting in signal-in-space range errors in the range of 0.75 to 1.0 m (RMS) (Ghassemi and Fisher, 1987). With the above improvements (even though the full benefit of the UHF crosslink capability will only be realised with a full Block IIF constellation), it could be expected that the accuracy with which the URA parameter will be determined, will satisfy the technical performance requirements for a SISA-based approach to integrity monitoring of the GPS satellites within the Galileo system. The question that arises is one of guaranteeing that this requirement will always be satisfied since the US DoD has expressed no such desire even after the GPS performance enhancements.

Impact on the Galileo global component

The determination and dissemination of the URA parameters for all the 24 GPS satellites will be carried out entirely by the GPS system. On the surface, this approach should have no major technical impact on the Galileo system. The determination and transmission of the offset between the GPS and Galileo system time references should have only a small technical impact (e.g. 70 bits extra data to transmit). However, the adoption of this approach will depend on the requirement for the *time-to-first-fix* (TTFF), which is still to be specified. On the institutional side, major problems associated with quality control and guarantee of the URA determination process will have to be resolved between Europe and the USA.

Impact on GPS

Based on the projected process of determining the URA parameters under initiatives proposed by the US government and assuming that the TTFF requirements can be achieved with the GPS navigation data rates, no significant technical impact is expected on the GPS system.

3.2.2 GPS OCS derived URA data disseminated by the Galileo global component

In this approach, the URA values are computed by the GPS OCS as described in Section 3.1.1 but disseminated via the Galileo global navigation message. The URA data for all 24 GPS satellites would be sent to the Galileo OSPF where the data would be incorporated into the global navigation message and sent to the ULS for transmission to Galileo satellites. This approach suffers from the same institutional problems identified in Section 3.1.1. Its main attraction is that the satellite parameters will be available to the Galileo system at 15-minute intervals (i.e. the output interval of the GPS OCS Kalman filter). The refresh rate required by the Galileo system (e.g. 30 minutes) could then be made possible. The specific impacts on the Galileo and GPS systems are summarised below.

Impact on Galileo global component

Infrastructure

a) Additional channel (platform) may be required (with redundancy) at the OSPF to handle the URA parameters for all the GPS satellites received from the GPS OCS.
b) New data transmission network capacity is required between the GPS OCS Master Control Centre and the Galileo OSPF to transmit the URA data for all 24 satellites.
c) Adequate network capacity is required between the OSPF and the ULS to cater for the extra URA data for the 24 GPS satellites.
d) Adequate uplink capacity is required for the GPS satellite URA data.
e) Adequate downlink capacity is required for the GPS satellite URA data.

Algorithms

New relatively simple algorithms are required to check the parameters coming from the GPS OCS. Galileo algorithms used to incorporate the Galileo SISA values within the navigation message could be re-used to process GPS satellite URA data.

Processing time

The main processing task at the OSPF will be to check and incorporate the parameters into the Galileo global navigation message. No significant impact is envisaged on the processing time at the OSPF as parallel processing could be adopted.

Data transmission

a) Table 3 shows an estimate of the data size and refresh rate required to transmit the extra URA data for all 24 GPS satellites every 15 minutes between the MCS OCS and the Galileo OSPF.

b) Adequate data transmission capacity is required between the OSPF and the ULS. Table 4 shows the extra data size and refresh rate required within the Galileo global component.

c) Adequate data uplink capacity is required for all 24 GPS satellites (*316 bits with a 30-minute refresh rate*).

d) Adequate downlink capacity is required for the URA parameters for all 24 GPS satellites (*316 bits with a 30-minute refresh rate*).

Table 3: New URA data transmission requirements between the MCC and the OSPF

Type of Data	**Size (bits)**
Time Stamp	30
GPS satellite ID for all 24 satellites	120 (5x24)
URA indicator for all 24 satellites	96 (4x24)
Total	**246**
Data update rate	**15 minutes**

Table 4: Extra data transmission capacity between OSPF and the uplink stations

Type of Data	**Size (bits)**
Time Stamp	30
GPS satellite ID for all 24 satellites	120 (5x24)
URA indicator for all 24 satellites	96 (4x24)
GPS/Galileo system time offset	70
Total	**316**
Data update rate	**30 minutes**

Impact on GPS

Infrastructure

a) Additional processing channel (platform) may be required (with redundancy) to prepare the URA data for onward transmission to the Galileo OSPF.

b) There will be new interface requirements between the Galileo network and the GPS OCS MCC.

Algorithms

c) New algorithms will be required to check and prepare URA data for transmission to the Galileo OSPF.

Processing time

d) This is an independent function from the general navigation product generation within the GPS ground segment. Parallel processing could be adopted to ensure that no significant impact results.

Data transmission

e) The Galileo global component capacity is assumed to be adequate hence no impact is envisaged.

3.2.3 GPS SISA computed and disseminated by the Galileo global component

In this approach the following main activities will be required.

a) The OSS network tracks all 24 GPS satellites on a continuous basis.
b) Data for the number of satellites visible over a given OSS is sent via the Global Area Network (GAN) to the OSPF for processing.
c) The OSPF carries out similar computations as for the Galileo satellites to determine the satellite ephemeris, clock and SISA parameters for all GPS satellites. Another variation to this is that the navigation data from OSSs are used at the OSPF to determine the SISA values without the need to perform a full orbit and clock estimation process. The advantage of the former approach is that it will not only support integrity but service availability as well.
d) The OSPF also determines the offset between Galileo and GPS system times.
e) The Global Uplink Interface (GUI) and the Uplink Link Station (ULS) handle the navigation message for additional GPS satellites.
f) The Galileo satellites transmit navigation messages for additional GPS satellites.

The impacts of this approach on the Galileo global component and the global positioning system are summarised below.

Impact on the Galileo global component

Infrastructure

a) Multi-frequency GPS capable receivers (with redundancy) will be required at all the OSSs. Additional processing channel (platform) may be required (with redundancy) to carry out a limited amount of pre-processing (e.g. formatting) of the data for all GPS satellites.
b) Additional computation channel (platform) is required (with redundancy) at the OSPF for the determination of the global navigation message (satellite ephemeris, clock and SISA) values for all 24 GPS satellites; and the Galileo/GPS clock offset parameters.
c) Adequate network capacity is required to transmit extra data from each OSS to the OSPF.
d) Adequate network capacity is required to transmit GPS navigation data from the OSPF to the ULS.
e) Adequate capacity is required to uplink the GPS navigation data to the Galileo satellites.
f) Adequate capacity is required to downlink the GPS navigation message to the user receiver.

Algorithms

g) The process of determining the GPS orbit, clock and SISA parameters could adopt the same algorithms used for the Galileo system with only minor modifications. New algorithms will be required to compute the offset between the two time references. A simple dynamic algorithm based on the single difference carrier phase observable could be used to determine this offset.

Processing time

h) No impact is envisaged on the processing time at the OSS as parallel processing could be adopted for the GPS satellite data before transmission to the OSPF.
i) No significant impact is envisaged on the processing time budget at the Galileo OSPF as the computation for GPS orbit, clock and URA data can be carried out largely in parallel with the Galileo satellite data computation. The time-offset computation implemented

using a simple single difference solution should have a very small impact on the processing time.

Data transmission

j) Adequate network capacity is required to transmit receiver data for additional satellites from each OSS to the OSPF, within the same time budget as with Galileo only OSS data. Table 5 shows an estimate of the data size and rate between a typical OSS and the OSPF. The maximum number of GPS satellites that can be seen from any point on the surface of the earth at any time has been determined by a coverage analysis as **12**. This has been used to estimate the extra data size and throughput required to be transmitted at a frequency of 1Hz.

k) Adequate capacity is required to transmit the navigation data for GPS satellites from the OSPF to the ULS (Table 6).

l) Adequate uplink capacity is required to transmit GPS navigation data for all 24 satellites (Table 6).

m) Adequate downlink capacity is required on the Galileo satellites for the navigation message for all GPS satellites (Table 6).

Table 5: Extra data transmission requirements between an OSS and the OSPF

Type of Data	**Size in bits for *n* satellites**
Time stamp	30
SVID	60 (5xn)
Navigation message	4392 (366xn)
L1 C/A code pseudorange	384 (32xn)
L1 Y1-Y2 code pseudorange	384 (32xn)
L5 C/A code pseudorange	384 (32xn)
L2 C/A code pseudorange	384 (32xn)
L1 Carrier phase	384 (32xn)
L2 Carrier phase	384 (32xn)
L5 Carrier phase	384 (32xn)
Total	**7140 bits**
Data rate @ 1Hz	**7.140 kbs**

Table 6: Extra transmission (navigation data) requirements between OSPF and ULS

Type of data	**Size in bits for all 24 GPS satellites**
Time stamp	30
SV ID	120 (5x24)
Keplerian navigation parameters	8592 (358x24)
GPS Clock parameters	1680 (70x24)
GPS/Galileo system time offset	70
Total	**10.492 kbits**

Impact on GPS

This approach has no potential significant technical impact on GPS and avoids potential institutional problems.

3.3 Derivation and dissemination of GPS integrity data

This will be a task for the so-called Galileo regional component. The general procedure for determining and disseminating integrity data for GPS satellites is similar to that described for Galileo satellites in Section 2. Once the SISA values (or their equivalent, i.e. URA) are determined and broadcast, the tracking pseudorange data for GPS satellites from the Integrity Monitoring Stations (IMS) are used to compute pseudorange residuals for satellites visible over a given region (i.e. Galileo regional component). A *check process* then carries out a statistical analysis based on SISA and residuals to determine integrity data for the GPS satellites. The data is then disseminated to users in the Galileo regional component integrity message via designated Galileo satellites as required (e.g. within the *time-to-alarm*, if a non-integrity event occurs).

Given that the Galileo system already caters for the derivation and dissemination of integrity messages for Galileo satellites, the major question that arises here is what level of impact is to be expected on the Galileo regional component by the addition of GPS satellites. A high level analysis has been carried out to attempt to address this question. The criteria used include *infrastructure (physical hardware), algorithms, processing time* and *data transmission*. The process of deriving and disseminating GPS satellite integrity data has been analysed under two headings, determination of pseudo-range residuals and the generation of integrity data.

3.3.1 Determination of pseudorange residuals

In order to derive the measured pseudo-range residuals the Galileo regional network of Integrity Monitoring Stations (IMS) will be required to track the GPS satellites on a continuous basis. This data will then be transmitted via the Regional Area Network (RAN) to the Integrity Processing Facility (IPF) where statistical tests will be performed using the SISA parameters and the measured pseudo-range residuals to generate the integrity message. The following impacts on the Galileo regional component could be envisaged.

Infrastructure

a) Multi-frequency GPS capable receivers (with redundancy) will be required at all the IMS.
b) Additional processing channel (platform) may be required (with redundancy) at each of the IMSs to carry out a limited amount of pre-processing (e.g. formatting) of the data for all GPS satellites.
c) Additional processing channel (platform) may be required (with redundancy) at the IPF for the computation of the pseudorange residuals for the GPS satellites.
d) Adequate network capacity to transmit data for additional satellites from the IMS to the IPF.

Algorithms

e) No significant impact is envisaged in terms of algorithms, as the Galileo algorithms could be re-used with only very minor modifications.

Processing time

f) No impact is envisaged on the processing time at the IMS as parallel processing could be adopted to process the GPS satellite data before transmission.
g) No impact is envisaged on the processing time at the IPF as parallel processing could be adopted to process the GPS satellite data before transmission.

Table 7: Extra data transmission requirements between IMS and IPF

Type of Data	**Size in bits for *n* satellites**
Time stamp	30
SVID	60 (5xn)
Navigation message	4392 (366xn)
L1 C/A code pseudorange	384 (32xn)
L1 Y1-Y2 code pseudorange	384 (32xn)
L5 C/A code pseudorange	384 (32xn)
L2 C/A code pseudorange	384 (32xn)
L1 Carrier phase	384 (32xn)
L2 Carrier phase	384 (32xn)
L5 Carrier phase	384 (32xn)
Total	**7140 bits**
Data rate @ 1Hz	**7.140 kbs**

Data transmission

h) Adequate network capacity is required to transmit receiver data for additional GPS satellites from each IMS to the IPF, within the same time budget as with Galileo only IMS data. Table 7 shows an estimate of the data size and rate between a typical IMS and the IPF. The maximum number of GPS satellites that can be seen from any point on the globe at any time has been determined by a coverage analysis as **12**. This has been used to estimate the extra data size and throughput required to be transmitted at a frequency of 1Hz.

3.3.2 Generation of GPS integrity data

Here, the SISA values for GPS satellites and the corresponding pseudorange residuals will be used to generate and transmit the integrity flags to users via designated Galileo satellites. The impacts of this process on the Galileo regional component are given below.

Infrastructure

a) Additional computation channel (platform) may be required at the IPF (with redundancy) for the determination of integrity flags for the GPS satellites visible over a given region.
b) Adequate network capacity required to transmit extra integrity data between the IPF and the ULS.
c) Adequate uplink capacity required to transmit extra integrity data.
d) Adequate downlink capacity required to cater for extra integrity data.

Algorithms

e) No significant impact is envisaged in terms of algorithms, as the Galileo algorithms could be re-used with only very minor modifications.
f) Processing time
g) No impact is envisaged on the processing time at the IPF as parallel processing could be adopted for the GPS satellite data before transmission.

Data transmission

h) Adequate capacity is required for transmission between the IPF and the ULS, and both for uplink and downlink of (within the same time budget as with Galileo satellites) integrity flags for all the 24 GPS satellites within the integrity table and for when one or more GPS satellites fail. Using expression 2 and setting the parameters as follows $n=24$, $r=4$, $AW=30$, $IF=2$ and $TS=30$ gives an extra data size of **432 bits** for the integrity table to be refreshed every **30 seconds**. The extra data to be uplinked when one or more (simultaneous) non-integrity events occurred was determined by analysing the potential failure modes of GPS satellites. The results show that instantaneous simultaneous unscheduled failure of more than 2 GPS satellites is highly unlikely. If this is true then expression 3 below can be used to calculate the extra data to be transmitted within the time-to-alarm budget for the Galileo uplink (Figure 1).

$$RI + AW + (SI + IF)\boldsymbol{m} \tag{3}$$

Where $\boldsymbol{m}$ is the number of GPS satellites for which an alarm message is to be sent. Setting the number of bits for the parameters RI, AW, SI and IF to 3, 9, 5 and 2 respectively, yields the extra data required to be uplinked to be **21 bits**.

i) Adequate downlink capacity is required on the Galileo satellites for the integrity data for the GPS satellites visible over a given region. Taking into account the result from the satellite failure analysis (i.e. instantaneous simultaneous failure of more than 2 GPS satellites is highly unlikely), expression 2 can be used to estimate the extra integrity data size for GPS satellites to be transmitted by the Galileo satellites within the same time-to-alarm budget given for the Galileo satellites. Setting parameter, r (number of regions) to 4 and the number of bits for the parameters RI, AW, SI and IF to 3, 9, 5 and 2 respectively, yields the extra data required to be downlinked (within the downlink TTA budget given in

Figure 1) to be **104 bits** (note that this includes *RI* and *AW* parameters which would be common to Galileo and GPS satellites as they are only region dependent).

3.4 Summary of Integrity monitoring options

Table 8 presents a summary of the options identified for consideration to support the definition of a pragmatic scheme for the monitoring of integrity of GPS satellites within the Galileo architecture. The strengths and weaknesses of each option are highlighted.

Table 8: Options for the provision of integrity data for GPS satellites

Option	Strength	Weakness
Option 1 • GPS URA data contained in navigation message • Galileo regional component uses the URA and GPS tracking data to determine GPS integrity data	• Cheapest approach technically • No major technical impact on Galileo global component. • No major technical impact on GPS.	• May be constrained by requirements for TTFF due to the low GPS navigation data rate. • Major impact on Galileo regional component • '*Half*' - incomplete monitoring of the integrity of GPS satellites by the Galileo system. • Safe service provision requires guarantees from the US DoD.
Option 2 • GPS URA data disseminated by the Galileo global component • Galileo regional component uses GPS tracking data with GPS URA data to determine GPS integrity data	• More expensive (technically) than Option 1 but cheaper than Option 3 • URA data available every 15 minutes • Minor technical impact on the Galileo global component • Not constrained by the requirements on TTFF due to low GPS navigation data rate.	• Major impact on the Galileo regional component. • Technical impact on GPS. • '*Half*' - incomplete monitoring of the integrity of GPS satellites by the Galileo system. • Safe service provision requires guarantees from the US DoD.
Option 3 • Galileo global component uses data from the OSSs to determine the SISA parameters for GPS satellites. • Galileo regional component uses GPS tracking data with the SISA parameters to determine GPS integrity data.	• Safest option as the Galileo system carries out a full monitoring of integrity of GPS satellites. • If a full orbit and clock parameter estimation is carried out, option can improve continuity of service and hence service availability • Service can be guaranteed. • No major technical and institutional impacts on GPS. • Not constrained by the requirements on TTFF due to low GPS navigation data rate.	• Most expensive (technically) • Major impact on the Galileo global component • Major impact on the Galileo regional component.

4 Conclusions

This paper has presented the key results of a study carried out to determine the options for the provision of integrity data for GPS satellites based on the GIC approach within the Galileo architecture. Three options have been identified for consideration to support the definition of a pragmatic scheme for the monitoring of integrity of GPS satellites within the Galileo architecture. The option based the Galileo global component determining the SISA parameters for GPS satellites and the regional component using GPS tracking data with the SISA parameters to determine the integrity data, is the safest but potentially most expensive.

Disclaimer

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