# Design and Architecture of a Performance Monitoring System for EGNOS and Galileo


Johann Vilzmann, *EADS Astrium GmbH*
Frank J.P. Wokke, *National Aerospace Laboratory NLR*
Henk J. Veerman, *National Aerospace Laboratory NLR*
Andreas Breitenacher, *EADS Astrium GmbH*
Michael Kirchner, *EADS Astrium GmbH*


## BIOGRAPHY

Johann Vilzmann graduated in Electrical Engineering at Technical University of Munich in 1997. He has been working in system engineering at EADS since 1997 and joined Astrium in 2003, Johann was involved in performance monitoring of GNSS systems and is currently head of the navigation system performance department.

Frank Wokke graduated in Aerospace Engineering from Delft University of Technology in 1995. He has been working in the Space department of NLR since 1998. Frank has been involved in the development and verification of EGNOS and is currently active in Galileo system and segment level verification and validation.

Henk Veerman holds a Masters Degree in Experimental Nuclear & High Energy Physics from the University of Amsterdam. He has been working at NLR since 1987 and is currently Senior Scientist in the Flight Trials department of NLR. Henk was involved in the dynamic verification of the EGNOS Test User Receiver and is preparing for the dynamic verification of the Galileo Test User Receivers.

Andreas Breitenacher graduated in Electrical Engineering at Technical University of Munich in 2001. He was involved in software and system engineering at EADS before joining Astrium in 2004. His work relates to architecture definition, processes, interfaces, and protocols for performance monitoring and he is currently active in the External Interface Support for Galileo on system level.

Michael Kirchner is Engineer for Navigation Systems at EADS Astrium. He studied Geodesy at the Dresden Technical University, Germany and Chalmers Technical University, Gothenburg, Sweden. After graduation in 2002 he was responsible for a near real time tropospheric sounding project and quality assessment of GNSS data at the University FAF Munich. He joined EADS Astrium in 2005 and is mainly working in system performance and processing algorithms related activities for Galileo.

## 1 INTRODUCTION

The main mission of the European satellite radio-navigation programmes EGNOS and Galileo is the provision of state-of-the-art navigation services to the European and global user communities. Special consideration needs to be given, amongst many other factors, to the quality of the services provided and the end-to-end performance perceived by the users.

The responsibility for the operation of the EGNOS and Galileo systems may be delegated to one or more private companies may be in charge. In order to ensure that the required performance is met by such a private party, adequate performance monitoring needs to be enforced by the public sector (assumed to be represented by the European GNSS Supervisory Authority - GSA). It is expected that a service level agreement will be in place between the public sector and the respective operators of the EGNOS and Galileo systems that ensures that the mission goals defined in the EGNOS [Ref. 2] and Galileo [Ref. 3] Mission Requirements Documents (MRDs) are achieved by the operator of the EGNOS and Galileo system.

The system performance objectives of the service level agreements between the public sector and the EGNOS and Galileo operators are expected to be based on a set of defined Key Performance Indicators (KPIs) and corresponding measurement methodologies covering both service and signal level. Both service and Signal-In-Space (SIS) KPIs contribute to the definition of a KPI regime, as they complement each other. The SIS KPIs intend to represent the quality of the signals output by the system, whereas the Service KPIs intend to cover the end-to-end concept.

The current paper summarizes potential KPIs and KPI regimes, presents a potential architecture and design for a future GSA Performance Monitoring and Analysis Facility (GPMAF), and gives an outlook on the possible re-use of tools and the implementation of a GPMAF.

This paper is based on the results from a study for the GSA on the GPMAF. EADS Astrium GmbH, the Dutch National Aerospace Laboratory NLR and Deimos Engenharia comprise the industrial team executing this study for the GSA.

## 2 KPI DEFINITION

The most important objective of the GPMAF is to provide the means and the necessary tools for a supervising authority to perform as much as possible an independent evaluation of the system performance by routine monitoring of the KPIs. As a further objective the monitoring results may be used as a means to initiate Failure Detection and Isolation Analyses and to support arguments and settle disputes between the system operator and its clients.

The KPI regime is intended to monitor the EGNOS and Galileo operational performance and to detect the underperformance thereof. This means that KPIs for the systems' operational performance shall be defined that uniquely determine realised performance figures over a period of time based on traceable observables and known algorithms. The MRD and SRD specify the performance of particular parameters. These parameters have been specified to drive the system design, not necessarily to allow for convenient monitoring. While for the design of a system the definition of the parameters and the respective performance as given in the MRDs is sufficient, for the verification and monitoring it may not be.

The definition of the KPIs includes the observables to be collected, together with the calculation methodologies to be applied and the required reporting methods required. Basically the KPIs will be determined by 'black box' monitoring, i.e. based on collecting EGNOS and Galileo SIS and monitoring sensor stations' environmental parameters without taking into account the internal details of the operational status of the systems and the ways the various subsystems interact. The definition of KPIs is detailed in [Ref. 1], in this section a summary is given for completeness.

### 2.1 EGNOS KEY PERFORMANCE PARAMETERS

For EGNOS, both Service and Signal in Space (SIS) KPIs are defined. Most Service and SIS KPIs are defined per EGNOS GEO channel. The reason to define a KPI per GEO channel is that the main EGNOS observables, i.e. EGNOS Message Types, are broadcast via multiple geostationary satellites (GEOs) and that these data streams may not be identical, although they are similar. For an EGNOS user there is a priori no reason to prefer one EGNOS GEO channel to another.

#### 2.1.1 EGNOS SERVICE KPIS

For EGNOS the following services as defined in the MRD are discerned:

- Safety of Life for Non Precision Approach (NPA SoL),
- Safety of Life for Approach Procedure with Vertical guidance (APV1 SoL),
- Open Service (OS),
- Timing Service (TS), and
- Commercial Data Dissemination Service (CDDS).

For each of these services, performance requirements are applicable with respect to accuracy, integrity, availability, continuity and/or timing and latency. As such, related KPIs have been defined. The following table provides an overview on EGNOS services and the relationship to the KPIs:

**Table 1: EGNOS KPIs**

| KPI | NPA | APV-1 | OS |
|---|---|---|---|
| Horizontal position error (95-percentile) | √ | √ | √ |
| Vertical position error (95-percentile) | | √ | √ |
| Percentage of ECAC area where the accuracy requirement is met | √ | √ | |
| Integrity risk | √ | √ | |
| Horizontal safety index in the position domain | √ | √ | |
| Vertical safety index in the position domain | | √ | |
| Availability of service per GEO channel | √ | √ | √ |
| Availability of service for all GEO channels combined | √ | √ | √ |
| Percentage of ECAC area where availability requirement is met | √ | √ | √ |
| Percentage of ECAC area where Availability requirement is met for all GEO channels combined | √ | √ | |
| Percentage of ECAC area where Continuity Risk requirement is met | √ | √ | |
| Percentage of ECAC area where Continuity Risk requirement is met for all GEO channels combined | √ | √ | |

*"√": KPI relevant for that service*

For the Timing Service the following EGNOS Service KPIs are defined:
- EGNOS Network Time to GPS Offset.
- EGNOS Network Time to UTC Offset.

For the CDDS service the following EGNOS Service KPIs are defined:
- Latency of EGNOS Data Products.
- Availability of EGNOS Data Products.

### 2.1.2 EGNOS SIS KPIS

EGNOS Signal-in-Space KPIs are proposed in the following categories:
- SIS Availability.
- UDRE (User Differential Range Error) Integrity.
- GIVE (Grid Ionospheric Vertical Error) Integrity.

The following SIS KPIs intend to measure the availability of EGNOS Signal-in-Space, i.e. the percentage of time that EGNOS messages are broadcast on several GEOs:
- Availability of EGNOS messages on N simultaneous operational GEO channels
- Availability of EGNOS messages per GEO channel

The following SIS KPI is proposed for measuring the integrity of EGNOS provided slow and fast corrections and UDRE:
- UDRE Safety Index (including UDRE Misleading Information (MI) rate) per GEO channel and GPS PRN.

In analogy to the UDRE's residual error, the GIVE residual error per Ionospheric Grid Point (IGP) may be also a source for integrity violations in the service domain. The following SIS KPI is proposed for measuring the integrity of EGNOS provided ionospheric corrections and GIVE:
- GIVE Safety Index (including GIVE MI rate) per GEO channel and IGP.

Other miscellaneous EGNOS SIS KPIs can be imagined in addition to the ones defined above:
- GPS satellite don't use (DU) rate,
- IGP GIVE don't use (DU) rate,
- number of monitored satellites,
- number of monitored IGPs, and
- Central Processing Facility (CPF) Switch Occurrence Rate.

These SIS KPIs are considered secondary SIS performance indicators. They can however be useful inputs for Fault Detection, Isolation and Analysis (FDIA).

### 2.1.3 EGNOS KPI REGIMES

A number of EGNOS Service and SIS KPIs have been presented in the previous section. The correlated KPI regime is discussed in [Ref. 1] and summarized here.

<u>Integrity:</u>

The proposed Service Integrity KPIs (per GEO channel) are:
- Integrity risk of NPA service.
- Integrity risk of APV1 service.
- Horizontal safety index in the position domain for NPA service.
- Horizontal safety index in the position domain for APV1 service.
- Vertical safety index in the position domain for APV1 service.

A preference for the first two ('Integrity Risk') or the last three KPIs ('Safety Index', SI) is almost a matter of taste. We prefer the 'Integrity Risk' KPI definitions because they allow various representations, e.g. Stanford diagram, Stanford-ESA diagram with or without extrapolation based on outliers, SI histograms and SI Cumulative Distribution Functions (CDF).

The proposed SIS Integrity KPIs are:
- UDRE Safety Index per GEO channel and GPS PRN
- GIVE Safety Index per GEO channel and IGP

The advantages of SIS Integrity KPIs with respect to Service Integrity KPIs are:
- SIS KPIs are independent of local effects (e.g. multipath) and real receiver characteristics,
- the observables of SIS KPIs can (in principle) be taken from just one sensor station, and
- a large number of samples (~ number of epochs x number of GPS satellites) can easily be collected for a statistically more relevant result.

Therefore it is essential for GPMAF to implement these SIS Integrity KPIs.

Accuracy:

The proposed Service Accuracy KPIs (per GEO channel) are:
- Horizontal Position Error (95-percentile) for NPA.
- Horizontal Position Error (95-percentile) for APV1.
- Vertical Position Error (95-percentile) for APV1.
- Horizontal Position Error (95-percentile) for OS.
- Vertical Position Error (95-percentile) for OS.

These KPIs are PVT based, so they will be realistic but may be affected by unknown local effects. The last two KPIs are essential for GPMAF because Accuracy is the critical performance parameter for the Open Service.

Availability:

The service availability KPIs per GEO channel or for all GEO channels combined are based on sensor station PVT solutions. The KPIs related to percentage of ECAC are User Equivalent Range Error (UERE) and GIVE based interpolations.

The proposed SIS Availability KPIs are:
- availability of EGNOS messages on N simultaneous operational GEO channels, and
- availability of EGNOS messages per GEO channel.

These performances are already included in the respective Service Availability KPIs, so in principle these KPIs are not essential for GPMAF.

Continuity:

The proposed Service Continuity KPIs are identified in Table 1. These KPIs are EGNOS message set based extrapolations. It is essential for GPMAF to monitor the continuity performance in the service domain. Because of the fact that users are able to identify a channel's loss of continuity and based on that may switch to another EGNOS channel not suffering continuity loss, the EGNOS system level continuity coverage should prevail as KPI.

## 2.2 GALILEO KEY PERFORMANCE INDICATORS

The definition of Galileo KPIs and the corresponding KPI regime is detailed in [Ref. 1] and summarized her to enhance understanding.

### 2.2.1 GALILEO SERVICE KPIS

For Galileo the following services as defined in the MRD are discerned:
- Open Service Mono Frequency (OS MF),
- Open Service Dual Frequency (OS DF),
- Safety of Life Service (SoL),
- Public Regulated Service (PRS),
- Commercial Service (CS), and
- Search and Rescue Service (SAR).

Within the large number of performance relevant requirements, the Galileo MRD defines a set of performance parameters which are essential to describe the performance of a particular service. Especially the different types of Safety of Life service levels and partly also the Open Service are characterized by the following parameters and thresholds:
- positioning, velocity, and timing accuracy,
- integrity risk,
- time to alarm,
- horizontal alarm limit,
- vertical alarm limit,
- continuity risk, and
- availability.

The definition of a particular KPI is to the first instance independent from the service it is going to be applied for. A set of KPIs has been defined which is to some extent generic. In a second step the applicability for the different services is identified and additional dedicated KPIs for particular services are defined.

The identified Galileo Service KPIs are together with their applicability for the different services are summarized in Table 2.

### 2.2.2 GALILEO SIS KPIS

A number of Galileo SIS KPIs can be identified which characterize the SIS RF performance. As respective monitoring is beyond the scope of GPMAF, the monitoring is focused on Service KPIs. Non fulfilment of SIS KPIs might then only be considered relevant if they lead to a non-fulfilment of Service KPIs. From this perspective it is assumed that a degradation of payload performance leading to a degradation of the system services can be monitored as per the Service KPIs. The main driver for this approach is cost effectiveness for the GPMAF.
In case monitoring performed by GPMAF is restricted to the performance monitoring of Service KPIs with available receiver networks only the SIS characteristic which can conveniently be determined by pseudo-range tracking is monitored, which is the received power level.

### 2.2.3 GALILEO KPI REGIMES

For the Galileo Services a number of KPIs have been identified in the previous section. In this section a few KPI regimes are summarized.

Integrity:

One of the most critical parameters of the Safety-of-Life services is the fulfilment of the integrity risk requirement. Due to the very low probabilities allocated, it obviously cannot be measured directly. Therefore it is proposed to base the monitoring on a set of quantities that essentially drive the integrity risk but individually do not necessarily cause a HMI at user receiver. Such suitable quantities are checks of a posteriori derived expected SISE (eSISE) distributions against SISA, eSISE samples against the user applied threshold, and the impact of the final eSISE to the user integrity risk.

Accuracy:

Accuracy requirements for Galileo cover position accuracy, velocity accuracy and timing accuracy. Timing (and velocity) accuracy assessment is done in parallel with the assessment of the position accuracy, since it is the result of the navigation solution for position and time. The timing service is provided on E1 and E5b. Therefore the timing service performance can be assessed together with the performance of the Safety of Life Service and the Open Service.

Continuity:

Continuity of a service is a parameter which is very difficult to monitor. In contrast to integrity there is no method to compute the instantaneous continuity risk from the broadcast navigation message. From a user perspective continuity is given if a (defined) maximum number of critical satellites is not exceeded. As continuity performance shall be met on average over meaningful time periods a monitoring procedure is identified based on statistics of discontinuity events. These events are:

- the SIS is not provided for one of the critical satellites by any reason,
- the broadcast message is not provided or is

**Table 2: Traceability and applicability of Galileo KPIs to different services**

| KPI | OS (MF) | OS (DF) | SoL | PRS | CS | SAR |
|---|---|---|---|---|---|---|
| Position Accuracy | high | high | high | high | n/a | n/a |
| Velocity Accuracy | medium | medium | medium | medium | n/a | n/a |
| SISA Overbounding Failure | n/a | n/a | high | high | n/a | n/a |
| Range Threshold Failure | n/a | n/a | high | high | n/a | n/a |
| Integrity Risk Sample | n/a | n/a | medium | medium | n/a | n/a |
| Integrity Risk Ratio | n/a | n/a | medium | medium | n/a | n/a |
| Discontinuity Event Rate | n/a | n/a | high | high | n/a | n/a |
| SIS Availability | low | low | low | low | medium | n/a |
| Open Service Availability | medium | medium | n/a | n/a | n/a | n/a |
| A Priori Availability of Critical Service | n/a | n/a | high | high | n/a | n/a |
| A Posteriori Availability of Critical Service | n/a | n/a | high | high | n/a | n/a |
| GTRF-ITRF Consistency | low | low | low | low | low | n/a |
| GST-TAI Offset | medium | medium | medium | medium | low | n/a |
| Timing Accuracy | high | high | high | high | low | n/a |
| Galileo-GPS Time Offset | high | high | low | low | n/a | n/a |
| Message Correctness | high | high | high | high | low | n/a |
| Distress Detection | n/a | n/a | n/a | n/a | n/a | low |
| SAR Return Link | n/a | n/a | n/a | n/a | n/a | low |

obviously not correct,
- an alert is sent for any critical satellite, or
- integrity service becomes not available.

Note, that for discontinuity monitoring only the transition from nominal to not nominal condition is relevant.

Availability:

Availability is one of the central performance requirements for the Galileo system. According to the definitions of the Galileo MRD, availability is given if the applicable requirements for accuracy, integrity, and continuity are simultaneously met for the Safety of Life service and the Public Regulated Service. The Open Service is available when the accuracy requirement is fulfilled.

For the evaluation of service availability a number of events were identified in [Ref. 1] to detect unavailability of the service.

## 3 ARCHITECTURE SCENARIOS

For the monitoring of the KPIs and the implementation of the KPI regime a GPMAF needs to be developed and implemented. In a first step the high level architecture has been identified. For that purpose four scenarios have been defined for further assessment in terms of suitability for the performance assessment tasks:

- *Scenario 1: GPMAF as physical facility owned and operated by the public sector*

The complete system including hardware and software elements and their subcomponents are physically located within the premises of the GPMAF operator

- *Scenario 2: GPMAF as externally provided service*

The GPMAF is completely located at an external service provider, which is fully responsible for the operation and provides regular reports to the public sector responsible.

- *Scenario 3: GPMAF as distributed facility*

This scenario is similar to the first one, with the exception that a number of performance assessment processing modules are excluded from the GPMAF system. Those modules are operated under external responsibility but the results are provided to the GPMAF and integrated into the overall GPMAF results.

- *Scenario 4: GPMAF as network of centres*

Performance assessment centres externally to the GPMAF report their results, and a limited core system residing within the GPMAF operator premises generates consolidated GPMAF reports on a regular basis

The first scenario provides a highly flexible and independent concept as the responsibility and operation is fully at the GPMAF operator hands. This however comes along with a higher maintenance and operation effort compared to the other scenarios. In the area of performance monitoring however, the ability to control the methodology for the KPI determination and the report generation should fully justify this approach. It is suggested to enrich the approach of scenario 1 with an aspect of scenario 3. External entities (e.g. universities, agencies) may contribute with results to cross-check the data generated within the GPMAF. These results are expected to include UERE or PVT processing results.

The suggested scenario provides some advantages:
- GPMAF operator keeps full control of the GPMAF core system.
- Usage of external results and products possible for internal GPMAF processing.
- Flexibility for further investigations of system parameters above the defined KPIs and FDIA analysis.
- Full control of progress of performance assessment.
- Full transparency of the methodologies and algorithms, however limited when external products and results are used.
- Highly flexible for any system extension and amendments.

## 4 OPERATIONAL CONCEPT

The operational concept for a performance monitoring facility drives the architecture and the implementation and needs therefore some analysis on the necessary operators and the operation periods, the expected monitoring and control, and the maintenance of the hardware and software elements.

The operation periods of GPMAF is suggested to be on a 24 hours / 7 day per week basis. As the acquisition of data and products and the KPI determination methodology are pre-defined tasks, this can be achieved without operator interaction. Unforeseen outages of the GPMAF or its external connections can be covered as the necessary input data is available offline (with the potential exception of the EDAS) and the KPI determination processes can be re-started. For actions requiring manual operator interactions, e.g. for FDIA purposes, an operation during normal office hours is sufficient.

The data acquisition is running autonomously within the GPMAF. It collects data and products for GPS, EGNOS, and Galileo from external service providers. For the EGNOS KPI monitoring a connection to the EDAS is necessary to receive EGNOS system data and verify EDAS performance; Galileo uses potentially a similar system in FOC, in which case a corresponding mechanism has to be implemented.

The GPMAF user types consist of administrators, normal users of the system, and advanced users of the system. The administrator is in charge of the hardware and software installation tasks, and is responsible for the maintenance of hardware and software. The normal user of the system has basically only the rights to read and evaluate the periodic reports generated by the GPMAF. The advanced user of the system can in addition start KPI assessment on demand, configure the KPI reports, configure the system, and perform FDIA assessment up to the capabilities installed in the GPMAF.

The automatic KPI reporting is planned to be with different frequencies, starting from daily reports, weekly (for EGNOS) or 10 days (for Galileo), monthly and yearly reports.

As a number of third party monitoring network providers are available, the deployment of dedicated GPMAF sensor stations may not be necessary. However, to increase the flexibility it is recommended to cater for a future deployment and operation of dedicated sensor stations. Furthermore it needs to be possible to include results generated by third parties in the calculation of the KPIs.

The basic FDIA operation has been defined in the operational concept. An FDIA process may be initiated by the operator of the GPMAF in case an underperformance has been detected by the KPI determination process. As a first step any reasons that led to the detection of the underperformance, coming from the GPMAF system itself or the data used by the GPMAF, needs to be eliminated. As a second step a liaison with the EGNOS or Galileo technical operators is necessary to obtain a first set of more general information. In case this does not explain the cause of the underperformance, low level technical discussions with the EGNOS or Galileo operators are necessary.

## 5 FUNCTIONAL ARCHITECTURE

After having identified the preferred scenario, focus is now given to the functional architecture, i.e. the functional components that build up the architecture of a GPMAF. The main components of such a system are listed and described below.

### 5.1 MONITORING AND CONTROL

This function is in charge of controlling and steering the GPMAF core system and sensor stations (if deployed), triggers processes and functions and monitors internal GPMAF system status. Also, it provides the interface to the user, through which the user can configure the system and acquire results and reports.

### 5.2 DATA ACQUISITION

This component is the main interface to receive data and products from external entities and GPMAF sensor stations, where the external interfaces are the Galileo system, the EGNOS system and independent organizations (e.g. IGS). The function uses adequate standard transfer protocols, e.g. FTP, to obtain the necessary data. For specific interfaces like the EGNOS EDAS, a dedicated client interface for real-time connection is used.

### 5.3 FORMAT CHECK AND ARCHIVE

This component is performing format checks, completeness checks, and plausibility checks on the acquired data. It consolidates the observation data and navigation messages, and compresses and decompresses data in accordance with standards within the GPMAF. The data is stored in a global archive and is made available to other GPMAF functions. Backup mechanisms are implemented to a GPMAF data storage and backup policy.

### 5.4 EGNOS PROCESSING

This component uses all acquired EGNOS relevant input data and generates intermediate results for the subsequent EGNOS performance assessment, which are PVT assessment, UERE assessment, CDDS assessment, and the Timing assessment.

For the EGNOS PVT assessment some pre-processing of the observation data is necessary to detect excessive environmental conditions, smoothing of the raw observables and potentially considering the P1 to C1 code biases. On the pre-processed observations EGNOS corrections are applied according to [Ref. 4], and the PVT solutions and horizontal and vertical protection levels (HPL/VPL) are determined using an all GPS satellites in view approach. PVT solutions need to be determined considering the different regulations for OS, NPA, and APV-1. For each PVT solution the horizontal and vertical position error (HPE/VPE) is determined using the antenna reference position of the sensor station. In addition Stanford Plots and Stanford-ESA plots are generated at each sensor station position.

The EGNOS UERE assessment is in charge of determining the individual contributors including the residual error in the satellite orbit and clock corrections, and the ionosphere and troposphere error. The residual orbit and clock error can be estimated by comparing the EGNOS corrected orbits and clocks with precise products from third parties. The residual error in the ionosphere corrections broadcast by EGNOS can be determined by comparing the broadcast values with precise ionosphere vertical delay parameters obtained in post-processing in each of the ionosphere grid points (IGPs) of the ECAC grid. The troposphere error can be determined by comparison of the Troposphere Reference Data for the provided measurement positions in the reference file with the User model. The UERE is transformed to accuracy at user level (i.e. horizontal and vertical navigation system error) for a (lat /lon) grid with many user locations covering ECAC.

Finally the worst user location (WUL) is determined. If the location of the WUL is determined to be outside the ECAC area, it is transferred to the nearby boundary point. The satellite residual error is determined at this WUL.

## 5.5 GALILEO PROCESSING

This component uses all acquired Galileo relevant input data and generates intermediate results for the subsequent Galileo performance assessment, which are PVT assessment, UERE assessment, Reference Frame Monitoring, Message Monitoring, and SAR Monitoring. Optionally a Galileo Reference Product Generation function generating products related to orbit determination and time synchronization (OD&TS) may be implemented. These products are seen complementary to products provided by third parties, however help to improve the independence and consistency of the products used within the GPMAF.

For the Galileo PVT assessment some pre-processing steps are necessary including plausibility checks of the observations and exclusion of outliers, detection of excessive multipath and interference conditions and exclusion of respective data, detection of cycle slips and, if possible and appropriate (i.e. for non SoL analysis), correction of data or exclusion of respective observations from the assessment, code-carrier smoothing of raw observables according to applicable system specifications for user algorithms, e.g. Hatch filtering, and application of corrections for propagation effects according to applicable system specifications for user algorithms. Within the pre-processing also the a-priori integrity risk to determine the availability of critical services (SoL) can be performed.
As a next step for the PVT calculation the satellites usable for PVT solutions according to user algorithms as defined by system specifications are determined, and the PVT solutions at the sensor station positions following the user algorithms as defined by system specifications are determined. As observations for both OS and SoL are available that may differ, the PVT solutions for both OS and SoL service are calculated. In case the difference is marginal, one PVT solution is taken as result of this process. Otherwise the cause for the difference needs to be investigated.

The Galileo UERE assessment aims at estimating the different contributors to the UERE. The focus is put on the contributors independent of local reception conditions since these are valid also for other user positions. These are:

- Ephemeris error.
- Broadcast group delay error.
- Ionospheric delay modelling error.
- Tropospheric delay modelling error.

To estimate these errors reference products are used that can be obtained from third party service providers.

In addition the SISE at the worst user location is determined by comparison of post processed precise satellite orbit and clock corrections with the broadcast parameters of the navigation message for all sampling epochs and satellites.

The a posteriori determined contributions to the user range error are combined. They cover satellite ephemeris error, BGD error, ionosphere modelling error, and troposphere modelling error. Further range error contributions are due to the local reception characteristic and vary individually to the dedicated user or monitoring station. These are thermal noise figures, multipath and interference. To representatively account for these contributors the values used in the system design (treated as Gaussian) are used.

The so combined instantaneous range error estimations of different satellites can be transformed from range domain to position domain taking into account the observation geometry. This allows obtaining an estimation (expected value) of the position error for any location in the service area. The procedure furthermore allows considering the uncertainties of the range error estimates leading to correct estimation of position error variance. This is necessary to ensure the required confidence of the KPI determination.

The procedure provides some flexibility in terms of treatment of multipath error. Range error caused by multipath is caused by different signal reflections with a wide variety of correlation lengths. Short period signals might be modelled as an additional noise contribution while long period signals are quasi stationary and should be modelled as a systematic bias. Therefore the multipath contribution is considered in one instance as additional noise, in the other as a stationary bias. When considering the multipath as a stationary bias, this needs to be specially treated as the direction of the bias is not known. Therefore all combinations are investigated to determine a (conservative) estimation of the convex envelope of the PVT error. The transformation to the position domain is superposed by a non-zero variance caused by the uncertainties of the a posteriori derived SISE. These uncertainties are also transformed to the position domain and the corresponding covariance matrix is determined.

### 5.6 PERFORMANCE EVALUATION

Finally, the intermediate result data from EGNOS and Galileo processing are used for analysis and statistic calculations and also for the KPI performance assessment as main result from the GPMAF system. The intermediate result data from the EGNOS and Galileo processing functions are buffered in the archive, as this avoids a huge computation overhead and enables also long-term report and assessment processing.

### 5.7 GPMAF SENSOR STATION (OPTIONAL)

This component receives SIS data and injects the measured data into the GPMAF system. The stations are considered to be optional to the GPMAF system as a number of monitoring networks are available and can be used for monitoring purposes. However, a GPMAF specific sensor network may provide an additional level of independence to the GPMAF overall system. SIS data reception comprises of GPS data, Galileo data, and EGNOS data messages. The SIS reception is conducted typically in real-time, whereas the received data is stored in a coded and decoded format on a receiving computer. Such a system shall include FTP-capabilities to enable access to the received data from the GPMAF data acquisition component.

## 6 PHYSICAL ARCHITECTURE

### 6.1 MONITORING NETWORK

The design of a monitoring network depends on the required characteristics of such a network. Important drivers are the necessary depth of coverage (DOC), minimum elevation angle required, satellite orbit characteristics and station availability. As a number of monitoring networks are available covering both the global area and the European area with the required characteristics, it is deemed not necessary to deploy a dedicated GPMAF sensor station network. It is expected that existing global monitoring networks will be upgraded to cover the Galileo constellation, so that information on Galileo will be available for GPMAF purposes.

The only need for dedicated GPMAF sensor stations may be to fill the gap at the beginning of the Galileo operational phase, when potentially a reduced number of sensor stations will be able to acquire the Galileo signals.

### 6.2 GPMAF SYSTEM

Figure 1 shows the physical deployment of the system. Remote entities such as the IGS, the optional GPMAF sensor stations, etc. are physically connected to the GPMAF processing centre via the Internet. EGNOS and (probably) Galileo Ground Segments will be connected via a real-time connection. Inside the GPMAF processing centre a number of workstations is connected to a 1Gb Ethernet network and share a common storage facility between them. Additional workstations can be added to increase the computation capabilities.

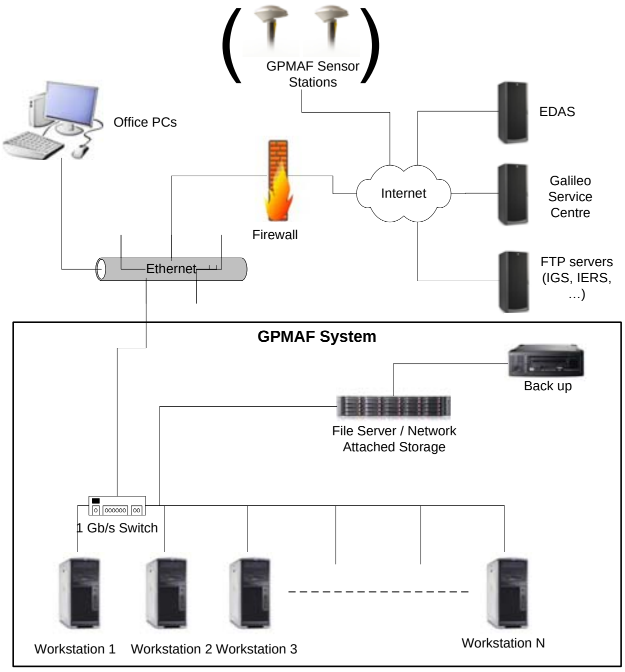


**Figure 1: GPMAF physical architecture**

## 7 IMPLEMENTATION PLAN

Taking into account the fact that the EGNOS and Galileo programme schedules and the current phase in each of these systems' lifecycle are completely different and non-related, the need for the GSA to monitor the two systems (or rather the respective service providers) arises at different moments in time. The performance monitoring capabilities for EGNOS are required much earlier than for Galileo An implementation plan and versioning approach has been established, describing the steps necessary for the full development of the GPMAF in line with the architectural concept, following a cost-effective strategy and taking into account constraints and drivers from the EGNOS and Galileo development and operational programmes.

## 8 CONCLUSION

The objective of a GPMAF system is the monitoring of the performance of the European navigation systems EGNOS and Galileo based on a set of Key Performance Indicators and associated measurement methodologies, integrated into a corresponding KPI regime.

In order to achieve this objective, an operational concept has been outlined. The selected high level scenario allows maximum flexibility and modularity to cover the potential upgrades of the KPI regime and allows development and improvement of FDIA techniques. It is expected that for a final implementation of the GPMAF significant re-use of existing platforms and tools, especially in the area of EGNOS, can be made.

The objective of the monitoring of the identified KPIs and the implementation of the KPI regime is to allow the public sector, i.e. the owner of the EGNOS and Galileo systems, to evaluate the performance of the private parties responsible for operating the system and thus to watch over the performance of the EGNOS and Galileo services vis-à-vis their users. Therefore the presented concept and architecture of a GPMAF may contribute to such an evaluation process.

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## REFERENCES

[Ref. 1] *Key Performance Indicators for Performance Monitoring and Analysis of EGNOS and Galileo,* presented at ENC-GNSS 2008, Toulouse (France), April 23-25, 2008.

[Ref. 2] *EGNOS Mission Requirements Document*, version 2.0, 8th May 2006, GJU.

[Ref. 3] *Galileo Mission Requirements Document*, version 6.0, 26th May 2004, GSA.

[Ref. 4] *Minimal Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment,* RTCA/DO-229C (MOPS), issue C, 28th November 2001