Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Key Performance Indicators for Performance Monitoring and Analysis of EGNOS and Galileo

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As part of the business model envisaged for EGNOS and Galileo, a private company may be responsible for the operation and commercial exploitation of EGNOS and Galileo. Given the strategic importance of these programmes, the Public Sector must ensure an adequate surveillance by putting in place the necessary means to guarantee that the mission goals as specified in the EGNOS and Galileo Mission Requirements Documents (MRDs) are achieved by the private operator of EGNOS and Galileo. As Public Sector's representative, the European GNSS Supervisory Authority (GSA) has been entrusted with this responsibility. The primary responsibilities of the EGNOS and Galileo operator shall be laid down in a Service Level Agreement (SLA), which covers at least the definition of the performance objectives and the ways to assess the achieved performances.

The verification of this SLA is going to be based on the monitoring of a set of performance parameters referred to as Key Performance Indicators (KPIs). Both Signal in Space (SIS) KPIs and Service 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, which represent (parts of) the navigation chain including navigation data, frequency channel and the user terminal, intend to represent the end-to-end concept.

The current paper presents potential KPIs and KPI regimes for EGNOS and Galileo, which are first results from an ongoing study for the European GNSS Supervisory Authority (GSA) on a future GSA Performance Monitoring and Analysis Facility (GPMAF).

The objective of the GPMAF is to monitor the performance of European navigation systems EGNOS and Galileo based on a set of Key Performance Indicators. The KPIs identified in this document are defined such that the performance

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of EGNOS and Galileo can be assessed by already available or quite realistic measurement means. The performance assessment does not require unfeasible or challenging monitoring technologies. Even for very critical parameters such as integrity related ones, measurement means could be identified allowing a performance evaluation within reasonable time spans between one week and one year.

A preliminary design for the GPMAF has been established, covering the main functions of data collection (from GPMAF specific and external monitoring stations), data processing, KPI analysis, and KPI reporting. It is expected that for the final implementation of GPMAF significant re-use of existing tools and facilities can be made.

With the here presented set of KPIs, the performance of the European navigation systems EGNOS and Galileo can well be characterized. To which level the assessment results are legally applicable has, nevertheless, still to be finally defined in the future by the GSA.

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Key Performance Indicators for Performance Monitoring and Analysis of EGNOS and Galileo

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Summary

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The verification of this SLA is going to be based on the monitoring of a set of performance parameters referred to as Key Performance Indicators (KPIs). Both Signal in Space (SIS) KPIs and Service 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, which represent (parts of) the navigation chain including navigation data, frequency channel and the user terminal, intend to represent the end-to-end concept.

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A preliminary design for the GPMAF has been established, covering the main functions of data collection (from GPMAF specific and external monitoring stations), data processing, KPI analysis, and KPI reporting. It is expected that for the final implementation of GPMAF significant re-use of existing tools and facilities can be made.

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Contents

Abbreviations

APV	Approach Procedure with Vertical guidance
BGD	Broadcast Group Delay
CDDS	Commercial Data Dissemination Service
CS	Commercial Service
DOC	Depth of Coverage
DOP	Dilution of Precision
EGNOS	European Geostationary Navigation Overlay Service
ENT	EGNOS Network Time
EPM	EDAS Product Messages
ESA	European Space Agency
FDIA	Fault Detection, Isolation and Analysis
GEO	Geosynchronous Orbit
GIVD	Grid Ionospheric Vertical Delay
GIVE	Grid Ionospheric Vertical Error
GMS	Ground Mission Segment
GNSS	Global Navigation Satellite System
GPMAF	Galileo Performance Monitoring and Analysis Facility
GPS	Global Positioning System
GSA	GNSS Supervisory Authority
GST	Galileo System Time
GTRF	Galileo Terrestrial Reference System
HAL	Horizontal Alarm Limit
HMI	Hazardous Misleading Information
HNSE	Horizontal Navigation System Error
HPE	Horizontal Position Error
HPL	Horizontal Protection Level
ICD	Interface Control Document
IGS	International GNSS Service
IONEX	Ionosphere Exchange Format
ITRF	International Terrestrial Reference Frame
KPI	Key Performance Indicator
MI	Misleading Information
MOPS	Minimal Operational Performance Standards
MRD	Mission Requirements Document
NLR	National Aerospace Laboratory NLR

NPA	Non-Precision Approach
NSE	Navigation System Error
OS	Open Service
PRS	Public Regulated Service
PTF	Precise Timing Facility
PVT	Position Velocity Time
RD	Reference Document
RF	Radio Frequency
RIMS	Range and Integrity Monitoring Station
RINEX	Receiver Independent Exchange Formant
RMS	Root Mean Square
RTCA	Radio Technical Commission for Aeronautics
SAR	Search And Rescue
SARSAT	Search And Rescue Satellite-Aided Tracking
SI	Safety Index
SIS	Signal In Space
SISA	Signal In Space Accuracy
SISE	Signal In Space Error
SISMA	Signal In Space Monitoring Accuracy
SL	Service Level
SRD	System Requirements Document
SRE	Satellite Residual Errors
SREW	Satellite Residual Error at the Worst User Location
SV	Space Vehicle
TAI	International Atomic Time
TS	Timing Service (EGNOS)
TTA	Time To Alarm
UDRE	User Differential Range Error
UERE	User Equivalent Ranging Error
UTC	Universal Time Coordinated
VAL	Vertical Alarm Limit
VNSE	Vertical Navigation System Error
VPE	Vertical Position Error
VPL	Vertical Protection Level
WAAS	Wide Area Augmentation System
WUL	Worst User Location
XAL	HAL and/or VAL

1 Introduction

The main mission of the European satellite radio-navigation programmes EGNOS [Ref. 1] and Galileo is the provision of state-of-the-art navigation services to the European and global user communities. The commercial uptake of both systems will depend, amongst many other factors, on the quality of the services provided and the end-to-end performance perceived by the users.

As part of the business model envisaged for EGNOS and Galileo, a private company (or companies) may be responsible for the operation and commercial exploitation of EGNOS and Galileo. Given the strategic importance of these programmes, the Public Sector must ensure an adequate surveillance by putting in place the necessary means to guarantee that the mission goals as specified in the EGNOS [Ref. 2] and Galileo Mission Requirements Documents (MRDs) [Ref. 3] are achieved by the private operator of EGNOS and Galileo. As Public Sector representative, the European GNSS Supervisory Authority (GSA) has been entrusted with this responsibility.

The primary responsibilities of the EGNOS and Galileo operator shall be laid down in a Service Level Agreement (SLA), which covers at least the definition of the performance objectives and the ways to assess the achieved performances. The verification of this SLA is going to be based on the monitoring of a set of performance parameters referred to as Key Performance Indicators (KPIs). Both Service KPIs 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, which encompass (parts of) the navigation chain including navigation data, frequency channel and the user terminal, intend to characterise the end-to-end concept.

Two main performance evaluation methodologies have been identified. On the one hand, the assessment of the EGNOS and Galileo service performances shall be solidly founded on the analysis of GNSS tracking data collected in a network of sensor stations. On the other hand, the monitoring of the KPIs cannot be effectively achieved just by analysing GNSS measurements, due to practical limitations in the size and density of the KPI monitoring network. Therefore evaluation of the KPIs over the whole service volume requires tools capable of inter- and extrapolating the system performance to areas which are not sufficiently covered by the KPI monitoring network. The GSA thus plans to make use of service volume analysis tools in order to complement and extrapolate the performance results derived from the real GNSS data analysis activities.

This paper reflects the first results from an ongoing study for the GSA on this future GSA Performance Monitoring and Analysis Facility (GPMAF). EADS Astrium GmbH, the Dutch National Aerospace Laboratory NLR and Deimos Engenharia comprise the industrial team executing this study for the GSA.

The current paper discusses potential KPIs and KPI regimes for EGNOS and Galileo, presents a preliminary design for the GPMAF, and gives a first outlook on the possible re-use of existing tools and facilities for the GPMAF.

2 KPI Definition Approach

The aim for the GPMAF is to derive an optimal set of measurable Key Performance Indicators together with appropriate threshold values. These parameters and threshold values enable the monitoring of the operation and services of EGNOS and Galileo. This monitoring shall verify that the systems are operating as required. In case they are not met, the KPIs may be the basis for further fault detection and could support the identification of the source of underperformance and – depending on the Service Level Agreement – also the responsible party.

The most important objective for the GPMAF is to provide the tools and means necessary for the GSA to carry out an as much as possible independent evaluation of the system performances through the routine monitoring of the KPIs. It is understood that for the intended objective of GPMAF, the KPIs defined should provide the qualitative and, together with the associated threshold values, the quantitative basis for a (future) Service Level Agreement between the GSA and the system operator. As a secondary objective, the monitoring results might be used as a means to settle disputes between the system operator and its clients on the achieved performances (i.e. the provided service). In both cases, parts or all of the identified KPIs have contractual and/or legal relevance.

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.

A KPI definition should also propose the observables to be collected, together with the algorithms to be applied as well as the 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.

A number of essential definitions and performance requirements for EGNOS and Galileo are specified in a way that makes a strict determination impossible. One example could be the definition of "global average". Certain parameters shall be fulfilled for each instance in time on a global average of for instance 99.5%. Due to the limited discretisation of the service volume by the monitoring network, the determination whether a certain parameter is fulfilled on a global average can only be determined with a limited confidence.

Other examples are performance requirements with specified confidence levels for which a strict interpretation of the requirement and relevant definitions would lead to the fact that only one single value is to be assessed for the monitoring. Since it is impossible to derive statistical evidence from a single value the interpretation of those requirements is done in an alternative way which does allow appropriate monitoring. This is the case for integrity monitoring, for which the Safety Index in the range domain is proposed for the integrity KPI.

The preconditions for a meaningful interpretation and thus a useful KPI are:

- to find an interpretation which leads to measurable quantities, and
- to find an interpretation which can be accepted by all stakeholders.

As a result, compromises may have to be accepted regarding mathematical correctness of the interpretation. It is highlighted that the selection of a mathematically correct interpretation, leading to a non-measurable performance indicator is of no use for the GPMAF.

The complete set of identified Service KPIs and SIS KPIs will include dependencies since it is questionable whether a set of measurable KPIs can actually be formulated that is both complete and at the same time completely independent.

Possible sources of underperformance for which the system operator cannot be held responsible shall be identified, isolated and quantified. In particular the User Terminal subsystem and the local environmental conditions under which it is operating, shall be excluded from the system operator's responsibility. This assumption leads to two consequences. First, KPI observables shall be obtained using a fault free receiver. Any deviation of the actual receiver from a fault free receiver shall be quantified and taken into account. Second, the local environmental conditions (multipath, RF interference) under which the monitoring sensor station has collected the observables shall be determined if possible.

In the systems' Mission Requirements Documents some central performance requirements are defined over the complete life time of the systems, i.e. 15 years for EGNOS and 20 years for Galileo. For monitoring purposes this is not a practical period. Therefore the KPI monitoring approach is based on shorter time periods. It is proposed to provide periodic KPI reports based on various intervals, i.e. on a weekly, monthly, quarterly and yearly basis, depending on the KPI. Considering the availability of KPI reports at various intervals, the trends in system performance and KPIs can be monitored as well, providing the possibility to establish early warnings for underperformance.

In practice, any performance measurement over a limited period of time will result into a statistical approximation of the real value. For this reason the measured value of a KPI shall always be reported together with associated measurement confidence levels, which depend amongst other things on the measurement duration.

3 Association Of Threshold Values To KPIs

For the routine monitoring of Key Performance Indicators meaningful threshold values need to be defined to distinguish between nominal performance as required by the Mission and System Requirements Documents, and underperformance which leads to the situation that the system cannot provide its services with the quality expected by the user. Considering the (contractual) consequences the detection of underperformance may have, strong confidence in the monitoring results is essential.

The central mission of the GPMAF is the monitoring of the performance of the EGNOS and Galileo systems. Monitoring of performance can be done by assessing an almost infinite number of performance indicators. Since the system is built to satisfy the MRD, which was defined taking into account user needs and expectations, performances should be measured according to those specifications.

Performance parameters defined by the MRD and usually also SRD, typically describe error budgets, error bounds or error percentiles. It is highlighted that hardly any such specification of performance parameters can be strictly verified. The reasons for this should become obvious with the clarifications given below.

The MRD and SRD specify the performance of particular parameters. These parameters are specified to drive the system design. They have not been specified to allow a convenient monitoring. So there might be a significant discrepancy between the definition of a particular parameter and a respective measurement methodology, since the latter is identified after the definition of the parameter. While for the design of a system the definition of the parameters and respective performance is sufficient, it may not be for the verification and monitoring. Due to measurement related limitations, it might not completely comply with the definition of the parameter. Whatever procedure of verification and monitoring is applied, it can rarely exactly describe the population of parameters implicitly defined by the requirements.

In case error bounds are specified, the measured value must be within that bound with a given probability. The same holds for requirements that refer to certain percentiles. In those cases no information is given or assumptions are made on the underlying distributions of the parameter within or beyond the given limits. In case performance is defined referring to sigma values, e.g. "…the parameter shall be within the limit of x (2 sigma)…", the specification is implicitly based on an underlying distribution of that parameter, while the type of distribution is not defined and hence for strict interpretation unknown. However, in general it should be assumed that the underlying distribution is Gaussian since only this distribution is characterized by a sigma value. Other common distributions are characterized by parameters typically not called sigma.

For the routine monitoring of Key Performance Indicators, meaningful threshold values need to be defined to distinguish between nominal performance as required by the Mission and System Requirements Document and underperformance which leads to the situation that the system cannot provide its services with the quality expected by the user. The latter state is the critical one and it is assumed that those situations could have further legal or contractual consequences. Therefore the decision whether or not the Key Performance Indicators are met, must have sufficient confidence. An important issue to consider is the fact that also the monitoring and analysis process has a certain level of uncertainty.

There are basically two strategies for the treatment of confidences and thresholds:

- Definition of required confidence for the assessment result. This confidence is fixed and the thresholds must be defined in accordance to the required confidence.
- Definition of thresholds and computation of confidence levels for the case that the threshold is exceeded.

4 EGNOS Key Performance Indicators

For EGNOS, both Service and Signal in Space (SIS) KPIs are defined. Most Service and SIS KPIs defined in this study 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.

It is possible to derive one or more KPI definitions at system level from a channel KPI definition by combining the performances or observables of different GEO channels. Possible interpretations of a ‘system KPI’ are:

- It represents the mean (best or worst case) performance of the contributing GEO channels. This kind of KPI can be defined as a function of channel KPI values.
- It represents the performance experienced by a user receiver capable of GEO channel switching. Channel switching is allowed in SoL applications under certain conditions. This kind of KPI requires a suitable monitoring process.

In the latter case the performance of the ‘system KPI’ may surpass the contributing GEO channel’s individual KPI performances. For those KPIs for which the user can identify the GEO channel’s underperformance, based on which the user may execute a channel switch, the performance of the ‘system KPI’ is of interest. Examples are availability and continuity related KPIs.

4.1 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.

For the NPA SoL service the following EGNOS Service KPIs are defined:

- Horizontal Position Error (95-percentile) for NPA service.
- Percentage of ECAC (European Civil Aviation Conference) area where NPA Accuracy requirement is met.
- Integrity risk of NPA service.
- Horizontal safety index in the position domain for NPA service.
- Availability of NPA service.
- Availability of NPA service for all GEO channels combined.
- Percentage of ECAC area where NPA Availability requirement is met.
- Percentage of ECAC area where NPA Availability requirement is met for all GEO channels combined.
- Percentage of ECAC area where NPA Continuity Risk requirement is met.
- Percentage of ECAC area where NPA Continuity Risk requirement is met for all GEO channels combined.

For the APV1 SoL service the following EGNOS Service KPIs are defined:

- Horizontal Position Error (95-percentile) for APV1 Service.
- Vertical Position Error (95-percentile) for APV1 Service.
- Percentage of ECAC landmasses where APV1 Accuracy requirements are met.
- Integrity risk of APV1 service.
- Horizontal safety index in the position domain for APV1 service.
- Vertical safety index in the position domain for APV1 service.
- Availability of APV1 service.
- Availability of APV1 service for all GEO channels combined.
- Percentage of ECAC landmasses where APV1 Availability requirement is met.
- Percentage of ECAC landmasses where APV1 Availability requirement is met for all GEO channels combined.
- Percentage of ECAC landmasses where APV1 Continuity Risk requirement is met.
- Percentage of ECAC landmasses where APV1 Continuity Risk requirement is met for all GEO channels combined.

For the Open Service the following EGNOS Service KPIs are defined:

- Horizontal Position Error (95-percentile) for Open Service.
- Vertical Position Error (95-percentile) for Open Service.
- Open Service Availability based on Position Error.
- Percentage of ECAC landmasses where Open Service requirements are met.

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.

4.2 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.

It is generally understood that the integrity requirements in the service domain as defined in the EGNOS MRD and SRD are extremely stringent. Therefore it is questionable whether it can serve as an adequate KPI, because collecting enough statistical evidence would take far too much time. One method to overcome this problem is to define alternative KPIs for integrity assessment that can be measured better. The UDRE Safety Index, an alternative KPI in the range domain that is implemented in the EGNOS Performance Assessment and Control. Facility (PACF) for instance, is tightly related with integrity in the service domain (see also below). It focuses on one of the possible sources of non-integrity: the UDRE’s residual error rate of each GPS satellite monitored by EGNOS.

Advantage of this approach is that higher statistics can be collected together with lower thresholds: an $SI_{UDRE} > 5.33$ event (considered as non-integer in the range domain) does not necessarily lead to non-integrity in the service domain. Another advantage is the virtual lack of sensitivity of this KPI to local effects, because the UDRE SI is based on comparison of the consolidated EGNOS message set from a large ensemble of sensor stations, with IGS reference products such as accurate orbits. These advantages may lead to useful KPIs. Disadvantages are the fact that no requirements are available in the MRD and SRD that can provide thresholds for such metrics in the range domain, the complex algorithms involved and the late availability of required input parameters, i.e. precise satellite orbit and clock.

The UDRE Safety Index gives the measured SREW/UDRE characteristics including measured MI in the range domain. The SREW is the Satellite Residual Error at the Worst user location. The $MAX(SI_{UDRE})$ can be a good indicator to detect integrity failures before they actually happen. The Misleading Information (MI) Rate, which will also be provided gives the number of independent MI events observed in a given reporting period. Possibly even more interesting is the MI-probability given by:

$$\text{MI probability} = \text{MI events} / \text{nr of epochs}$$

The following SIS KPIs are proposed for measuring the integrity of EGNOS provided slow and fast corrections and UDRE:

- UDRE Safety Index (including UDRE 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. Therefore the SI_{GIVE} is defined: SI_{GIVE} = (GIVDe/GIVE) where GIVDe is defined as the Grid Ionospheric Vertical Delay error.

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).

5 EGNOS KPI Regimes

A number of candidate EGNOS Service and SIS KPIs have been presented in the previous section. In this section it is discussed which KPIs are most useful for a KPI regime.

5.1 Integrity

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.

Integrity is a critical performance of EGNOS. These KPIs are based on statistical analysis of PVT solutions from sensor stations. Sensor station PVT is the best observable to obtain realistic position errors. Therefore it is essential for GPMAF to implement some of these KPIs.

A preference for the first two (‘Integrity Risk’) or the last three KPIs (‘Safety Index’) 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 [Ref. 1], 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.

Integrity is a critical performance of EGNOS. These SIS KPIs are defined in the pseudorange domain based on observed EGNOS messages and precise orbit, clock and ionosphere data from an external source. The UDRE and GIVE outputs correspond to the main functions of EGNOS and are therefore complementary.

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.

5.2 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.

EGNOS is expected to easily fulfil the Accuracy requirements for NPA and APV1, so the first four KPIs are less essential. They are however useful counterparts for KPIs:

- percentage of ECAC area where NPA Accuracy requirement is met, and
- percentage of ECAC landmasses where APV1 Accuracy requirements are met.

In addition, an accuracy assessment at user level is provided by KPI:

- percentage of ECAC landmasses where Open Service requirements are met.

These last three KPIs are UERE (User Equivalent Range Error) and GIVE based interpolations of locally obtained PVT results. They are useful to obtain a contour of the service volume where EGNOS users can expect a certain service. Therefore these KPIs are essential for GPMAF.

5.3 Availability

The proposed Service Availability KPIs are:

- availability of NPA service per GEO channel,
- availability of NPA service for all GEO channels combined,
- availability of APV1 service per GEO channel,
- availability of APV1 service for all GEO channels combined,
- availability of OS service per GEO channel,
- availability of OS service for all GEO channels combined,
- percentage of ECAC where NPA Availability requirement is met per GEO channel,

- percentage of ECAC where NPA Availability requirement is met for all GEO channels combined,
- percentage of ECAC landmasses where APV1 Availability requirement is met per GEO channel, and
- percentage of ECAC landmasses where APV1 Availability requirement is met for all GEO channels combined.

UERE is translated to Accuracy at user level (Navigation System Error or xNSE) via the DOP of the user / satellite geometry:

$$\sigma_{xNSE} = xDOP * \sigma_{UERE}$$

This computation is efficiently performed for a (lat, lon) grid with many user locations covering ECAC. The grid point performance can be represented as a surface map over ECAC using spatial interpolation.

Because the availability performance does not depend on the position error (this is arguably the case for NPA and APV1), there is no specific need for a PVT based approach. Therefore the last four KPIs are more essential for GPMAF than the first three. Because of the fact that users are able to identify a channel's loss of availability and based on that may switch to another EGNOS channel not suffering availability loss, the EGNOS system level availability coverage should prevail as KPI.

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.

5.4 Continuity

The proposed Service Continuity KPIs are:

- Percentage of ECAC area where NPA Continuity Risk requirement is met per GEO channel.
- Percentage of ECAC area where NPA Continuity Risk requirement is met for all GEO channels combined.
- Percentage of ECAC landmasses where APV1 Continuity Risk requirement is met.
- Percentage of ECAC landmasses where APV1 Continuity Risk requirement is met for all GEO channels combined.

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.

6 EGNOS Monitoring Methodology

The GPMAF shall monitor the performance of the EGNOS system for the entire service area (ECAC). The central assessment means are a monitoring network, composed of monitoring stations, and a processing facility that carries out the necessary computations and assessments.

Monitoring stations will perform the following functions for GPMAF EGNOS KPI monitoring:

- Collect EGNOS messages broadcast by EGNOS GEOs, allowing to create in the GPMAF a contiguous EGNOS message set per GEO channel without data loss due to receiver failure.
- Collect GPS single frequency (L1) observables to be used for performance assessment in the position domain by applying EGNOS corrections to real SIS observables, as would be the case for an EGNOS user.

Each monitoring station shall comply with the default operating conditions of EGNOS for SoL applications as defined in the EGNOS MRD. It is assumed that these conditions are also correct for OS applications. Excessive local environmental conditions should be detected (masking, multipath, interference) but it is not necessary to detect excessive ionospheric conditions. Monitoring stations in the very north of ECAC should be robust against the particular ionospheric conditions ('scintillation') in those regions.

The monitoring network can be composed of:

- GPMAF KPI monitoring stations: these stations will be independent and specifically designed for their role in GPMAF.
- EGNOS RIMS: these stations are part of the EGNOS system.
- 3rd party receiver networks operated by e.g. Air Navigation Service Providers (such as Eurocontrol), ESA, or IGS [Ref. 4].

A subset of the monitoring stations should be located where EGNOS availability is good (e.g. > 99% for APV1) and the others could be placed outside this region at locations of special interest, e.g. Canary Islands and the polar region.

The basic principle of the GPMAF performance assessment strategy for EGNOS is the comparison of the results of the offline reference observation data processing, with the navigation parameters predicted by the core system components. This includes the comparison of the navigation solution with the reference coordinates of the monitoring site. With this comparison a major subset of KPIs and performance related requirements can be monitored directly or indirectly by further statistical analysis of the results.

The objective of PVT-based KPI monitoring is to assess End-to-End navigation performances of the deployed EGNOS system. The monitoring facility puts itself at the position of a (static) user and calculates the navigation performances using the applicable standards (e.g. MOPS/SARPS) from monitoring station receiver observables. By doing so for a number of monitoring stations at various locations in ECAC, the GPMAF will be able to present a realistic view on the day-to-day performance of the EGNOS system.

7 Galileo Key Performance Indicators

Also for Galileo, both Service and Signal-in-Space (SIS) KPIs are addressed.

7.1 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, so identical KPIs have not been defined for all services individually. Of course not all KPIs are applicable for all services (in particular considering the SAR service).

The identified Galileo Service KPIs are:

- Position Accuracy
- Velocity Accuracy
- Range Threshold Failure
- Integrity Risk Sample
- Integrity Risk Ratio
- Discontinuity Event Rate
- SIS Availability
- A Priori Availability of Critical Service
- A Posteriori Availability of Critical Service
- GTRF-ITRF Consistency
- GST-TAI Offset
- Timing Accuracy
- Galileo-GPS Time Offset
- Message Transmission Correctness
- Message Content Correctness
- Distress Detection
- SAR Return Link

7.2 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 fulfillment 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 sensed 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 those SIS characteristics are monitored which can conveniently be determined by pseudo-range tracking, i.e. received power level.

8 Galileo KPI Regimes

A number of candidate Galileo Service and SIS KPIs have been discussed in the previous section. In this section a few KPI regimes are discussed.

8.1 Integrity

One of the most critical parameters of the Safety-of-Life services is the fulfilment of the integrity risk requirement. The integrity risk of a particular service defines the probability of Hazardous Misleading Information at the user receiver, i.e. that the system should have warned the user about a condition leading to a position error exceeding the alert limits but it has not. The requirement for this HMI probability is at the order of $2x10^{-7}$ per 150 seconds, which is extremely low. It corresponds to one HMI-event in roughly 100 years. Obviously, it cannot be measured whether the required service performance is provided. Nevertheless, the negative case could be measured, e.g. in case several HMI-events occur in a short timespan it can be concluded that the service is not provided with the required performance. While monitoring this case is sensible to detect strong system malfunctions it can be expected that no HMI event will be detected for systems of stable design. It is thus proposed only as secondary parameter.

The main integrity monitoring shall be based on a quantity that is essentially driving the integrity risk but will individually not necessarily cause a HMI at user receiver. Such a suitable quantity is the eSISE threshold TH, which is defined at user receiver as:

The system has to ensure that for all ranges the eSISE is overbounded by the threshold TH. Therefore the Range Threshold Failure KPI is defined as the probability of range threshold failure, i.e. that the threshold does not bound the true SISE, shall not exceed the given limits. Please note that the range domain integrity analysis needs further consolidation.

8.2 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 Open Service timing accuracy is an important system performance parameter and must be monitored by GPMAF. Timing accuracy is driven by essentially two contributions:

- the consistency between GST and TAI, and
- the accuracy of user receiver clock synchronization.

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.

8.3 Continuity

Continuity of a Galileo service is defined as the probability that the service – provided it was available at the beginning of a certain period in time – is available at the end of this period of time. Continuity Risk is the risk that continuity is not given in that respective period in time.

Continuity of a service is a parameter which is very difficult to monitor. In the system design process the risk of service discontinuity is broken down in a discontinuity tree and allocated to different contributors. In contrast to integrity there is no method to compute the instantaneous continuity risk from data of the broadcast navigation message. Only a simple procedure is identified how the user shall determine whether continuity is given: A maximum number of critical satellites must not be exceeded (loss of a critical satellite will cause the integrity risk to exceed the acceptable value). This procedure is derived from the discontinuity tree and holds for safety of life service level A only.

From the treatment of the discontinuity risk for the system design there is no way to reliably determine the quantitative continuity risk. Instead, a procedure is identified for the monitoring by GPMAF in which events leading to service discontinuities are identified and evaluated over time. There are basically four events leading to a discontinuity

- the SIS is not provided for one of the critical satellites by any reason,
- the broadcast message is not provided or is not correct to meet the required performance,
- an alert is sent for any critical satellite, and
- integrity service becomes not available.

It is assumed that the first event can be detected quite easily and is monitored by a SIS availability KPI. The correctness of navigation information from the integrity point of view is detected by the KPIs monitoring integrity performance. The correctness of navigation information regarding ephemeris is monitored by the message correctness KPI. The assessment of discontinuity performance is thus focused on the evaluation of transmitted alerts. For SoL service level A the requirement allows for an unpredicted discontinuity of $8x10^{-6}$ per 15 seconds, which corresponds roughly to one event per 22 days. Continuity is evaluated over a certain monitoring period leading to a mean risk of discontinuity. The average SoL service continuity will be measured as a by-product of a service volume SoL availability assessment replaying the Galileo messages recorded by a monitoring network.

8.4 Availability

Availability is one of the central performance requirements of the Galileo system. Depending on the different services it varies between 99.5% and 99.8%. 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. The availability requirement refers to any time and any place.

Availability shall be determined by a combination of design, analysis, modelling and measurement. However, the MRD definition already identifies that it may not be possible to unambiguously determine whether the required availability is actually reached. Regardless of the monitoring strategy a reliable determination seems not to be possible as described below. Therefore, to allow performance monitoring, certain assumptions must be introduced.

Specific service availability is only identified for services providing integrity. The Open Service Availability is only driven by accuracy. As such, a separation of unavailability and violation of accuracy is not possible. Therefore, no availability KPI is identified for Open Service. Instead it is expected to be covered to the extent possible by the accuracy KPI.

9 Galileo Monitoring Methodology

The GPMAF shall monitor the performance of the Galileo system for the entire service area. To derive the necessary measurement means, the measurement basis of identified KPIs has been evaluated. Most of the KPI assessments rely on the precise characterisation of instantaneous range error. The range error is defined by several individual contributions which are:

- Satellite orbital and synchronisation error
- Satellite BGD error
- Ionosphere propagation error

- Code-Phase divergence
- Troposphere error
- Multipath error (stationary part)
- Noise (thermal noise, interference, stochastic multipath part)

The central assessment means are a global monitoring network and a processing facility which carries out the computations and assessments necessary. The global monitoring network shall comply with the following specification:

- The stations shall allow a continuous observation of the relevant observables necessary to characterize the performance of the different services, i.e. observation of:
    - E1-C, E5a for Open Service,
    - E1-B, E5b for Safety of Life Service,
    - E1-A, E6-A for Public Regulated Service, and
    - E6-B for Commercial service (TBC).
- The stations shall use calibrated equipment in order to minimize potential systematic errors.

The basic principle of the GPMAF performance assessment strategy for service related KPIs is the comparison of the reference products of the offline reference processing with the navigation parameters predicted by the core system components. This means estimating the SISE with an offline reference process. With this comparison a major subset of KPIs and performance related requirements can be monitored directly or indirectly by further statistical analysis of the results.

For cost effectiveness it is reasonable to make use of available reference products for relevant parameters and not implement the entire reference process within GPMAF.

The parameters which shall be determined by the reference process are mainly identified by the contributions to the UERE budget and are in particular:

- precise satellite orbits,
- precise satellite clocks,
- satellite broadcast group delay,
- ionosphere behaviour,
- troposphere characteristic, and
- local reception characteristics.

The processing facility will apply meaningful algorithms to separate error contributions which are caused by the system, and those only characteristic for one particular monitoring station, since the latter must be separated from the system quality assessment monitoring. From the mentioned set of core parameters the assessment of different KPIs can be derived either directly or indirectly by further analysis. An important strategy thereof is the estimation of true UERE and the transformation to the position domain. The big advantage is that with the a posteriori known single error contributions to the UERE this analysis can be performed independent of locations of monitoring sites and it is thus well suited to globally characterize the service performance. GPMAF functionalities must further ensure that the individual error characterizations of the monitoring processes are possible in order to determine the confidence of the monitoring result.

10 GPMAF Preliminary Design

An extensive set of Key Performance Indicators for both EGNOS and Galileo is defined in the above. For all of those KPIs reasonable measurement methodologies have been defined, which are also briefly addressed in the above. From the definition of measurement approaches it is obvious that a high level three step approach can be applied for all KPI assessments which consist of:

- basic processing of raw input data,
- statistical evaluation and analysis of results, and
- reporting of final results.

With the identification of this three step approach it is possible to define common modules for the assessment of different KPIs which is an essential precondition to define a cost efficient design of GPMAF.

A preliminary generic design for the GPMAF discerns the following main functional blocks:

- GPMAF Monitoring network.
- Data collection and management.
- Data processing and analysis.
- Result reporting.

In the above, first requirements for a GPMAF EGNOS and Galileo monitoring network have been established. Depending on the required level of independence not all of the data required for KPI assessment need to be autonomously collected by GPMAF. For cost effectiveness, external sources of data can be used with the risk of adding external constraints to GPMAF which might degrade also the independence. However, there are several options for making use of external data or products for GPMAF performance assessment. For instance, there are a number of GNSS monitoring networks already established (such as the IGS) which provide free or restricted access to their observation data and analysis products. In addition, data and products may come from EGNOS or Galileo system internal sources. While this will certainly be the cheapest solution for GPMAF, the derived results fully rely on the quality of those external data and are biased by – to some extent – unknown errors and data integrity is usually not ensured.

One important contribution to the instantaneous range error is the ephemeris error. It can be estimated by computing the difference between the ephemeris broadcast by the navigation message and a precise reference for satellite orbit and clock. There are a number of analysis centres providing satellite orbit and clock estimates based on the IGS network data. These single solutions are combined by the IGS to derive a combined precise solution where the single solutions are differently weighted. This combined solution is the most accepted one in the scientific community.

The Data Collection and Management function covers all data acquisition from the GPMAF Monitoring Network and from external providers of data and products. This function is also responsible for data storage, data pre-processing and overall data plausibility.

The Data Processing and Analysis component provides functions for data conversion, data analysis (including statistics and trends), threshold estimation / prediction, result comparison. All GPMAF KPI outputs are provided through the Result Reporting component.

It is foreseen that the individual components and the GPMAF as a whole provide a certain level of autonomy, including autonomous data collection, processing and result reporting.

These functionalities, however, will evolve and be revised as implementation drivers are identified in the following stages of the study.

Several operational scenarios for the GPMAF can be considered:

- Full implementation and operation of the GPMAF under direct GSA responsibility.
- External parties providing KPI assessment data, which are further analysed by the GPMAF / GSA.
- External parties providing KPI monitoring and analysis results as service to the GSA.

At the current stage of this study, the first scenario is considered the baseline, as it appears to provide the highest flexibility and transparency to the GSA. This scenario is also expected to have in the long run the lowest cost (although high up-front costs are necessary). In addition, considering the primary purpose of the GPMAF, the involvement of external parties may complicate the relation between the GSA and the EGNOS and Galileo system operator(s).

Irrespective of the scenarios identified above, the re-use of existing tools for GPMAF is seriously considered. The primary benefits of re-using existing tools for GPMAF are:

- lower development cost,
- reduced development time, and
- a wider user base, which may provide added confidence in the quality of the tool.

When considering re-using tools for GPMAF, special attention is required for:

- Transparency; actual implementation of KPIs, methodologies, statistics and confidence levels.
- Independency.
- Reporting formats.

As a next step in this study, a thorough assessment will be done of existing tools and tools that are under development with respect to their usefulness for GPMAF.

In the following stages of this study, all scenarios will be considered in much greater detail. Nevertheless, the final trade-off between level of independency to external means versus cost and effort of GPMAF, is to be done by the GSA taking into account the constraints of future Service Level Agreement with the EGNOS and Galileo system operator(s).

11 Conclusion

The objective of the GPMAF is to monitor the performance of European navigation systems EGNOS and Galileo based on a set of Key Performance Indicators. The KPIs identified in this document are defined such that the performance of EGNOS and Galileo can be assessed by already available or quite realistic measurement means. The performance assessment does not require unfeasible or challenging monitoring technologies. Even for very critical parameters such as integrity related ones, measurement means could be identified allowing a performance evaluation within reasonable time spans between one week and one year.

A preliminary design for the GPMAF has been established, covering the main functions of data collection (from GPMAF specific and external monitoring stations), data processing, KPI analysis, and KPI reporting. It is expected that for the final implementation of GPMAF significant re-use of existing tools and facilities can be made.

The goal of monitoring the identified KPIs for both EGNOS and Galileo, is to allow the Public Sector, who is the owner of these systems, to evaluate the achievements of the Private Sector parties that are responsible for operating these systems. It is assumed that the Service Level Agreement between the Public Sector, represented by the GSA, and the operator is in part based on the defined KPIs and associated monitoring strategies.

With the here presented set of KPIs, the performance of the European navigation systems EGNOS and Galileo can well be characterized. To which level the assessment results are legally applicable has, nevertheless, still to be finally defined in the future by the GSA.

References

[Ref. 1] *EGNOS – The European Geostationary Navigation Overlay System – A cornerstone of Galileo*, SP-1303, European Space Agency.

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

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

[Ref. 4] *International GNSS Service*, Homepage: http://igscb.jpl.nasa.gov/

[Ref. 5] *A Statistical Outlier Detection Method of EGNOS Integrity Performance Data*, H. Kannemans (NLR), presented at ION Technical Meeting 2008, San Diego (USA), January 28-30, 2008.

Biography

Frank Wokke graduated in Aerospace System 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.

Roberto Vidal studied Electrical Engineering at Eindhoven Technical University. He has been working at NLR since 1989. Roberto was lead designer for the NLR contributions to the EGNOS Application Specific Qualification Facility and has been working since 2004 in the EGNOS Performance Qualification team at Thales Alenia Space. Roberto has recently left NLR.

Johann Vilzmann joined EADS Military Aircraft after graduation at Technical University of Munich in 1997. He was working in System Engineering and Software Engineering (including safety critical software) in the Eurofighter project. In 2004 he joined EADS Astrium and contributed to the Phase C0 of the Galileo Ground Mission Segment.

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.

Javier Perez Bartolome holds a M. Sc. degree in Aerospace Engineering from Universidad Politecnica de Madrid. Since 2006 he has been working as GNSS performance engineer at the European GNSS Supervisory Authority (GSA). Before joining the GSA he worked for four years as onsite contractor at ESA/ESOC. There he contributed to the IGS processing routine tasks and was involved in research areas like GNSS based precise orbit determination and real time filtering for time synchronisation.