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SENSORS SESSION

Operational GNSS Integrity

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Abstract

The paper discusses the concept of Operational GNSS Integrity as one of the key performance parameters of a GNSS solution. A main point is to make this discussion relevant for real-life operations and not restrict it to the scientific domain.

Operational GNSS Integrity is fundamentally a question about how GNSS data can be trusted. Neither the question nor the answer is a straight forward matter. To emphasis this out the Navigation Performance Pyramid defining the relation between accuracy, integrity, continuity and availability, is presented.

Since the methodology related to the Navigation Performance Pyramid has its origin in aviation, an overview of performance requirements from the CAT I precision approach in aviation operations, is presented. The CAT I horizontal accuracy requirement defined by ICAO is just 16 m, 95% CEP with a respective Alarm Level of 40 m.

A discussion about the many operational differences between a CAT I precision approach and the variety of different maritime and offshore operations, is given. Despite the stringent and safety oriented regime of aviation there are many constraints making the use of GNSS easier in aviation than in a maritime environment.

The paper also discusses the challenge of utilizing results from scientific oriented work for improved GNSS integrity into real operational usefulness. One limitation is the perceptional challenge of relating to a concept of integrity, another is the difficulty of defining integrity in an operational context.

The last chapter of the paper gives an introduction of Stanford Plots as a way to visualize the concept of GNSS integrity and presents a starting point of a discussion about relevant Alarm Limits for different maritime and offshore operations.

Introduction

Most GNSS users (where GPS users constitute the majority) have an intuitive perception of what is meant by accuracy of their GNSS equipment. There is, of course, some confusion about confidence levels (e.g. 1σ, 2σ and 95% CEP) but the concept of GNSS equipment measuring a position with some kind of unknown error margin and that this error margin, usually is limited by some statistical value, is not hard to understand.

Unfortunately, the world is not that simple. We also need to take into consideration other performance parameters. One of the most important is integrity. Integrity, is however, much more difficult to understand and explain than accuracy. To make things even more complicated it is important to interpret integrity in an operational context. This means that we cannot only look at integrity of individual systems, like a GNSS receiver, but we need to consider integrity contribution from e.g. GNSS for the real operation.

Against this background Operational GNSS Integrity can be defined as the answer to the following simple question:

Can I trust my GNSS data?

As we all know, many questions are not always answered by a proper answer but by a new question. Some possible alternatives in this case are:

Did you really mean…

- Can I trust the GNSS data sent from the satellite?
- Can I trust the GNSS corrections from the service provider?
- Can I trust the data from my receiver?
- Can I trust the GNSS data received by the DP?
- Can I trust that the DP is making the right decisions from the GNSS data?
- Can I trust the GNSS data used in SIMOPS?

Obviously, the answer might be different depending on the phrasing of the question. But even worse, we cannot expect a simple YES or NO either.

The answer can be anything BETWEEN YES and No.

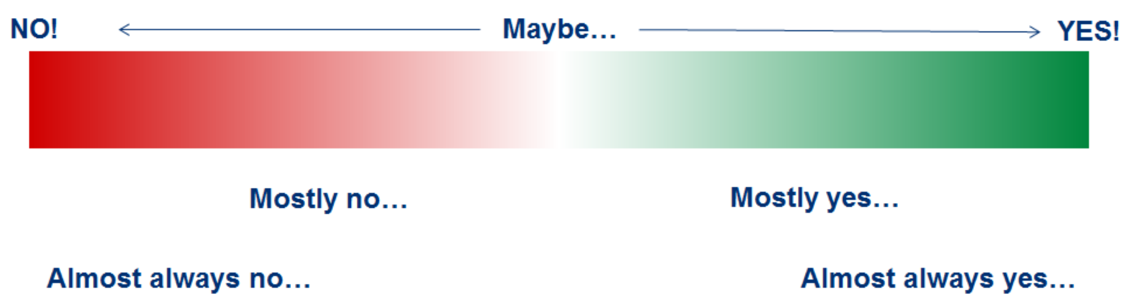

Figure 1: Can I trust my GNSS data?

The ultimate goal of any developer of GNSS solutions is of course to get as close to YES as possible. Unfortunately, we can never reach the 100% YES.

In this paper we will try to explain the concept of Operational GNSS Integrity and how it can be addressed.

GNSS Performance

Omitting the operational aspect for a while, the performance of a GNSS receiver is usually described by four key parameters:

- Accuracy
- Integrity
- Continuity
- Availability

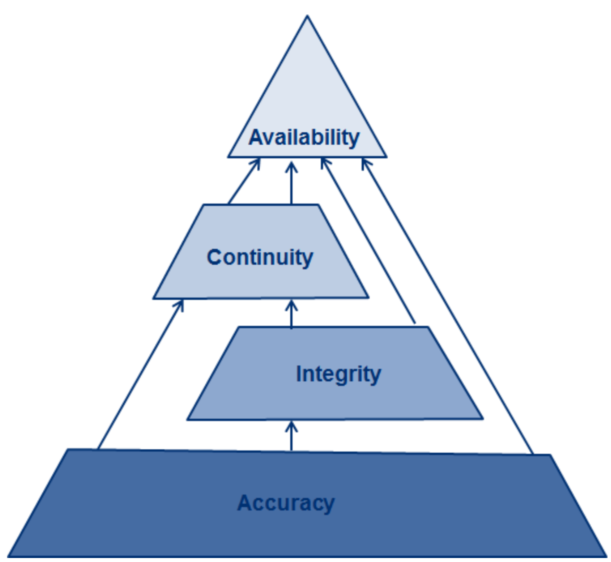

Figure 2: The Navigation Performance Pyramid

These performance parameters are related in some way or another. Usually the following relations are used:

Accuracy is the starting point and specified at a certain confidence level (e.g. 95% Circle Error Probable).

Then integrity is specified given a certain accuracy.

Continuity is the probability that accuracy and integrity will be maintained over a certain period into the future.

Availability is assuming certain levels of accuracy, integrity and continuity.

These relations are illustrated in the Navigation Performance Pyramid (Figure 2).

More precise definitions of the performance parameters are:

Accuracy is the difference between the position estimated by the navigation sensor and the true position of the vessel which is only exceeded 5% of the time in the absence of system failures.

Integrity and continuity, address performance of the navigation system in the presence of failures or rare natural events. Integrity measures the ability of the system to protect the user from inaccurate position estimates in a timely fashion. Continuity measures the navigations system's ability to complete an operation without raising an alarm. These are the instantaneous metrics of navigation safety and are computed at e.g. 1 Hz.

Integrity risk is defined as the probability that the error exceeds Alert Limit and the navigation system alert is silent beyond the time-to-alarm. On the other hand, continuity risk is defined as the probability that the navigation system alarm will drop during the operation. These are competing constraints on the system; integrity failures shall not lead to Hazardously Misleading Information favouring a small alert limit but continuity failures lead to false alarms favouring a large alert limit.

The final metric is availability which emphasizes the operational economy of the navigation system. It is computed as the fraction of time the system is providing position fixes to the specified level of accuracy, integrity and continuity.

GNSS Integrity Inherited from Aviation

The aviation community has for a very long time taken strong interest in using GNSS for different phases of flight from en route navigation to precision approaches. This work is the origin of the definitions of GNSS performance parameters, including the definition of integrity.

The traditional definition of GNSS integrity consists of three elements:

Alarm limit	If the position error exceeds a certain limit in metres I want to know.
Integrity risk	The probability that the position error exceeds the limit without me knowing.
Time-to-alarm	The time in seconds from the position error exceeds the limit until

someone lets me know

The International Civil Aviation Organization (ICAO) has specified Signal-in-space performance requirements for different phases of a flight such as Category I (Cat I) approaches. A CAT I approach is a precision instrument approach and landing with a decision height not lower than 200ft (61m) above touchdown zone elevation and with either a visibility not less than 800m (2,600ft) or a runway visual range not less than 550m (1,800ft).

In Figure 3 the ICAO GPS requirements for different aviation operations are listed, and there are a few points that should be noted.

First of all, the requirements refer to “signal-in-space”. That means they do NOT take into account e.g. the following error sources:

- Disturbance from troposphere or ionosphere
- Multipath from the environment of the GPS antenna
- Error caused by noise in the GPS receiver
- Error caused by the transformation of antenna lever arms caused by the movements of the aircraft
- Time-delays in the interface between the GPS receiver and the autopilot

The accuracy requirements are rather relaxed. Even for CAT I approaches the horizontal 95% accuracy is just 16 m.

The integrity risk requirement of $1 – 2 \times 10^{-7}$ is related to a relatively short period of a few minutes covering the precision approach phase.

The continuity requirement of $1 – 8 \times 10^{-6}$ is looking only 15 s into the future during the precision approach phase.

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Table 3.7.2.4-1 Signal-in-space performance requirements

Typical operation	Accuracy horizontal 95% (Notes 1 and 3)	Accuracy vertical 95% (Notes 1 and 3)	Integrity (Note 2)	Time-to-alert (Note 3)	Continuity (Note 4)	Availability (Note 5)
En-route	3.7 km (2.0 NM) (Note 6)	N/A	$1 - 1 \times 10^{-7}$/h	5 min	$1 - 1 \times 10^{-4}$/h to $1 - 1 \times 10^{-8}$/h	0.99 to 0.99999
En-route, Terminal	0.74 km (0.4 NM)	N/A	$1 - 1 \times 10^{-7}$/h	15 s	$1 - 1 \times 10^{-4}$/h to $1 - 1 \times 10^{8}$/h	0.99 to 0.99999
Initial approach, Intermediate approach, Non-precision approach (NPA), Departure	220 m (720 ft)	N/A	$1 - 1 \times 10^{-7}$/h	10 s	$1 - 1 \times 10^{-4}$/h to $1 - 1 \times 10^{-8}$/h	0.99 to 0.99999
Approach operations with vertical guidance (APV-I)	16.0 m (52 ft)	20 m (66 ft)	$1 - 2 \times 10^{-7}$ per approach	10 s	$1 - 8 \times 10^{-6}$ in any 15 s	0.99 to 0.99999
Approach operations with vertical guidance (APV-II)	16.0 m (52 ft)	8.0 m (26 ft)	$1 - 2 \times 10^{-7}$ per approach	6 s	$1 - 8 \times 10^{-6}$ in any 15 s	0.99 to 0.99999
Category I precision approach (Note 8)	16.0 m (52 ft)	6.0 m to 4.0 m (20 ft to 13 ft) (Note 7)	$1 - 2 \times 10^{-7}$ per approach	6 s	$1 - 8 \times 10^{-6}$ in any 15 s	0.99 to 0.99999

Figure 3: ICAO Signal-in-space performance requirements

Typical operation	Horizontal alert limit	Vertical alert limit
En-route (oceanic/continental low density)	7.4 km (4 NM)	N/A
En-route (continental)	3.7 km (2 NM)	N/A
En-route, Terminal	1.85 km (1 NM)	N/A
NPA	556 m (0.3 NM)	N/A
APV-I	40 m (130 ft)	50 m (164 ft)
APV- II	40.0 m (130 ft)	20.0 m (66 ft)
Category I precision approach	40.0 m (130 ft)	15.0 m to 10.0 m (50 ft to 33 ft)

Figure 4: ICAO Integrity alert limits

The integrity risk is defined as the probability of the position error exceeding the alarm limit of 2.5 x the accuracy requirement. As Figure 4 shows, this means a horizontal alarm limit of 40 m.

These are the requirements systems like WAAS and EGNOS has to fulfill.

GNSS Integrity in Marine Operations

There have been a lot of attempts to adapt the GNSS performance requirements from aviation to maritime applications. However, there are several conditions simplifying the situation for a precision approach (CAT I) operation compared to the daily life in maritime operations:

- A Cat I approach is a well-defined operation with very little room for improvisation
- A Cat I approach is always done in a strictly regulated environment (like an airport)
- The duration of a Cat I approach is just a few minutes while an offshore operation can be going on for hours or days
- The accuracy requirement is rather relaxed (16 m, 95% CEP)
- The GPS antenna location and the GPS antenna installation follow strict guidelines and procedures
- The GPS receiver is always certified
- The GPS antenna environment is almost ideal to avoid multipath
- Because of the regulated environment, there is a low risk of GPS signal interference / spoofing
- Airports are usually located in areas with little obstruction of GPS signals (there are exceptions…)
- No other aircraft are coming too close (at least in civil aviation)
- The aircraft can usually go to another airport if conditions are too bad

In offshore operations these conditions cannot always be expected to be fulfilled.

A well-known technique to overcome some of these challenges with regard to integrity, is Receiver Autonomous Integrity Monitoring (RAIM). RAIM is based on two main factors:

- the principle of over determination, or making more measurements than needed to solve the navigation equation
- an apriori expectation of the accuracy of each measurement

RAIM will then give:

- a measure of how well each individual measurement fit these expectations
- a method of rejecting bad measurements from the navigation equation

RAIM is a powerful method, but does not necessarily solve everything. One of the greatest challenges is to match apriori expectations of measurement accuracy with reality. One other challenge is to adapt the RAIM algorithm to different ways of forming and solving the navigation. A RAIM algorithm will be different, depending on the mode of processing:

- GPS only
- GPS + Glonass
- Multiple differential corrections processing
- Relative GNSS
- GNSS & INS aiding

RAIM needs to be done right, and there are a lot of things that can ruin integrity.

Theory vs. Real Life

Several scientists have spent great efforts solving the problem of GNSS integrity. However, scientists need a well-defined problem to find well-defined solutions. Therefore, it is not always obvious how to transfer the results of all this scientific work into operational best practice.

Much of the scientific work has been focused on describing the statistical properties of GNSS errors. The ideal solution is to find a standard deviation that represents the real GNSS measurement errors. To maintain a high integrity risk requirement, it is usually necessary to be rather conservative or pessimistic on behalf of the expected measurement errors. The problem with this conservatism is that accuracy and availability have to be sacrificed.

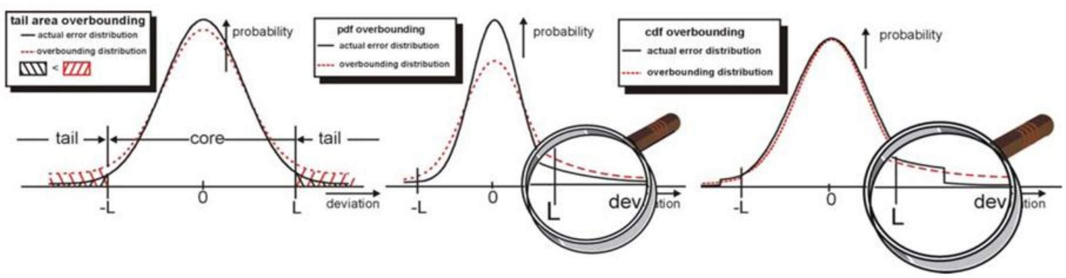

Figure 5: Alternative methods of finding an overbounding function (ref: Pieter Bastian Ober)

In reality, there is no easy way out of making a good RAIM algorithm. A lot of hard work is necessary, including:

- Studying unexpected events in detail to get down to root-causes
- Endured learning of the physics of GNSS measurements
- Active use of a GNSS signal simulator
- Replying a lot of measurement data

The integrity algorithms also have to take into account the complexity of an advanced processing engine, like shown in Figure 6.

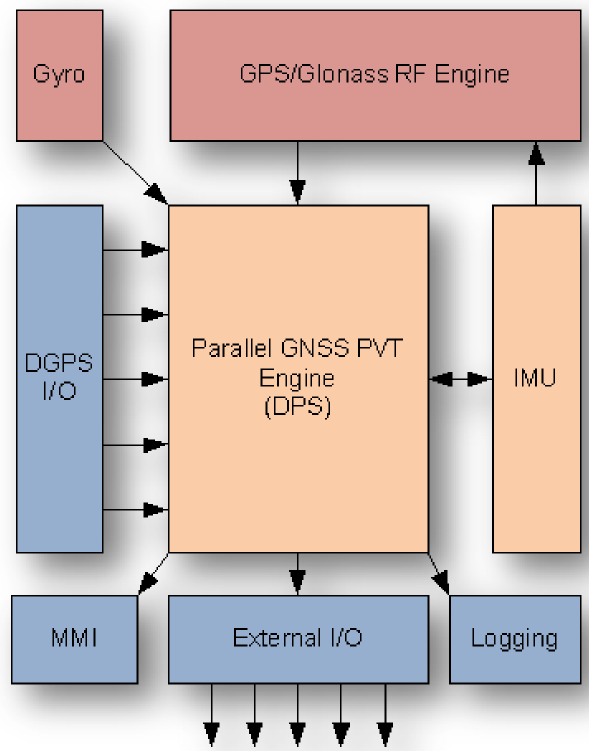

Figure 6: A complex GNSS processing engine

There are even more considerations to take into account to be able to extend the concept of integrity into real operational value which is necessary in order to use the term presented in the title of this paper:

Operational GNSS Integrity

For a DP the point-of-interest is usually the Centre of Gravity (). This is a real challenge for large and complex installations as described in Figure 7. A poor installation or inaccurate lever arm transformation can effectively ruin integrity irrespective of the quality of the GNSS solution.

The situation is even more challenging for a Simultaneous Operation (SIMOPS) as indicated in Figure 8. Here the Operational GNSS Integrity in principle needs to be related to any point on the hull of any vessel involved. This introduces the need to consider not only the lever arm transformation, but also the construction of the vessel into the Operational Integrity concept.

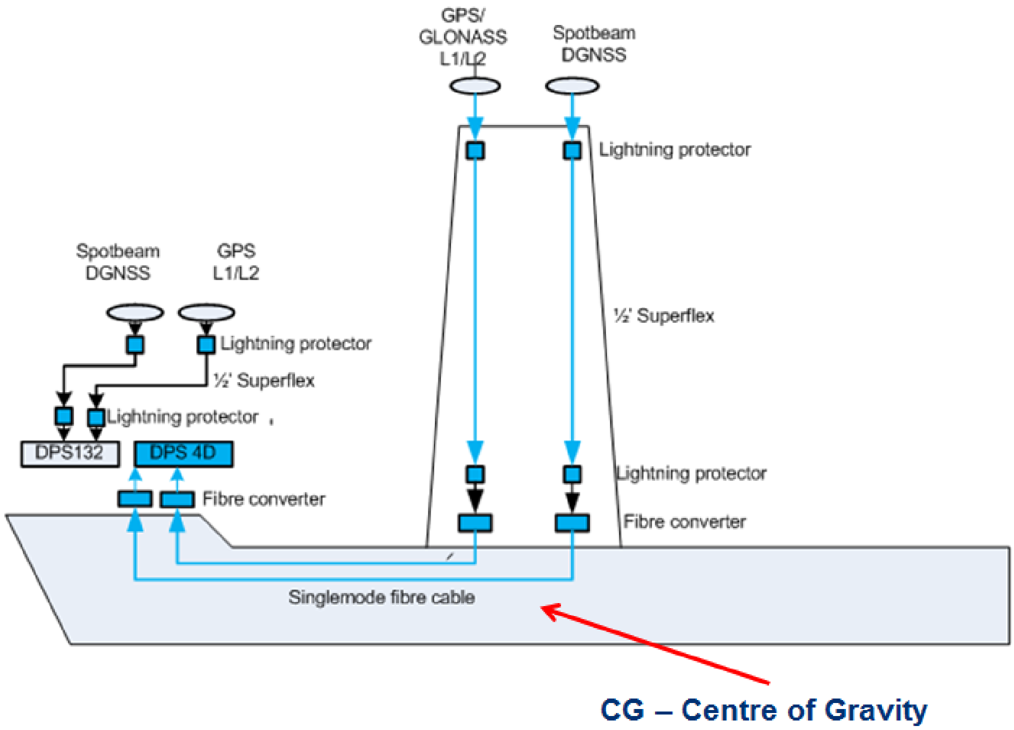

Figure 7: Complex GNSS installation

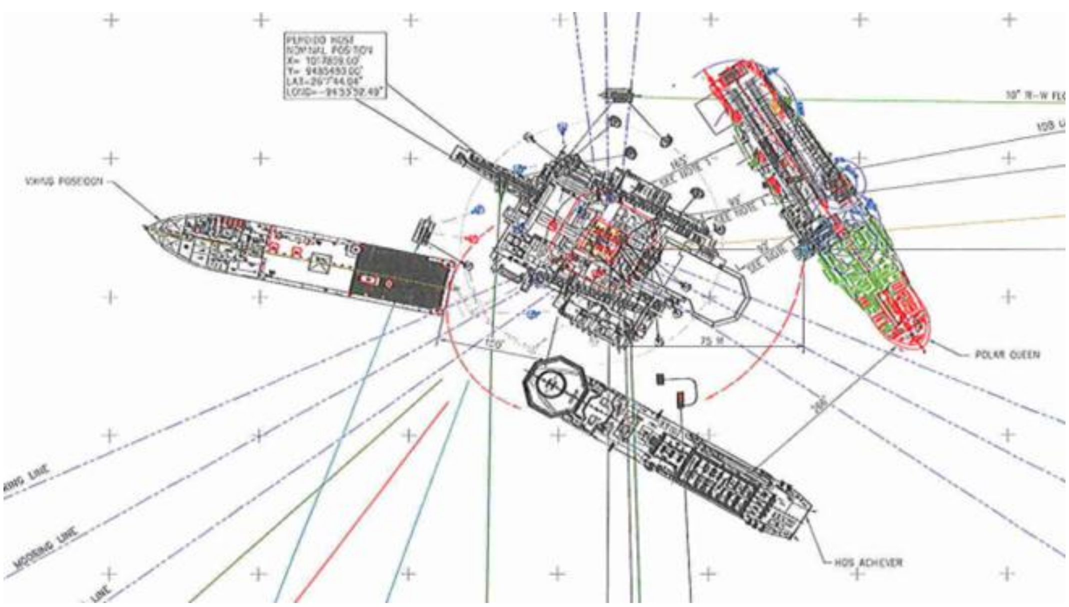

Figure 8: SIMOPS scenario

Accuracy vs. Integrity

A popular way to visualize the relation between real position error and integrity is by using so-called Stanford plots. An example is shown in Figure 9. A Stanford plot can only be made if it is possible to determine the real position error (e.g. when the antenna is located at a known point).

The x-axis of the Stanford plot expresses the position error, while the y-axis expresses the estimated accuracy or protection level (e.g. the output from the RAIM algorithm). The level of integrity is defined by an alarm limit given by operational constraints.

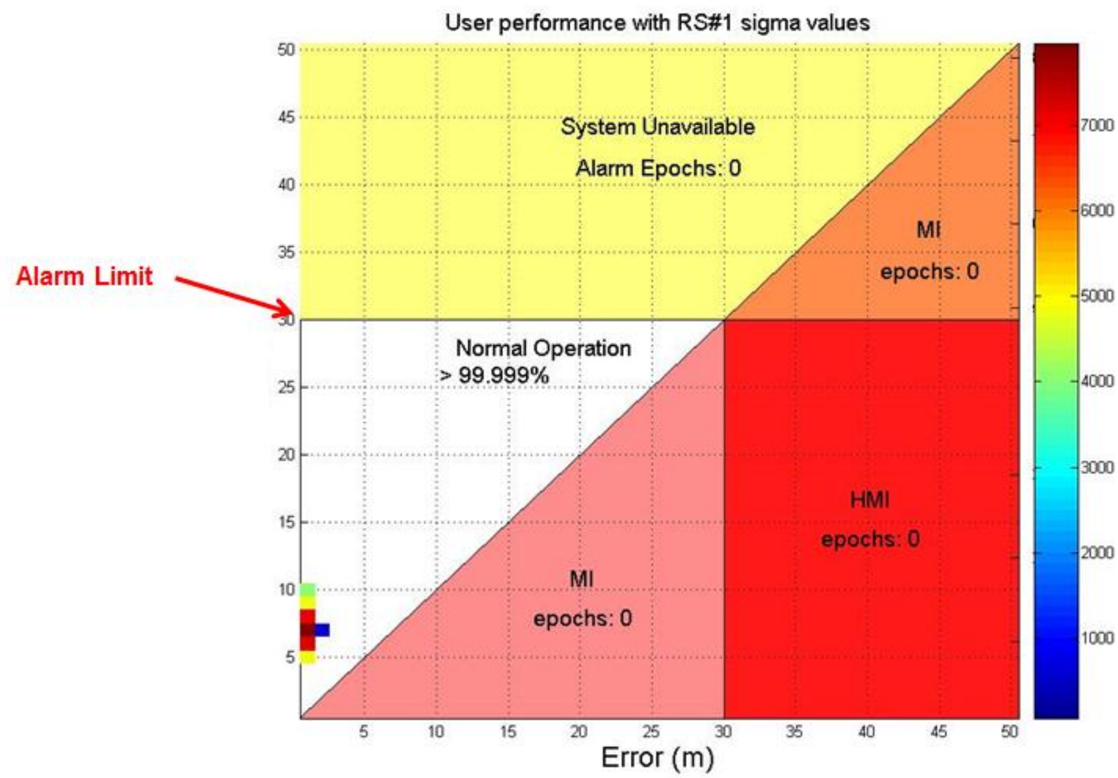

Figure 9: Example of Stanford plot (simulation)

If the measured error exceeds the estimated accuracy or protection level, the output of the navigation algorithm is giving Misleading Information (MI). If the error also is exceeding the Alarm Limit, the Misleading Information is regarded to be Hazardous (HMI).

If the output of the navigation algorithm indicates an accuracy or protection level in excess of the Alarm Limit, the system providing the data is defined to be unavailable.

In addition to visualizing some of the concepts of integrity in an intuitive way, the Stanford Plot is ideal for presenting really large amounts of data. Just one occurrence of MI or HMI will easily be detected among data recorded over a very long time-span.

A future discussion about GNSS integrity (or the integrity of any other reference system) should consider relevant Alarm Limits.

IMO Resolution A.915(22) indicates an alarm limit of 25 m for some relevant categories of general navigation related to an horizontal accuracy requirement of 10 m. There are, however, no known recommendations for DP operations, none the less for SIMOPS. Maybe the Alarm Limits indicated in Figure 10 can be used as discussion starting points?

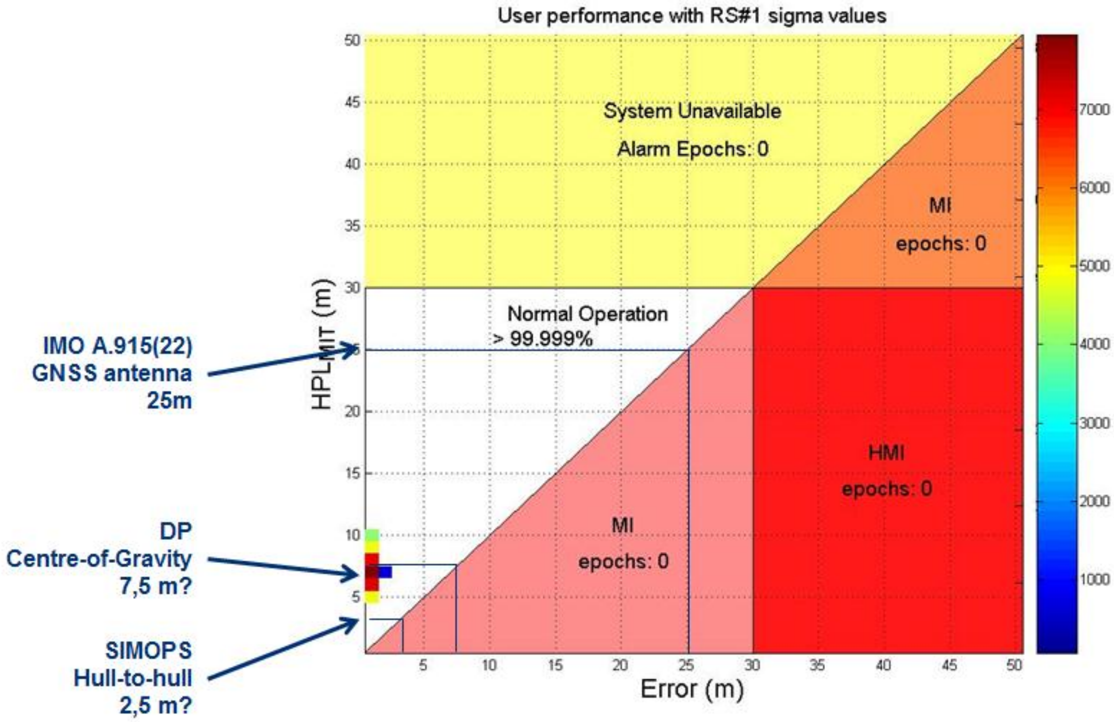

Figure 10: Possible Alarm Limits for different operation

Conclusion

Achieving a certain level of accuracy of a GNSS solution relevant for maritime or offshore operations is no longer a technology challenge. High precision services and dual frequency solutions are available for accuracy down to the 10-20 cm level. However, integrity is probably the most important quality differentiator between a low-cost GPS receiver, and e.g. a professional DP reference system.

It is important to note that integrity should comprise many other factors than just the integrity of GNSS signal-in-space for maritime or offshore operations. It is necessary to consider integrity in an operational context, i.e. Operational GNSS Integrity. It is furthermore important not to just adapt the integrity concepts from aviation without a proper discussion about the underlying operational differences.

The discussion about Operational GNSS Integrity should also be used as a trigger for similar discussions regarding other DP reference systems.