Towards High Integrity Positioning

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BIOGRAPHY

Bastiaan Ober's areas of experience include the influence of multipath on GPS positioning, carrier phase differential GPS, ambiguity resolution and integrity monitoring, especially for aviation applications. He is currently working as a Ph.D. student doing research on integrity design and analysis of integrated navigation systems for safety critical applications.

ABSTRACT

Integrity is one of the most crucial performance parameters when a positioning system is to be used for safety critical operations, such as in aviation applications. However, currently known positioning algorithms are optimised for *accuracy* instead. Even when they are combined with fault detection and exclusion schemes, these algorithms still give sub-optimal integrity.

This paper promotes a new way of thinking: to *design* integrity into positioning and error detecting methods – arriving at so-called high integrity positioning algorithms- rather than design for accuracy and evaluate integrity performance afterwards. It first shows *why* algorithms should be designed for optimal integrity rather than accuracy. Then, the paper explains how integrity can be obtained by either error accommodation, or fault detection and exclusion. Using the insights obtained, it is shown why current algorithms are not optimal and where a remedy could be found.

The new class of high integrity positioning algorithms that is thus described aims at obtaining improved integrity with both current and new systems; not by improving the physical infrastructure, but by using clever algorithmic optimisation in the receiver. A small simulation example shows that the integrity and availability of unaugmented GPS for non-precision approach can indeed be improved substantially.

Along the way, the same philosophy is shown to be not only exploitable for position estimation but for other parameter estimates in an integrated navigation as well, making the approach equally valuable for computing, for example, differential corrections for WAAS or LAAS.

1. INTRODUCTION

This paper will focus on general methods to design integrity into a positioning system. This is of particular importance for safety critical applications such as aviation. Literature still lacks a systematic overview of general ways to obtain a certain amount of integrity in a system. Many books and papers [Sturza88] [Brenner90] [Brown96][Leva96][Kelly97] discuss the analysis of a given method, usually fault detection and exclusion (FDE) schemes, without considering the question whether there are other, possibly more appropriate, alternatives. This paper aims at broadening the current views by describing a systematic and general approach to design integrity into a system's algorithms.

The paper first introduces all relevant RNP performance parameters including the integrity parameter, and shows how its meaning seems to have been changed over the years. It then discusses the way (integrated) systems work, which algorithms they contain, and how they are related to performance. It is shown that integrity is distributed over two algorithms: the position computation and the error detector. Current implementations optimise both for accuracy, which is shown to lead to sub-optimal integrity. Therefore, the paper advocates a different design strategy that takes integrity as a starting point.

2. INTEGRITY

The main idea about integrity is that it allows safe use of the navigation system. Formal definitions have been given in many official documents, such as [ICAO94][AWOP]. One of the problems that occur when defining an exact, narrow and technically usable definition is, that the technicalities often hinder a straightforward interpretation. Therefore, it might be instructive to develop some basic intuition using a broader and more general definition, which can be narrowed down later on. Webster's new 20th century dictionary gives three different definitions of the word 'integrity', of which the third one is the most appropriate:

> Integrity is the quality or state of being of sound moral principle; uprightness, honesty and sincerity

Applying this definition to a navigation system, such a system can be said to possess integrity when it is trustworthy. It is generally -technically or economically- infeasible to design a system that virtually always provides sufficiently accurate position data. However, as long as the system is able to notify the user of out-of-tolerance conditions, trustworthiness is a sufficient guarantee for the system to be used safely.

In system analysis and design, a more quantitative, measurable notion of integrity will be required. The coming sections will therefore elaborate on the requirements for navigation system performance. First, the Required Navigation Performance (RNP) concept is briefly reviewed. Then, it is shown that the concept has changed over the years, in particular with respect to the accuracy and integrity parameters. This change has important consequences for the optimal use of positioning information and makes integrity even more important than it already was.

2.1 The required navigation performance concept

Required Navigation Performance (RNP) is a concept designed to achieve a desired Target Level of Safety (TLS). It was developed by the International Civil Aviation Organization (ICAO) in the period from 1992 to 1995. ICAO's All Weather Operations Panel (AWOP) has defined RNP as *a statement of the navigation performance necessary for operation within a defined airspace*, where navigation performance is the joint performance of the positioning sensor and the flight control system (FCS). The concept therefore allows for different ways to achieve the required performance, as the performance requirements can be distributed in different ways between the positioning sensor and the FCS.

The original concept from [Kelly94] starts with defining the outer tunnel, a containment surface in space, centred on the assigned flight path, that defines the obstacle clearance, terrain avoidance or aircraft separation criteria. The aircraft should remain within the outer tunnel with a probability near to one. When the aircraft leaves the outer tunnel unintentionally, this is called a tunnel incident. Since the events that cause a tunnel incident are uncertain, the tunnel incident must be quantified by probabilities called risks. The concept also defines an inner tunnel that relates to the nominal system performance and should contain the aircraft most (typically 95%) of the time.

Using the tunnel concept, RNP defines four performance parameters: accuracy, integrity, continuity and availability. Each parameter corresponds to the risk of some event that could cause a tunnel incident. In brief: accuracy covers the risk that excessive system error causes a tunnel incident. The risk associated with latent system failures is covered by the integrity requirement, while the risk of an unscheduled guidance function loss is specified by the continuity requirement. Finally, availability covers the risk of a lack of guidance at the start of the operation. The definition of accuracy reads as follows:

> *Accuracy* is the ability of the total system to maintain the aircraft position *within the inner and outer tunnel* with a sufficiently high probability.

[Kelly94] has allocated probabilities of 0.95 for the inner tunnel, and of $1\text{-}10^{-7}$ per approach for the outer tunnel. The 'ability' in the accuracy requirement refers to a correctly working system only. Note that the requirement to stay within the inner tunnel is not directly related to the tunnel incident risk and is therefore of a rather different nature than the other RNP requirements.

Integrity is defined as follows:

> *Integrity* is that quality which relates to the trust that can be placed in the correctness of the information supplied by the total system. Integrity risk is the probability of an undetected (latent) failure of the specified accuracy. Integrity includes the ability of the system to provide timely warnings to the user when the system should not be used for the intended operation. Such a warning is called a tunnel incident alarm.

As is clear from the definition, integrity is related to the system's capability to generate alarms in situations of insufficient accuracy. This capability might vary with time and should therefore be monitored by an integrity monitoring system. When the integrity risk becomes too high, the user should be notified that there is insufficient guarantee that a timely alarm can be generated in case of lacking accuracy.

Although the basic RNP concept is still intact, some of its definitions and terms are currently used in a different form [DO-236][DO-229]. The changes that are most relevant for this paper are summarised in Table 1. In [DO-236] the accuracy requirement is given as

> Each aircraft operating in RNP airspace shall have total system error components in the cross-track and along track directions that are less than the RNP value 95% of the flying time.

while the integrity requirement reads:

> The probability that the total system error of each aircraft operating in RNP RNAV airspace exceeds the specified cross-track containment limit without annunciation shall be less than 10^{-5} per flight hour[1]. The cross track containment limit is twice the RNP RNAV value.

Table 1. RNP terminology and definitions

[Kelly94]	[RTCA DO-236]	[RTCA DO-229]
Outer tunnel	Containment region/limit	Alert limit
Inner tunnel	Accuracy requirement / RNP Level	Accuracy requirement
Tunnel incident alarm	Loss of RNAV capability	TSE alert
Accuracy defined at inner and outer tunnel	Accuracy defined at RNP level only	-
Integrity defined at inner and outer tunnel	Integrity defined at containment limit only	Integrity defined at containment limit only

These definitions differ considerably with the earlier ones. First of all, accuracy now refers only to the nominal system performance and is no longer specified at the containment limit level. Furthermore, integrity risk is no longer the probability of an undetected lack of accuracy, but refers to the probability of an undetected violation of the containment region instead.

As a result, the whole integrity alarm mechanism no longer seems to apply to the nominal system performance. Therefore, to make the new set of RNP parameters comparable to the old ones, a lack of nominal system performance should be indicated by a separate alarm mechanism. However, such a mechanism is not described, probably because a lack of accuracy is no longer considered a safety issue as long as the probability of unannounced violation of the containment limit remains sufficiently small. Note that with the new definitions, due care should be taken that the computation of this probability also incorporates the behaviour of a failure free system, as the accuracy risk of the original concept has now become part of the integrity risk.

3. NAVIGATION SYSTEMS

In general, integrated navigation systems aggregate:

- data from a variety of sensors
- data from databases

Sensors can provide a wide variety of data for example on distances, angles, speed or acceleration. Databases can contain data on the position of navigation transmitters, on signal characteristics or flight plans. [Breeuwer98] describes how different data is usually combined to provide the user with a more accurate and/or more reliable position. Typically, the available signals have to undergo several processing stages before a position is obtained. Although each stage might have its peculiarities, it will prove useful here to emphasise the similarities that exist between the different stages. This is illustrated in the representation of an integrated navigation system in Figure 1.

Each of the processing stages outputs parameter values and parameter quality information extracted from sensor and database information. Sometimes, parameter values are fed back into earlier stages of the system, for example for calibration purposes. Feedback changes the way the system operates considerably and should be taken into due account whenever it is used. Yet, the canonical description from Figure 1 is a useful generalisation of many different systems. It shows how similar techniques can be applied to all different stages. As an example, a differential GNSS system with multiple ground and airborne receivers (such as a WAAS or LAAS system) is represented in Figure 2, to stress that the same methods that will be discussed for positioning may be applied to the estimation of other parameters as well.

In the most general set-up, each system-block can be assumed to contain four different functions that together provide a parameter estimation with sufficient accuracy, integrity and continuity. For convenience, we will only describe the last stage that outputs the user position and possible other navigation and guidance information, keeping in mind that all that is said also applies to other stages.

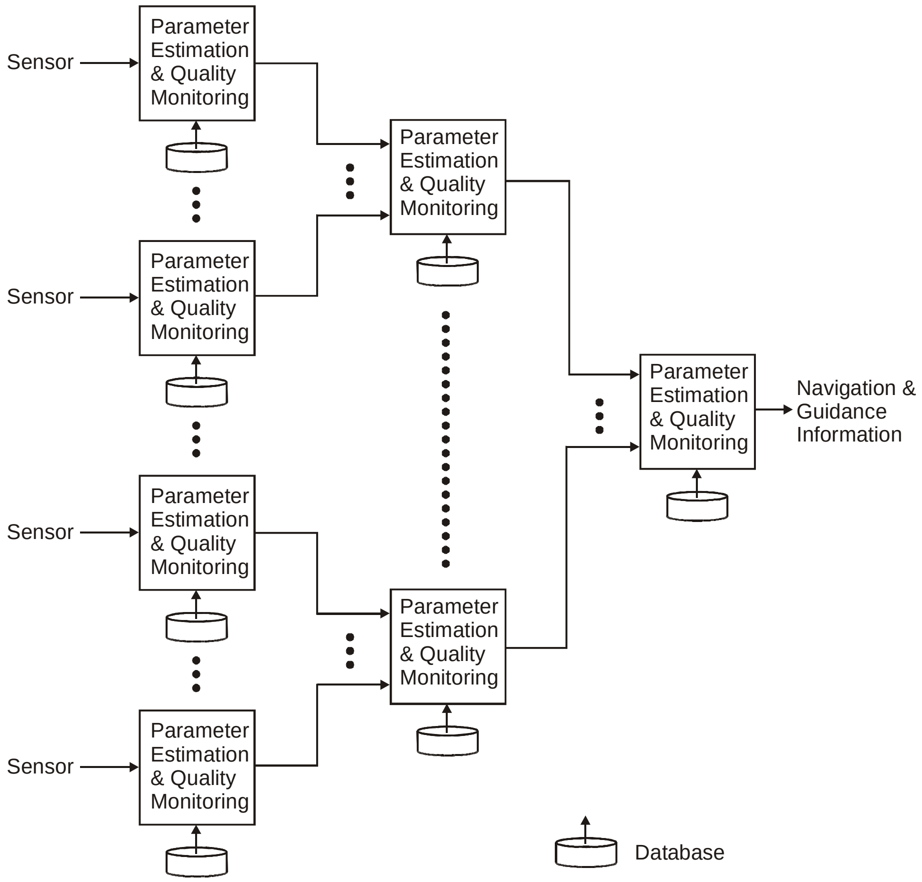

Figure 1. A canonical description of a navigation system.

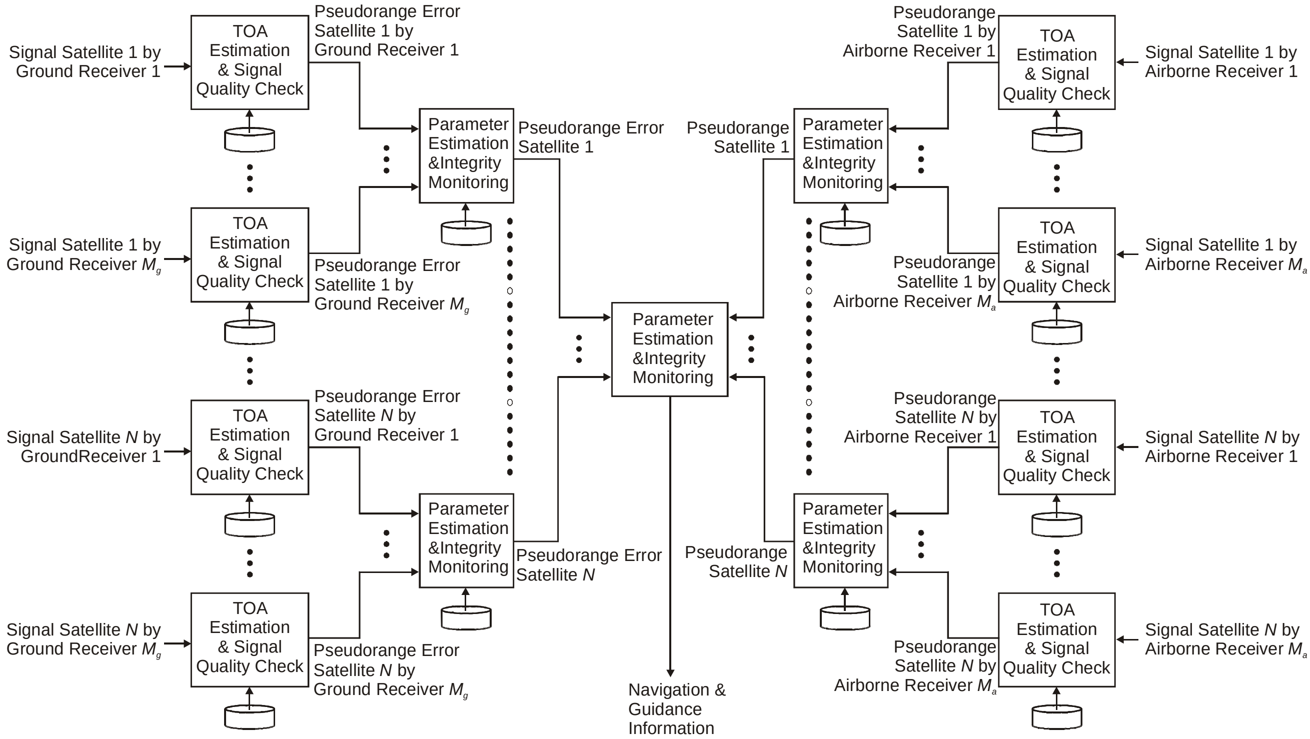

Figure 2. Representation of a differential GNSS system with multiple ground and airborne receivers

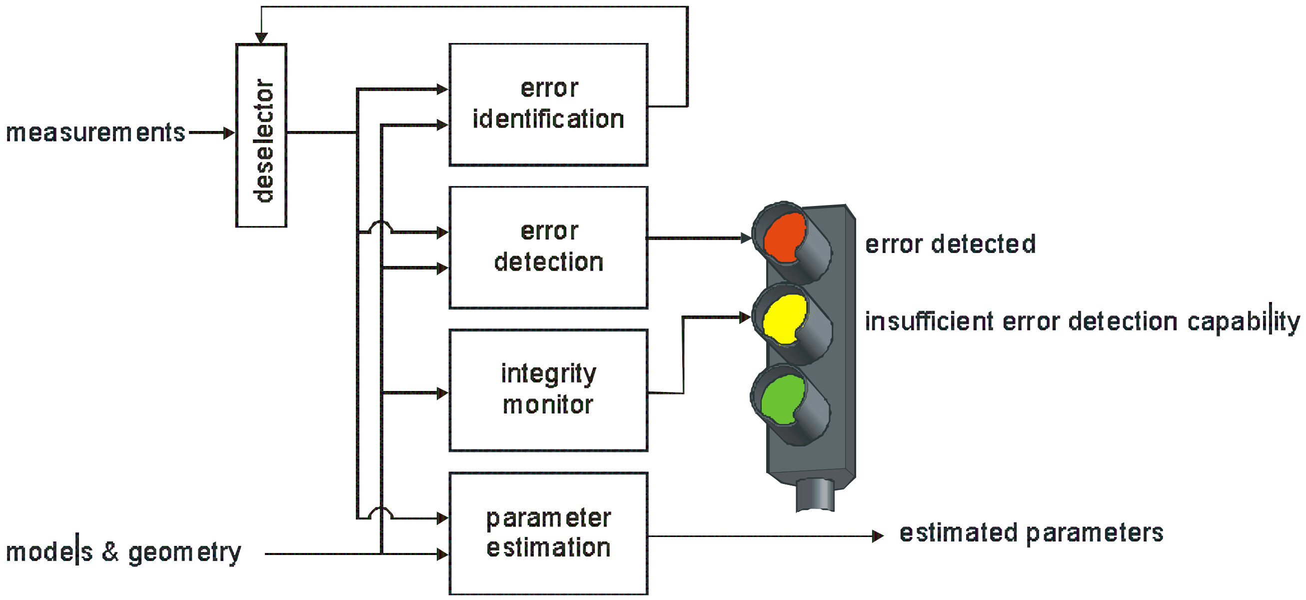

Figure 3. The traffic light analogy of a navigation system and the relation between its algorithms and its output.

The 'positioning stage' generally contains the following four functions:

1. A positioning algorithm
2. An error detection algorithm
3. An error identification algorithm
4. An integrity monitor

Error detection attempts to provide an alarm whenever there is a position failure. It is usually combined with error identification, that tries to identify the erroneous measurements and enables the system to operate normally by removing them from the position computations. Finally, the integrity monitor measures the performance of the error detection algorithm, and warns the pilot in case of a lack of error detectability.

The output of the system can be compared to the operation of a traffic signal, the three lights of which correspond to the three different conditions that can occur, see Figure 3. While a green light indicates the presence of sufficient accuracy and integrity, "yellow" indicates a potential presence of accuracy but with a lack of integrity due to insufficient failure detection power. The red light corresponds to the tunnel incident alarm and thus stands for a detected loss of accuracy. Note that the yellow light already means, that the system can not be guaranteed to be safe, which is -in a way- true for ordinary traffic signals as well.

4. POSITIONING SYSTEM DESIGN

As a natural consequence of the way performance is quantified, a position system's design goals can be defined in terms of achieving the best possible accuracy, integrity, continuity and availability. Obviously, all parameters will benefit from the addition of more position information in the form of more or better signals, better measurement geometry or removal of certain failure modes. Therefore, adding more position information is the obvious, but sometimes prohibitively expensive, solution to obtain sufficient performance. Determining how many sensors of which quality will be required to obtain sufficient integrity for a sufficient percentage of time is extremely important when designing (parts of) a radionavigation infrastructure. However, whether the system is existing or still in the design phase, it remains important to know what performance can be expected from a given system, to see whether either the design or the real-life system lives up to the standards required for its operational use. Therefore, this paper will consider navigation performance *under the condition that a system with signals of a certain quality, geometry and failure rate is given*.

In general, one could say that – within the constraint of such given infrastructure - there is a trade-off between all four performance parameters. A realistic system design should therefore optimise for one parameter, preferably within explicit minimum requirement constraints for the others. Up till now, the usual way to design positioning algorithms has been to optimise *accuracy*, while all other parameters are evaluated *a posteriori* to see whether they obey the requirements. The following sections will show, that is it feasible to optimise integrity instead[2].

5. OBTAINING INTEGRITY

Most positioning systems will have to deal with system failures in order to obtain sufficient integrity. In general,

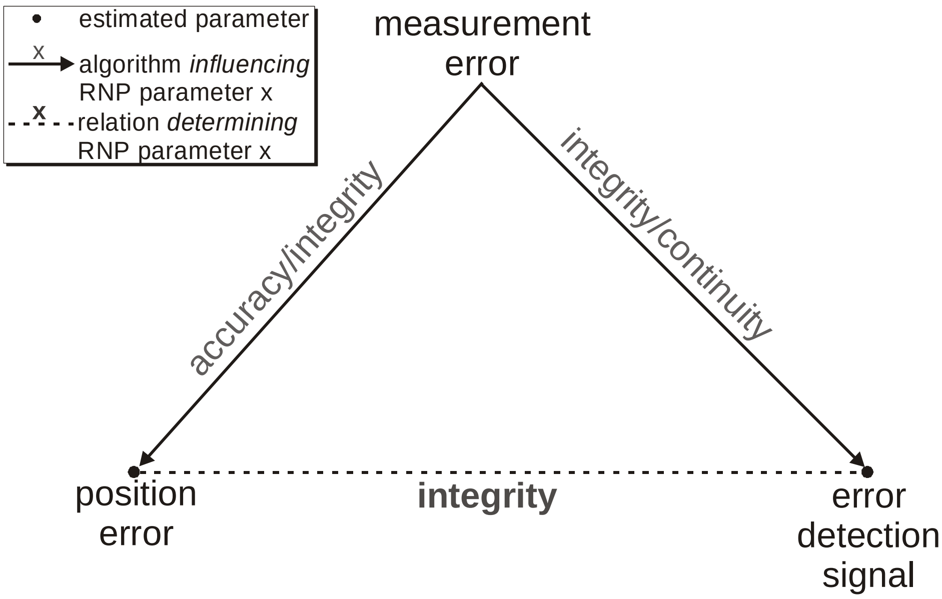

Figure 4. The relations between RNP performance parameters, measurement error, position error and error detection.

there are two ways to do so:

1. Error accommodation / robust estimation
2. Error detection (and identification)

[Barnett94] explains these two different philosophies and the ways in which they have been applied. For our purposes it suffices to say that error accommodation tries to limit the effect of system failures on the navigation solution in order to avoid position failures. In other words: the position is estimated robustly and becomes error resistant at the price of a reduced accuracy [Huber81].

The required performances of the positioning, error detection and error identification algorithms are strongly related to each other:

1. The better the positioning algorithm, the lower the amount of position failures and the less error detection capability will be required. In the case that the position failure rate drops below the integrity requirements, the need for an error detection algorithm effectively disappears. This shows that the integrity requirement can in fact be distributed among these two algorithms.

2. The better the error detection algorithm, the more errors will be detected, and the more important it becomes to identify the erroneous source. When the error detection rate drops below the continuity requirements, the need for an error identification algorithm effectively disappears. This shows that the continuity requirement can in fact be distributed among these two algorithms.

Figure 4 shows schematically which relations are important for integrity. Measurement errors cause position errors via the positioning algorithm. As seen above, the positioning algorithm therefore influences both accuracy and integrity. Furthermore, they effect the error detection signal. Therefore, the algorithms that derive these signals influence integrity.

We therefore see that when error detection is used, integrity is determined by the relationship between position error and error detection signal. The “stronger” this connection is the better integrity gets. In case error accommodation is used, integrity is determined by the relationship between measurement error and position error only. One of the ways to optimise integrity could therefore be to design an optimal robust position estimation scheme.

It should be noted here that – although the philosophy is quite different – error accommodation and error detection have much in common. Robust estimation methods often use the error detection signal *implicitly* to down-weigh measurements that might be erroneous. This can be seen as an implicit form of error detection, in which the error detection signal is fed back into the positioning algorithm. Unfortunately, this makes both the accuracy and integrity of these algorithms hard to analyse. Robust estimation literature [Huber81] [Hampel86] evaluates both accuracy and error resistance properties by using asymptotic metrics that are only valid for large quantities of data measurements, while positioning systems typically have only a small amount of measurements available.

5.1 Current approach

Current positioning algorithms are almost always least squares estimation schemes. When the system is linear and measurement noise is normally distributed, this gives optimal accuracy: it is the best way to mitigate the effects of noise on the position. On the other hand, the obtained position is sensitive to failures: a single wrong measurement can cause an arbitrarily large position error. To improve on this, error detection has to be used. Thus, rather than attempting to optimise integrity and deal ith the connection between position error and error detection signal, current positioning algorithms focus on the link between measurement error and position, by optimising positioning accuracy only.

For error detection a test statistic is used that is based on the least squares residual; this residual is the most accurate estimation of the measurement error. When the residual becomes too large, an error is detected. It can be proven that the residual and the position error are statistically independent and have a mutual information content equal to zero. The reason that detection still works is that both residual and position are influenced by the same –deterministic- bias. However, the noise in the position error is not reflected at all in the residual, indicating that the error detection properties – and therefore integrity- might not be optimal.

6. TOWARDS HIGH INTEGRITY POSITIONING

We have shown that in order to optimise integrity, a new approach to algorithm design is required that focuses on the connection between position error and error detection signal, rather than on positioning and error detection separately. We propose to refer to this kind of algorithms as high integrity positioning (HIP).

Although the HIP framework is only in the starting phase of its development, the feasibility and potential of HIP have already been proven. Describing the exact algorithm that has been prototyped is beyond the scope of this paper. Suffice it to say that the algorithm searches for a position solution that has:

- Optimal integrity
- Sufficient accuracy

In other words: integrity is optimised under the explicit condition that sufficient accuracy is maintained. A small simulation has been performed to obtain an impression of the performance improvements that might be obtained.

In the simulations, non-augmented GPS performance for lateral navigation has been compared to the requirements for non-precision approach[3] from [DO-208]. Accuracy is expressed in terms of the horizontal dilution of precision (HDOP), integrity in terms of the horizontal protection level (HPL) [Leva96]. The simulation is performed with a nominal 24-satellite GPS configuration. The performance parameters are computed over a world-wide grid with a resolution of 3 degrees, giving a total of about 6500 data points.

Table 2 gives the mean performance parameters of both HIP and traditional least squares over all simulated points. The advantages of HIP are clearly expressed in the largely improved system availability that is obtained thanks to the higher integrity. Note that there is –as expected- a loss of accuracy. This loss, however, is controlled by the algorithm, and never leads to unavailability. Table 3 presents a comparison between the methods by comparing the performance parameters on a point-to-point basis; it leads to very similar conclusions.

7. CONCLUSIONS AND RECOMMENDATIONS

We have seen that using the current interpretation of RNP parameters, integrity has become the prime safety parameter. Moreover, we have seen that current positioning algorithms are optimised for accuracy while integrity is only evaluated afterwards. Therefore, when one wants to optimise integrity, a new way of thinking is required, focussing on the connection between position error and error detection signal rather than on positioning and error detection separately. This way, it becomes

Table 2. Overall comparison of HIP and traditional least squares

Performance parameter	**HIP**	**Least Squares**
Unavailability	0.027	0.13
Integrity (mean HPL in meters)	245	356
Accuracy (mean HDOP)	1.6	1.3

Table 3. Point-to-point comparison of HIP and traditional least squares

Unavailability improvement ($Unavailability_{LS}$/ $Unavailability_{HIP}$)	4.9
Integrity gain (mean HPL_{LS} / HPL_{HIP})	1.5
Accuracy loss (mean $HDOP_{HIP}$ /$HDOP_{LS}$)	1.2

possible to develop methods to design integrity into a system's algorithms and achieve High Integrity Positioning (HIP).

First results show that a substantial integrity improvement is possible. The first developed HIP algorithm optimises integrity under the explicit condition that sufficient accuracy is maintained, and reduces the non-availability of standalone GPS for non-precision approach from 13% to 2.7% when compared to least squares positioning. The integrity, measured by the protection limit, improved by 50%. Possibly, these figures can still be improved upon when HIP matures, or when the accuracy requirements – that have no direct safety impact in the current RNP context- would be relaxed to give the algorithms more freedom to optimise integrity.

To conclude, we express the hope that the new way of thinking promoted in this paper might assist in exploring a whole new class of algorithms, obtaining improved integrity with both current and new systems; not by improving the physical infrastructure, but by using clever, integrity optimised positioning and error detection algorithms.

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NOTES

[1] This figure differs for different phases of flight. We will use this particular example from [DO-236] in the remainder of the text.

[2] Recognise that an improved method to obtain integrity can also be used to gain continuity or availability while maintaining sufficient integrity when there are no other limiting factors.

[3] The GPS parameter values used are:

Accuracy required: 100 meters 95%
Alarm limit: 555 meters
Missed detection probability in case of failure: 0.001
Maximum alarm rate per 2 minutes: 1/15000
GPS noise sigma: 33.3 meters
Selective availability correlation time: 2 minutes