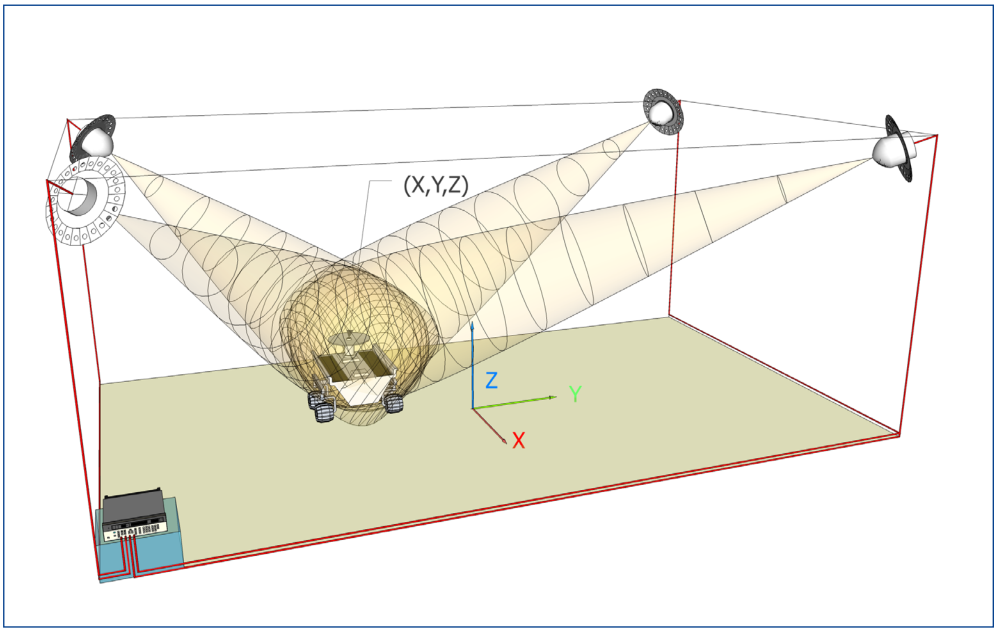
JRC Scientific and Technical Reports

Scoping Study on Pseudolites

C. O'Driscoll, D. Borio, J. Fortuny



EUR 24798 EN

JRC
EUROPEAN COMMISSION

ipsc
Institute for the Protection
and Security of the Citizen

The mission of the IPSC is to provide research results and to support EU policy-makers in their effort towards global security and towards protection of European citizens from accidents, deliberate attacks, fraud and illegal actions against EU policies

European Commission
Joint Research Centre
Institute for the Protection and Security of the Citizen

Contact information
Address: Via E. Fermi 2749, 21027 Ispra (VA), Italy
E-mail: Joaquim.Fortuny@jrc.ec.europa.eu
Tel.: +39 0332 785104
Fax: +39 0332 786565

http://ipsc.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

Disclaimer
Certain commercial equipment and software are identified in this study to specify technical aspects of the reported results. In no case such identification does imply recommendation or endorsement by the European Commission Joint Research Centre, nor does imply that the equipment identified is necessarily the best available for the purpose.

JRC64608

EUR 24798 EN
ISBN 978-92-79-19990-5
ISSN 1018-5593
doi:10.2788/10293

Luxembourg: Publications Office of the European Union

Printed in Italy

Executive Summary

Pseudolites or pseudo-satellites are an emerging technology with the potential of enabling satellite navigation indoors. This technology found several applications that are not limited to indoor navigation. Precise landing, emergency services in difficult environments and precise positioning and machine control are few examples where pseudolite technology can be employed.

Despite the great potential of this technology, severe interference problems with existing GNSS services can arise. The problem can be particularly severe when considering non-participating receivers, i.e., legacy devices not designed for pseudolite signals. The design of pseudolite signals is thus a complex problem that has to account for market requirements (modifications of existing receivers for enabling the use of pseudolite signals, measurement accuracy, target application), regulatory aspects (frequency bands to be allocated for pseudolite services) and interference problems.

In the following document, JRC investigates the main aspects to be considered for the design of a pseudolite signal standard minimizing the interference problem without compromising the location capabilities of the system. The focus is on the signal characteristics and topics relevant for the signal design. A literature review on the different pseudolite applications, prototypes and solutions adopted for minimizing the interference problem is first conducted. Recommendations on the aspects that should be further investigated are then provided.

Contents

List of Figures

List of Tables

1 Introduction

Pseudolites, or pseudo-satellites, are ground based transmitters of Global Navigation Satellite System (GNSS)-like signals. They have been proposed as a solution to the problem of navigation in scenarios where the reception of GNSS signals is problematic, such as indoors, in urban canyons, open pit mines, and also as an aid to GNSS-only navigation for the purposes of increasing the accuracy, availability or integrity of the final navigation solution.

From the beginning pseudolites, or Local Elements, have been considered as part of the Galileo system. While the pseudolite concept has been around for over three decades, there are have been many changes in the GNSS landscape over this time period. There are, therefore, some interesting technical challenges to be overcome and opportunities to be exploited in the field of GNSS pseudolites.

This scoping study is organised as follows. A literature review of the existing work on pseudolite technology, highlighting the primary technical issues associated with pseudolites, is given in Section 2. Section 3 addresses the issue of pseudolite signal design, highlighting the important parameters to be considered. Section 4 discusses those aspects of receiver design which should be considered, with emphasis on both participating and non-participating receivers. A brief overview of the non technical aspects of pseudolite systems is given in Section 5. Finally, the recommendations of this scoping study are given in Section 6.

2 Literature Review

As defined above, a pseudolite is a ground transmitter of GNSS-like signals to aid in navigation. In fact, there is no generally accepted definition of a pseudolite, but for the purposes of this scoping study the preceding broad definition will be used. The use of pseudolites was originally recommended in a number of papers by Parkinson (for example [2]) in the late 1970's and early 1980's. There are a number of reasons for using pseudolites, primarily: increasing navigation availability in degraded environments; increasing integrity for Safety-of-Life (SoL) applications; increasing accuracy by improving the overall geometry, particularly in the vertical dimension.

The original use of pseudolites was to mimic Global Positioning System (GPS) satellites prior to full operational capability. In fact, pseudolites are still used in this capacity by both the GPS and Galileo systems to test new signals prior to satellite launch. In the early to mid 1980's interest in pseudolites intensified, particularly in the context of Differential GPS (DGPS) [3]. The impetus for pseudolite development at this time arose from the restriction of the GPS constellation to 18 satellites, thereby creating significant time spans during which the available satellite geometry would be very poor [2]. The pseudolite served a two-fold purpose in this application, providing differential corrections through its navigation message and improving the geometry by providing ranging information. In order to facilitate integration of pseudolite signal processing in GPS receivers, the Radio Technical Commission for Maritime Services (RTCM) decided that the pseudolite signals should match as closely as possible the existing GPS signal structure. In fact, Klein and Parkinson *defined* a pseudolite as:

1. Receiving GPS signals and computing range and range rate corrections to act as a DGPS reference station
2. Transmitting the correction information in the L-band at 50 bps
3. Transmitting a signal which is “GPS-like”, in that it is modulated by a PRN in order to enable ranging
4. Transmitting a signal which is designed to prevent interference with other GPS equipment.

This definition is highly restrictive and it is recommended that a much broader definition be adopted for this study.

Since the 1980's interest in pseudolites has waxed and waned at various intervals, as new applications, signal structures and receiver designs came and went. Some excellent review papers can be found in, for example, [1, 4, 5, 6, 7, 8]. In the following a brief review of the literature on the most important aspects of pseudolites is given.

2.1 Pseudolite Applications

As discussed above, the initial application of pseudolites was in proving the concept of GPS. Following this, much effort went into defining a pseudolite component for the RTCM's DGPS specifications [3].

In the mid-1990's a number of researchers at Stanford University demonstrated the use of pseudolites for improving the reliability and integrity of Carrier-Phase DGPS (CDGPS) for aircraft precision approach and landing systems. Their system, referred to as Integrity Beacon Landing System (IBLS), was successfully used on many occasions to perform fully automated landing with position accuracies on the order of centimetres. This work is described in some detail in, for example, [9, 10, 1].

At about the same time, the Radio Technical Commission for Aeronautics (RTCA) in the U.S. began the process of standardising pseudolites for approach and landing applications as part of the Local Area Augmentation System (LAAS) specification [11]. It is interesting to note that by 2005 all references to pseudolites (at least on L1) had been removed from the RTCA's LAAS specifications.

In the commercial sector, alumni of Stanford's IBLS programme established IntegriNautics Corporation in 1994, which appears to have been the first commercial provider of pseudolites. Their pseudolite technology was later used by many research groups working on pseudolites. The company changed its name to Novariant in 2004 and sold its pseudolite technology (applied in the mining sector) to Trimble in 2010.

In the late 1990's and early 2000's, the first applications of pseudolite technology to urban and indoor navigation began to appear [12, 13, 14, 15]. These can be roughly divided into two types of application: those aiming to achieve centimetre-level accuracy using CDGPS, and those achieving accuracy on the order of metres using undifferenced pseudorange measurements. Both applications have very different requirements in terms of signal structure, infrastructure and receiver design. Again most applications were developed by research groups with limited commercial applicability. The exception is Space Systems Finland [14, 15], which is a commercial venture.

In 2003 a new commercial pseudolite, providing centimetre-level accuracy both outdoors and indoors was introduced by the Australian company Locata Corp. [16]. In 2011 it was announced that this technology had been licensed to Leica [17].

In 2008, Japanese Aerospace Exploration Agency (JAXA) announced an annex to their Quazi-Zenith Satellite System (QZSS) ICD which specified the signal structure for a ground based signal called Indoor Messaging System (IMES). While it is not a ranging signal *per se* IMES transmitters can be considered as a form of pseudolite. This signal will be discussed in more detail below.

A fourth company involved in the development of pseudolite applications is Insiteo. In March 2010 the company made a presentation at the Galileo Application Days event on the possibilities for pseudolites in Galileo [18]. Their interest is also in high precision indoor applications for the mass market.

Broadly speaking, pseudolite applications can be classified as [8]

1. Mixed pseudolite/GNSS– such as aviation applications, open pit mining, etc.
2. pseudolite-only – essentially indoor applications.

Within these classifications the application may require high (centimetre-level) accuracy, or coarse (metre-level) accuracy.

2.2 Issues

From the very beginning a number of issues have been widely known and well understood when it comes to the deployment of pseudolites [2, 3]

- Legal issues: the GPS L1 band is reserved for aeronautical use, to use pseudolites transmitting in this band for other uses may require a change in legislation
- Interference with existing GNSS signals: any signals broadcast in the navigation bands will interfere with existing GNSS signals, the issue is to quantify and minimise this interference

- The “near/far” problem: received pseudolite signal powers vary greatly over their operational range, and can be significantly stronger than satellite signals. Receivers therefore require a large dynamic range, much larger than standard GNSS receivers unless specific counter measures are employed in the transmitter
- Synchronisation: some mechanism must be designed to account for asynchronicity between the pseudolite clocks
- Monitoring: the GPS satellites are constantly monitored by a network of ground stations, problems can be quickly identified and isolated, how would the equivalent be managed for a network of pseudolites?

While much progress has been made in the last three decades on resolving these issues, it is perhaps telling that despite all the early promise there is currently no widely deployed pseudolite system in general use. A good discussion of the potential reasons for this can be found in, for example [6, 7].

2.2.1 Legal Issues

As early as 1986 Stansell pointed out that the use of pseudolites for applications other than aeronautical was not sanctioned by existing legislation for the L1 band. While the L2 band is not protected in this way, it has been primarily reserved for military use. A good overview of these issues is given by Kranli [6]. Perhaps the simplest solution to this issue is to allocate a separate band in the spectrum for pseudolite use. For example, Zimmerman et al. (all of IntegriNautics) suggested the use of multiple sub-bands of the Industrial Scientific and Medical (ISM) band [19]. This approach was recommended as early as 1997 by Cobb [1]. At least two current commercial systems transmit outside the GNSS bands, *i.e.* the XPS system from Novariant (now Trimble) [6] and the Locata system [20]. Whether or not a device transmitting in a non-GNSS band can be considered a pseudolite is another issue. Of course, transmitting in a separate licensed band creates other issues, such as differential delays between GNSS signals and pseudolite signals in combined receivers.

An alternative is to legislate for ground-based transmitters in the GNSS bands. Martin et al. [8] give a good outline of the legislative process and call for the following steps to be followed on the road to legislating pseudolite transmissions in the Radionavigation Satellite Service (RNSS) bands:

1. Determine the radionavigation service to be provided by the pseudolite.
2. Determine the reasonable constraints that may be imposed to protect the existing RNSS and other services in-band.
3. Determine how to license, monitor and arbitrate their implementation

2.2.2 Interference with Existing GNSS Signals

Interference with existing RNSS signals is unavoidable if pseudolites are to transmit into the same bands as these signals. At present there are hundreds of millions of users of the L1 GPS signal. It is, therefore, of paramount importance that pseudolite signals be designed so as to minimise their impact on these existing, so called *non-participating* receivers. As far back as 1984 Klein and Parkinson identified the following potential approaches to mitigating this interference [2]

1. Pulsing the pseudolite signals – the interference with the existing GNSS signals is limited to the pulse duration, if this is significantly less than the integration time in the receiver then the equivalent interfering power is greatly reduced
2. Frequency offset – either completely out of band, or a sufficient offset in band to reduce the cross-correlation between desired satellite signal and the pseudolite interferer
3. Alternative codes – a careful choice of code can reduce the cross-correlation level

Of these approaches that of pulsing has the greatest potential (other than shifting the pseudolite signals completely out of band). For any signal transmitted in-band there is a fundamental limit to how low the cross-correlation with existing GNSS signals can be made to go. For example, even for the case of a white noise pseudolite signal, the result will be an increase in the noise floor as seen by the non-participating receiver.

2.2.3 The Near/Far Effect

The near/far effect arises in pseudolite systems due to the fact that receivers which are close to the transmitter experience much stronger signals than those that are far away. For example, a receiver 100 m from a transmitter will experience a 20 dB stronger signal than a receiver at 1 km from the same transmitter, if the antenna gains are constant [2]. A receiver, therefore, requires a large dynamic range to process pseudolite signals. This issue relates to the issue of interference with existing RNSS signals, since the interference level will be greater closer to the transmitter. In addition, since GNSS signals are all transmitted from space, the near/far problem does not exist for a ground-based receiver and, as a consequence, the vast majority of existing GNSS receivers exhibit a very low dynamic range.

The methods suggested for overcoming the near/far problem are essentially the same as those for solving the interference issue.

2.2.4 Synchronisation

Synchronisation is vital for accurate one-way ranging. In GNSS systems synchronisation is maintained by using highly stable atomic oscillators on-board the satellites, which are continuously monitored by ground stations. Clock corrections and clock model parameters are uploaded to the satellites on a daily basis. Clearly this approach is not feasible for most pseudolite applications. A typical pseudolite is expected to be relatively inexpensive, usually using a Temperature Compensated Crystal Oscillator (TCXO), which experiences significant drift over time.

A number of synchronisation architectures have been proposed over the years:

1. Co-locate the pseudolite with a GNSS receiver, the pseudolite clock is driven by co-located receiver [21]. Of course this has a number of drawbacks, including increased cost and the requirement that all pseudolites be located with a clear view of the sky

2. Operate the pseudolites in a differential mode [21]. The reference receiver tracks all pseudolite signals and broadcasts corrections. The drawback here is the requirement for a reference receiver, a secondary communications link (for the differential corrections) and constraints on the locations of the pseudolites, since all pseudolites must be visible by the reference receiver.

3. Network synchronisation of the pseudolites [15, 16]. Here a network of pseudolites are synchronised to one another, either through a master control station [15], which requires that the master has a view of all pseudolites in the network, or a distributed synchronisation scheme [16]. The distributed scheme is particularly interesting for networks of pseudolites, as it is easily scaled.

4. Use a completely asynchronous scheme, such as IMES.

It is interesting to note that the majority of existing pseudolite implementations are based on a differential mode of operation, using the second synchronisation architecture described above. A good overview of the synchronisation problem can be found in [6].

2.2.5 Monitoring

One issue that is rarely raised with pseudolites is that of monitoring. As discussed by Kanli [6], small errors in pseudolite positions can translate to large positioning errors, so great care must be taken with the installation of pseudolites. With distributed networks the potential for spoofing or deliberate re-location of pseudolites is high [22]. Over time pseudolites will fail as components degrade. For these reasons it is essential that some form of monitoring system is in place. For differential systems, the reference station provides this function automatically, for other schemes (such as IMES), this remains an open issue [22].

2.2.6 Non-linear Navigation Problem

One other issue that has attracted some attention, particularly for the case of indoor pseudolites, is that the navigation problem becomes highly non-linear the closer the receiver is to the transmitter. The standard navigation algorithms (iterated least-squares, or extended Kalman filtering) must be modified to operate under these conditions [9, 13, 23]. While, for most receivers, this can be achieved with a simple software upgrade, the computational complexity is increased and this introduces an extra cost to the receiver manufacturer.

2.3 Signal Structure

The issues described above have been the major driving factors in pseudolite signal design. A typical pseudolite signal therefore consists of the following components:

- A spreading code (Pseudo-random Number (PRN) sequence) to enable ranging and chosen to limit interference with existing GNSS signals and other pseudolites
- A pulsing scheme chosen to limit both the near/far effect and interference with existing GNSS signals
- A centre-frequency that may be: one of the GNSS frequencies to simplify receiver design; slightly offset from the GNSS frequencies to reduce interference; in another frequency band

Other factors, such as signal polarization and maximum/minimum power levels, are chosen as a function of the particular application.

The above signal components are considered in more detail in the following sections.

2.3.1 Pseudolite Spreading Codes

The choice of spreading code is driven by three main factors

1. Simplicity of receiver design [3]
2. Minimisation of interference between pseudolites and with existing GNSS signals
3. Ranging performance

The first complete description of a pseudolite signal structure was given by the RTCM in the mid 1980's [3]. One of the primary design constraints with this signal was that it be easily implementable using current technology without significant modifications to existing receiver designs. For this reason, the spreading codes were chosen from the same Gold code family as the GPS C/A codes. Furthermore, a subset of codes was chosen such that the existing hardware used to generate the C/A codes could be re-used with only a minor modification (use of a different initial state for a shift register). These spreading codes exhibit the same ranging performance as the C/A codes, in terms of multipath rejection and additive white Gaussian noise (AWGN) performance. The interference between these codes and the C/A codes is at the same level as the interference between C/A codes.

For these reasons, the use of different members of the Gold code family from which the C/A codes were selected was a common approach in many pseudolite applications, for example [1, 12, 13, 14, 20, 24]. In fact it appears that the Locata scheme uses precisely the same codes as are used for GPS, albeit transmitted in a different frequency band and with ten times the chipping rate [20].

The RTCA, in their LAAS specifications, followed a different approach [11]. For this application, ranging performance was considered to be of greater importance than ease of implementation in existing platforms. As a result, a 10.23 MHz spreading code, derived from the GPS P-code, was chosen for the pseudolite signals. This code exhibited superior multipath rejection and AWGN performance compared to the C/A codes, and also had a lower level of cross-correlation with the C/A codes. The disadvantage was that the chipping rate was 10 times higher than the C/A codes, thereby requiring a much larger bandwidth for processing.

It is interesting to note that very little work appears to have been done on the potential interference of pseudolite signals and any modernised codes, such as the Galileo E1 signals or the GPS L1-C signal, with the exception of [25].

2.3.2 Pulsing Schemes

Pulsing of pseudolite signals is the most effective way of reducing both the near/far problem and the impact of the pseudolites on non-participating receivers. The basic concept is to transmit the pseudolite signal for only a fraction (called the pulse duty cycle) of the code period. The peak power during the pulses should be large enough that receivers within the operating range of the pseudolite are driven into saturation. Thus, during the pulse the non-participating receiver sees only the pseudolite signal with a near infinite signal to noise ratio (SNR). As the pulse duty cycle increases the impact on the non-participating receivers becomes greater. In the limit a 100% duty cycle would result in complete denial of service to all GNSS receivers in the operating region. Pulsing can be thought of as "bounding the near/far problem to a manageable range ratio" [1], since during the pulse the amplitude of the signal at the output of the Analog to Digital Converter (ADC) in the receiver is fixed, and does not increase as the receiver gets closer to the transmitter.

A given pulsing scheme can be defined by a duty cycle and pulse pattern. The duty cycle is the most important parameter in determining the impact on non-participating receivers; a longer duty cycle implies greater degradation of existing GNSS signals. The pulse pattern is vital for the correct tracking of the pseudolite signal itself. A number of key considerations for the pulse pattern include:

- Spectrum: Multiplying the spreading code by a pulse train in the time domain is equivalent to convolving the spectrum of the spreading code with the spectrum of the pulse train in the frequency domain. Therefore, any sidelobes in the spectrum of the pulse train will cause aliasing of the spectrum of the spreading code. A good pulse pattern will have a spectrum that is as close as possible to a single impulse in the frequency domain [3].

- Auto-correlation effects: The spreading codes are usually chosen to ensure a near unit slope in the correlation peak near the origin. When the signal is pulsed it is possible that pseudolite ranging measurements will be made using partial code period integration. This can lead to significant degradation of the correlation peak, potentially leading to range biases. A careful choice of pulsing scheme can ensure that the full code is cycled through in the minimum possible time [3], or a spreading code with good partial correlation properties must be chosen [11].

- Pseudolite multi-access: In many applications it is desirable to have multiple pseudolites in view. If the pseudolites are pulsed then it is important that different pseudolites have different pulsing schemes with minimal overlap. In addition, when the pseudolites are designed to operate in conjunction with existing GNSS signals, it is important that the *aggregate* duty cycle observed by any given receiver is kept to a reasonable level.

The first complete pulsing scheme was proposed as part of the RTCM specification for DGPS [3]. The pulsing scheme had a 10% duty cycle, with each code period divided into 11 slots of 93 chips. In each millisecond only one slot is actually transmitted, except that the 1^{st} and last slots are transmitted together. There are therefore a total of 10 indices which vary in a pseudorandom way from epoch to epoch. This pseudorandom variation ensures that the spectrum of the pulse sequence has very low side-lobes, thereby ensuring minimal aliasing of the pseudolite signal when pulsing was applied. This last point is very important in pseudolite signal design, and one that appeared to be neglected in some subsequent pulsing schemes [21, 26]. This effect was observed in some field trials of simple pulsing schemes in the mid-1990's [27, 28]. Another useful feature of the RTCM pulsing scheme was that the full spreading code was cycled through in each 10 ms period. In addition, the standard stipulated that the signal should be integrated over 10 ms, thereby ensuring that the auto- and cross-correlation properties of the C/A code would be preserved (at least for a participating receiver). The issue of pseudolite multi-access was not considered in this case, a minimum separation of 54 km was recommended between pseudolites using different codes

The RTCA devised a second pulsing scheme in the mid-1990's as part of its development of the LAAS specification [11]. Due to the higher chipping rate of the RTCA codes, a lower duty cycle, of only $\sim 2.7\%$ was considered in this case. In this scheme the pulses are generated in a pseudorandom manner using a 19-stage Linear Feedback Shift Register (LFSR) clocked at $1/20^{\text{th}}$ of the code chipping rate [25]. The pseudorandom nature of the pulsing scheme meant that multiple pseudolites could be placed in proximity, with limited overlap between their pulses. It has, however, been noted that standard receivers had trouble tracking signals using this scheme, possibly due to the fact that about 12% of pulses are separated by more than 1 ms.

In 2009 Cheong et al. reverse engineered the Locata pulsing scheme [20]. In this case the pulsing scheme is chosen to eliminate the near/far effect only, since the Locata pseudolites transmit in the ISM band, so interference with existing GNSS signals is not an issue. Not much detail is given, but the pulsing scheme appears to have a selectable duty cycle from $3 - 100\%$. Pulses are generated in a pseudorandom fashion, the full sequence of pulses repeating every 200 ms, which corresponds to 2000 code periods.

A recent investigation has addressed the issue of pulsing schemes for Galileo based pseudolites [25]. This work is based on the analysis of Cobb [1] and LeMaster [29] and the properties of the Galileo spreading codes. Based on this analysis a maximum aggregate pulse duty cycle of 3.8% is recommended for the Galileo E1 signals. A pseudorandom pulsing scheme similar to that of the RTCA is proposed, but with the added proviso that all possible pulse positions appear once and only once in each full cycle of the shift register. There are a total of 128 positions and the shift-register generates the full sequence from 1 to 128 in a random order. The authors consider all possible shift registers that can be used to generate such pseudorandom sequences, but the optimal solution had yet to be found at the time the paper was written.

2.3.3 Centre Frequency Selection

The original RTCM pseudolite specification was specifically designed to facilitate implementation in existing receiver structures [3], as such the centre frequency was chosen to be at L1. Subsequently Van Dierendonck [21] proposed a 30 kHz offset from L1, which he argued would help reduce the cross-correlation between the pseudolite codes and the existing GPS C/A code signals. Elrod and Van Dierendonck [30] later proposed an even greater shift, to $L1 \pm 1.023$ MHz, rationalising that by broadcasting in the nulls of the C/A codes the cross-correlation effects would be greatly mitigated. McGraw [31] subsequently showed that the impact of placing the pseudolite signal in the nulls of the C/A code spectrum was less than had been anticipated due to the potential for non-integer code phase offsets between pseudolite and satellite signals, and the impact of the significant code Doppler difference between the signals (of the order of 600 chips/s). The overall effect is a reduction in cross-correlation noise of about 8 dB. The QZSS interface specification draft version 1.2 also includes a frequency offset from the nominal L1 frequency for the IMES signal. In this case the offset is only 8.2 kHz [24].

Out of band pseudolite signals have been recommended for at least the last 13 years. To quote Cobb [1]

> It is not unreasonable for GPS receivers built for pseudolite use to include a second RF tuner to receive out-of-band pseudolite signals. ... Imposing the cost of an additional RF tuner on a small, specialized market seems preferable to imposing the cost of degraded and sporadically unavailable navigation on the rest of the civil GPS user community.

As discussed previously, at least two current commercially available pseudolite systems currently broadcast their ranging signals outside of the RNSS bands: Novariant XPS and Locata. This is the most effective way to minimise the impact of pseudolites on existing GNSS infrastructure.

The set of frequencies currently used, or suggested for use in pseudolite applications is summarised in Fig. 1.

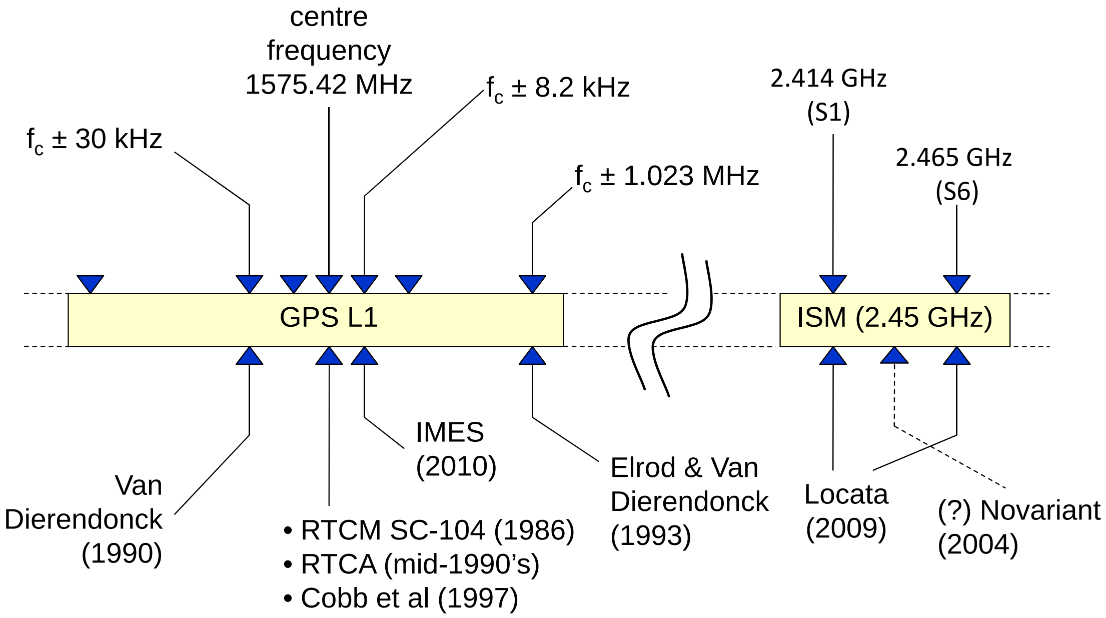


Figure 1: Currently Used or Suggested PL Centre Frequencies

2.4 IMES

In the context of emerging pseudolite technologies, the IMES proposed as an extension of the Japanese augmentation system QZSS has to be mentioned. IMES was first introduced in 2008 [32] and described in an annex of the QZSS Interface Control Document (ICD). It differs from other pseudolite systems since IMES transmitters do not broadcast ranging information but directly their position. The basic concept behind IMES is illustrated in Fig. 2: when a user enters an area covered by a specific IMES transmitter, his position is estimated as the position of the transmitter. The coverage area of a single IMES transmitter should have a radius of about 10 metres, limiting the maximum positioning error committed by the receiver to about the same distance [33].

The main advantage of this system is its relative simplicity. IMES transmitters do not need to be synchronized and they are not affected by multipath. In addition to this, GPS receivers may be upgraded to use IMES with a simple firmware change.

According to the current version of the QZSS ICD [24], there will be two different formats for IMES signals: L1 C/A and L1C modulations. The L1 C/A IMES signal will closely mimic the current GPS L1 C/A modulation whereas the L1C specifications will follow the same format as the future GPS L1C signal. The main difference is represented by the navigation message that will be used for broadcasting the transmitter position. In [24], only the characteristics and navigation message of the L1 C/A signal are specified. The main characteristics of the IMES L1 C/A signal are summarized in Table 1 [24]. It is noted that the signal centre frequency is offset 8.2 kHz with respect to the GPS L1 centre frequency (1575.42 MHz). This offset was introduced in the second revision of the IMES signal definition to mitigate the interference problem with GPS. In [32], it is claimed that this offset led to a 30% increase in the GPS L1 signal acquisition success rate in the presence of a IMES signal at -130 dBW. The IMES navigation message is organized in words of 30 bits. Words are then grouped into frames with a variable length. Each frame contains a message characterized by a specific type. Message type 0 and 1 provide the

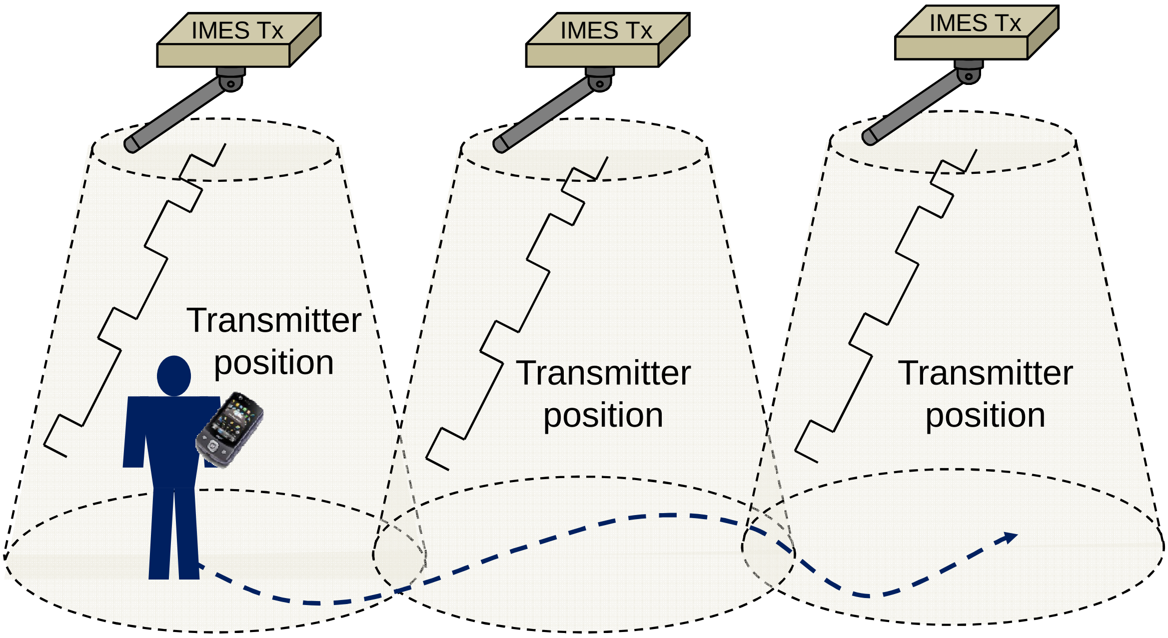


Figure 2: Basic concepts behind IMES: IMES transmitters continuously broadcast their position. When a user enters an area covered by a specific IMES transmitter, he estimates his position as the position of the IMES transmitter.

Table 1: Signal Characteristics of the IMES L1 C/A signal

Nominal centre frequency	$f_i = 1575.42 \pm 8.2$ kHz
Code Chipping Rate	$1/154 f_i$ for maintaining code/carrier coherence
Subcarrier	BPSK(1)
Minimum Received Power Level (0 dBi antenna)	-158.5 dBW
Maximum Received Power Level (0 dBi antenna)	-140 dBW, if the received GPS signal power is estimated $>= -158.5$ dBW -150 dBW,if the received GPS signal power is estimated < -158.5 dBW
Maximum Power at the transmitter output	-94.35 dBW
PRN codes	GPS L1 C/A Gold Codes from $173 - 182$

user location in terms of longitude, latitude and floor number. The altitude is replaced by the number of the floor in the building where IMES is installed. The floor number ranges from -50 to 204. Message 1 also contains the user altitude. Message 3 and 4 will contain an ID number that will be used in conjunction with a database. More specifically, IMES has been designed specifically for mobile phone users and in this case a database containing building information can be downloaded and used along with the IMES messages. The ID number sent by the IMES transmitter can be used for determining the user position using the information in the building database. In [34], several projects founded by the Japanese government are described. In these projects, several IMES transmitters (up to 70) have been deployed in public buildings, most of all shopping malls, and smart-phones with modified firmware have been used for navigating using IMES. The reported results are promising.
Despite the positive results reported by [33, 34, 32] and the intention to commercialize IMES in 2011, some doubts still remain on the effective interference between IMES and GPS [22]. The IMES technology is however an interesting solution for indoor navigation and should be considered as a valid alternative to traditional pseudolite location.

2.5 Analyses on the Impact of Pseudolites

In this section some existing work on the analysis of the impact of pseudolites is discussed.

In [3], the impact of the pseudolite signal on the correlator output of a non-participating receiver was modelled as follows. It was assumed that the receiver front-end clips the pulse level at twice the standard deviation of the noise in the absence of a pulse (this figure of 2σ can be easily generalised to $A\sigma$). The power of the pseudolite signal input to the correlators during a pulse is therefore $A^2\sigma^2$. The pulse is attenuated as it passes through the correlator, with a minimum attenuation of 24 dB. This attenuation factor is denoted by α. Furthermore, the duty cycle, d, leads to a further attenuation, which Stansell modelled as being a factory of d^2. Note that this implicitly assumes that the pseudolite power in the correlator output grows quadratically with integration time. While this is described in words in [3], it can be represented more compactly with the following equation

$$P_{\mathrm{PL,corr}} = A^2 N_0 B \alpha d^2, \tag{1}$$

where $P_{\mathrm{PL,corr}}$ denotes the power of the pseudolite signal at the correlator output, N_0 is the single sided noise spectral density and B is the two-sided IF bandwidth.

Van Dierendonck later argued that the assumption that the pseudolite power grows quadratically with the integration time is erroneous [21]. In fact, the cross-correlation between the pseudolite and the local code should be modelled as a white random process, with power growing linearly with integration time. Thus, Van Dierendonck suggests that (1) should be replaced with

$$P_{\mathrm{PL,corr}} = A^2 N_0 B \alpha d. \tag{2}$$

It is interesting to note that the attenuation factor α in the above equations is a function of the delay and frequency offset between the local replica and the incoming pseudolite signal. In [3] and [21] the impact of frequency offset was ignored and α was conservatively modelled as the worst case cross-correlation between C/A codes at zero frequency offset (approximately -24 dB), though the average attenuation is about -32 dB. Van Dierendonck and others also suggested offsetting the pseudolite carrier frequency from L1 in order to attenuate the cross-correlation further still [21, 30]. In fact, [30] suggests placing the pseudolite carrier in the null of the C/A code, thereby providing the maximum attenuation possible. Later McGraw showed that, even in this case, the peak attenuation is only about 3.5 dB better and on average the improvement is about 8 dB [31] relative to a pseudolite broadcasting directly at L1.

Later analyses focused on considering the signal to noise plus interference ratio (SNIR) at the output of the correlator. Cobb [1] seems to have been the first to use this as a metric, for which he gives the following expression (in linear units)

$$\left(\frac{S}{I+N}\right)_{\mathrm{corr}} = \frac{s(1-d)}{pd+1-d}, \tag{3}$$

where s is the SNIR in the absence of a pseudolite, d is the duty cycle and p is the equivalent pseudolite signal to noise ratio at the output of the correlator. It appears in this model, which was provided without derivation, that it is assumed that the signal power decreases linearly with the duty cycle. This is surely an error, perhaps a typographical one, since the signal power should vary quadratically with the duty cycle. Unfortunately, this equation has been widely cited in subsequent literature.

In the same year that Cobb's thesis appeared, Van Dierendonck et al. proposed a similar model, but with the following expression given for the SNIR [11]

$$\left(\frac{S}{I+N}\right)_{\text{corr}} = \frac{s(1-d)^2}{1-d+A^2B\sum_i \frac{T_{c,i}}{G_i}d_i}, \tag{4}$$

where, in this case, numerous pseudolites are considered, each with its own duty cycle d_i, chip period $T_{c,i}$ and "processing gain" G_i, and $d = \sum_i d_i$. In this case the quadratic dependency of the signal power on the duty cycle is seen in the numerator. What is clear from this expression is that the only way to reduce the impact of pseudolites on non-participating receivers is to: a) reduce the total (aggregate) duty cycle seen by the receiver; b) reduce the $T_{c,i}/G_i$ factors representing the cross-correlation between the pseudolite signals and existing GNSS signals. It is worth noting that some implicit assumptions appear to have been made in (4). Most notably, the random sequence model for the pseudolite cross-correlation from [21] appears to have been used, modified in this case to account for the processing gain accruing from having a frequency offset between the pseudolite and the satellite signals.

While (4) is correct, it does not tell the whole story. Modeling the cross-correlation between the pseudolite signal and the desired satellite signal as a white noise process ignores potential time correlation between these signals. Any such time correlation will lead to tracking errors and subsequently to potential navigation biases. This effect has been observed in experiments [35], but its impact has yet to be fully assessed.

A similar expression to (3) was developed by LeMaster for the impact of the presence of multiple interfering pseudolites on the SNIR of the desired pseudolite signal [29]. Thus, in a pseudolite tracking receiver that does not implement pulse blanking, the expression for the SNIR at the output of the correlator with the desired pseudolite signal is given by

$$\left(\frac{S}{N+I}\right)_{\text{corr}} = \frac{sd}{p(K-1)d+(1-(K-1)d)}, \tag{5}$$

where there are a total of K pseudolites, each with a duty cycle d, s represents the SNR of the desired pseudolite signal, and p represents the equivalent SNR of the other pseudolites at the output of the correlator (accounting for attenuation due to cross-correlation), pulses from all pseudolites are assumed to be non-overlapping and each pulse saturates the receiver. There appear to be a couple of issues with this expression since, similar to (3), the signal power appears to grow linearly, rather than quadratically, with the duty cycle, and the impact of noise appears to be incorrect. This expression was later used by Abt et al. in their analysis of pseudolite pulsing schemes for Galileo [25].

In terms of practical analysis, the first demonstration of the operation of a non-participating receiver in the vicinity of a pseudolite appears to have come from Cobb [1], who showed a number of standard receivers operating approximately 18 cm away from a pulsed pseudolite transmitter while the signals from the same transmitter were being processed by an aircraft approximately 18 km away. No quantitative measures were made of the impact of the pseudolite on the non-participating receivers, although the author noted that "the only interference detected was the unavoidable loss of satellite signal power due to the 12% duty cycle of the pulsed transmissions themselves".

In the context of IMES, which is a continuous signal, Manandhar et al. [33] conducted a test where the distance between the pseudolite transmitter and a commercial non-participating receiver was adjusted and the impact of the pseudolite measured in terms of Mean Time To First Fix (MTFF) and C/N_0. The results of this analysis suggest that the IMES transmitter should be kept approximately 1.5 m from any non-participating receivers when the transmitted power level is -70 dBm or lower, and at least 3 m for transmitted power levels of -64 dBm.

A detailed simulation analysis of the impact of pseudolite signals on existing services in or near the RNSS bands was conducted by European Conference of Postal and Telecommunications Administrations (CEPT) in 2009 [36]. While this simulation analysis ignored the impact of the cross-correlation between codes, focusing only on the spectral overlap of the various signals, some interesting results did emerge. For example, while the pulsing schemes described above help to solve the near/far problem and to reduce the cross-correlation between pseudolite signals and non-participating receivers, their impact on other navigation aids, such as Distance Measuring Equipment (DME), can be significant. This is due to the high peak power levels produced in pulsed pseudolite signals. In participating or non-participating GNSS receivers the average power over the integration time is what matters, for DME and other radar ranging applications the peak power is the critical parameter. This is of particular importance for any potential pseudolite applications in the L5 band, due to the overlap between L5 and the DME bands.

A recent study by the Joint Research Centre of the European Commission (JRC) measured the impact of both continuous and pulsed interference on two different commercial non-participating receivers. The effect of the pulsing scheme on tracking of pseudolite signals in participating receivers was measured by transmitting one of the standard C/A code signals from the pseudolite. The impact on non-participating receivers was measured in terms of the average C/N_0 loss experienced by all signals tracked, and by the impact on the navigation solution. Two interesting points emerged from this work: 1) the impact of the pulsed pseudolite signal was remarkably different for the two receiver types; 2) For the continuous pseudolite signal a significant tracking bias was induced in one satellite, suggesting that the error induced by the pseudolite signal was correlated over time.

2.6 Summary

There are many aspects to be considered when choosing a pseudolite signal structure. The key parameters are likely to vary from application to application, but the most important considerations will be:

1. Definition of the service provided (indoor location, integrity enhancement for SoL applications, etc.)
2. Interference with existing services
3. The near/far problem
4. Ease of integration/implementation in existing receiver architectures
5. Legal issues associated with allocation, regulation and monitoring.

While the last point is outside of the scope of a technical study, it is one which will require careful consideration. In the remainder of this report, those technical aspects of pseudolites that require further study are presented. In Section 3 aspects associated with the signal structure are considered, while Section 4 discusses the impact of the non-participating receiver.

3 Signal Aspects

In the following sub-sections those aspects of the signal design which most warrant further investigation are considered. In each case it is important to remember that the best choice of parameters will be very much a function of the application, thus the best pseudolite signal design for indoor applications may be quite different from that for SoL applications.

3.1 Possible Frequency Band Allocation

There are three possibilities when selecting the frequency band for the pseudolite signal:

1. At an existing GNSS frequency, *e.g.* L1.
2. At a small offset from an existing GNSS frequency, such that the pseudolite signal is passed through the same front-end filter as the GNSS signals,

3. In a separate frequency band, such that a separate RF tuner is required to receive the pseudolite signals.

Each of these choices has its own merits and drawbacks, which have, for the most part, been addressed in the literature. There are two primary reasons to choose frequencies at or near existing GNSS frequencies:

1. For ease of implementation in existing receiver architectures
2. For aeronautical applications the L1 and L5 bands have been reserved for this use and are protected by law.

Of course, this last point highlights one of the major disadvantages of these frequencies for non-aeronautical applications. In some jurisdictions, such as Japan, the L1 band at least is open for broadcast below certain power levels, which is how the IMES signal came to be placed near L1. The advantage of slightly offsetting the pseudolite carrier from the GNSS signal is that the average cross-correlation between the GNSS ranging codes and the pseudolite codes can be reduced. However, there are some issues associated with the fact that the timescale of the pseudolite is no longer the same as that for the GNSS system, since the code period becomes slightly longer or slightly shorter due to the effect of code Doppler. This effect can be accounted for with messages broadcast from the pseudolite, but this does complicate the design of the participating receiver. In addition, for a sufficiently large offset there will be a differential delay between the GNSS and pseudolite signals, which could introduce ranging biases, though this effect does not appear to have received much attention in the literature.

Broadcasting in non-GNSS frequency bands is the best way to reduce the impact on non-participating receivers, but of course, greatly increases the cost of the participating receiver.

It is worth noting that most work done on pseudolite signals in the past was performed in the days before the recent explosion in the number of GNSS signals. At present, in the L1 band alone, three separate GNSS (GPS, Galileo and Compass) transmit, or plan to transmit, multiple signals. In choosing a frequency band for pseudolite signals it will be necessary to consider the impact on all signals currently (or planned for) broadcast in that band. In fact, recent studies indicate that the noise floor for GNSS-only receivers will be greatly increased in coming years due to the vast array of signals being received in each band [37]. Very careful consideration must be given to any plan to increase this noise floor still further.

3.2 Code Selection

The selection of the ranging codes for any proposed pseudolite scheme must consider a number of factors:

- Cross-correlation with existing codes in-band
- Potential for partial correlation effects when a pulsing scheme is used
- Which sub-carrier to use.

The issue of sub-carrier selection is one that has not received much attention in the past, though Cobb made a reference to the possibility to a BOC-like sub-carrier [1, Section 3.7.4]. For Galileo it should be expected that the pseudolite signals are compatible with the Galileo signal structure, hence the impact of CBOC sub-carriers should be assessed. Whatever the choice of spreading code and sub-carrier, it should be borne in mind that there is a fundamental limit to the performance gain that can be achieved simply by choosing the spreading code. For example, consider the case of a perfectly white sequence, the equivalent of a one time pad that never repeats. To a non-participating receiver this would appear as a white sequence with a bandwidth equal to the lesser of the receiver's IF bandwidth and the bandwidth of the transmitted signal. This corresponds to setting $T_{c,i} = 1/B$ in (4). This can be seen as a bound on the achievable reduction in the SNIR in a non-participating receiver due to the choice of the spreading code.

One further important aspect which must be carefully considered in choosing the spreading code is the impact of partial correlation when a pulsing scheme is used. Partial correlation implies that less than one full code period is used during the integration process. For long codes, such as the P-code and the GPS L2CL codes, partial correlation is expected and the codes have been chosen specifically for this case. The GPS C/A codes on the other hand have been designed for full correlation, and there may be significant performance degradation if partial integration is used, particularly for shorter duty cycles. The impact of partial correlation is two-fold:

1. Partial cross-correlation between pseudolite and satellite signals leads to a reduction in the cross-correlation margin between the two signals
2. Partial auto-correlation of the pseudolite signal in a participating receiver can lead to a degradation of the auto-correlation peak.

The former effect can only be mitigated against by choosing codes with good partial cross-correlation properties, or by increasing the duty-cycle. The latter effect has not received much attention in the literature, though the RTCM specification did insist on a 10 ms integration time in participating receivers, thereby ensuring that one full code was used for every correlation. For low duty cycle pulsing schemes the problem of partial auto-correlation can only be addressed by using codes with good partial correlation properties, probably with higher chipping rates than the C/A codes, or by ensuring, as the RTCM did, that at least one full code period is used in each integration time.

It is also worth noting here that the correlation margin provided by the codes is significantly less than the auto- to cross-correlation peak ratio. For example, the C/A codes have approximately 24 dB difference between the auto-correlation peak and the largest cross-correlation peak. However, a pseudolite signal which is, say, 18 dB above the desired signal can still have an impact on tracking as it will have up to 25% of the power of the tracked signal at the correlator output. This is discussed in more detail in Section 4.2.

3.3 Pulsing Scheme

The purpose of a pseudolite pulsing scheme is two-fold:

1. To minimise the impact on non-participating receivers
2. To overcome the near/far problem in the case of multiple pseudolites.

The key to reducing the impact on non-participating receivers is to keep the aggregate duty cycle seen by any given non-participating receiver low. A rule of thumb has asserted that a receiver can track reasonably well with up to 20% aggregate duty cycle [1], though it would be well to reassess this figure for any particular pseudolite application. While the choice of spreading code will also have some impact here, the performance degradation experienced by non-participating receivers should be dominated by the duty cycle.

Even if the pseudolite signals are allocated to frequency bands outside of the existing GNSS bands, it will still be necessary to overcome the near/far problem. Again, pulsing appears to be the best way to achieve this for ranging signals. This can be viewed as a multi-access issue, with multiple transmitters all broadcasting into the same channel. The dynamic range of this system is expected to be large, and it is difficult to achieve this dynamic range using Code Division Multiple Access (CDMA) alone. At the same time, for ranging applications there are advantages to transmitting PRN signals at the same centre frequency (PRN signals are good for ranging, while any variation in the centre frequency leads to differential delays). As such some form of Time Division Multiple Access (TDMA) seems to be the most suitable approach. While much work has been published on pseudolite pulsing schemes, it is perhaps important to highlight here the important design consideration for any such scheme:

1. The pulse pattern should be chosen to minimise the impact on the spectrum of the transmitted signal
2. Different pseudolites should be assigned different patterns with low probability of pulse overlap

3. The pulse sequence should ensure sufficient diversity of code sub-sequences such that tracking is not affected by partial correlation effects

4. The duty cycle should be chosen both to minimise the impact on non-participating receivers and to ensure that sufficient pseudolites can be deployed to meet application requirements.

To elaborate on these points a little, consider the RTCM pulsing scheme. This scheme consisted of a pseudorandom arrangement of pulses with a 10% duty cycle that repeated every 200 ms. The pseudorandom nature of the pulse sequence yielded a spectrum with a single peak at DC and no significant side-lobes, thereby meeting the first requirement. Unfortunately, there was only one sequence, so the separation between pseudolites had to be large (54 km) to avoid pulse overlaps. The entire C/A code was transmitted every 10 ms, thereby meeting the third requirement, and a 10% duty cycle was fixed, thereby meeting the fourth. Subsequent pulsing schemes from the RTCA followed a similar approach.

It is recommended that some investigations be carried out on families of pulsing schemes that meet these requirements.

4 Receiver Aspects

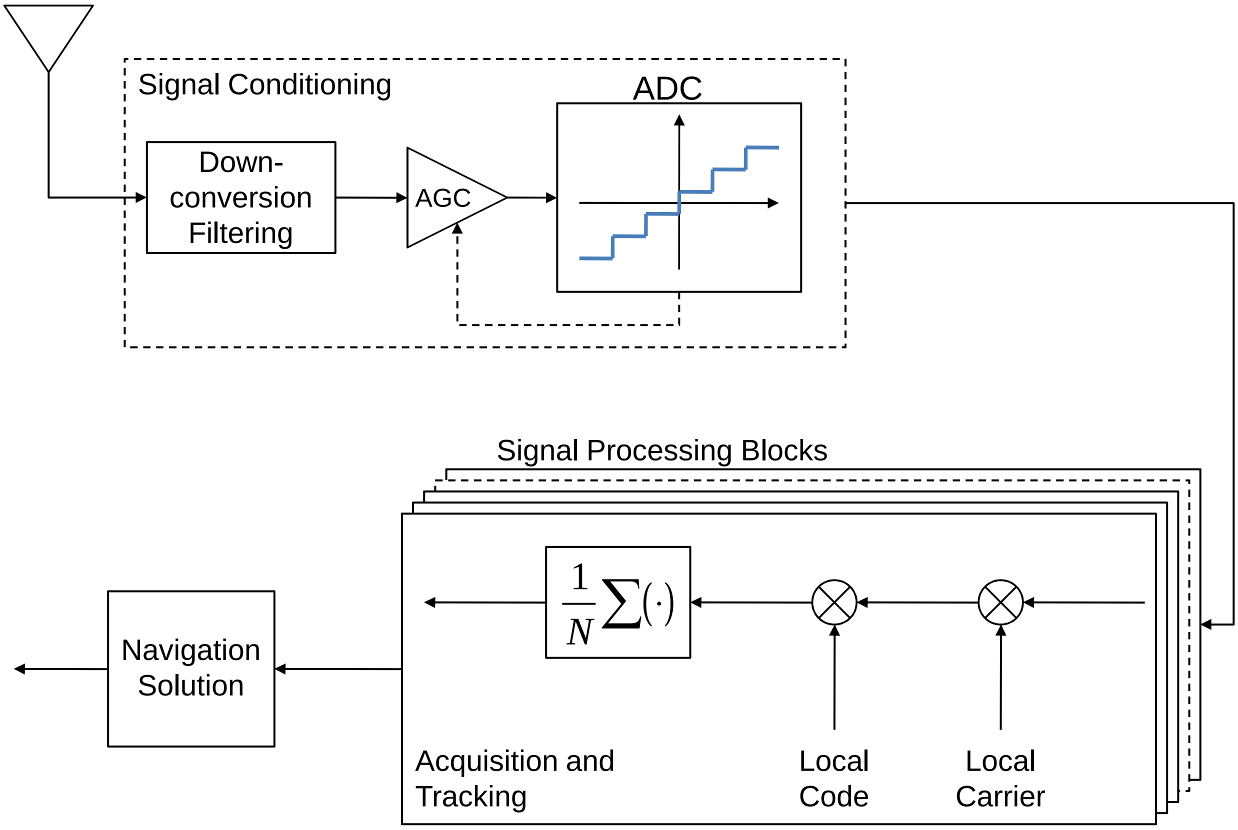


Figure 3: Schematic representation of the different processing blocks present in a GNSS receiver

The presence of pseudolites signals can impact a GNSS at different stages. A schematic representation of the different processing blocks of a GNSS receiver are shown in Fig. 3. The received signal is at first down-converted and filtered. The signal is then digitized through an Automatic Gain Control (AGC) and an ADC. The AGC is used to maintain the input signal amplitude within the ADC dynamic range [38] and reduce the quantization error. Several works [1, 29] recognized the fundamental role played by the AGC with respect to the impact of pulsed pseudolite signals. Different AGC types are available [39, 38] and the responsiveness of this device with respect to changes in the inputs signal amplitude strongly impacts the receiver performance in the presence of pseudolite signals.
After digitalization, the GNSS signals is passed to the signal processing blocks, acquisition and tracking,

that are responsible for determining which GNSS signals are available and providing the measurements that will be used for the computation of the navigation solution. The core of the signal processing blocks is the correlation of the input signal with local code and carrier replica. Correlation acts as a filter that reduces the noise and interference impact. Pseudolite components will thus be passed through the correlation block and attenuated depending on the cross-correlation properties between pseudolite modulation and local code. The final impact of the pseudolite signal strongly depends on the attenuation provided during the correlation process. This point and the importance of designing pseudolite code with good correlation properties was briefly discussed in Section 3.2. It is noted that pseudolite signals do not only cause an increase of the noise floor at the correlator output but can lead to biases in the pseudoranges and Doppler measurements. These biases are then reflected in the computation of the navigation solution.

The following aspects should be considered:

- **pre-correlation effects:** the impact of pseudolites on the signal conditioning block should be considered. This analysis is in principle complex, due to the large variety of AGC/ADC available and their inherent non-linear nature. The identification/analysis of the wost case scenario should be considered;
- **post-correlation effects:** analysis of the correlation margin and indication of potential biases that pseudolite signals can introduce;
- **navigation solution degradation:** impact of the increased noise level and biases in the measurements used for the computation of the navigation solution.

4.1 Impact on Signal Conditioning

The impact of pseudolites on the signal conditioning stage of a GNSS receiver has been only marginally studied. More specifically, only heuristic approaches have been proposed for the analysis [1, 29]. In [1], four types of AGC have been considered:

- **Ideal AGC**: it should simply ignore the presence of the pseudolite pulses. The gain provided by the AGC is constant and the GNSS signals are impacted by the pseudolite pulses only when the interfering signal is actually present. When a pulse enters the receiver, it saturates the ADC and its digital representation assumes the maximum/minimum value allowed by the ADC. During a pulse, the GNSS signal is completely masked;
- **Fast AGC**: the AGC is able to follow almost instantaneously the amplitude variations caused by the pseudolite pulse. In this way, the pseudolite signal is scaled within the ADC dynamics. During a pulse, the GNSS signals are strongly attenuated, however, due to the fast response of the AGC, this occurs only during the pulse duration and the useful signals are scaled correctly in the absence of pseudolite signal;
- **Slow AGC**: the AGC is unable to follow the amplitude variations due to the pseudolite pulse. The AGC is also slow in recovering from the pulse presence and signal degradations occur also in the absence of pseudolite pulses;
- **Very-slow AGC**: it averages the impact of pseudolite pulses and provides a gain lower than the one required for exploiting the full ADC dynamics. The behavior is similar to the ideal AGC case, although an additional loss is experienced during the absence of pulses because of the suboptimal gain provided by the AGC.

The response of the different AGC models to a single pseudolite pulse is shown in Fig. 4. In [1], only the case of ideal AGC is considered and a formula quantifying the loss caused by the presence of pulsed pseudolite signals is provided without proof as discussed in Section 2. Given the lack of a formal proof for the formula, further investigations are required to determine its validity.

[29] tried to extend the analysis provided in [1] by considering the case of multiple pseudolites broadcasting in the same area. In this case, several pulses with different amplitudes are present during a single

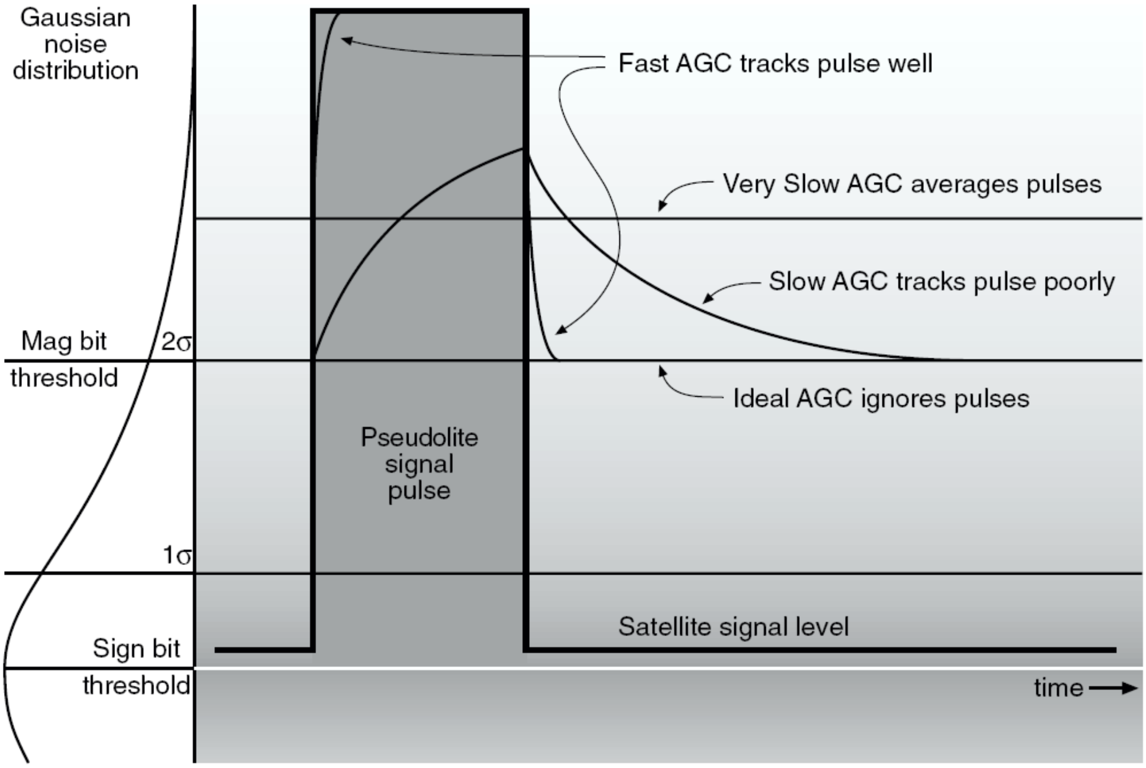


Figure 4: Response of different AGC models to a single pseudolite pulse. (From [1]).

code period of the useful signal. The case of slow and fast AGCs are considered and the inadequacy of slow AGCs is shown. [29] also provides a generalization of the formula given by [1] in the presence of several pseudolites. Also in this case, the formula is provided without proof and further analysis is required for assessing its validity.

4.2 Impact on Non-participating Receivers

Apart from the signal conditioning, receivers also vary greatly in the signal processing blocks. There are many different types of GNSS receiver on the market, for example, consumer grade, high sensitivity, survey grade, military, integrated with external sensors, stand-alone, etc.. As discussed in Section 2.5, very few actual field measurements have been performed, at least in the open literature. For any proposed pseudolite scheme it will be vital to have a detailed assessment of the impact on existing receivers of all types. To quantify this impact it is proposed to investigate the following metrics:

- C/N_0 degradation – this has been the most commonly used metric in the past
- Impact on measurements, pseudorange, Doppler and carrier phase – bias and noise contributions of the pseudolites
- Impact on navigation performance – accuracy, availability, reliability.

This will require a test-bed for evaluating the impact in a consistent manner.

It is vital to emphasise here the importance of considering the impact of the pseudolite signals on the measurements and navigation solution. While previous metrics such as the SNIR give an indication of the degradation suffered by a non-participating receiver, it is the measurements which are the most important output of the receiver signal processing. If the pseudolite signal is highly correlated with a satellite signal for a period of time, then the observed SNR may be large, even if the measurements are biased.

4.3 Impact on Participating Receivers

There are two primary motivating factors when considering participating receiver design:

1. Ease of implementation/integration with existing architectures
2. Optimising the receiver, to enable reduced transmit power levels in order to lessen the impact on non-participating receivers.

These factors will more than likely be at odds with one another. The ease of implementation issue was one of the primary driving forces behind the original RTCM pseudolite signal design, and was also an important consideration for the IMES signal. An optimal receiver design will require greater design effort, and hence cost, but may lead to greater overall system efficiency. A simple example is a participating receiver that implements pulse blanking. This may require significant hardware modifications, but can significantly improve the SNR for a participating receiver for a given transmitted power level.

Apart from the signal processing aspects, the synchronisation and positioning schemes may have a significant impact also. A standard GNSS receiver is a one-way ranging device which assumes all transmitters are at least approximately synchronous. A DGPS-enabled receiver will be able to process differential corrections, or in the case of CDGPS resolve carrier phase ambiguities to yield a differential position. However a stand-alone receiver will need some modifications to operate if the pseudolites have been designed to operate in a differential mode. In addition, to account for the highly non-linear nature of the pseudolite positioning problem will require a modification of the navigation algorithms, which will add cost to the initial development and deployment of pseudolite-enabled receivers. A simple solution like that of IMES may greatly simplify this process, at the expense of reduced navigation accuracy.

These barriers to implementation of participating receivers are not trivial, and may account, at least in part, for the lack of widespread implementation of pseudolite systems to date.

5 Other Aspects

Apart from the signal and receiver aspects for further study, it is important to highlight that there are a number of legal an logistical issues which have to be addressed. Following Martin et al. [8], the following are the key steps:

1. Identify the services to be provided by the pseudolites, and which frequency bands can be allocated to these services
2. Determine the constraints that must be placed on the pseudolite signals to meet compatibility requirements within those bands
3. Determine how to regulate for the licensing, monitoring and arbitration of licenses for the pseudolites.

Any technical advances that may be made in terms of signal structure and receiver design will be to no avail if the primary issues identified above are not resolved.

6 Recommendations

While the above study is necessarily incomplete, it is clear that the choice of pseudolite signal structure is intimately tied to the application. The most appropriate signals for indoor navigation are not necessarily the same as those for open-pit mining applications or positioning of high altitude platforms, for example. Any proposal for research on pseudolites must therefore specify clearly the application(s) being considered. The choice of frequency band into which to broadcast the pseudolite signals must be specified and justified, and a thorough assessment of the impact of any proposed scheme on existing GNSS, and, indeed, other RF infrastructure must be proposed. The impact on GNSS infrastructure must include a diversity of receiver types and assessment not just of the impact on C/N_0, but also on navigation performance.

Based on a survey of the existing literature on pseudolite technology, the following areas have been identified for further study

- Investigation of cross-correlation between Galileo-compatible signals and all other current or planned GNSS signals
- Study of pulsing schemes to meet spectral and multi-access requirements
- Determination of bounds on the allowable aggregate duty cycle for non-participating receivers
- Assessment of the impact of the receiver signal conditioning for participating and non-participating receivers
- Investigation of the impact of pseudolite signals on a range of existing receivers
    - Emphasis on assessing impact on navigation performance, particularly for continuous pseudolite signals.

References

[1] H. Stewart Cobb. *GPS pseudolites: Theory, Design and Applications*. Phd thesis, Stanford University, http://waas.stanford.edu/ wwu/papers/gps/PDF/Thesis/StuCobbThesis97.pdf, September 1997.

[2] Dale Klein and Bradford W. Parkinson. The use of pseudo-satellites for improving GPS performance. *Navigation: Journal of the Institute of Navigation*, 31(4):303–315, Winter 1984.

[3] Thomas A. Stansell. RTCM SC-104 recommended pseudolite signal specification. *NAVIGATION: Journal of The Institute of Navigation*, 33(1):42–59, Spring 1986.

[4] Jonathan M. Stone, Edward A. LeMaster, J. David Powell, and Stephen M. Rock. GPS pseudolite transceivers and their applications. In *Proceedings of the National Technical Meeting of the Institute of Navigation (ION NTM 99)*, San Diego, CA, January 25–27 1999.

[5] J. Wang. Pseudolite applications in positioning and navigation: Progress and problems. *Journal of Global Positioning Systems*, 1(1):48–56, 2002.

[6] M. O. Kanli. Limitations of pseudolite systems using off-the-shelf GPS receivers. In *Proceedings of the 2004 International Symposium on GNSS/GPS*, Sydney, Australia, December 6–8 2004.

[7] Chris Rizos. Pseudolite augmentation of GPS. In *Workshop on Geolocation Technology to Support UXO Geophysical Investigations*, Annapolis, MD, 1–2 June 2005.

[8] S. Martin, H. Kuhlen, and T. Abt. Interference and regulatory aspects of GNSS pseudolites. *Journal of Global Positioning Systems*, 6(2):98–107, 2007.

[9] Boris Steven Pervan. *Navigation Integrity for Aircraft Precision Landing Using the Global Positioning System*. PhD thesis, Stanford University, 1996.

[10] David Gary Lawrence. *Aircraft Landing Using GPS: Development and Evaluation of a Real Time System for Kinematic Positioning Using the Global Positioning System*. PhD thesis, Stanford University, 1996.

[11] A. J. Van Dierendonck, Pat Fenton, and Chris Hegarty. Proposed airport pseudolite signal specification for GPS precision approach local area augmentation systems. In *Proceedings of the Internation Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 97)*, Kansas, MI, September 1997.

[12] Christian Altmayer. Experiences using pseudolites to augment GNSS in urban environments. In *Proceedings of the 11th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 98)*, pages 981–991, Nashville, TN, 15–18 September 1998.

[13] Changdon Kee, Haeyoung Jun, Doohee Yun, Byungyeon Kim, Youngbaek Kim, Bradford W. Parkinson, Thomas Langenstein, Sam Pullen, and Jung Taek Lee. Development of indoor navigation system using asynchronous pseudolites. In *Proceedings of the International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 00)*, Salt Lake City, UT, 19–22 September 2000.

[14] Stefan Söderholm, Tuomas Juhola, Timo Saarnimo, Vesa Karttunen, and Timo Toivanen. Indoor navigation using a GPS receiver. In *Proceedings of the 14th International Technical Meeting of the Satellite Division of the Insititute of Navigation (ION GPS 01)*, Salt Lake City, UT, 11 – 14 September 2001. 1479–1486.

[15] Stefan Söderholm and Timo Jokitalo. Synchronized pseudolites – the key to indoor navigation. In *Proceedings of the International Technical Meeting of the Satellite Division of the Insititute of Navigation (ION GPS 02)*, Portland, Or., 24 – 27 September 2002.

[16] Joel Barnes, Chris Rizos, Jinling Wang, David Small, Gavin Voigt, and Nunzio Gambale. High precision indoor and outdoor positioning using locatanet. *Journal of Global Positioning Systems*, 2(2):73–82, 2003.

[17] Leica lays out augmentation network. GPS World magazine, February 2011.

[18] Arnaud Masson. Towards a fully global system? Presented at Galileo Application Days, Brussels, 4 March 2010.

[19] Kurt R. Zimmerman, Clark E. Cohen, David G. Lawrence, Paul Y. Montgomery, H. Stewart Cobb, and Walter C. Melton. Multi-frequency pseudolites for instantaneous carrier ambiguity resolution. In *Proceedings of the 13th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 00)*, pages 1024 – 1033, Salt Lake City, UT, 19–22 September 2000.

[20] Joon Wayn Cheong, Xiaowei Wie, Nonie Politi, Andrew G. Dempster, and Chris Rizos. Characterising the signal structure of Locata's pseudolite-based positioning system. In *Proceedings of the International Global Navigation Satellite Systems Society IGNSS Symposium*, Queensland, Australia, 1 – 3 December 2009.

[21] A. J. Van Dierendonck. The role of pseudolites in the implementation of differential GPS. In *Proceedings of the IEEE Position, Location, and Navigation Symposium (PLANS 90)*, pages 370–377, Las Vegas, NV, March 20 – 23 1990.

[22] Andrew Dempster. QZSS's indoor messaging system GNSS friend or foe? *Inside GNSS*, 4(1):37–40, January/February 2009.

[23] Christian Altmayer. Accuracy improvements of pseudolite systems – first results. In *Proceedings of the ION National Technical Meeting (ION NTM 01)*, pages 491–500, Long Beach, CA, 22 – 24 January 2001.

[24] Japan Aerospace Exploration Agency. *Quasi-Zenith Satellite System Navigation Service - Interface Specification for QZSS*, March 2010.

[25] Tin Lian Abt, Francis Soualle, and Sven Martin. Optimal pulsing schemes for Galileo pseudolite signals. *Journal of Global Positioning Systems*, 6(2):133–141, 2007.

[26] Bryant Elrod, Kevin Barltrop, and A. J. Van Dierendonck. Testing of GPS augmented with pseudolites for precision approach applications. In *Proceedings of the 7th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 94)*, pages 1269–1278, Salt Lake City, UT, 20 – 23 September 1994.

[27] Bryant D. Elrod, K. Barltrop, J. F. Stafford, and D. Brown. Test results of local area augmentation of GPS with an in-band pseudolite. In *Proceedings of the National Technical Meeting of the Institute of Navigation (ION NTM 96)*, pages 145–154, Santa Monica, CA, 22–24 January 1996.

[28] K. J. Barltrop, J. F. Stafford, and Bryant D. Elrod. Local DGPS with pseudolite augmentation and implementation consideration for LAAS. In *Proceedings of the 9th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 96)*, pages 449–459, Kansas City, MO, 17 – 20 September 1996.

[29] Edward Alan LeMaster. *Self-Calibrating Pseudolite Arrays: Theory and Experiment*. Phd thesis, Stanford University, Aerospace Robotics Lab, Stanford, CA, May 2002.

[30] Bryant D. Elrod and A. J. Van Dierendonck. Testing and evaluation of GPS augmented with pseudolites for precision approach applications. In *Proceedings of the 2nd International Symposium on Differential Satellite Navigation Systems (DSNS 93)*, Amsterdam, The Netherlands, April 1993.

[31] Gary McGraw. Analysis of pseudolite code interference effects for aircraft precision approaches. In *Proceedings of the 50th Annual Meeting of the Institute of Navigation (ION AM 94)*, Colorado Springs, CO, June 1994.

[32] K. Yajima. IMES (indoor messaging system) the solution for deep indoor navigation. In *Proceedings of the 23rd International Technical Meeting of The Satellite Division of the Institute of Navigation ION GNSS*, pages 1779–1799, Portland, OR, September 2010.

[33] Dinesh Manandhar, Kazuyuki Okano, Makoto Ishii, Hideyuki Torimoto, Satoshi Kogure, and Hiroaki Maeda. Development of ultimate seamless positioning system based on QZSS IMES. In *Proc. of the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2008)*, pages 1698–1705, Savannah, GA, September 2008.

[34] Dinesh Manandhar, Seiya Kawaguchi, and Hideyuki Torimoto. Results of IMES (indoor messaging system) implementation for seamless indoor navigation and social infrastructure platform. In *Proc. of the 23rd International Technical Meeting of the Satellite Division of The Institute of Navigation*, pages 1184–1191, Portland, OR, September 2010.

[35] Daniele Borio and Joaquim Fortuny-Gausch. Impact of pseudolite signals on non-participating GPS receivers: Compatibility analysis for commercial receivers. Scientific and Technical Report JRC62608, Joint Research Centre of the European Commission (JRC), December 2010. ISBN: 978-92-79-19522-8.

[36] Electronic Communications Committee (ECC). Compatibilities studies between pseudolites and services in the frequency bands 1164-1215, 1215-1300 and 1559-1610 MHz. Technical Report ECC Report 128, European Conference of Postal and Telecommunications Administrations (CEPT), Dublin, January 2009.

[37] A.R. Pratt. Frequency diversity or no frequency diversity. In *Proceedings of the 23rd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2010)*, pages 3021–3040, Portland, OR, 21–24 September 2010.

[38] Dennis R. Morgan. On discrete-time AGC amplifiers. *IEEE Transactions on Circuits and Systems*, Cas-22(2):135–146, Feb 1975.

[39] Jack R Smith. *Modern Communication Circuits*. McGraw-Hill Science/Engineering/Math, 2 edition, August 1997.

European Commission

EUR 24798 EN – Joint Research Centre – Institute for the Protection and Security of the Citizen
Scoping Study on Pseudolites
C. O’Driscoll, D. Borio, J. Fortuny
Luxembourg: Publications Office of the European Union
2011 – 31 pp. – 21 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593
ISBN 978-92-79-19990-5
doi:10.2788/10293

Abstract

Pseudolites or pseudo-satellites are an emerging technology with the potential of enabling satellite navigation indoors. This technology found several applications that are not limited to indoor navigation. Precise landing, emergency services in difficult environments and precise positioning and machine control are few examples where pseudolite technology can be employed.

Despite the great potential of this technology, severe interference problems with existing GNSS services can arise. The problem can be particularly severe when considering non-participating receivers, i.e., legacy devices not designed for pseudolite signals. The design of pseudolite signals is thus a complex problem that has to account for market requirements (modifications of existing receivers for enabling the use of pseudolite signals, measurement accuracy, target application), regulatory aspects (frequency bands to be allocated for pseudoliteservices) and interference problems.

The main aspects for the design of a pseudolite signal standard minimizing the interference problem without compromising the location capabilities of the system are considered. The focus is on the signal characteristics and topics relevant for the signal design. A literature review on the different pseudolite applications, prototypes and solutions adopted for minimizing the interference problem is first conducted. Recommendations on the aspects that should be further investigated are then provided.

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

LB-NA-24798-EN-C

JRC

EUROPEAN COMMISSION

Publications Office

ISBN 978-92-79-19990-5

9 789279 199905