GPS PSEUDOLITE SIGNAL DESIGN

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Presented at ION-GPS-94
Salt Lake City, Utah
September 1994

BIOGRAPHY

Awele Ndili received the B.Eng. degree in Mechanical Engineering with First Class honors, from the University of Nigeria, Nsukka in 1988. He received the MS degree in Mechanical Engineering from Stanford University in 1991. He is currently working on his Ph.D. in ME/EE, also at Stanford. His current research interests include Pseudolite signal design, and spread spectrum methods for aircraft collision avoidance. Between 1988 and 1990 he worked with Dornier/AIEP, a German/Nigerian aviation company, as the Systems Engineer and computer analyst.

ABSTRACT

Pseudolites (PLs), ground-based satellites transmitting GPS-like signals, are becoming increasingly useful for a variety of applications, including differential GPS correction broadcasting and aircraft precision approach - Category I, II and III. PLs have the capability to augment the GPS constellation, providing better geometry for greater positioning accuracy, reliability, availability, continuity, and integrity monitoring. In addition they can be used to speed up integer ambiguity resolution in differential carrier phase applications, due to the large geometry change possible with the PL signal.

However the use of PLs is not without its problems, the most notable being the "near-far problem". This problem occurs due to the large dynamic range between a PL and a user, in contrast with the approximately constant distance of the GPS satellites from the user. Within some range, a PL signal can be orders of magnitude more powerful than the GPS satellite signal, and thus jam a user's receiver.

The paper discusses the design of a PL signal to mitigate the near-far problem using CDMA methods. The use of longer pseudo random (PR) code at C/A code rate, as well as the use of faster code (P-Code rate) is explored. Longer codes are formulated by concatenation of length-1023 Gold codes, scrambled by a 'Switching Sequence'. By applying selected switching sequences one can achieve signal-to-interference level improvements of up to 6 dB. Application of P-Code rate sequences shows even larger improvements, from 23 dB.

I. INTRODUCTION

The Department of Defense's Global Positioning System (GPS) has found increasing applications since its inception. Applications such as aircraft high precision approach and landing place high performance demands on GPS. Specifically there is the need for high accuracy, integrity, availability and continuity of the GPS information. The Pseudolite is ideally suited to augment the GPS space vehicle constellation and aid the achievement of the specifications mentioned above.

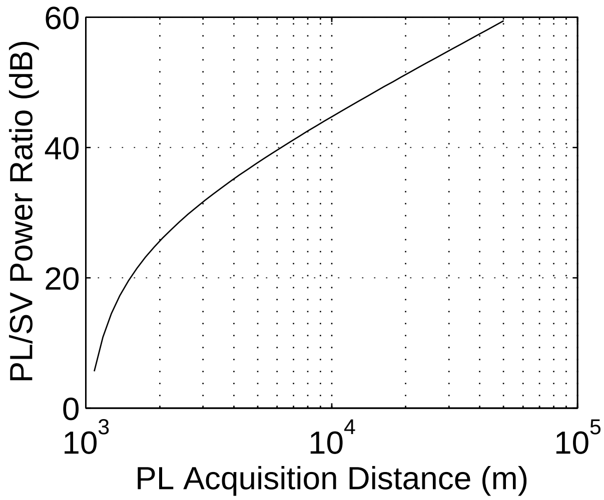
A Pseudolite transmits a GPS-like signal which can be received by modified GPS receivers. A PL used as a data link transmits differential GPS error corrections and integrity information to users in a terminal area, thereby increasing GPS accuracies. Also by transmitting a ranging signal, the PL can augment the GPS satellite constellation and thereby provide better geometry with a lower GDOP, resulting in greater positioning accuracy, availability and continuity.

In addition the Pseudolite can be used in carrier phase ranging, to hasten the resolution of integer ambiguities, due to the large changes in user/transmitter geometries possible. In this capacity the PL can provide accuracies down to 10cm, which is necessary for the use of GPS in Category II and III high precision approaches and landings (see Cohen et al. [3]). The PL also boosts reliability by providing for greater integrity, availability and continuity of the navigation system.

The major problem with the use of PLs, the 'near-far' problem, arises because of the large variation of the user-to-PL range. The average power being received from the GPS space vehicles (SVs) remains approximately constant due to the large distance of the SVs from users. The Pseudolite power on the other hand, varies a great deal, inversely proportional to the square of the user's distance from the pseudolite, and can overwhelm incoming GPS SV signals.

The near/far problem occurs to varying degrees of severity in the different applications of Pseudolites mentioned above. It is most severe in the terminal-area-data-broadcast application, since its service area is widest. A signal being received by a user 50km away from the Pseudolite would become 60dB stronger when the user is 50m away. On the other hand an aircraft on a precision approach would experience a 45dB PL/SV power ratio, if the PL signal were acquired with equal strength as the GPS SV's, 10km from start of runway, and the aircraft flew a 3-degree glide slope directly over a PL located 1000m from runway base (see fig. 1 below).

Fig. 1. PL/SV Power Ratios



If the same aircraft were to acquire the PL signal 5km from runway threshold, the maximum PL/SV power ratio experienced would be 38dB.

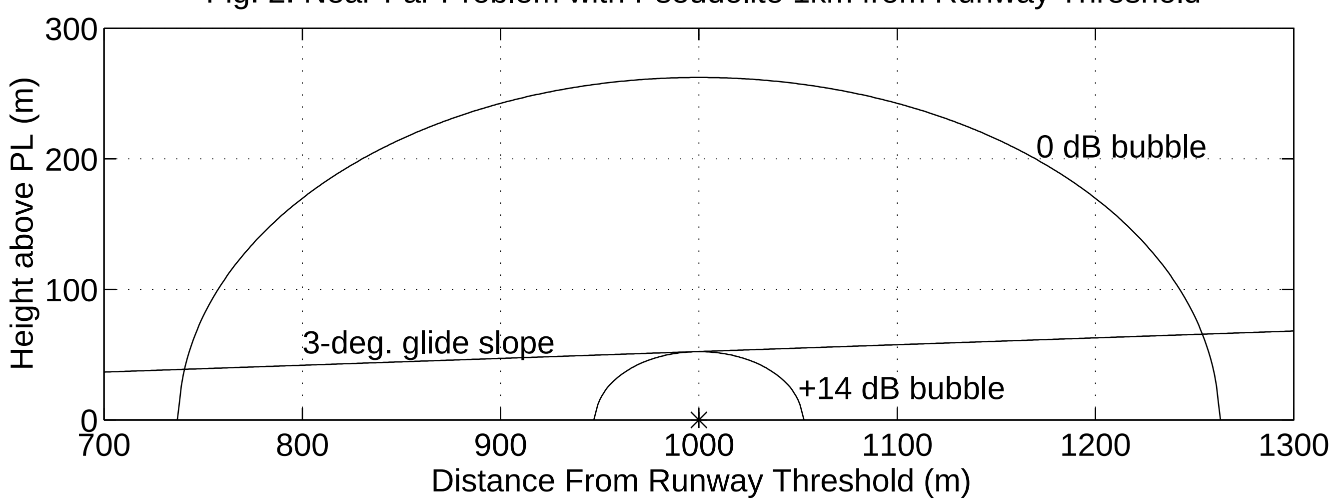
For PL-aided carrier phase ambiguity resolution in aircraft high precision approach, the PL provides a ‘bubble’ through which the aircraft must pass to resolve carrier cycle integer ambiguities [3].

The size of this bubble is limited by the near/far problem. Fig. 2 shows the maximum size of a PL ‘bubble’ if the PL transmits a C/A code. This figure is based on the 24dB signal-to-interference (S/I) margin inherent in length 1023 Gold codes, and on receivers that require a 10dB minimum S/I margin for operation. It is desirable to increase the size of the PL bubble.

The PL signal should therefore be designed to minimize this interference, especially to non-participating receivers. A non-participating receiver is a GPS receiver which is not re-designed or modified in any way to receive or ignore the PL signal. Therefore to guarantee the efficient operation of this class of receivers in the vicinity of a PL, effort should be focused primarily on the design of the PL signal, rather than the redesign of specific receivers. This approach is adopted for this work. It is desirable also to have the PL signal compatible with current receiver design, and therefore minimize cost of integration into participating receivers.

Fig. 3 shows a generic coherent delay lock loop used by a GPS receiver to track C/A or P code. Incoming signals go through a demodulator and low-pass filter. The resulting signal is baseband and consists of the spread spectrum signal (C/A code or p-code) modulated by data. This signal is fed to the early, late, and prompt correlators

Fig. 2. Near-Far Problem with Pseudolite 1km from Runway Threshold



which correlate with a locally generated synchronized version of the spread spectrum signal. The magnitude of the output of the correlators gives an indication of the degree of synchronization between the received and locally generated codes. It is desirable to have very low output for correlation between non-synchronized versions of the same code, and for correlation between two different codes. C/A codes, which are Gold codes of length 1023, have a 4-valued autocorrelation function: 0 dB (perfect match), -23.9 dB, -24.2 dB, and -60.2 dB. The cross correlation function, a measure of the level of interference from other signals, is 3-valued, with values -23.9 dB, -24.2 dB, and -60.2 dB. With small differences in the carrier frequencies between two signals, say due to Doppler effect, we should expect no more than a 3 dB degeneration in cross correlation performance [10]. To minimize the near-far interference from the PL signal, one should therefore seek to minimize the cross correlation level of the PL signal with the GPS Gold codes.

gating the PL signal for fractions of a full duty cycle. Thomas Stansell [12] proposes using a 10% duty cycle by transmitting 93 out of 1023 chips each cycle of the PL signal. A 10dB improvement in signal-to-interference level is expected using this method [12],[13].

This work focuses on the use of CDMA-only methods. While CDMA-only methods may not be adequate for terminal area applications, they show promise for Category II/III applications. CDMA-only methods have the advantage of lower costs of implementation due to their high degree of compatibility with current receiver design. Codes of length 4092 (4x1023) at the L1 frequency band are explored. These codes are formed using length-1023 Gold codes at the C/A code rate, 1.023MHz. Use of P-Code rate code (10.23MHz) is also investigated. It is shown that one can achieve greater levels of signal-to-interference margin gains, while maintaining reasonable compatibility with current receiver design.

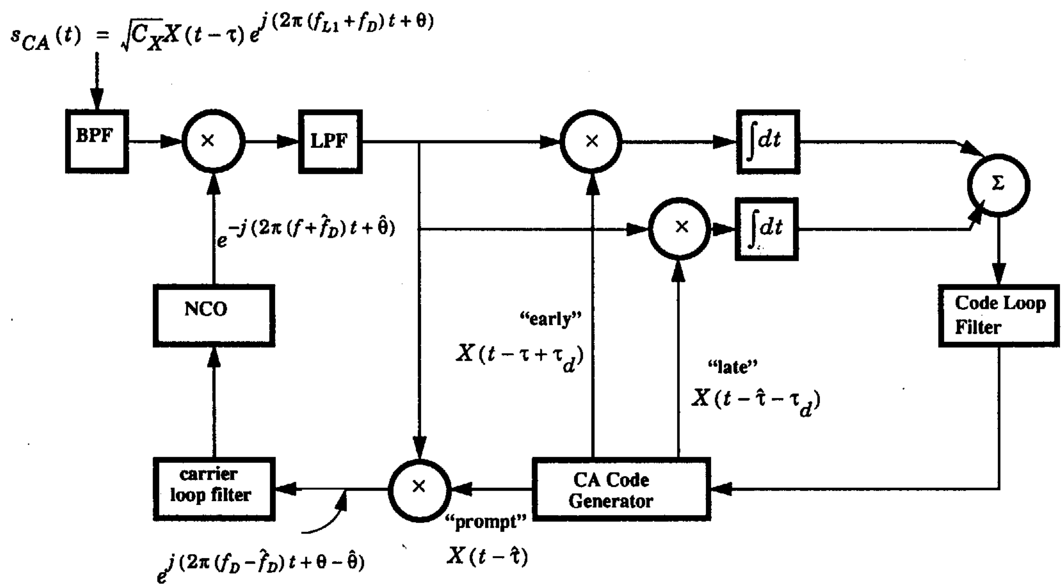


Fig. 3. Coherent delay lock loop in a GPS receiver (Courtesy of P. K. Enge)

There have been various methods proposed to solve the near-far problem (see references). These generally fall under three categories: FDMA (frequency division multiple access), TDMA (time division multiple access), and CDMA (code division multiple access) methods. Generally FDMA involves placing the signal on a carrier frequency different from that being used by the GPS signal (1575.42 MHz). The frequency offset may be large or small. Alison Brown [2] proposes a frequency offset of about 40 MHz by placing the PL signal in the 1610-1626.5 MHz band. A. J. Van Dierendonck [15] suggests placing the PL signal on the first null of the spectrum of the GPS SV signal, an offset of 1.023MHz from the L1 center frequency. This minimizes interference from the PL signal. However this also requires considerable modification to current receiver design. TDMA involves

Section II discussed the statistical basis for code design, based on purely random binary sequences. The expected performance of a random code of specified length is derived, and compared to computed results for pseudo-random (PR) codes. This forms the basis for performance predictions of PR codes. An analyses of p-code rate sequences is also presented here.

Section III presents the design of length-4092 codes using switching sequences. Performance of switching sequences are evaluated, and an optimized selection is presented. Analytical results of length-4092 codes formed with 8-bit switching sequences are also presented.

Section IV concludes with a discussion of the implications of the preceding results. This section also discusses the effect of aircraft fuselage shielding on the near-far problem. On-going research is mentioned.

II. RANDOM SEQUENCE ANALYSES

Given two binary sequences x and y, each of length N, consisting of +1s and -1s, we desire to know what is the expected RMS value of cross-correlation value, $Ø_{xy}(\tau)$, between x and y. The following assumptions are made about the sequences x, and y:

i) x and y are purely random sequences:
  x_i is independent of x_j for $i \neq j$.
  y_i is independent of y_j for $i \neq j$.
ii) x and y are statistically independent:
  x_i is independent of y_j for all i, j.

$$E\{RMS(Ø_{xy}(\tau))\} = \mathrm{sqrt}(\ E\{\{Ø_{xy}(\tau)\}^2\}\ )$$

where $$Ø_{xy}(\tau) = \int_{t=0}^{t=NTc} x(i)y(i+\tau)dt \qquad (2.1)$$

Tc = duration of 1 chip in seconds;
τ = time offset.

For square pulses eqn. 2.1 can be replaced with:

$$Ø_{xy}(\tau) = \sum_{i=0}^{N-1} x(i)y(i+\tau)$$

where τ is the chip offset.
Therefore:

$$E\{(Ø_{xy}(\tau))^2\} = E\{x_0^2 y_\tau^2 + x_1^2 y_{\tau+1}^2 + ... + x_{N-1}^2 y_{\tau+N-1}^2 + x_0 x_1 y_\tau y_{\tau+1} + ... \text{ other cross terms}\}$$

Since x and y are statistically independent:

$$E\{x_i x_j y_k y_l\} = 0 \text{ for } i \neq j \text{ or } k \neq l$$
and
$$E\{x_i x_j y_k y_l\} = 1 \text{ for } i=j \text{ and } k=l$$

Therefore $\mathrm{mean}(Ø_{xy}(\tau))^2 = \sum_{i=0}^{N-1} 1 = N$

and $E\{RMS(Ø_{xy}(\tau))\} = \sqrt{N}$

Normalized, $E\{RMS(Ø_{xy}(\tau))\} = \sqrt{N}/N = 1/\sqrt{N}$

This implies that the expected rms cross correlation value between two equal length random independent binary sequences is inversely proportional to the square root of the code length.

For random codes of length = 1023, the expected normalized rms cross correlation value is 1/32 = 30.1dB.

By increasing code length to 2046 one would expect a 3dB improvement in cross correlation level. A code length of 4092 (4x1023) gives an expected rms correlation value of 36.1dB.

These results can be compared to computed values for Gold codes formed from pseudo random sequences. GPS utilizes length 1023 Gold codes, which produce a 3-level cross correlation function, with the values -1, -65, and 63 occurring in the ratios 50%, 25%, and 25% respectively [10].

$$\mathrm{sqrt}(E\{\{Ø_{xz}(\tau)\}^2\}) = \mathrm{sqrt}\{.5(-1^2) + .25(-65^2) + .25(63^2)\}$$
$$= 45.3 = 27.1 \text{ dB}$$

This gives an expected rms value of 27.1dB, within 10% of the value predicted from purely random code analysis. In addition GPS Gold codes give a worst case cross correlation level of 23.94dB, corresponding to the -65 cross correlation level. This performance is expected to degrade by 3dB (to 20.94dB) when Doppler shifts in carrier frequency are introduced (see Spilker [10]).

It is therefore to be expected that by using a PR code of length 4092, we would expect a 6dB improvement in cross correlation level. This is verified in the next section.

On the other hand, correlating a faster code with a slower one gives different results. Let x be the purely random binary sequence described in the paragraphs above, and let z be another purely random binary sequence of +1s and -1s, at a chipping rate 10 times the rate of sequence x. As in the previous analysis x and z are assumed to be statistically independent. The expected rms value of the cross correlation function between x and z is given by:

$$E\{RMS(Ø_{xz}(\tau))\} = \mathrm{sqrt}(\ E\{\{Ø_{xz}(\tau)\}^2\}\ )$$

with $$Ø_{xz}(\tau) = \sum_{i=0}^{10N-1} x(i/10)z(i+\tau)$$

As before,
$$E\{x_i x_j z_k z_l\} = 0 \text{ for } i \neq j \text{ or } k \neq l$$
and
$$E\{x_i x_j z_k z_l\} = 1 \text{ for } i=j \text{ and } k=l$$

Following similar steps as in the previous case, we arrive the result:

$$E\{RMS(Ø_{xz}(\tau))\} = \frac{1}{\sqrt{10N}} \text{ normalized.} \qquad (2.2)$$

Extrapolating to PR sequences, this results implies an additional 10dB cross-correlation margin may be gained by having the PL sequence at P-code rates, and correlating for 1 ms. This result gets better as the length of the PL code is extended. A 20 ms period for the PL sequence would be an optimal choice as this corresponds to the period of the 50 bps data modulating the C/A code, and therefore is the maximum time between decisions in a receiver. Such a code would contain 204600 chips, and would result in an additional cross correlation margin gain of 23 dB.

III. CODE REALIZATIONS

This section presents a number of actual sequences to achieve the theoretical margins discussed in the previous section.

Let x be a sequence of length $2N$, formed by concatenating a single sequence from a family of length-N Gold codes. Let y be another sequence of length $2N$ formed in a similar manner as x above, from a different sequence in the same length-N family of Gold codes. Let the sign on the second half of y be reversed (see fig. 4 below).

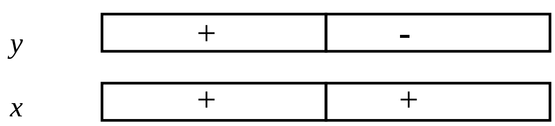


Fig. 4. Length $2N$ Sequences

Then

$$\text{Ø}_{xy}(\tau) = \sum_{i=0}^{2N-1} x(i)y(i+\tau) = 0 \qquad (3.1)$$

Cross-correlating x and y with a cross correlator integration time equal to twice the duration of the period of sequence-x (equal the period of sequence y) would result in zero correlation output, or absolutely no interference (infinite dB) to signal x, assuming y is the interfering signal.

The caveat however appears when there are Doppler offsets in carrier frequency. With differences in carrier frequencies of x and y equation 3.1 becomes:

$$\text{Ø}_{xy}(\tau) = \sum_{i=0}^{2N-1} x(i)y(i+\tau)\exp(j2\pi f_d T_c i) \neq 0 \qquad (3.2)$$

where f_d is the difference in carrier frequency.

Equation 3.2, the Ambiguity function, is plotted in fig. 5 using two Gold codes of order 5 (length 31) for a frequency range of 0 to 6.5KHz. The figure shows that for zero frequency offset there is perfect cancellation - or zero correlation. However as the frequency departs from zero, so does the value of the cross correlation function.

Fig. 4 introduces the concept of "Switching Sequences". A switching sequence is one which when applied to another sequence, changes the signs of corresponding code segments. In the example above a two bit switching sequence [+ -] was applied to a length $2N$ sequence to produce y. However as is shown in Fig. 5, the perfect cancellation from this simple switching sequence degrades when differences in GPS carrier frequencies exist. Under normal circumstances one may expect up to $\pm$ 6KHz variation in carrier frequencies due to Doppler. A good switching sequence would therefore produce longer sequences with good correlation properties over both time and frequency offsets.

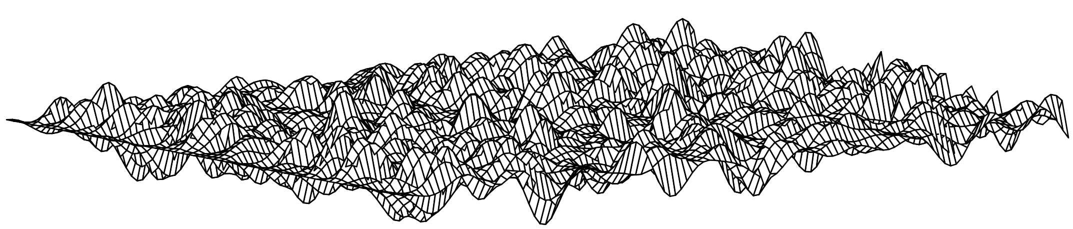
Simulation Setup:

By using longer and more complex switching sequences it is possible to achieve low cross-correlation over time and frequency. To verify this and to ascertain characteristics of good switching sequences, we have exhaustively applied length-8 switching sequences to Gold codes of order 5 (length-31), with quadruple length ($4N$ = 124). The Gold codes were generated from two maximal length pseudo random sequences (m-sequences). One m-sequence was generated from a five-stage linear feedback shift register (LFSR) with the generating polynomial :

$$p(x) = x^5 + x^2 + 1$$

(see fig. 6). The second m-sequence was obtained by

Fig. 5. Ambiguity Function for 2 Gold Codes of order 5 (Length 31x2, Switch = +-)



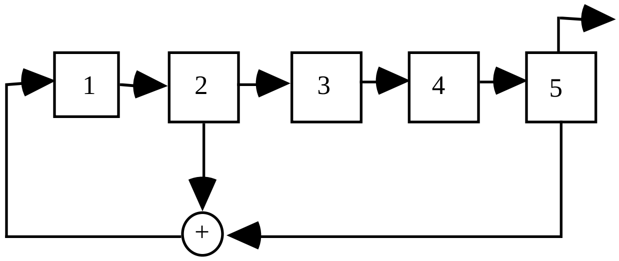


Fig. 6. Five-Stage Linear Feedback Shift Register

decimating the m-sequence from this polynomial with at factor of 7. The reader is referred to the paper by Robert Gold [5] for details on the characteristics and properties of Gold codes, and to refs. [6], [7] and [9] for more detailed treatment of m-sequences. Each bit in the 8-bit switching sequence switches segments of length 16 or 15 in the 124-bit sequence. The chipping rate of the composite sequence was selected to give similar characteristics as GPS codes when correlated over 0-6.5KHz. Cross-correlation was performed over all 124-chip time offsets, and over 0 - 6.5KHz in increments of 55Hz.

An exhaustive analyses of the results of all possible 8-bit switches indicate that the switching sequences which produce the best codes have low periodic autocorrelation sidelobes, as well as low sums. This combination of properties is necessary to provide good performance over both time and frequency. The simple switching sequence shown in fig. 4., '+ -', though having a low sum (+1 - 1 = 0), produces poor results when cross correlation is performed over shifts in frequency (fig. 5) since it has a high autocorrelation sidelobe.

A summary of the nominal performance (no switching sequence applied), the 4 best performance results of cross-correlation over time and frequency, and the best cross-correlation result over time-only, are contained in Table 1. This table shows the switching sequence, the worst-case cross correlation peaks of each switching sequence over time and frequency, as well as the corresponding cross-correlation peak over time-only (no Doppler frequency shifts). The gains over nominal performance are also shown.

Switching	Over Time Only		Time & Frequency	
Sequence	Proc.Gain	Improved	Proc.Gain	Improved
++++++++	10.7424	0	8.28981	0
+-+++---	15.02	4.2776	15.02	6.73019
++++-++-	16.763	6.0206	14.4853	6.19549
+-+-++--	15.02	4.2776	14.4684	6.17859
+++++--+	16.763	6.0206	14.3104	6.02059
++--++--	inf	inf	10.9666	2.67679

Table 1. Processing Gain using Length-4x31 Codes(dB)

The best time-only cross-correlation result is the zero-interference case, or infinite dB, as shown in fig. 5. However this performance drops to 2.67dB improvement only, when Doppler shifts in carrier frequency are considered.

An exhaustive search was also performed using sequences based on GPS Gold codes. A pseudolite signal was formed from four runs of an unused sequence from the GPS family of length-1023 Gold codes. This sequence was cross correlated with one of the 35 Gold codes used by the GPS satellites. The results are shown below. The best 'worst case' gain of 5.88dB is based on the worst case time-frequency cross correlation value, 21.3 dB, with no switch applied.

Switching	Over Time Only		Time & Frequency	
Sequence	Proc.Gain	Improved	Proc.Gain	Improved
++++++++	23.9392	0	21.348	0
+-++-+++	29.9598	6.0206	27.2378	5.8898
+----+--	29.9598	6.0206	26.7108	5.3628
+++++--+	29.9598	6.0206	26.3312	4.9832
+--+----	29.9598	6.0206	26.3284	4.9804
++--++--	inf	inf	23.585	2.237

Table 2. Processing Gain using Length-4x1023 Codes(dB)

Once more the best performing switching sequences show the same characteristics as in the previous simulation. Cross-correlation results over time only produce infinite gains in signal to interference levels with the simple switching sequence '++--++--'. This theoretically implies absolutely no interference from a PL using this code to a non-participating receiver, irrespective of range[1], so long as there are no Doppler shifts in carrier frequencies. With as little as 300Hz difference in carrier frequencies, this performance drops to nominal (23.94dB). Worst case peak over 0-6.5KHz for code formed using this switch was 23.58 dB, 0.36 dB worst than nominal performance.

IV. CONCLUSION AND FUTURE WORK

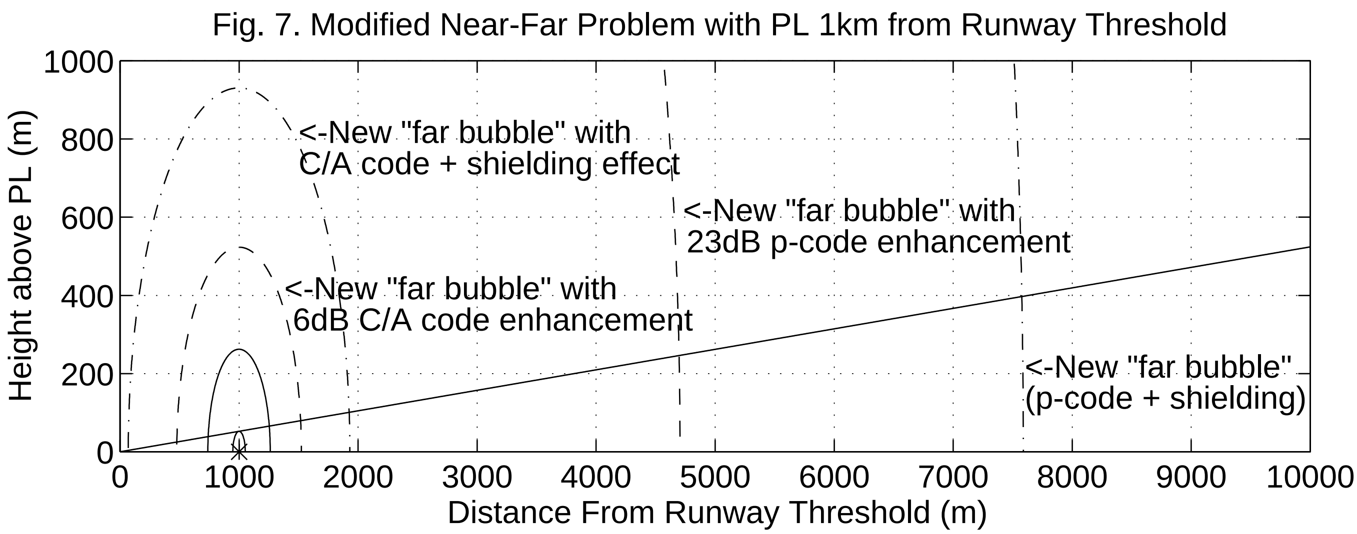
Fig. 7 shows the modified near-far problem for an aircraft on a 3-degree glide slope approach, with a PL located 1 km from runway threshold. This plot contains the original near-far bubble (innermost pair plotted with continuous lines), as well as the bubbles that would result from PLs utilizing length-4092 codes at C/A code rate, and from length 20460 codes at 10.23 MHz (both plotted with dashes). The figure shows that the radius of the PL bubble can be doubled by a PL using a length-4092

[1] In reality non-linearities in the receiver front end would produce interference as the PL signal power becomes very large.

sequence broadcast on L1 band. A x14 increase in bubble radius is expected by using a length-20460 code with a chipping rate of 10MHz.

The effect of airframe attenuation of the PL signal has not be addressed in the previous discussions. Fig. 8 shows the spherical antennae pattern for an antennae mounted on top of a BAC1-11 aircraft. It can been seen that the aircraft fuselage attenuates GPS signals by as much as 20dB for a transmitter directly below. This property can be an advantage in the PL application, as it provides a natural shield to the GPS-satellite antennae mounted on top an aircraft.

For an aircraft on a 3-degree glide slope, a top mounted antennae would experience a minimum attenuation of 5dB



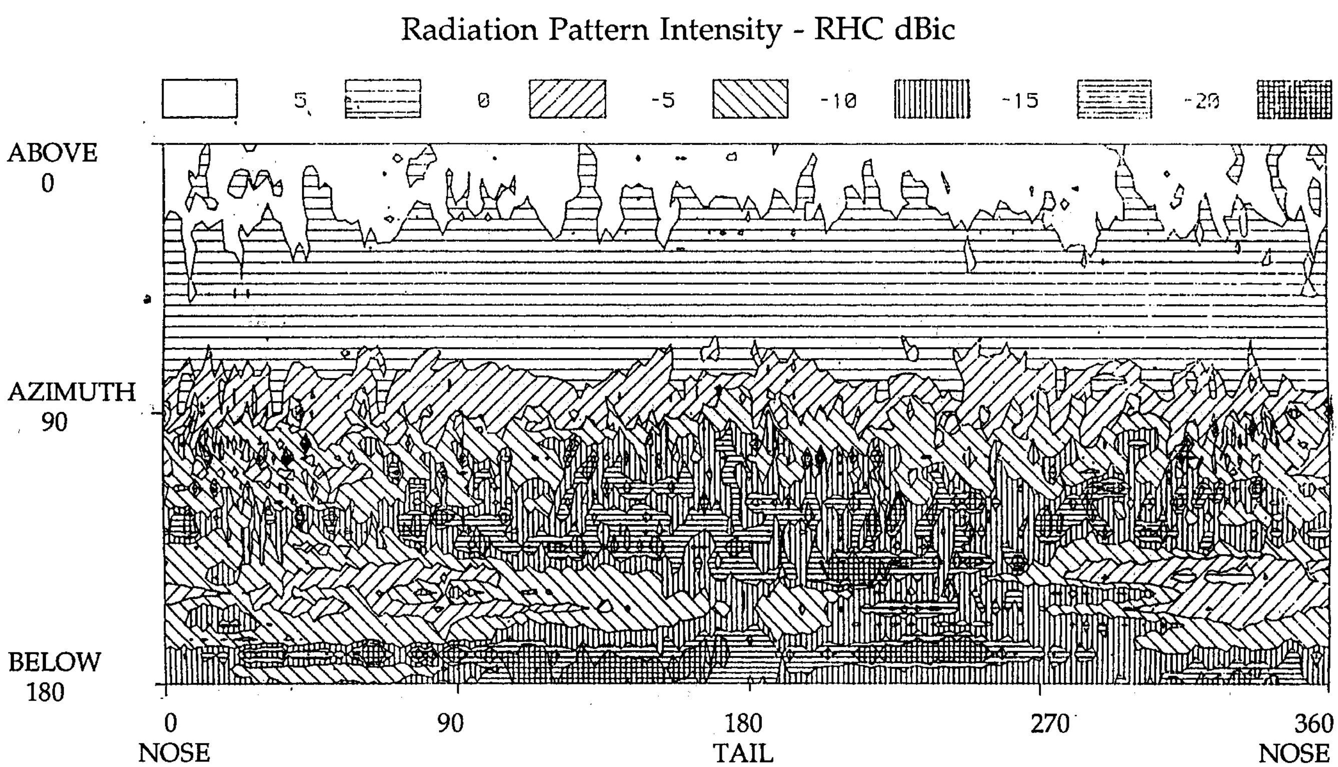


Fig. 8. BAC 1-11 Radiation Pattern Spherical Coverage (Courtesy of J. I. R. Owen)

for the signal of a PL located as shown in fig. 2. This is the minimum expected along the chosen flight path. In reality the effect of fuselage shielding increases as the aircraft approaches overhead the PL. The PL antennae, mounted underneath the aircraft, will not experience this attenuation. Therefore shielding from the aircraft fuselage is expected to add at least an extra 5 dB gain over the performance of the proposed schemes.

Taking this shielding into account the expected minimum overall performance is plotted in fig. 7 (shown with dash-dot plot). With length-4092 sequences at C/A code rate, we expect a minimum gain of 11 dB with a top mounted antennae for an aircraft in the approach configuration shown in fig. 2. With length-20460 sequences at 10.23MHz we expect a 28dB improvement.

Current work includes the set up of physical experiments to verify the theoretical code performance predictions. Flight tests would be performed over a PL with both types of code, and data taken. Analyses of experimental results is expected also to produce a better understanding of the effects of aircraft fuselage shielding on PL signals.

ACKNOWLEDGMENTS

The author gratefully acknowledges the following for their contribution to this research effort: my research adviser Per K. Enge, J. Dave Powell, Bradford Parkinson, the FAA's Satellite Program Office (AGS-100) and the FAA Technical Center. However, the opinions and views expressed in this paper belong to the author alone, and do not necessarily represent the position of any other organization of person.

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