Proposed Airport Pseudolite Signal Specification for GPS Precision Approach Local Area Augmentation Systems

A. J. Van Dierendonck, *AJ Systems*

Pat Fenton, *NovAtel, Inc.*

Chris Hegarty, *The MITRE Corporation*

BIOGRAPHIES

Dr. A. J. Van Dierendonck received a BSEE from South Dakota State University and MSEE and PhD from Iowa State University. Currently, he is self-employed under the name of AJ Systems and is a general partner of GPS Silicon Valley. In 1993 Dr. Van Dierendonck was awarded the Johannes Kepler Award by the Institute of Navigation Satellite Navigation Division for outstanding contributions to satellite navigation. A. J. has over 23 years of GPS experience.

Pat Fenton received his B.Sc. in Survey Engineering from the University of Calgary in 1981. He worked at Nortech surveys developing specialized survey equipment including INS/GPS and Laser primarily for oil exploration applications. In 1989 he joined NovAtel to lead the technical development of their line GPS receivers. He was the inventor of NovAtel's narrow correlator technology. He is currently the Vice President of Research and Development of at NovAtel Inc.

Dr. Chris Hegarty has been with The MITRE Corporation since 1992, working mainly on aviation applications of GPS. He received his BSEE and MSEE from Worcester Polytechnic Institute and his D.Sc. from The George Washington University. He currently serves as RTCA SC159, Working Group 4a, Airport Pseudolite Subgroup chairman.

ABSTRACT

The availability and continuity of accuracy and integrity are major concerns for GPS-based precision approach and landing systems without augmentation. Thus, following the lead of the FAA baseline Local Area Augmentation System (LAAS) architecture that includes pseudolites, RTCA Special Committee 159 Working Group 4a for GPS/Precision Landing Guidance has set up an Airport Pseudolite (APL) subgroup. The purpose of this subgroup is to develop LAAS pseudolite standards. This subgroup is responsible for trade studies necessary for the development of an APL signal structure. This development is well underway, starting with a set of basic assumptions to be considered in that development. Minimum performance criteria for a viable pseudolite signal structure are also being established.

This paper presents these basic assumptions to be considered and the resulting minimum performance criteria for the APL signal structure. Then, the details of the proposed APL signal specification currently under review that meets those criteria are described. Also, the analytical results that justify the proposal against the defined considerations and minimum performance requirements are presented.

INTRODUCTION

The availability and continuity of accuracy and integrity for differential GPS precision approach systems cannot be achieved without augmentation with additional ranging sources. Additional satellites could provide this augmentation. However, to date, there has not been any significant movement towards that direction to satisfy Category II and III precision approach and landing requirements. The geostationary satellites being programmed for the Satellite Based Augmentation Systems (SBAS) do not provide the augmentation required for these approach and landing categories. GLONASS could provide the necessary augmentation if problems associated with that system were corrected and if the system were more mature. Without additional satellites, we must rely on other augmentations. The most promising of these other augmentations is the use of pseudo-satellites located on the ground, or Airport

Pseudolites (APLs) as they are called by the FAA and RTCA. APLs are part of the FAA's recommended LAAS architecture (LARC) [1].

The APL augmentation concept is illustrated in Figure 1. The APL, or multiple APLs, provide additional ranging signals to the user to augment the geometry provided by the GPS constellation. These ranging vectors can be so different than those provided by the satellites that their geometric contribution can be quite significant, usually more so than that provided by an additional satellite or two. With appropriate siting of the APL relative to the runway, the contribution can be quite dramatic. In fact, even without applying any effort is optimizing the siting, the availability of accuracy and integrity can be improved by an order of magnitude in most locations with only one APL [2], and more importantly, shorten outage periods from being intolerable to being quite reasonable [3, 4]. Of course, while no siting optimization was applied, no siting constraints were either. However, the improvement is significant enough to warrant further exploration of the feasibility of using APLs.

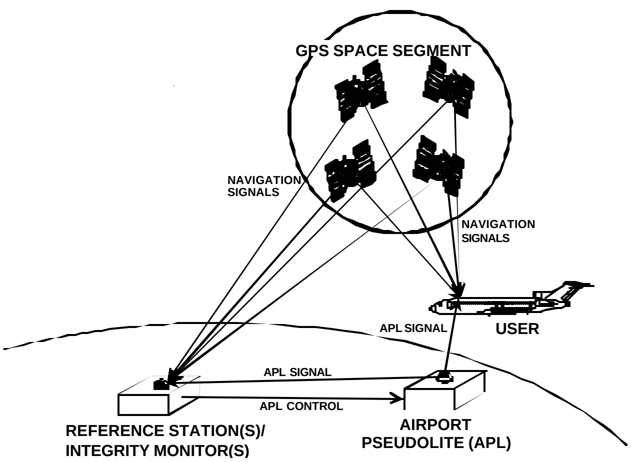

Figure 1. APL Augmentation Concept

The fact that APLs can significantly improve availability and eliminate long outage periods is not new. These facts have been known since the late 1980s [5, 6]. Since these facts have been established, it is not the purpose of this paper to present these availability and geometric considerations, but to further explore the feasibility of using APLs from a signal and receiver design point of view.

DESIGN CONSIDERATIONS

The following are assumptions and operational requirements for APLs that have been established by RTCA: 1) all APLs are on airport property, 2) APL coverage extends to a radius of at least 10 nautical miles, with a goal of 20 nautical miles, including throughout roll-out, 3) up to 4 APLs per airport must be accommodated, 4) the APLs do not broadcast differential corrections, but may broadcast a nominal set of useful data, 5) the APL signals must be positively monitored by the ground reference stations, and 6) both APL code and carrier measurements must be accurately received by a top mounted aircraft antenna [7].

Minimum performance criteria for a viable pseudolite signal structure are also being established. Of these criteria, primary concerns are signal code and carrier accuracy (including multipath), interference to GPS satellite signals (and other APL signals), the impact on receiver design and APL siting constraints. Interference concerns are not only for the participating receiver (one that is using the APLs), but for non-participating receivers as well, including those also on precision approach as well as any other receiver within line-of-sight of the APL.

BACKGROUND

The Near-Far Problem

The GPS satellites are far away. Because of that, and because their antenna broadcast beam is shaped, the received GPS signal power varies only slightly over the earth coverage (above 5° elevation angle. However, because the APLs are near-by, the APL received power varies with 20 $\log_{10}R$, where R is the range between the APL and the user's receiving antenna. Thus, if the average APL received signal power is made to match that of the satellite at one range, it will dominate at another range while being too weak at yet another. The effect of this is that, unless carefully designed, the APL signal will act as a strong jammer to the satellite signals at short range and the APL signal will be too weak to be useful at long range.

To solve this near-far problem, the APL signal structure must be modified with respect to the GPS signal structure to minimize the interference to the GPS signals. Furthermore, if codes from the GPS C/A-code family are used, the modification must also include provisions to minimize cross-correlation with the GPS C/A-codes. With these modifications, a GPS receiver must be able to acquire and track the signal with minimum impact on receiver design.

Potential Near-Far Problem Solutions

In order to solve the near-far problem, three signal diversity options provide partial solutions – frequency offsets, different PN codes and/or signal pulsing. The use of all three options is possible.

Frequency Offsets Frequency offsets can either be in-band or out-of-band. In-band offsets have the advantage that the same receiver front-end can be used, which minimizes inter-frequency biases when comparing APL measurements to satellite measurements. Placing the APL signal is a satellite signal spectral null is best for minimizing cross-correlation between PN codes. Out-of-band frequency offsets would usually require a different receiver front-end, which increases receiver cost and can create an inter-frequency bias problem. However, this solution could eliminate APL interference to GPS entirely.

Different PN Codes Using different PN codes in the GPS family of codes would minimize the impact on receiver design. There are about 700 usable codes in the GPS C/A-code family. There are also many usable wideband codes compatible with the GPS P-codes. Using a different code family should be avoided to minimize GPS receiver design modifications. Longer codes or ones with higher chipping rates are desirable. However, the near-far problem cannot be solved using different PN codes alone. There is not enough dynamic range separation between codes.

Signal Pulsing Signal pulsing is the most effective interference solution, using low-duty cycle, high-energy pulses. This is because GPS receivers are naturally robust against low-duty cycle pulsed interference. The APL signal only interferes when a pulse is present. The down side of low-duty cycle pulses is that APL signal reception is degraded by the square of the duty cycle, which dictates the necessary APL peak power required for the desired radius of operation.

Combination of Techniques For using the C/A-code, all three techniques are required unless a large frequency offset (out-of-band) is used to eliminate the need for pulsing. Offsets to near the GLONASS frequency band were suggested, but later rejected by the APL Subgroup because of inter-frequency bias problems. If a long wideband code is used, no frequency offset is required, but pulsing is still required to minimize interference to the GPS signals and other APL signals.

Limitations of C/A-Code Signal Structures

In the past few years, extensive analysis, development and testing has been performed using in-band pulsed C/A-code APLs [8, 9, 10]. In order to solve problems of interference and cross-correlation, these signals have been offset from the GPS L1 frequency to minimize interference. Pulsing at low duty cycles is a necessity no matter what signal structure is chosen, unless larger frequency offsets are used [11]. However, because of the autocorrelation properties of the C/A code, very low-duty cycles are not possible. The pulses must cover most of the code sequence during a reasonable receiver processing time interval. This becomes a problem when the number of APLs is increased. Thus, either the frequency offset had to be increased dramatically (such as near the GLONASS frequency band), or an alternative to the C/A code had to be considered. As stated earlier, the former is not desirable for a number of reasons. This leads to the proposed use of time-separated wideband codes, which have much better accuracy and correlation properties than do the C/A codes.

Advantages of a Wideband Code Signal Structure

The reduced duty cycle is only one of the advantages of using to a wideband (and longer) code for the APLs. Other advantages include better accuracy, both due to noise and multipath, lower susceptibility to CW interference, less cross-correlation with satellite codes, (which allows operation right at the L1 frequency), causing less interference to C/A-code receivers and possible compatibility with DoD receivers. These advantages will be discussed further. Of course, the major disadvantage is compatibility with C/A-code GPS receivers. However, a poll of receiver manufacturers interested in Category II and III approach and landing applications revealed that they had no problems with using the wideband code provided that it was compatible with the GPS P-codes.

Better Accuracy Pseudorange measurement noise accuracy is directly proportional to chip width of the PN code, which is inversely proportional to the chipping rate. Thus, the wider bandwidth code will provide better accuracy, everything else being equal. It is true that the C/A-code narrow correlator technologies has provided better noise accuracy as well if the signal (not code) has the bandwidth to support it [12]. However, that accuracy is only proportional to the square-root of the correlator spacing, which, in turn, is inversely proportional to the signal bandwidth. Thus, a factor of the square-root of the bandwidth is gained using the wideband code with respect to the C/A-code with the same signal bandwidth.

Depending upon the source of multipath, the pseudorange measurement accuracy in presence of multipath could improve significantly using the wideband code, especially in the case of long delays between the direct and multipath signals. This is illustrated in the multipath error envelopes of Figure 2 [12, 13]. This is important because, as shown in Figure 3, the high level APL signals can be reflecting from many surfaces around an airport, including paths to the user. Better long delay multipath performance eases the requirements for APL siting.

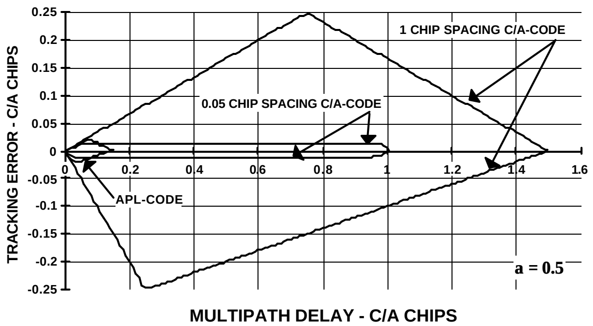

Figure 2. Multipath Error Envelope of Wideband APL-Code Compared to C/A-Code

Lower Susceptibility to CW Interference Because a long wideband code has a continuous power spectral density, it is much less susceptible to CW interference [13]. CW interference is truly spread over the code bandwidth, making it into a wideband noise source, whereas the CW interference may even correlate with a C/A-code spectral line and cause the receiver to either break lock or temporarily track the CW signal. Although additional processing gain of the wideband code against narrowband interference is truly significant, that significance doesn't have much meaning, since the GPS signals at the same L1 frequency would be jammed.

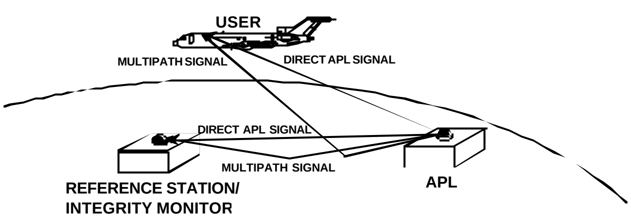

Figure 3. APL Multipath Scenarios

Lower Cross-Correlation Levels The C/A-codes only provide 22 to 24 dB cross-correlation separation, unless offset in frequency. The proposed wideband code is a much more random code, making cross-correlation satellite codes highly unlikely. This allows the use of APLs on the L1 frequency, which, in turn, simplifies receiver design. This capability also allows the use of a lower pulse duty cycle, which causes less of the code to be transmitted.

Less Interference to C/A-Code Receivers Ninety percent of the proposed wideband code energy will be rejected by the C/A-code correlation process, providing an additional 10 dB of interference rejection when compared to a C/A-code APL. Although this benefit does not completely carry over to P-code receivers, it is shown later that the wideband code interference to the DoD's P-code receivers is quite acceptable for other reasons.

Compatibility with DoD GPS Receivers The proposed wideband code is a variation on the GPS P-code. Thus, it should be compatible with existing and future DoD GPS receivers. This is important, since DoD aircraft will also be using LAAS facilities for approach and landing.

THE PROPOSED APL SIGNAL SPECIFICATION

The proposed APL signal specification is described in the GNSS Based Precision Approach Local Area Augmentation System Signal-in-Space Interface Control Document (ICD) [14]. It specifies the APL signal characteristics (frequency, spurious transmission levels, modulation technique, carrier phase noise, bandwidth, short term frequency stability, polarization, pulse sequence and pulse repetition rate, peak user received signal levels, correlation loss and maximum code phase deviation), the APL-code definition, data content and format, signal timing and a tropospheric delay model.

Mostly, the APL signal specifications are similar to those for a GPS satellite (frequency at L1, etc.). The major differences are the polarization, signal pulsing, received signal levels, code definition and data content and format. These differences are described below.

Signal Polarization

The broadcast APL signal, if possible, will be vertically polarized to minimize the effects of multipath and to maximize reception power into top-mounted antennas [15]. The multipath advantage is because, theoretically, only the horizontal component of a signal reflects from an ideally reflective surface. The signal reception advantage is because the reception antenna is basically vertically polarized at negative elevation angles.

Signal Pulsing

A pseudorandom pulse sequence will be used to prevent the user receiver from locking on to the pulse pattern. This pseudorandom sequence will result in a random pulse repetition rate. The average pulse repetition rate will be sufficiently high so that the APL signal will appear to be continuous in the user's receiver post correlation signal processing, while appearing to be pulsed during wideband processing prior to correlation. The pulse sequence will be guaranteed to have at least one pulse every millisecond. For the required low duty cycle, a relatively high pulse repetition rate results in relatively narrow pulses (on the order of a few microseconds). The exact details of the pulse sequence are still to be determined. It will be defined so to be transparent to the user receivers. A suggested pulse sequencing scheme is provided later in this paper.

Received Signal Level

A user will receive the APL signal at negative elevation angles, except possibly at low altitude when closer to the APL where the received signal will be at a high power level. Because of this, using a top mounted antenna, a right-hand-circularly-polarized (RHCP) gain is essentially that of the vertical component, making it more efficient for the vertically polarized signal [15]. Thus, no loss is anticipated for polarization mismatch.

The received signal level at 20 NM is defined such that receiver tracking performance of the APL signal will be approximately the same as for the tracking of a nominal GPS wideband signal at -133 dBm, but through a budgeted antenna gain of -10 dB. The loss in C/N_0 due to pulsing (without receiver pulse gating) is approximately

$$\Delta C/N_{0,\text{pulsing}} = 20\log_{10} PDC \qquad 1)$$

so that the desired peak vertically polarized signal power at the user's antenna at 20 NM is

$$P_{APL,\text{received},20} = -123 - 20\log_{10} PDC \text{ dBm} \qquad 2)$$

Thus, for a 2% duty cycle, the peak received power into the user's antenna should be -89 dBm at 20 NM. For other distances, the peak power will increase with $20\log_{10}(20/R)$ for range R in NM. Thus, the peak power into the antenna at 0.2 NM is -49 dBm. For the 4% duty cycle, the peak power requirement would be reduced by 6 dB.

The required APL radiated power is then

$$EIRP_{APL} = P_{APL,received,20} - 20\log_{10}\left(\frac{\lambda}{4\pi\times 20}\right) \qquad 3)$$

where λ is the signal wavelength in NM (1.0275×10^{-4}). The peak $EIRP_{APL}$ for a 2% duty cycle would be 38.75 dBm (7.5 watts), for an average eirp of 21.75 dBm (150 milliwatts).

The APL-Code Generator

A block diagram of the proposed APL-code generator is provided in Figure 4. It is comprised of 4-12-bit short-cycled shift registers, whose outputs are combined to generate a code that is approximately 38 weeks long when clocked at a rate of 10.23 MHz. The code is itself short-cycled at exactly one week in length. One of the shift registers (S1A) is illustrated in Figure 5. Details of the other shift registers and timing details are provided in the ICD [14].

Each APL-code is the same one-week long code, but delayed in Time-of-Week (TOW) increments of one minute. This allows for the definition of 10079 one-week codes using a single code generator (in addition to the one-week code with no delay, which is not used). That is, APL 1 has a one-week code delayed one minute, APL 2 has the same one-week code delayed two minutes, etc. Using these time delayed codes does not require hardware modifications to existing GPS P-code receivers, provided that they can be initialized at any TOW. Of the 10079 codes available, only 72 are assigned to APLs (Delays 139 through 210, consistent with PRNs defined in the SBAS signal specification [16]). An APL identification takes on one of the values between 139 through 210, which is provided in the APL Acquisition Message broadcast by the LAAS data link [14].

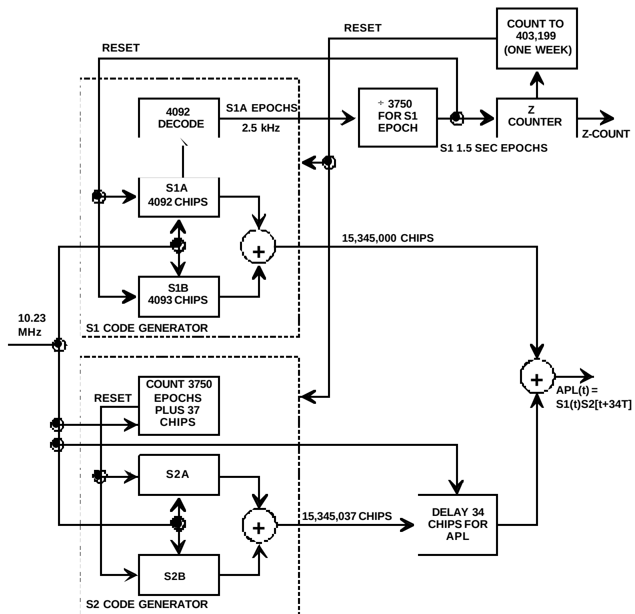

Figure 4. APL Coder Block Diagram

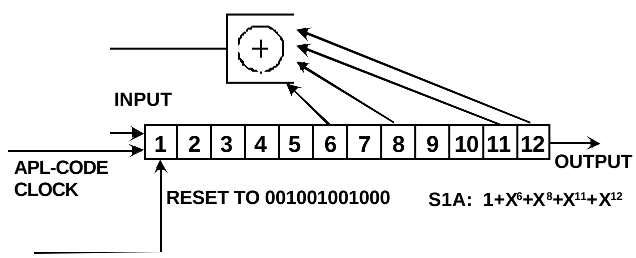

Figure 5. One of Four APL Coder Shift Registers

Data Modulation

Bi-phase modulation will be used for the code and the data. Message data at a rate of 50 bits per second (bps) will be added modulo-2 to the APL-code, which will then be bi-phase shift-keyed (BPSK) modulated onto the carrier. Code/data coherence will be maintained as described in [17]. The 50 bps data will be synchronized with the 1.5 second APL-code S1 epochs.

The block format and definition for the 50 bits per second data rate will be fixed for a given APL as shown in Figure 6. The single data block is 25 bits long and is repeated every 0.5 seconds. The block starts with a 14 bit integer word defining the code delay (1 - 10079), followed by 11 - "1s". These "1s" provide for full-integer carrier phase cycle ambiguity resolution and an unambiguous code delay. Only 72 code delays in the range of 139 to 210 will be used for APLs. The 14-bit code delay starts at bit 0 of the 25-bit message, of which every third one is lined up with APL-code S1 epoch.

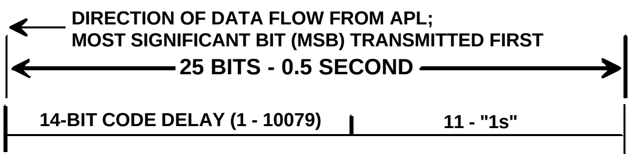

Figure 6. APL 0.5-Second Fixed Data Message

INTERFERENCE PERFORMANCE ANALYSIS

The most critical performance issue with respect to APLs is their potential interference to GPS signals. Here, this interference is analyzed.

Receiver Processing Model

To do that analysis, a model of the GPS receiver processing must be assumed. Figure 7 presents a model of the signal processing of current day digital GPS receivers. There are 4 key points in that processing: 1) precorrelation sampling, 2) correlator spreading, filtering or correlation, 3) post-correlation accumulation, and 4) acquisition and tracking processing. As far as processing of the pulsed signal is concerned, it is key that the pulses are transparent in the acquisition and tracking process, and the APL signal appears to be a continuous signal.

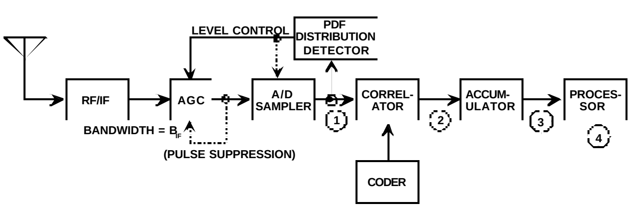

Figure 7. Receiver Processing Model

Precorrelation Sampling Depending upon how the Automatic Gain Control (AGC) is mechanized, the precorrelation analog-to-digital (A/D) sampling process "clips" the APL signal pulses when they dominate the background noise in the front-end of the receiver. Pulse suppression, usually implemented in DoD receiver, could prevent this using a very fast AGC loop that detects and suppresses the pulses. However, most commercial receivers use a relative slow AGC that doesn't necessarily respond to the low-duty cycle pulses, and the clipping occurs. Some lower cost receivers use 1-bit samplers (hard-limiting) with no AGC. Of course, in this case, clipping always occurs. With respect to the pulses, clipping is good. It limits the amount of pulse power entering into the correlator. However, 1-bit clipping of the background noise results in at least 2 dB of GPS signal-to-noise ratio loss. Pulse suppression is the best of both worlds, but requires much more AGC dynamic range. If either 1-bit sampling or pulse suppression limits the energy of the APL pulses to the noise floor level, there is still enough pulse energy entering the correlator to acquire and track the APL signal, unless the duty cycle is extremely low.

At some point on the approach, the pulses will likely be strong enough to saturate the front-end of the receiver. In an ideal world, this will not matter if the effect is the same as clipping. However, pulse stretching, signal distortion, etc. could cause problems. The receiver front-end should be designed to prevent these problems.

Correlation Depending upon which reference code is applied to the correlator, the pulses will be processed differently.

Pulse Correlation In the APL tracking channel, the code is identical to that in the pulse, while the pulse is present, and full correlation over the period of the pulse will occur. In between the pulses, the code will either spread interference of filter wideband noise. The output of the correlator will have a bandwidth equal to the noise bandwidth of the reference code. At this point, if the pulse timing were known, this period in-between the pulses could be blanked out (zeroed), for a significant improvement in APL signal-to-noise density. However, as a minimum, this is not required for the LAAS receivers, since it would require the implementation of the pulse generation in the receiver.

Spreading and Filtering In a satellite tracking channel, the wideband pulse is filtered by the correlation process using the satellite code. If the satellite code is a C/A-code, 90% of the pulse power is rejected in the correlation process. If the satellite code is a P-code, approximately a 3rd of the power is rejected. In-band interference is spread over the wideband APL-code bandwidth.

At this point, if the pulse timing were known, the pulse period could be blanked out (zeroed), for an improvement in GPS signal-to-noise density, since the pulse power would not enter the post-correlation accumulation. However, again, this is not required for the LAAS receivers, since it would require the implementation of the pulse generation in the receiver.

Post-Correlation Accumulation After the correlator, samples are accumulated over a time interval ranging from a millisecond to up to 20 milliseconds. This accumulation has the effect of "averaging" the pulse energy over the entire accumulation interval. Additional post detection filtering in the Processor will add to that effect. If the pulse density is high enough and the pulse pattern is uniform enough, the pulses become transparent in this process, and the APL signal will appear to be continuous, whether it is being tracked or being spread or filtered.

APL Signal Processing

Using the receiver signal processing model described above, equations were derived to determine the equivalent received APL signal-to-noise density and the degradation of GPS satellite signal-to-noise density. These equations are presented here.

APL Received Signal-to-Noise Density When the APL signal is not saturating the receiver's A/D converter, the equivalent signal-to-noise density is

$$\frac{S_{APL}}{N_0} = \frac{S_{APL,peak}}{N_{0T}} \left(PDC \right)^2 \qquad 4)$$

if there is no blanking of the periods between the pulses. The square would be removed if there were blanking because the noise during that period would be removed. Once the A/D converter is saturated, only the clipped pulses get through to the correlator and the equivalent signal-to-noise density becomes

$$\frac{S_{APL}}{N_0} = \frac{R^2_{\max,N} B_{IF} PG_{APL,APL} \left(PDC \right)^2}{1 - PDC} \qquad 5)$$

where $R_{max,N}$ is the ratio of the maximum A/D level to the RMS noise power in A/D level units, B_{IF} is the precorrelation noise bandwidth and $PG_{APL,APL}$ is a processing gain adjustment of the signal tracking correlator with respect to the PL signal. In this case, the adjustment could be due to correlation loss due to band-limiting, etc., or an adjustment in the noise level due to correlator filtering of wideband noise. The 1 - *PDC* in the denominator is due to the fact that the noise is suppressed when the strong pulse is present. Equations 4 and 5 are combined to provide the results of Figures 8 and 9 for duty cycles of 2% and 4%, respectively, as a function of distance from the APL. The results are shown for three different receiver configurations – a DoD P-code receiver, a 2.5-bit wideband (16 MHz) receiver and a 1-bit wideband receiver. Note that saturation starts to occur at 13 - 16 NM for the 2% case and 6 - 8 NM for the 4% case, in order to provide an adequate signal-to-noise density at 20 NM.

Loss in GPS Signal-to-Noise Density When the APL signal is saturating the receiver's A/D converter, the loss in GPS signal-to-noise density is

$$\frac{\Delta S}{N_0} = \frac{\left(1 - \sum_{i=1}^{N_{APL}} PDC_i \right)}{1 + \dfrac{R^2_{\max,N} B_{IF}}{1 - \sum_{i=1}^{N_{APL}} PDC_i} \sum_{i=1}^{N_{APL}} \dfrac{T_{c,\min,i}}{PG_{s,APL,i}} PDC_i} \qquad 6)$$

where N_{APL} is the number of APL signals saturating the A/D converter, $T_{c,\min,i}$ is the inverse of the maximum APL or tracked GPS signal code chipping rate (representing either C/A-code filtering of the APL wideband signal or the P-code spreading of an APL C/A-code signal), and $PG_{s,APL,i}$ is the processing gain of the signal tracking correlator on the APL signal. For example, if the signal tracked is a P-code and the APL signal is a wideband signal, the processing gain is 1.5, representing correlator filtering of a code-modulated signal or noise with the same spectral density, resulting from integrating the sinc^4 function. If the APL signal were a C/A-code signal centered in the first null of the GPS C/A-code signal, the processing gain would be about 6.31. If pulse blanking is implemented, the denominator of Equation 6 becomes identically 1, since the pulses would no longer add noise to the correlation process. This equation has been validated for the C/A-code cases against test results reported on in [8].

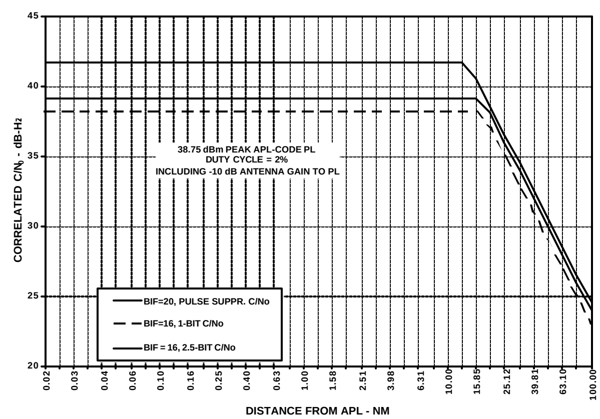

Figure 8. Received C/N_0 for APL With 2% Duty Cycle

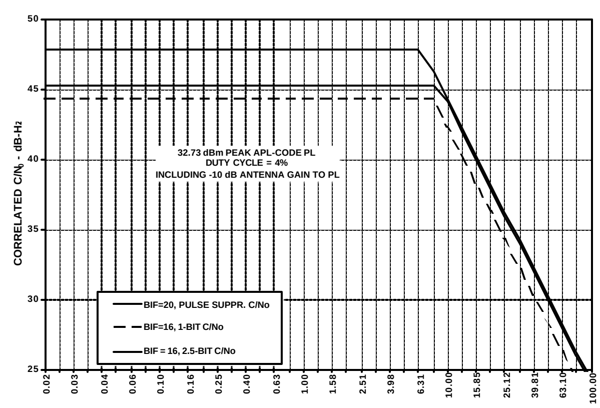

Figure 9. Received C/N_0 for APL With 4% Duty Cycle

Figures 10 and 11 present the results of applying Equation 6 for GPS signals in the presence of 4 saturating wideband APL-code signals. The results for one or two APLs would be approximately ¼ or ½ of that shown, respectively. Note that the higher performance multi-bit C/A receiver is affected more than the others, primarily because more of the pulses get through to the correlator. However, that multi-bit implementation has at least 2 dB better performance in absence of the APL signals, so their interference performances are essentially equal. Sampling losses are not accounted for in these plots.

PULSING PATTERN CONSIDERATIONS

When testing with C/A-code APLs with a somewhat uniform pulse pattern [8], it was discovered and verified by analysis that the pattern created spectral lines about 700 Hz apart [9, 10]. During wideband acquisition of the signal, the receiver locked up to the 700 Hz line. Although a receiver should never have to do a wideband acquisition of an APL, this could lead to hazardous misleading information (HMI). Thus, it would be better to generate a pseudorandom pulse pattern with "smeared" spectral lines.

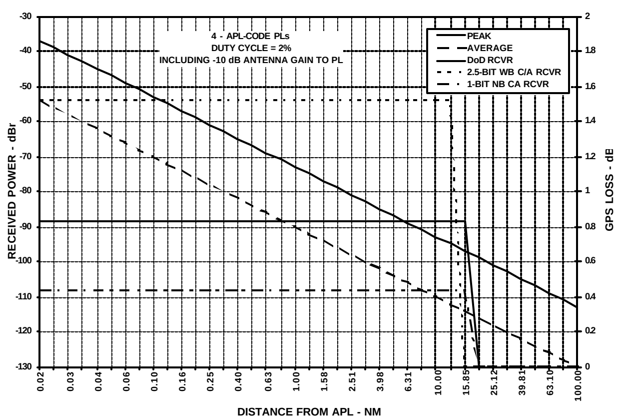

Figure 10. Interference from Four APLs to GPS Using 2% Duty Cycle

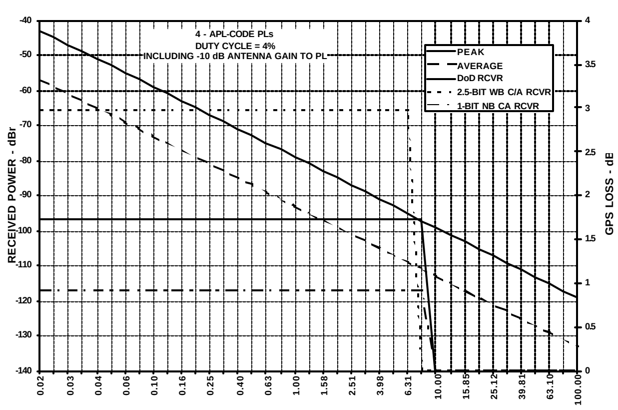

Figure 11. Interference from Four APLs to GPS Using 4% Duty Cycle

Pulse Collisions from Multiple APLs

It is also possible for pulses from multiple APLs to "collide" when received by the user, causing APL to APL interference, or even total blanking. This is illustrated in Figure 12 for two APLs. It is important to control the relative pulse timing between APLs such that

$$T_1 + d_1/c \neq T_2 + d_2/c \ \forall \ d_1, d_2 \qquad 7)$$

in range of APLs. This is accomplished rather easily by staggering the timing of the APLs provided that the pulsing scheme allows that. However, a pseudo random pulse pattern may not allow it entirely, but a few collisions would be acceptable if the resulting signal loss is minor. Results of collisions for an example pulse pattern are described below.

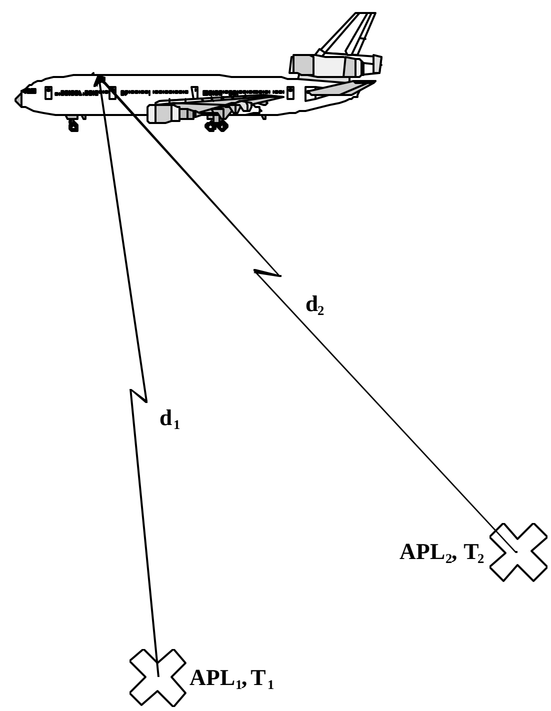

Figure 12. Pulse Collision Possibilities Using Multiple APLs

An Example Pseudorandom Pulse Pattern

The details of a pulsing pattern have not yet been established by the RTCA SC159 Working Group 4a APL Subgroup [14]. However, an example pseudorandom pulse clock generation process has been developed using a maximum length shift register as illustrated in Figure 13. This mechanism is based upon the fact that such a shift register generates "runs" of 1s or 0s with known probabilities. For example, there are exactly

$$N_p = 2^{n-(p+2)} \quad 8)$$

runs of p 1s or 0s from a maximal length shift register with n stages [18]. For the mechanism shown in Figure 13, there are 2^{13} = 8192 runs of exactly five 1s. If the register is clocked at a rate of 1.023 MHz, the sequence length would be approximately 1.025 seconds. For better timing, it could be reset every second, in which case there would be 7981 runs of exactly five 1s in 1 second. If an APL pulse were generated with each of those events, there would be 7981 pulses per second with a mean time between pulses of 125.27 μseconds, and with a standard deviation of 118.23 μseconds. The maximum time between pulses would be 991.2 μseconds, and the minimum time is 5.85 μseconds, ensuring that there would be at least one pulse per millisecond. (Pulses could be arbitrarily added to ensure another maximum time between pulses.) The distribution of pulses is shown in Figure 14. Using pulse-widths of 2.44 or 4.88 μseconds (25 or 50 APL-code chips) would produce *PDC*s of approximately 2% and 4%, respectively. These narrow pulses could be a problem for pulsing power amplifiers, so some adjustments to this approach may have to be made.

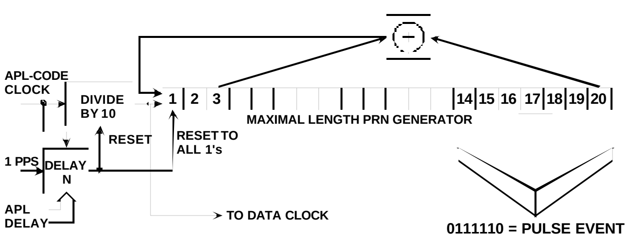

Figure 13. Example APL Pulse Clock Generator

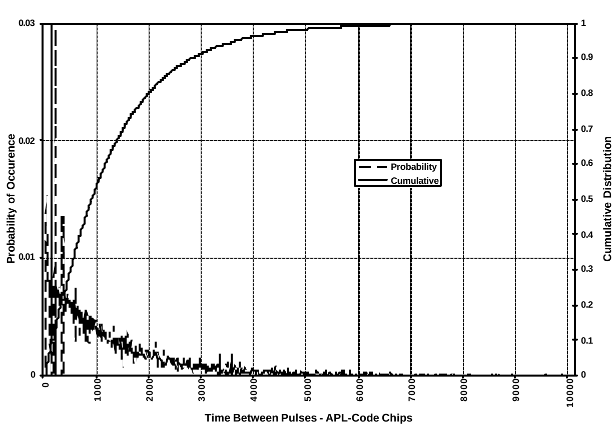

Figure 14. Pulse Time Distribution for Example Pulse Clock Generator

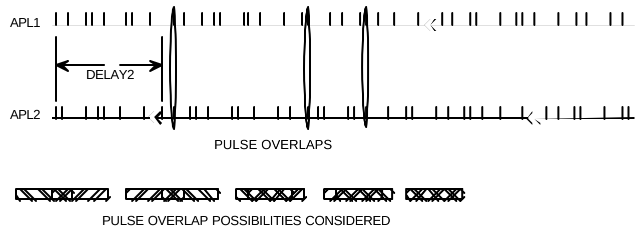

Figure 15. Multiple APL Pulse Overlap Example

Pulse collisions can occur with this pulse pattern mechanism. Note that in Figure 13, there is a delay selection applied to the reset of the shift register. The effect of such a delay for multiple APLs is illustrated in Figure 15, resulting in some overlap of pulses. If this delay is selected to be a multiple of 3720 APL-code chips (equivalent to multiples of 109 km in distance) the average pulse overlap would only be 155 pulses (of 7981), including partial overlaps. This amounts to a signal loss of only 0.085 dB per APL for a 2% duty cycle. This is quite acceptable.

OTHER APL RANGING ISSUES

There are two APL ranging issues that are still in the process of being resolved – the effect of using a top-mounted antenna on the aircraft, and the effects of receiver front-end saturation. More testing is required to resolve these issues.

There has been flight testing performed using top-mounted antennas. In fact, most testing used top-mounted testing. However, testing to-date has been limited to smaller aircraft, for which no ranging errors have been apparent or have been allocated to the top-mounted problem. Future testing is planned using wide-body air-transports.

The effects of receiver front-end saturation are still unknown, although there have been group delay variations observed on some testing. More testing is planned to evaluate these effects as well. If these effects prove to be a problem, some front-end redesign may be in order.

SUMMARY

Unless there are launches of a significant number of navigation satellites in addition to the nominal 24 GPS satellites, ground augmentation in the form of Airport Pseudolites (APLs) is required to provide the necessary availability and continuity of accuracy and integrity for Category II and Category III Precision Approach and Landing of aircraft. APLs are included in the FAA's recommended LAAS architecture (LARC). In this paper, an APL signal structure is recommended based upon considerations and requirements derived by RTCA SC159 WG4a. The basic recommendation is to use pulsed wideband PN-code signals centered at the GPS L1 frequency. This structure provides the best performance/receiver implementation tradeoff of all implementations considered. Performance analysis is described, especially relating to the APL interference to GPS signals, showing that, although there will be interference, up to 4 APLs can be accommodated at any given airport.

The RTCA recommendations are not complete. Pulsing pattern mechanization must still be fine-tuned. An example mechanization has been presented.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the inputs of RTCA SC159 Working Group 4a participants for the development of the APL Signal Specification and critiques of the various concepts presented in this paper.

REFERENCES

1) R. Swider and B. DeCleene, "Recommended LAAS Architecture," Presented to RTCA SC-159, WG-4, Anaheim, CA, November 12, 1996.

2) C. Shively and T. Hsiao, "Impact of Pseudolite Performance on Availability of LAAS," Briefing presented to APL Subgroup, RTCA SC159 Working Group 4a, Sunnyvale, CA, May 12, 1997.

3) C. Shively and T. Hsiao, "Impact of Pseudolites on LAAS Outage Characteristics," Briefing presented to APL Subgroup, RTCA SC159 Working Group 4a, Washington, DC, July 14, 1997.

4) B. DeCleene, "LAAS Requirements, Part II," Briefing presented to RTCA SC159 Working Group 4a, Lynnwood WA, August 19, 1997.

5) B. W. Parkinson and K. T. Fitzgibbon, "Optimal Locations of Pseudolites for Differential GPS," Navigation: The Journal of the Institute of Navigation, Vol. 33, No. 4, Winter 1986 - 87, pp. 259 - 283.

6) L. Schuchman, B. D. Elrod and A. J. Van Dierendonck, "Applicability of an Augmented GPS for Navigation in the National Airspace System," Proceedings of the IEEE, Vol. 77, No. 11, November 1989, pp. 1709 - 1727.

7) T. Murphy and R. Hartman, "Core Assumptions and Assumed Minimum Performance Requirements with respect to Pseudolite Signal Structure Design," distributed to APL Subgroup, RTCA SC159 Working Group 4a, January 27, 1997.

8) B. Elrod, K. Barltrop and A. J. Van Dierendonck, "Testing of GPS Augmented with Pseudolites for Precision Approach Applications," *Proceedings of ION GPS-94, 7th International Technical Meeting of The Satellite Division of the Institute of Navigation*, Salt Lake City, UT, September 20 - 23, 1994, pp. 1269 - 1278.

9) B. Elrod, K. Barltrop, J. Stafford, and D. Brown. "Test Results of Local Area Augmentation With an In-Band Pseudolite," *Proceedings of the National Technical Meeting of the Institute of Navigation*, Santa Monica, CA, January 22 - 24, 1996, pp. 145 - 154.

10) K. J. Barltrop, J. F. Stafford, and B. D. Elrod. "Local DGPS with Pseudolite Augmentation and Implementation Considerations in LAAS," *Proceedings of ION GPS-96, Ninth International Technical Meeting of the Satellite Division of the Institute of Navigation*, Kansas City, MO, September 17 - 20, 1996, pp. 449 - 459.

11) C. Bartone and F. van Graas, "Airport Pseudolite Subsystem for the Local Area Augmentation System," *Proceedings of ION GPS '97, Tenth International Technical Meeting of the Satellite Division of the Institute of Navigation*, Kansas City, MO, September 16 - 19, 1997.

12) A. J. Van Dierendonck, P. Fenton and T. Ford, "Theory and Performance of Narrow Correlator Spacing in a GPS Receiver," Navigation: The Journal of the Institute of Navigation, Vol. 39, No. 3, Fall 1992, pp. 265 - 283.

13) B. W. Parkinson and J. J. Spilker, Jr., Global Positioning System: Theory and Applications, Volume I, Chapter 8 and Chapter 14, American Institute of Aeronautics and Astronautics, Inc., Washington, DC, 1996.

14) GNSS Based Precision Approach Local Area Augmentation System Signal-in-Space Interface Control Document (ICD), Draft 1, RTCA SC159 Working Group 4a, August 28, 1997.

15) C. Bartone, "Advanced Pseudolite for Dual-Use Precision Approach Applications," *Proceedings of ION GPS-96, Ninth International Technical Meeting of the Satellite Division of the Institute of Navigation*, Kansas City, MO, September 17 - 20, 1996, pp. 95 - 105.

16) Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, Change No. 1 to RTCA/DO-

229, RTCA, Incorporated Paper No. 206-97/TMC-284, July 15, 1997.

17) Global Positioning System Standard Positioning Service Signal Specification, U. S. Department of Defense, Washington, DC, June 2, 1995.

18) R. C. Dixon, Spread Spectrum Systems, Second Edition, John Wiley & Sons, New York, 1984.