TECHNIQUES FOR IMPROVED RECEPTION OF 1090 MHZ ADS-B SIGNALS *

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Background

The recent development of ADS-B (Automatic Dependent Surveillance-Broadcast) is based on the use of the Mode S transponders now carried by all air carrier and commuter aircraft. ADS-B aircraft broadcast aircraft positions, identity, and other information via semi-random Mode S transponder squitters. Other aircraft or ground facilities receive the squitters and the associated position and status.

Squitter reception includes the detection of the Mode S 1090 MHz waveform preamble, declaration of the bit and confidence values, error detection, and (if necessary) error correction. The current techniques for squitter reception are based upon methods developed for use in Mode S narrow-beam interrogators and for ACAS. In both of these applications, the rate of Mode A/C fruit that is stronger than the Mode S waveform is relatively low, nominally less than 4,000 fruit per second.

Extended squitter applications now include long range (up to 100 nmi) air-air surveillance in support of free flight. This type of surveillance is sometimes referred to as Cockpit Display of Traffic Information (CDTI). In high density environments, it is possible to operate with fruit rates of 40,000 fruit per second and higher. Operation of extended squitter in very high Mode A/C fruit environments has led to the need to re-evaluate squitter reception techniques to determine if improved performance is achievable.

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The purpose of this paper is to provide a summary of work in progress to investigate improved squitter reception techniques. Elements of improved squitter reception being investigated include (1) the use of amplitude to improve bit and confidence declaration accuracy, (2) more capable error correction algorithms, and (3) more selective preamble detection approaches.

Current Squitter Reception Techniques

Extended squitter uses the 112-bit Mode S waveform shown in Figure 1. This waveform encodes data using pulse position modulation (PPM). A chip in the leading half of the bit position represents a binary ONE. A chip in the trailing half bit position represents a binary ZERO. Reception of the reply begins with the detection of the four-pulse preamble. At preamble detection, a dynamic minimum triggering level (DMTL) is set 6 dB below the level of the preamble. Any signal received below this DMTL will not be seen by the reply processor. This eliminates the effect of low level Mode A/C and Mode S fruit on the reception process.

Once all of the bits have been received, error detection is performed using the 24-bit CRC contained in the reply. If no error is detected, the reply is passed on to surveillance processing. If an error is detected (indicated by a non-zero error syndrome), an error correction technique is applied. The current error correction algorithm can correct the errors caused by one stronger overlapping Mode A/C reply.

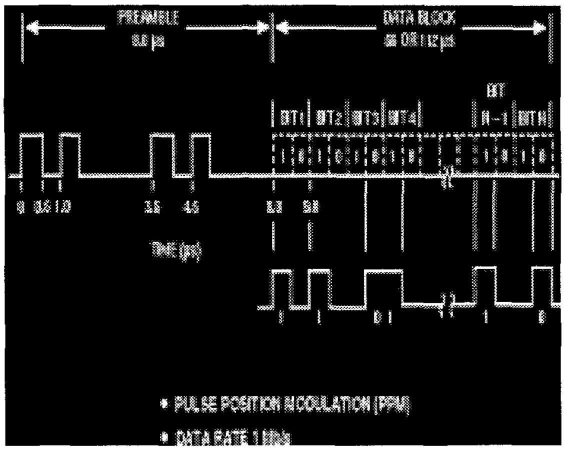

Figure 1. Mode S Reply Waveform.

Bit values are declared by comparing the amplitudes of the centers of the two chips; the chip with the greater amplitude is declared the bit value. This amplitude comparison technique limits bit errors caused by fruit of lower level than the squitter being received.

Confidence in the bit declaration is declared by observing if signals are above threshold in both chips. If only one chip is above threshold, it is declared to be high confidence since there is no evidence of overlapping fruit. If both chips have amplitude above threshold, low confidence is declared since some form of interference had to be present to cause this condition.

When a Mode A/C reply interferes with a Mode S reply, some of the Mode S bits may be declared in error. The Mode S error correction algorithm attempts to correct these errors by locating a string of 24 consecutive bits such that the low confidence bits in the window cover the bits in the corresponding error syndrome. If such a window is found, all low confidence bits matching the syndrome are flipped, and the reply is declared correct.

Use of Amplitude in Bit Declaration

The current technique of declaring a bit based upon the higher of the two chips will generate bit errors in cases of higher level overlapping ATCRBS fruit. The use of amplitude to correlate the received pulse with the preamble pulse level will improve bit declaration accuracy. Two techniques have been investigated. One is a very simple approach that uses only the amplitude measured at the center of each chip. The second is a somewhat more complex approach that takes advantage of four amplitude samples per chip. Note that current implementations already used such sampling to establish bit confidence. Each of these techniques is described in the following paragraphs.

An improvement in the declaration of Mode S data bits can be achieved if the actual amplitudes of the center samples of the '1' and '0' chips can be measured for each data position, rather than just a comparison of which chip sample is greater. All Mode S pulses, including those of the preamble, have approximately the same level (within 1 or 2 dB). Thus if the preamble level is measured, the expected level of each data pulse will be known. Then if both center samples of a data position are above threshold, but only one is within a 3 dB band centered at the preamble level, it would be reasonable to assume that the corresponding chip is the correct Mode S pulse location.

Figure 2 illustrates the new data and confidence declaration algorithms that result when the actual sample amplitudes can be measured, and both samples are above threshold. A bit is high confidence when 1 and only 1 of the two samples correlate with the preamble level. The correlating sample, rather than the larger sample, is declared to be the true data value. If both samples, or neither sample, correlates with the preamble, a low confidence bit is declared. In this case, the larger sample is selected as the bit value, as in the current technique.

With the center amplitude technique, a low confidence bit is declared only when the ATCRBS reply is within 3 dB of the Mode S reply. ATCRBS replies of either lower or higher power in general cause neither errors nor low confidence bits. Thus the region of concern

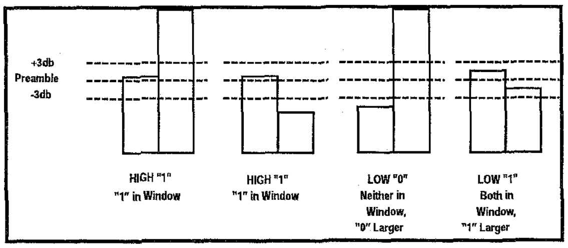

Figure 2. Center Amplitude Bit and Confidence Declaration.

for ATCRBS aircraft is reduced from all the aircraft at closer range to just those at approximately co-range. This is particularly significant when the system is attempting to listen to far-range Mode S aircraft.

The above amplitude data declaration approach can be improved if all 8 samples (4 per chip) that are taken for each Mode S bit position are utilized in the decision process. In particular, much more complex overlap situations can be resolved. For example, Figure 3 presents samples that might be observed when 2 ATCRBS interfering pulses are present, one in the '1' data chip and the other in the blank '0' data chip. The overlap of the Mode S pulse and the ATCRBS pulse, because of small frequency differences (nominal allowable range is 2 MHz), produce 4 different sample amplitudes, while the ATCRBS pulse by itself produces all samples at the same level. Even though the '0' center sample is the only center sample in the window, the full set of samples suggests that the correct data value is a '1'.

The algorithm developed for utilizing all 8 samples is a form of pattern matching. Each sample is defined with one of four values:

0: below threshold (-6 dB from preamble)
1: above threshold, but below the 3db preamble window
2: within the +/- 3db preamble window
3: above the 3db preamble window

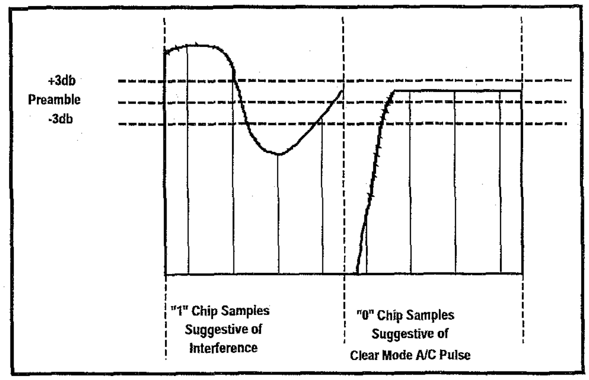

Figure 3. Multi-Amplitude Bit and Confidence Declaration Example. Only "0" Center Sample in Window, But High Confidence "1" Declared.

Since there are 8 samples, with 4 possible values each, a Mode S data position can have 4^8 = 65536 (64K) different sample patterns. Two 1-bit tables, each stored in a 64K x 1 ROM, are defined over the set of patterns: the first declaring the bit position to be a '1' or '0', the second high or low confidence. Once the pattern existing for a given bit is determined, two table lookups supply the proper declaration.

These tables are generated by running millions of simulations of Mode S replies in 40,000 fruit per second environments. For each bit of each trial, the pattern and the correct Mode S bit value are noted. A sample result could be, for example, 5876 examples of pattern 16453 were encountered, of which 5477 occurred when the Mode S bit was a '1'. The table values are then defined as follows, where the percents are sample occurrences when the bit was a '1':

H1: 90% or more
L1: 50% - 90%

LO: 10% - 50%

HO: 10% or fewer

The above 8 sample approach requires lookup tables of size 64K, adding significant cost to the hardware implementation of the decoder. A variation of this method that only requires tables of size 256, called the 4-4 approach, has been designed to reduce this expense.

The 4-4 method forms two estimates of the bit data and confidence values, one using the odd samples (1-3-5-7) and the other using the even samples (2-4-6-8); the final decision is then a combination of the individual estimates. Since each set includes samples in both chip positions, pattern matching is still possible, although the fineness of the pattern variation is cut in half. Since only 4 samples are in each set, and each sample is quantized to the same 4 levels as above, $4^4 = 256$ patterns are possible for each set.

To counteract the loss of resolution, and to aid in the combining operation, 3 levels of confidence (high, medium, and low) are defined for each pattern. Following the simulation generation scheme described above, the table values are defined as follows:

H1: 90% or more

M1: 70% - 90%

L1: 50% - 70%

L0: 30% - 50%

M0: 10% - 30%

H0: 10% or fewer

Once the values and confidences are determined for each set of samples, odd and even, the composite values actually declared for the bit are found according to the following table:

Odd (1357) \ Even (2468)	H1	M1	L1	H0	M0	L0
H1	H1	H1	H1	L0	H1*	H1
M1	H1	H1	L1	H0*	L0	L1
L1	H1	L1	L1	H0	L0	L0
H0	L0	H0*	H0	H0	H0	H0
M0	H1*	L0	L0	H0	H0	L0
L0	H1	L1	L0	H0	L0	L0

* alternative is Low confidence; correct decision under study

Brute Force Error Correction Technique

If the bit declaration algorithm has performed its function properly, all errors in Mode S data values will reside in bits declared low confidence. If this is true, a simple approach to error correction is to try all possible combination of low confidence bits, and accept the set that matches the error syndrome (provided only one success is discovered). For obvious reasons, this method has been named the Brute Force Technique. It is applicable to any method of data and confidence declaration, with or without amplitude, and is applied after the other error correction techniques have failed.

Clearly, for processing time and error bounding reasons, the maximum number of low confidence bits to process must be limited. The number of cases to consider is given by 2^n if n low confidence bits exist for a reply; this grows exponentially with n (32 at n=5, 4096 at n=12). The undetected error rate is proportional to the number of cases, and thus also grows exponentially with n. Fortunately, the Hamming distance of 6 for the Mode S parity code implies that undetected errors are essentially zero if n<=5 is enforced. For this reason, a value of n=5 has been used chosen.

Improved Preamble Detection Algorithm

When a heavy Mode A/C fruit environment exists, squitter preambles are often lost due to the existence of earlier apparent preambles produced by Mode A/C reply pulses. Since preamble detection can be suppressed for up to 130 microseconds after each preamble located, a Mode S squitter starting during the false preamble dead time will be lost.

The PPM encoding used in the Mode S downlink data block requires that there be a pulse in either the '0' or '1' chip of each data block position. This is a pattern that is difficult to generate with ATCRBS fruit replies. Ideally, the improved algorithm could attempt to find pulses in all 56 (or 112) data positions. However, ATCRBS fruit interference could make it difficult to accurately find all the pulses – simulation and experiment have shown that high fruit rate environments often destroy one or more data pulses in a Mode S downlink message. Trying to qualify all the data pulse positions would also entail quite a bit of processing time. A compromise is to check for the pulses in the first 5 bits of the data block – the Mode S downlink "data format" (DF) field.

Figure 4 illustrates the results of the improved preamble detection algorithm as a function of fruit rate. The current algorithm, at 40K fruit per second (the target CDTI case), finds only 57% of the squitter preambles. The suggested method, of using 9 pulse preamble detections, increases this to 93% of the squitter preambles.

Simulation

The acceptance rate for alternative reply declaration and error correction technique combinations is shown in Table 1 for the case of 40 K fruit per second uniformly distributed between -5 and +10 dB relative to the squitter. The rows correspond to the degree of amplitude information employed in bit declaration. The first column gives the performance with no error correction, the second column the performance for the current Mode S error correction technique, and the third column gives the performance with the addition of the Brute Force technique (limited to 5 low confidence bits).

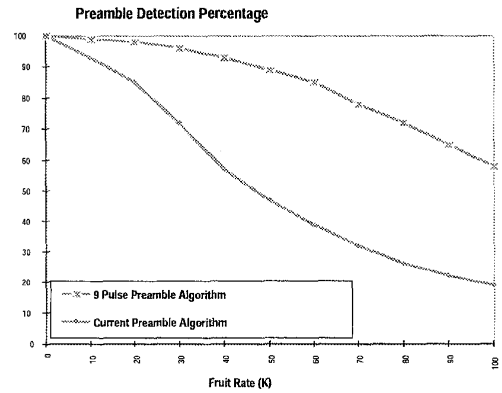

Figure 4. Preamble Detection Improvement with New Technique.

Table 1. Algorithm Performance Comparison

40K Fruit/Second (-5 dB To +10 dB)
Percent Acceptance Rate

	Error Correction Algorithm Employed		
Amplitude Information	**None**	**Conservative Mode S**	**+ Brute Force @5**
None (Current)	**3**	**8**	**18**
Center Sample	**13**	**23**	**36**
Multiple Samples	**40**	**52**	**63**

Measurements

The simulation work developing improved reception techniques is now being followed by a measurement program to validate the conclusions from the simulation. A 1090 MHz receiver is being used to receive signals that happen to exist at the time of the measurements, having been transmitted by aircraft flying in the area. The receiver has high sensitivity for receiving weak signals, which is appropriate for the final application of these techniques. Initially the receiver was used in a ground-based installation in the Boston area, and subsequently it has been installed on an aircraft for airborne reception, flying to the New York metropolitan area.

Plans are being made for flights to other areas, including the Los Angeles Basin.

The main objective of these measurements is to validate the simulation. Additional objectives include: (1) validate a proposal to reduce receiver bandwidth from 8 MHz (which is used by TCAS* receivers) to 4 MHz, and (2) assess possible limitations caused by man-made noise.

Configuration of Measurements

The configuration of the ground-based installation is illustrated in Figure 5. The receiving antenna, which is mounted on a tower, is a DME* antenna. This antenna provides omnidirectional reception in azimuth and some directivity in elevation, with maximum gain (7 dB) near the horizon.

The receiver was designed with the intention of having the maximum sensitivity that can be practically achieved in operational avionics. It uses a low-noise preamplifier, having a noise figure of 1.0 dB. The noise figure of the full receiver (including front end filter, limiter, cables, and all other effects) is 2.5 dB referred to the antenna port. This results in a system noise power of -105 dBm referred to the antenna port, when the system bandwidth (3 dB) is 4 MHz. For an aircraft installation, the same receiver is used without the long cable and its associated preamplifier. In this configuration, the system noise figure is also about 2.5 dB.

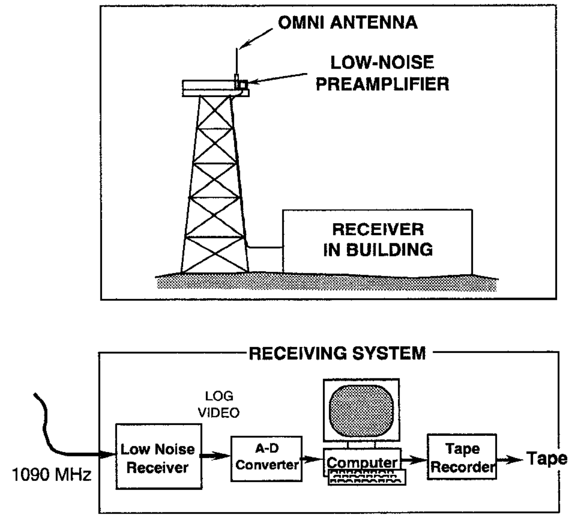

Figure 5. Receiver Ground Based Installation.

The receiver includes a mixer to convert to an intermediate frequency of 60 MHz, a bandpass filter, which can be changed to test different bandwidths (8 MHz and 4 MHz for example), and a log-video amplifier. The log-video signal is sampled at the rate 8 samples per μs and digitized by a 12 bit A/D converter. The receiving system was carefully calibrated in power level such that the recorded amplitudes can be associated with the absolute power levels received.

The nature of the data recorded by this system is shown in Figures 6 and 7. The data plotted in Figure 6 includes an ATCRBS reply, as marked. Note that this is a relatively weak reply, which would not have been detected by current 1090 MHz receivers. In TCAS, for example, the nominal receiver sensitivity is -74 dBm, whereas this reception is -88 dBm. Note also that the recording process samples everything, even the noise between pulses. Similarly a Mode S reply is shown in Figure 7.

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* Traffic Alert and Collision Avoidance System (TCAS) is an airborne system for avoiding mid-air collisions.

* Distance Measuring Equipment (DME) uses an omnidirectional antenna.

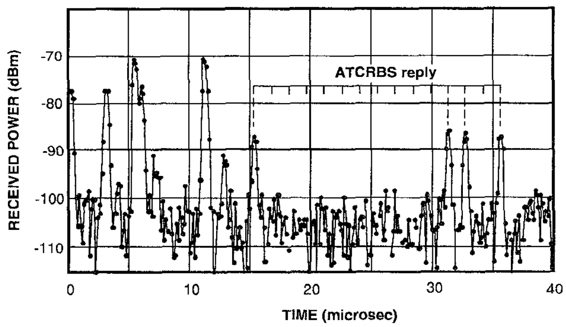

Figure 6. Received Waveform, an ATCRBS Reply.

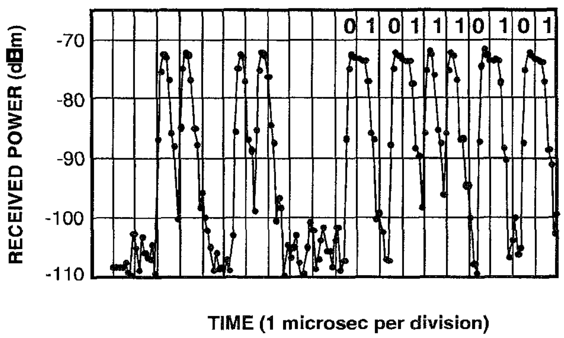

Figure 7. Received Waveform, Mode S Reply.

Measurement Results

While assessing reception performance, it is of interest to measure the fruit environment at this receiving station. Figure 8 gives the cumulative distribution of ATCRBS and Mode S fruit rates, as a function of received power level. Each point is the fruit rate for receptions at that power or stronger. The total fruit rate is seen to be 11,000 ATCRBS replies per second, which is a substantial rate. The results also indicate that the received power levels are primarily between -75 and -85 dBm. This appears to be a result of the range distribution of the aircraft in view.

Before making comparison between measured Mode S reception performance and that seen in simulation, it was necessary to modify the simulation in several ways. The original simulation runs were focused on reception of Extended Squitters, whereas these are not present in the measurement environment. Accordingly, the simulation was modified to focus on short squitters, which are received at a substantial rate in the measurements. Another change applies to bandwidth. Originally, the simulation was developed for a bandwidth of 8 MHz, which has previously been the standard for Mode A, C, and S reception. When these measurements were done with 4 MHz bandwidth, this caused an increase in the pulse risetimes. A corresponding change was made to the simulation to apply to the 4 MHz case.

Probability of correct reception is given in Figure 9 as a function of received signal power. This figure shows a comparison between simulated results and results from measurements. It should be noted that the processing is simulated in both cases. Measured waveforms were used in one case and simulated waveforms in the other. The lower plot applies to the simulation only, in which the presence of a desired signal is known.

In the upper plot, the presence of desired signals is inferred from the received waveform. This inference can be done effectively, but not perfectly as seen in these plots.

The comparison shows that the measurements yield results that are approximately the same as the results from simulation. These are preliminary comparisons, now being repeated and carried out for more cases.

Bandwidth reduction to 4 MHz was also investigated via measurements. The original proposal to reduce bandwidth was based on the

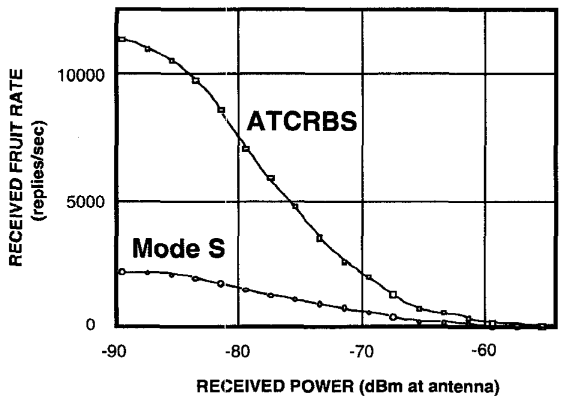

Figure 8. Fruit Environment, Measured at Lexington, MA.

following reasoning. Whereas Mode A, C transmission standards allow the carrier frequency to deviate by as much as +/-3 MHz, for Mode S the deviation is +/-1 MHz. This allows a bandwidth reduction for a receiver that is intended only for Mode S. Furthermore, for reception of Extended Squitters, it is not necessary to perform accurate time-of-arrival measurements and therefore the bandwidth can also be reduced for that reason.

Measurements have been made using both 6 MHz and 4 MHz bandwidths. Preliminary comparisons have been made between these cases, yielding an indication that 4 MHz bandwidth appears to be satisfactory. Mode S signals are still detectable, and the probability of correct reception is approximately the same as for 6 MHz.

An objective of the measurement program was to gain experience with effects such as man-made noise that might limit performance when using a high-sensitivity receiver. In fact, the first data collection indicated a significant problem of interference, in a form that appeared to be a very high noise level. Using a spectrum analyzer, the noise was identified to be a signal transmitted by a newly installed cellular phone tower about a mile away. This transmits a very strong signal at about 960 MHz. The cellular interference was eliminated by addition of a more effective front-end filter centered on 1090 MHz. Subsequently, man-made interference of much lower levels has been observed in some of the data collections. Further investigations are on-going.

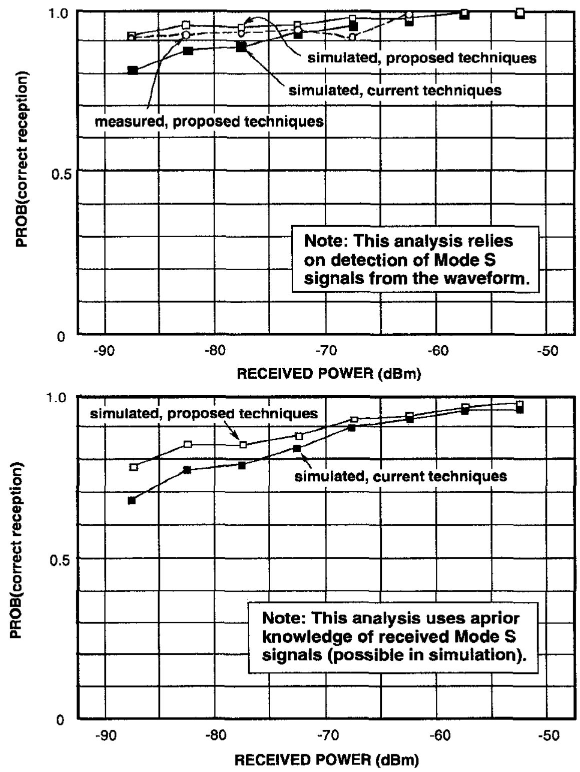

Figure 9. Performance Comparisons.

Airborne measurements are also being made with this system. In November 1997, the receiver was installed in a Convair 580 aircraft for data acquisition in the Boston and New York areas. Analysis of the data indicates significant differences in the fruit environments relative to the ground-based environment described above. A major change expected is that the aircraft antenna gain (approximately 0 dB) is much lower than the gain of the ground based antenna (approximately 7 dB). Therefore, the fruit rate above a given power level would be lower airborne, and this effect was seen to be true in the airborne data. Another expectation was that New York would have a higher interference environment than Boston, and this also was seen to be true in the recorded data. Performance assessments using the airborne data are in progress. Plans are being made for additional airborne measurement in other locations, including the Los Angeles Basin.

Summary

Several techniques have been identified to improve Mode S reception in a high interference environment. Initial assessments through simulation indicate that these techniques would yield significant improvements in reception reliability. Measurements are also being conducted to validate the simulation results. Results to date tend to indicate that the simulation is valid for predicting Mode S reception performance. More comparisons of this kind are in progress. The measurements have also yielded useful results relating to receiver bandwidth and man-made noise. Further progress is expected as more data is analyzed. When the simulation validation is complete, the simulation tool will be useful for predicting performance in very high interference environments.

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