Current Issues in Demanding ILS Ground and Flight Measurement Environments

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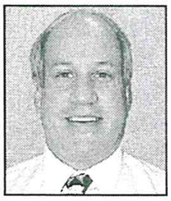

ABSTRACT

This is a continuation from previous International Flight Inspection Symposia of a series of discussions and papers by the authors on demanding flight inspection measurements. It presents the results of investigations into current technical problems encountered during preliminary flight inspection and ground measurements of (new) Category III ILS installations. Some of the issues presented include:

- Capture effect (two-frequency) performance of contemporary receivers
- Basic simulation and measurement issues, from the measurements point of view
- Differences between ground and airborne structure measurements
- Appropriateness of accepted receiver design standards
- Flight measurement anomalies due to receiver sampling, filtering, and detector characteristics

This paper presents current Category III ILS installation issues, and contrasts results between simulation predictions and ground/airborne measurements. Laboratory measurements of the capture effect performance of contemporary flight inspection and general aviation receivers are included, and the resulting practical effects on ground and flight measurements are discussed. The paper concludes with recommendations in areas such as improvements in receiver design, flight inspection system specifications, and ground and airborne measurement techniques.

INTRODUCTION

This paper continues an ongoing discussion of challenging measurement issues for low-visibility Instrument Landing Systems (ILS). Previous papers have dealt primarily with aircraft positioning, airborne antenna patterns, threshold crossing heights, and digital receiver design techniques and their effects on ILS measurements.[1,2]

This paper focuses on additional topics that make high-accuracy predictions and measurements challenging:

- Capture Effect (CE) principle of ILS ground facilities and corresponding receiver response characteristics
- Variability between receivers due to detection methods or effective detection characteristics
- Dynamic nature of measurements
- Differences between airborne and ground measurements

BACKGROUND

Category II and Category III ILS installations often exhibit challenging measurement problems. These typically arise from common characteristics of the installations, including very tight tolerances over the runway, almost exclusive use of capture effect or two-frequency antenna systems, variability between measurements, and large reflection or multipath effects from ground structures, buildings, and taxiing aircraft. Because the environment on these major hub airports is constantly changing, and the impacts of the unplanned loss of an instrument approach are huge, mathematical modeling is routinely used to predict the effects of the changes.[3]

As a result, the engineering and flight inspection communities experience an increasing number of occasions for which differences between high-performance modeling and ground/airborne measurements are significant. In some instances, the differences between predictions and measurements, or between ground and airborne measurements, easily exceed Category III tolerances. The situation is particularly challenging because it is often not obvious on where the problems lie – simulations, measurements, or both.

CAPTURE EFFECT ISSUES

Review of Capture Effect Principles

Capture effect or two-frequency arrays are used when reflection or multipath effects on a one-frequency array produce unacceptable course roughness. Only the Localizer (LOC) subsystem of the ILS will be considered here.
A common source of such reflections is a large hanger.
If a highly directional array is installed instead, it produces smooth course guidance by greatly reducing or eliminating the illumination of multipath-producing objects. As an example, Figure 1 shows a typical course carrier (Cse CSB) pattern with a 3 dB beamwidth of approximately 5 degrees, which will greatly reduce the illumination of airport hangers, since they are usually at higher azimuth angles.

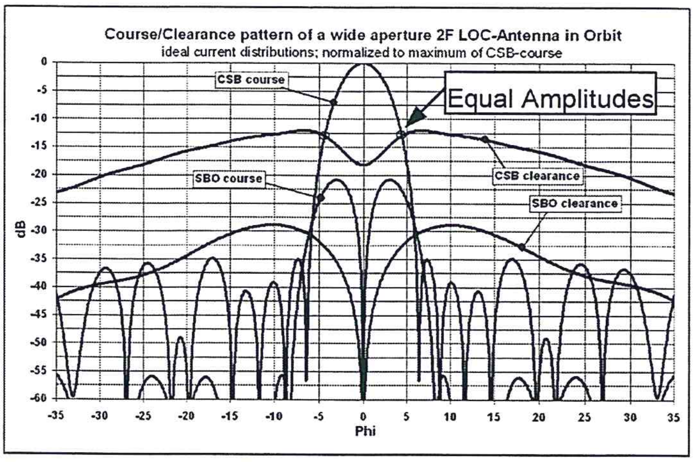

Figure 1. Typical Two-Frequency Array Patterns

However, this array will not provide fly-right or fly-left "clearances" coverage to aircraft at azimuth angles outside approximately ± 6 degrees. Therefore a separate transmitter and less directional array are used to provide this wide-angle coverage. Figure 1 shows a typical clearance carrier (Cl CSB) which supports coverage to at least 35 degrees azimuth. Note that this array still illuminates the hangers and other reflecting objects, but the resulting multipath energy is now on a different frequency than the course-producing Course array.

Both antenna patterns must be received simultaneously by an ILS receiver tuned to a single ILS channel. If the radio frequencies (RF) of the two signals differ by only a small amount, both can be accepted by the channel selection circuits and passed to the detector and audio processing circuits.

The ILS receiver's detector is a *linear envelope* detector, conceptually identical to that used in early crystal radio sets decades ago. Figure 2 shows a simplified circuit of such a detector, consisting of a diode, resistor and capacitor. The time constant of the resistor/capacitor combination is usually chosen to be the geometric mean of the input RF and output audio frequencies.

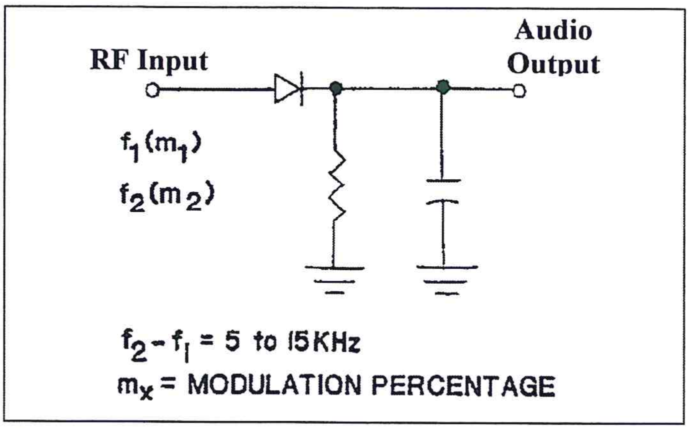

Figure 2. Linear Envelope Detector

The capture effect of a linear envelope detector is encountered when two amplitude modulated signals of differing frequencies are introduced at the input of the detector, as for the antenna patterns just described. If the input radio frequency difference is small (approximately 5 to 15 kHz) and the amplitude difference of the two signals sufficiently large (10 dB for an ideal diode, ~15 dB for typical diodes), the audio output of the detector will be comprised predominantly of the modulation on the stronger of the two input signals -- the weaker signal and its related reflections are suppressed.

Figure 3 shows an idealized "acoustic ratio" or relationship between the two input signals' modulation (course line and clearances) at the output of the detector, as a function of the input signal ratio. If the input signals are of equal amplitude (ratio of 1.0 or 0 dB), as occurs at two points in Figure 1, approximately half of the output will be due to each input signal. For this condition, the detector is not "captured" on either signal, and the phasing of the fly-left/right signals must be controlled since both contribute to the pilot's guidance. In this case, the multipath reflections of the clearance signals will easily contaminate the otherwise smooth course guidance from the directional array in this angular transition region where fortunately the desired DDM is not zero.

If the input signal amplitude ratio is 10:1 (10 dB or 0.1 on the graph), the detector output will be primarily from the modulation on the stronger signal by a high ratio of perhaps 20:1 or better. It is this improvement in ratios between the input RF signal levels and the output audio levels that leads to the term "capture effect" – the output is "captured" on the modulation of the stronger input signal. For even higher input signal ratios, (e.g., 16 dB or 0.05:1 ratio), the detector is said to be "fully captured," and its output generally can be considered to be solely due to the modulation on the stronger input signal.

In summary, the capture effect characteristic of the linear envelope detector allows the ILS receiver to "select" the appropriate signal – fly-left or fly-right clearances from the wide pattern array, or the smooth course guidance of the directional array. The capture ratio determines how completely the detector output is comprised of the desired Course signal along the centerline.

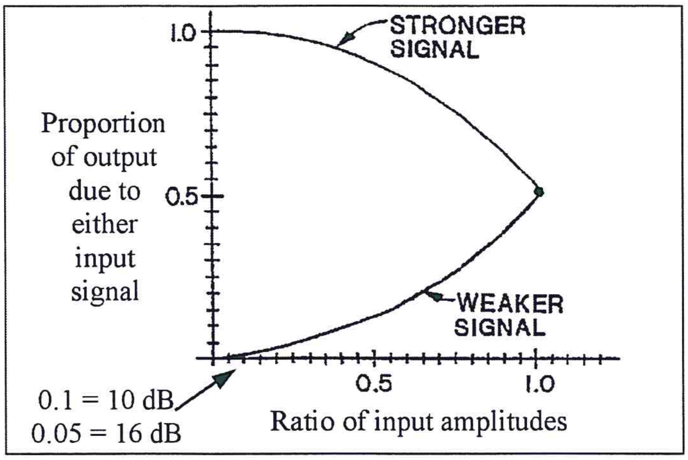

Figure 3. Detector Acoustic Ratio

Application of Capture Effect

If ILS receivers were fully captured on the course signal when inbound to the runway, ground maintenance and flight inspection personnel would never see the effects of Clearance transmitter reflections from objects at wide azimuth angles. In practice, it is difficult to achieve full capture of the detector, and particularly for Category III installations we must deal with incomplete capture. This issue has been studied in several early reports for which then-contemporary ILS receivers were characterized for their capture effect performance.[4,5,6] Subsequent improvements have been proposed since by the "quadrature clearance" or the more generalized "out-of-phase-clearance" technique.[6]

The International Civil Aviation Organization specifies a minimum centerline ratio between Course and Clearance signals of 10 dB.[7] This ratio is easily achieved with modern antenna systems. However, this value (18 dB in Figure 1) is an adjusted value determined at the localizer antenna, and achieved only in the absence of multipath reflections. The actual ratio between Course and Clearance CSB signals at the input to the user receiver can be substantially worse than this adjusted 18 dB value wherever reflected Clearance signals cross the runway centerline, which is precisely where the tolerances are tightest. If the reflection is sufficiently strong, the receiver will not be fully captured.

How well does a 10 dB capture ratio work in suppressing the effects of Clearance reflections? Figure 4 shows how four specific early receiver types react to an (incomplete) capture ratio of 10 dB, for varying Difference in Depth of Modulation (DDM) values on a reflected signal. Assuming the course signal is by itself perfect (0 µA roughness), a clearance signal of approximately 125 µA will cause the receiver to display 5 uA of roughness. Since the tolerance for Category III localizers is 5 µA over most of the runway, a 10 dB capture ratio is clearly unacceptable, because the clearance signal is required to exceed 150 µA – i.e., any acceptable Clearance signal will cause the combined signal to exceed course roughness tolerances. A higher capture ratio is required.

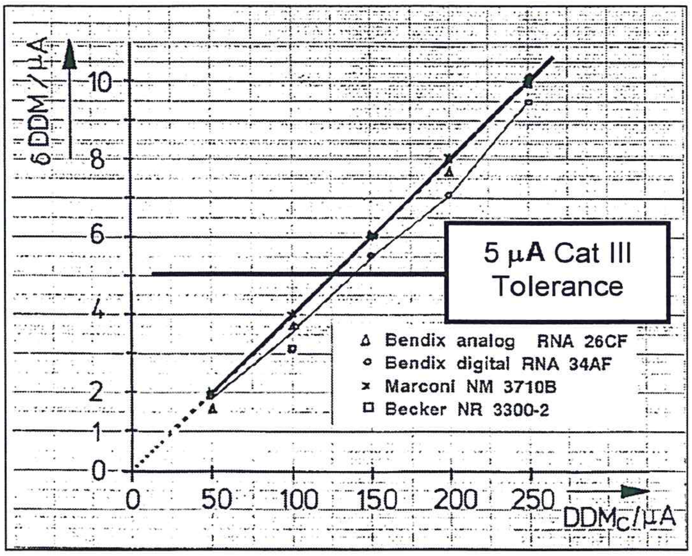

Figure 4. Measured DDM Distortions, 10 dB Capture Ratio, Clearance DDM Variable

What capture ratio is required to meet 5 uA roughness for these early receivers? Figure 5 shows how a more typical reflected 200 µA Clearance signal affects the combined output, for varying ratios of capture. For the four receivers tested, a minimum of 12 dB is required to limit distortions to Category III limits, assuming the directional array itself has no roughness caused by in-beam reflections from its intended SBO energy, or out-of-beam reflections from any insufficiently suppressed SBO sidelobes.

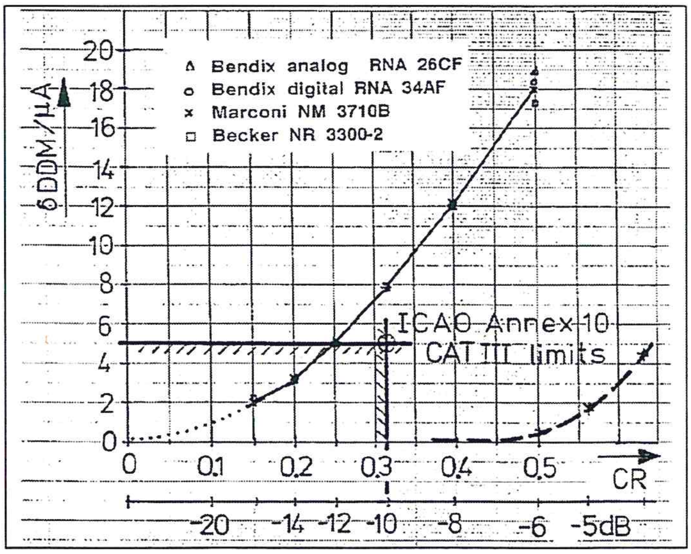

Figure 5. Measured DDM Distortions, 200 µA Clearance DDM, Variable Capture Ratio

RECEIVER ISSUES

Simulations Versus Measurements

State-of-the-art modeling tools must of course incorporate a mathematical expression for the capture effect for two-frequency ILS applications. The early work shown in the above figures and similar measurements have often been used to derive an expression which is presumed to match actual measurements. An example is:

$$DDM_{total} = \frac{DDM_{cl} \cdot CR^{X} + DDM_{co}}{1 + CR^{x}}$$

where cl = Clearance, co = Course, and CR = the capture ratio, or…

$$CR = \frac{CSB_{clearance}}{CSB_{course}}$$

However, the number of commonly used receivers is increasing, with attendant changes in architecture, signal processing, and filtering characteristics. At the same time, the modeling environment places higher demands on predicting faithfully the results of reflections from increasingly larger objects and aircraft near Category III runways. It is not surprising when differences between predictions and actual flight and ground measurements occur, especially in a tight-tolerances environment. These differences have caused a renewed interest in characterizing contemporary receivers for their capture effect performance.

Variations Between Receiver Types

It is common that different receivers or aircraft produce varying announcements for Category III Localizer structure measurements, sometimes by amounts approximating or exceeding the tolerances. Recent experiences have caused newer model receivers to be characterized for their two-frequency performance, to compare these designs against those discussed in the previous section. Several popular receivers were selected, including models intended for airborne (general aviation and cabin class) and ground measurements. Data corresponding to that shown in Figure 5 were collected, to contrast the generational and individual model number differences among them.

Figure 6 shows the results from the previous studies (Figure 5), with those from the general aviation receiver used in FAA's portable Navigational Aid Signal Evaluator (NASE) package for engineering purposes, and lab-quality test equipment used for ground measurements in Europe.

Even though these results were taken from single serial number examples of each type, it is clear that large variations exist between receiver types. The older generation of receivers required approximately 12dB of capture ratio to limit clearance distortions to 5μA on an otherwise perfect Course guidance signal. The tested lab receiver requires approximately 12.5 – 13dB, and the tested general aviation receiver requires 14 dB for the same results. This difference in capture effect performance is one reason that repeated measurements by different receivers can produce varying structure results.

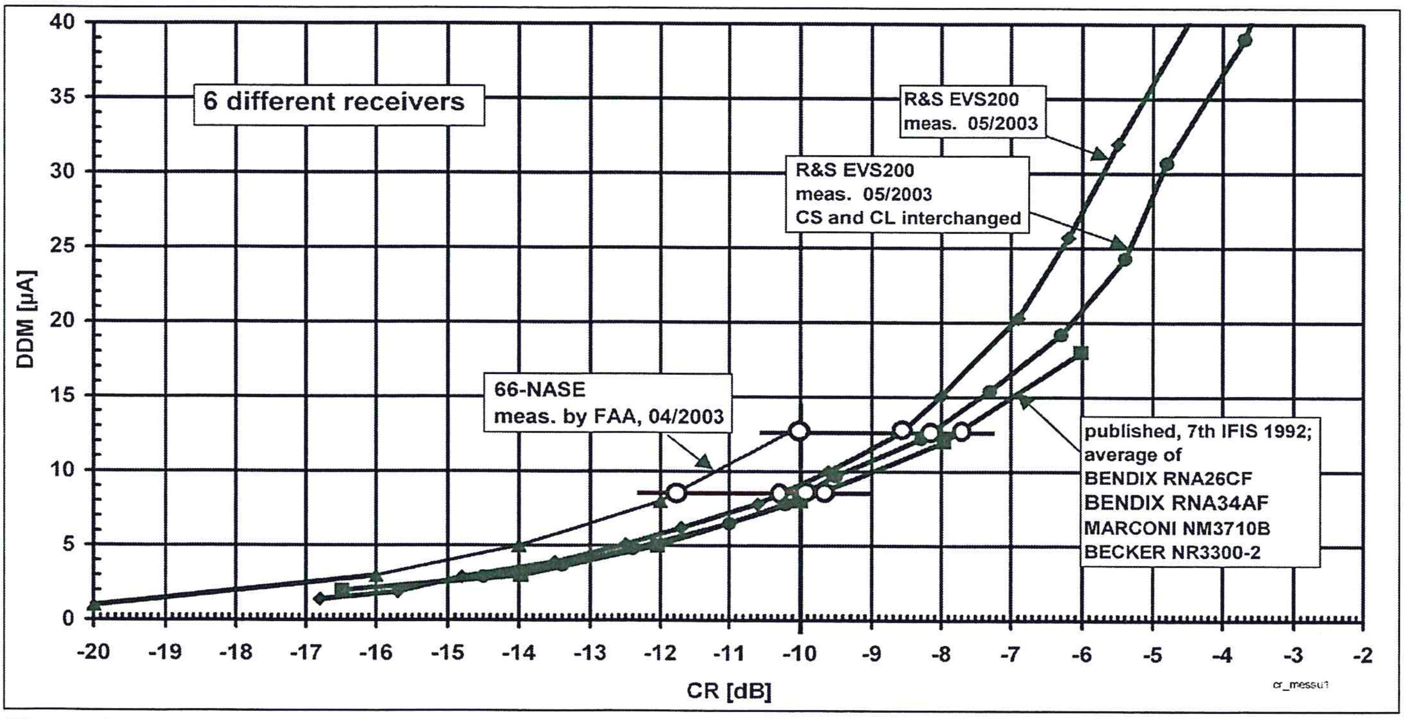

Figure 6. Measured DDM Distortions, 200 μA Clearance DDM, Variable Capture Ratio

Variations Between Receivers of the Same Type

Flight Inspection organizations know that even on single flights, multiple receivers of the same model number or type produce different LOC structure results. While a variety of internal design characteristics such as filtering time constants and varying signal processing techniques are typically responsible, they cannot explain differences between receivers of a common type.

One explanation for such differences is differential gains or losses in the receiver between the Course and Clearance carrier frequencies. Although the frequency separation is typically only 8-9 kHz., the receiver's intermediate frequency (I.F.) filter that selects the operating channel may have ripple in its passband -- up to 6 dB of ripple is allowed by RTCA standards.[8] Since the filter precedes the detector in the signal flow, if the two frequencies are treated unequally by the filter, the actual capture ratio presented to the detector is different than expected, and can easily be different for different receivers.

Figure 7 depicts schematically a worst-case passband shape with 6 dB of ripple. Assume the filter's response is symmetrical around the channel center frequency F_0, as shown with the solid line. If the Course and Clearance signals both fall on peaks or troughs of the ripple, the capture ratio presented to the detector will be the same as presented to the receiver's input terminals. In this case, a 12 dB capture ratio at the receiver input will produce a 5 uA structure measurement, as shown in Figure 5.

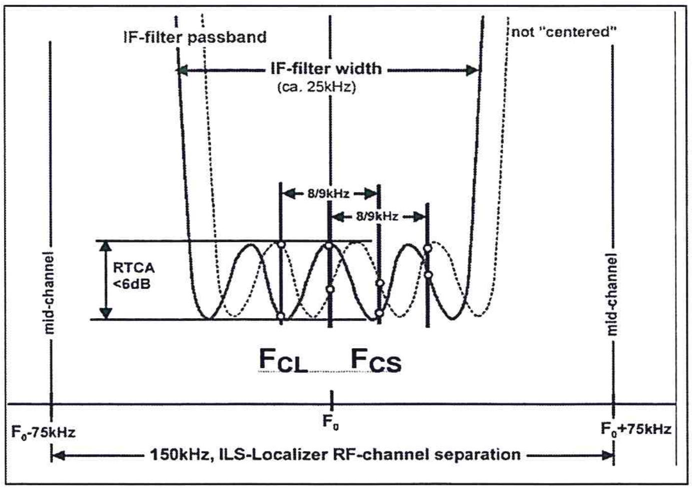

Figure 7. Example I.F. Filter Passbands

However, due to manufacturing and alignment tolerances a second receiver of the same type may have its filter response curve asymmetrically placed around the channel frequency, or its peaks and troughs may occur at different spacings from the channel frequency, or have unequal amplitude responses. If the same 12 dB capture ratio is input to this second receiver, the effective ratio at its detector can appear to be as low as 6 dB, or as high as 18 dB, depending on where the peaks and troughs of the filter ripple occur.

These capture ratios correspond to a range of displayed Localizer roughness between approximately 1 and 18 uA, again per Figure 5. For opposite worst-case ripple conditions, and assuming two of these earlier receivers on the same flight inspection run, their reported Localizer structure measurements can be dissimilar by ratios as high as 18:1!

Further Receiver Investigations

Since the results in Figure 5 show both a high quality lab receiver and a popular general aviation receiver with significantly different capture performance than the four older receivers, further measurements were conducted to determine if the variations were due to filter ripple problems as shown in Figure 7.

The lab quality receiver and three of the general aviation receivers were tested again by reversing the Course and Clearance frequencies. If filter passband ripple is large, the effective capture ratio will be different than for unreversed frequencies, and the effects of a reflected Clearance signal of 200 uA on course roughness will be different.

The results for the lab-quality receiver are depicted in Figure 6, showing that at low capture ratios (e.g., 4-10 dB), there is up to one dB between the two tests. At more typical capture ratios, the difference is smaller. The differential ripple at the Course and Clearance frequencies is perhaps at most 0.5 dB, which is quite reasonable.

The results for two of the general aviation receivers are shown in Figure 8. Receiver #00 exhibited almost no difference in performance with the Course and Clearance frequencies reversed, indicating that filter ripple is minimal. However, receiver #10 exhibited approximately ± 1 dB of ripple. While this is not excessively large, it illustrates how different the capture effect performance of two receivers of the same type can be. Even at capture ratios of 12-14 dB, which are quite common, this 1 dB variation represents a 50% difference in reported Localizer structure.

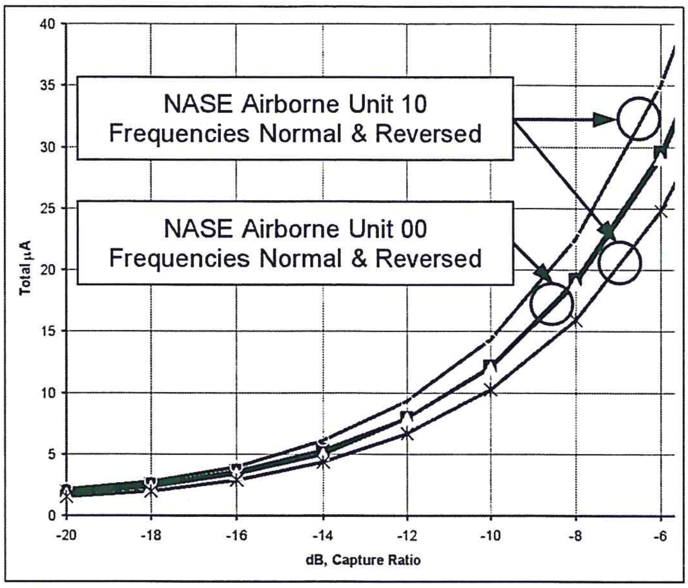

Figure 8. Two General Aviation Receivers, Course/Clearance Frequencies Normal/Reversed

To visualize how the I.F. filter passband can cause these differences, Figure 9 illustrates the actual filter response of the third general aviation receiver. A 2 dB variation exists across the passband, which is not symmetrical but fairly well centered. If the localizer transmitter frequencies happen to be 2 kHz high (within ICAO tolerances), or if the receiver's channel selection oscillator is off by 2 kHz, the Course and Clearance signals will be positioned in the passband as shown. For this condition, a 14 dB capture ratio presented to the receiver input would appear as a 12 dB ratio at the detector. Course roughness would be increased by 40 to 60 per cent, using Figures 5 or 6 respectively, compared to a Localizer or receiver with correctly centered frequencies.

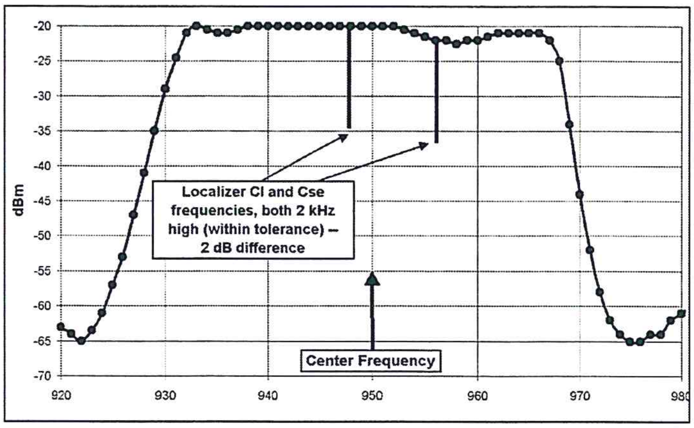

Figure 9. NASE Unit 01 Filter Response

Six flight inspection receivers were also tested for passband flatness. Figure 10 shows the results, which are reasonably symmetrical and well centered. Two of the receivers exhibit 1 dB of filter ripple, while the other four exhibit less than 0.5 dB, which was the measurement resolution. One of the six exhibited its ripple on or near the Course transmitter frequency (4 kHz. above the channel frequency). Depending on a Localizer's actual frequency, a 14 dB capture ratio presented to the receiver input could be 13-15 dB at the detector. Using Figure 6, this one receiver could display a Localizer roughness range of between 2.5 and 4 uA (60 % variation) for a 200 uA Clearance reflection.

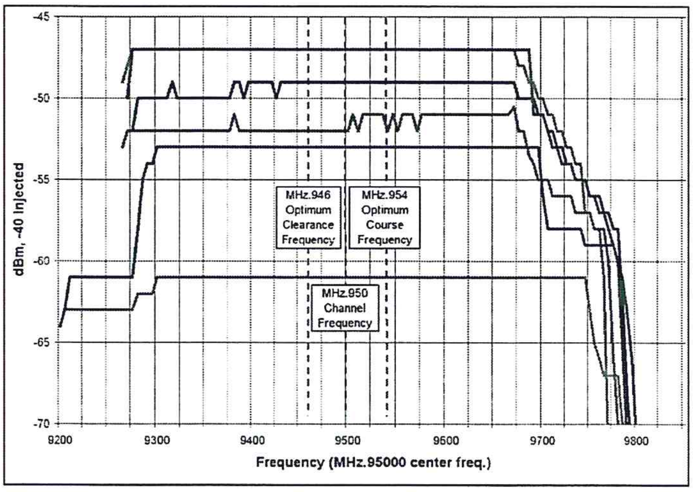

Figure 10. Six Flight Inspection Receiver Filters

DYNAMIC NATURE OF MEASUREMENTS

Vehicle Speed and Receiver Processing

A previous paper by the authors[2] addressed in some detail the changing design concepts used in receivers, including the increasing use of digital signal processing, the effects of filter time constants, and sampling rates. Recent experiences have highlighted these issues in a Category III environment, where simulation results and measurements often differ by appreciable amounts.

Figure 11 shows on-the-runway measurements taken by a ground vehicle driven at varying speeds, using two different receivers. The reflector causing the scalloping is a large crane typically used for airport construction activities.

The two superimposed recordings at the top were taken with a modern digitally processed receiver, an RS EVS 200, driven at slow and medium speeds. Although difficult to see without the benefit of color graphics, the maximum scalloping amplitudes for the 10 and 25-30 km/h recordings are essentially identical at 7 uA. However, the minimum scalloping amplitude for the 10 km/h recording is actually lower (2.5 uA) than for the 25-30 km/h recording (4.5 uA). In other words, the peak-peak scalloping magnitude at the extreme of the bend is 4.5 uA at 10 km/h, and 2.5 uA at 25-30 km/h. If filtering were added, the resulting bend amplitude would be smaller at the lower speeds, i.e., the bend amplitude is proportional to speed, at a ratio of nearly 2:1. This characteristic is termed "peak riding", and is one also seen on other modern receivers.

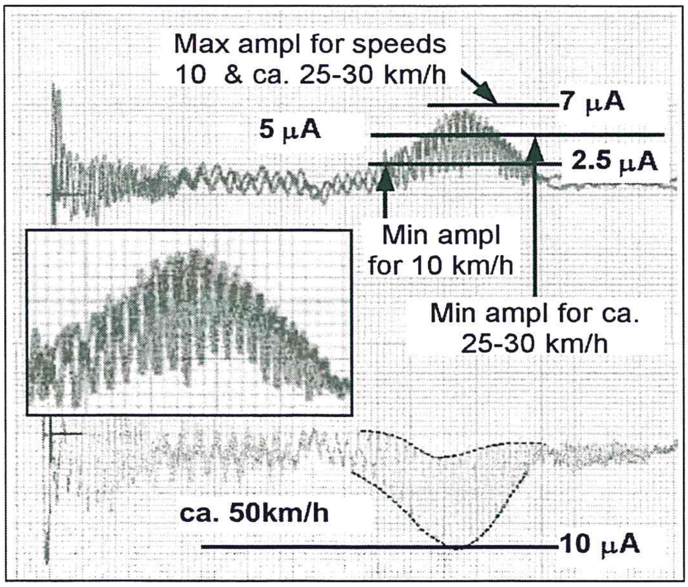

Figure 11. Digital Processing Receiver at Two Speeds (top), Analog Receiver (bottom)

The recording at the bottom of Figure 11 was taken on the same runway at a higher speed of 50 km/h, but with an older completely analog receiver intended for ground measurements, a Thomson CSF RSE392. This receiver is able to display accurately the high scalloping rates, not only at amplitudes substantially larger than for the digitally processed receiver, but also at approximately twice the vehicle speed.

These three measurements exhibit results that consume 90% (10 km/h), 40% (~25-30 km/h), and 200% (50 km/h) of the Category III Localizer roughness tolerance on the runway, and the nature of the recordings is very different. Clearly, one cannot expect to make comparable measurements on multiple facilities unless sampling rates, vehicle speed, and other signal processing parameters are appropriately selected.

Runway Reflections, Ground vs. Airborne

ILS Category III Localizer measurements in Zones 4 and 5 (beginning at 3000' inside the threshold, ILS Point D, and ending at 2000' prior to the stop end of the runway, ILS point E) are made on the ground or during flight, depending on the flight inspection organization. However, large variations in results can occur if insufficient attention is paid to DDM filtering time constants, sampling rates in digital processing receivers, receiver antenna patterns, and measurement antenna heights.

Figure 12 illustrates these details for a recent measurement problem resulting from the construction of a new control tower. In the figure, all three numerically calculated traces indicate the expected results for both unfiltered and filtered (ICAO specification) measurements.

- The center trace, which has been offset in DDM by 2 uA from zero for illustration purposes, shows expected course errors from the control tower when measured in flight at a 50' height above the runway, at 250 km/h. The very high sampling rate for the receiver is 69 samples per second. This rate is more than sufficient to accurately display the small amplitude but very high frequency errors between 2000 and 3000 meters from the localizer. Maximum filtered course roughness is approximately 1 uA (peak to peak) at 3150 meters from the Localizer.

- The upper trace, which has been offset by 4 uA, uses a typical 10 Hz sampling rate, which is insufficient for the 250 km/h velocity. This is evident in the distortion in frequency and scalloping character between 2000 and 3200 meters from the localizer. Maximum filtered course roughness is approximately 0.8 uA.

- The bottom trace, which is not offset in DDM, illustrates the results from a ground-based measurement, with a sampling rate appropriate for the vehicle speed and an antenna height of approximately 4 meters. It is immediately evident that the change in antenna height has placed it in a completely different multipath environment, with a bend in the course caused by greater Clearance signal reflections, with much larger Course signal high-frequency scalloping. The maximum filtered course roughness is approximately 1.7 uA, or 170 per cent of the airborne measurement at a 50' height (center trace).

Clearly, the two top "airborne measurements" do not properly document the course structure as seen by a typical Category III user aircraft, for which the antenna will be close to the 12' height.

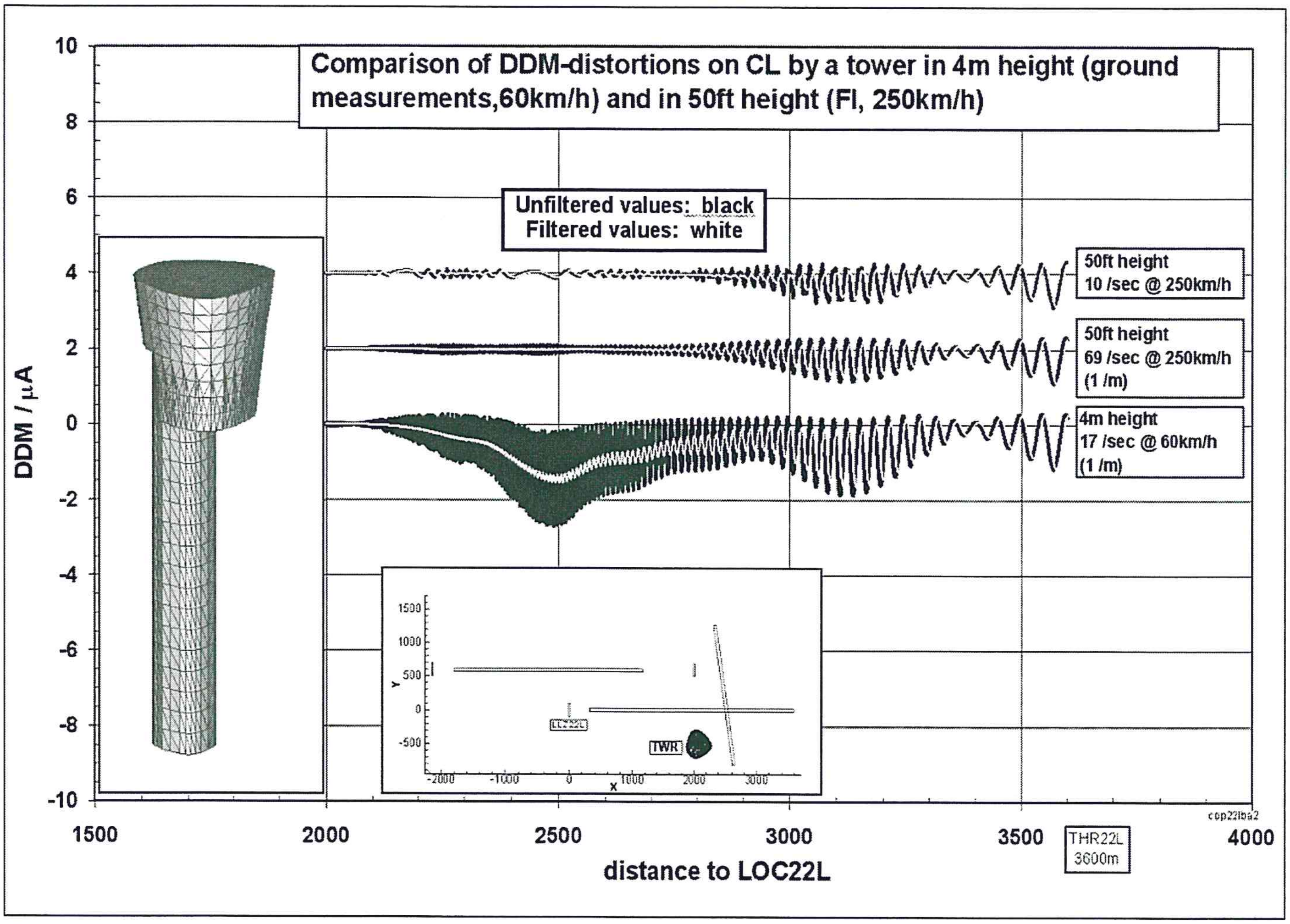

Figure 12. Control Tower Reflections as Measured with Different Heights, Speeds, and Sampling Rates

Ground Runway Measurements, Single Receiver

Additional unfiltered (raw data) ground measurements for the construction crane shown in Figure 11, used to construct the control tower shown in Figure 12, were made with a single receiver, at varying speeds and for two levels of Clearance sideband power. For all measurements, the crane was positioned for a worst-case effect.

Figure 13 shows the results for Transmitter 1 and 2, which were adjusted for identical power and phasing. The measurements were made at a speed of 30 km/h; the vertical scale is in uA of unfiltered DDM; the horizontal scale is in meters from the runway threshold. Each recording has a nominal misalignment of 1 uA. The second transmitter exhibits a Clearance bend of approximately 30 per cent greater magnitude than for transmitter 1. High frequency Course reflections are approximately 4 and 5 uA respectively. From Figure 6, these differences can be explained eventually if the effective capture ratio at the detector differed for the two transmitters by 1.5 dB.

The two recordings in Figure 14 show the same measurement made with the same receiver, but at speeds of 5-10 km/h and 60 km/h. It is apparent that at the higher speed, the

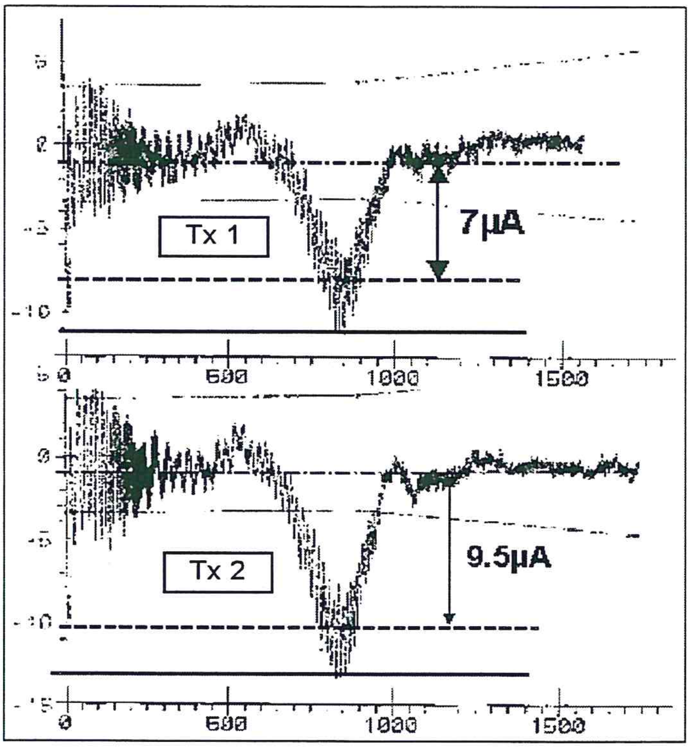

Figure 13. Runway Measurements, 30 km/h, Collins RV51 Receiver

frequency response of the receiver is insufficient to show the Course scalloping at the same magnitude as for the slower speed – 7 uA at 5-10 km/h, and 2 uA at 60 km/h.

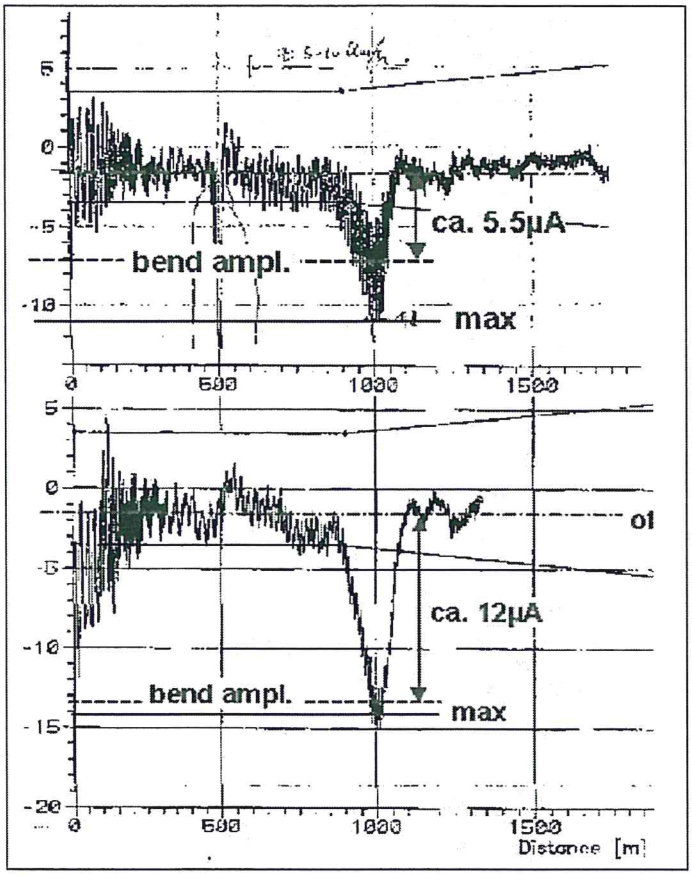

Figure 14. Runway Measurements, 5-10 and 60 km/h, Collins RV51 Receiver

Also in Figure 14, the bend magnitude from reflections of the Clearance transmitter is smaller for the low-speed measurement (5.5 uA) than for the high-speed measurement (12 uA). This difference is explained by a reduced Clearance sideband power, which decreases the DDM on the reflected Clearance signal. This results in less distortion of the course line, according to Figure 4, regardless of the capture ratio. This predictable characteristic illustrates why clearances should not be maintained unnecessarily higher than required in the presence of reflecting objects.

When a Clearance-caused bend and a high-frequency Course-caused scalloping occur together, the flight inspection results with two different receivers can vary widely, as shown in Figures 11, 13, and 14. Taken together, the peak-riding effect in Figure 11 and the frequency response limitation in Figure 14 can result in a 2:1 or higher ratio in announced structure results.

NEW SIMULATION EQUATION

The empirical results described in this paper make clear that many characteristics of the ILS signal and the measurement receiver greatly affect the results. The parameters that define the transmitter and the radiating ILS antenna pattern are well known and easily confirmed. However, variations between measurement receivers can be large. The primary causes include detector design and the shape and ripple of I.F. filter passbands, as well as the centering of the filter or the ILS transmitters on the desired channel.

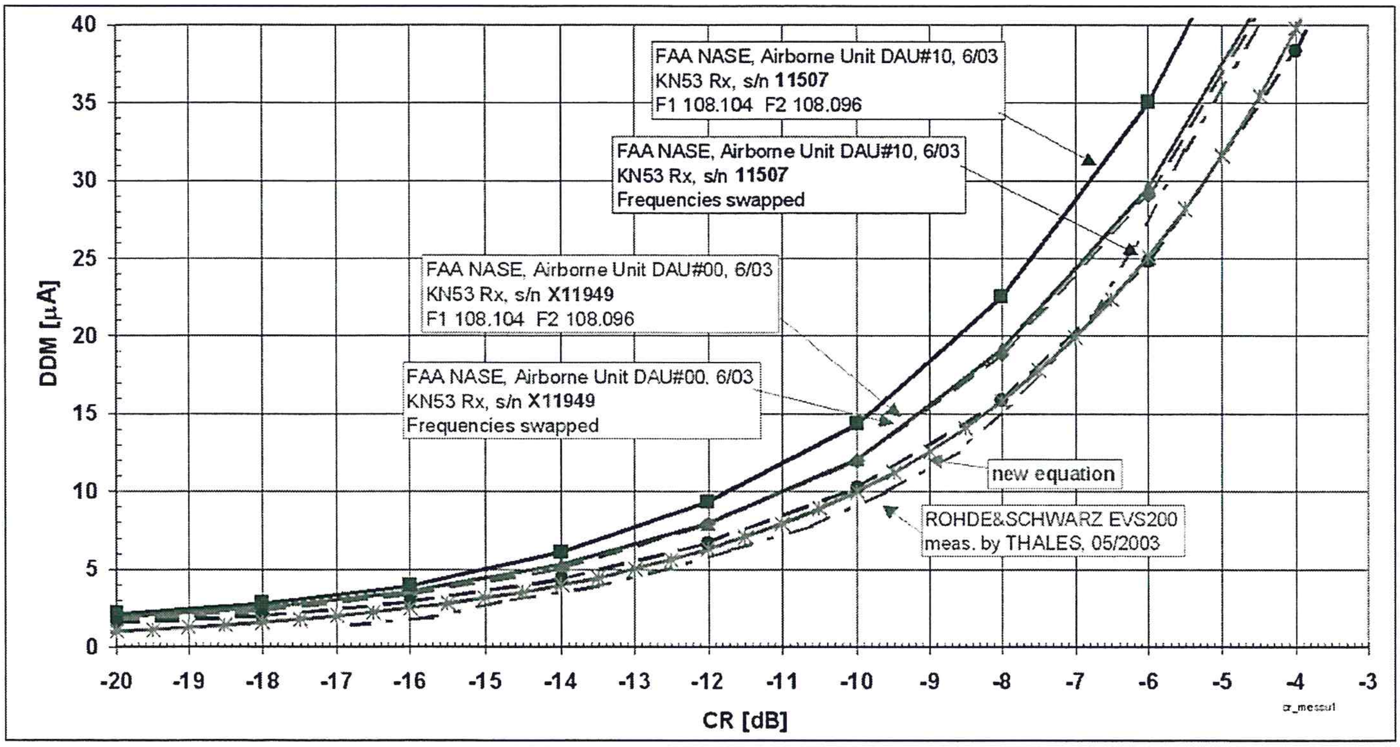

Figure 15. New Two-Frequency Simulation Equation and Contemporary Capture Ratio Performance

Each of these variables can degrade the correlation between simulations or modeling and the actual field measurements. To minimize these differences, a new equation has been derived theoretically to better describe capture performance. It applies over a wide range of capture ratios, and more faithfully describes contemporary ILS receiver capture effect performance, as shown in Figure 15.

CONCLUSIONS

The following conclusions are drawn from the information presented in this paper:

1. Unlike earlier receivers for which capture effect performance has been published, current receivers exhibit different performance and a wider variation between different types, and between receivers of the same type.
2. Some ground and airborne receiver types require a higher capture ratio to limit the distortion effects of a given reflector to a specific value, when compared to other current and older models.
3. Previous empirically-derived formulas for simulating capture effect performance of a receiver need to be revised.
4. Intermediate Frequency (I.F.) filter passband ripple directly affects the effective capture ratio of signals presented to an ILS receiver's detector.
5. Industry specifications for allowed I.F. passband ripple are unacceptably large.
6. Differences in capture effect performance between receiver types and between identical models can be attributed to known receiver characteristics, and should be expected unless these characteristics are controlled.
7. Differences between modeling predictions and actual measurements should be expected when tolerances are small and receiver variations large.
8. Large differences between measurements can be expected unless ILS receiver sampling rates, vehicle speed, and filtering characteristics are controlled.
9. Airborne measurements of Localizer structure in Zones 4 and 5 do not document the signal from the user's perspective, and are both too high and too fast for predictable DDM processing with most contemporary receivers.
10. A new mathematical formula for calculating two-frequency, capture effect performance is necessary to increase the correlation between simulations and measurements.

RECOMMENDATIONS

The following recommendations are made based on the information and conclusions in this paper:

1. Characterize additional receiver types for their capture effect performance, and integrate this information into high-fidelity simulation efforts.
2. Tighten substantially the industry standards for ILS receiver I.F. filter passband ripple.
3. Measure and maintain I.F. filter passband ripple in ILS flight inspection receivers to 1 dB or less.
4. Commission ILS facilities with receivers exhibiting only the best capture effect characteristics, to validate engineering and modeling predictions.
5. Conduct "flight inspection" measurements of Localizer Zones 4 and 5 structure on the ground, to qualify low-visibility ILS signals as the user experiences them.
6. Conduct Zones 4 and 5 measurements using controlled speeds, appropriate DDM filter time constants, antenna pattern, and antenna height.
7. Improve the capture effect performance of the Navigational Aids Signal Evaluator.
8. Implement capture effect simulations using a capture ratio equation that applies over a wide range of capture ratios.

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FAA receiver data were gathered by Mr. Carl Specht of Raytheon and Mr. Larry Gage of FAA.

Many of the remaining runway and receiver measurements were performed by persons intentionally unnamed. Although their contributions are anonymous, they are nevertheless much appreciated.

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