Current Issues in Demanding Flight Measurement Environments

Dr.-Ing. Gerhard GREVING
NAVCOM Consult
Ziegelstr. 43, 71672 Marbach, Germany
Fax: +49 7144 862561
E-mail: navcom.consult@t-online.de

L. Nelson Spohnheimer
Spohnheimer Consulting
Auburn, WA 98001, USA
Fax: +1 508 526 8273
E-mail: Nelson@SpohnheimerConsulting.com

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 investigations into current technical problems encountered during simulations and ground/airborne ILS and VOR measurements. Some of the issues presented include:

- Measurement uncertainties on Glide Slope flight inspection recordings
- Performance characteristics of differing reference systems
- Measurement policies and practices for large angular offset ILS approaches
- The continued need for more explicit ILS Guidance Material in Annex 10
- Aberrant receiver behavior in the presence of strong multipath conditions
- Flight measurements validation of a general simulation solution for near-field objects near a VOR

This paper analyzes recent experiences on a variety of ground-based navaids, including Localizer structure in Zones 4 and 5, glide slope measurements in Zones 2 and 3, and VOR orbital/radial measurements. It contrasts results between simulation predictions and ground/airborne measurements, between receivers, and between flight inspection reference systems. Appropriate and practical measurement of large offset ILS approaches is addressed. The paper concludes with recommendations in areas such as improved international policy recommendations and guidance material, publication of appropriate policies for the newer applications of ILS, and further investigations into avionics characteristics.

DISCLAIMER

Measurement locations and methods are intentionally kept anonymous. The authors intend only the constructive use of the examples included in this paper.

FLIGHT INSPECTION REFERENCE SYSTEMS

Truth System Application and Challenges

During any flight inspection activity, the raw measurements obtained include both facility errors and aircraft positioning errors. Modern systems are typically based on sampling techniques, and therefore on a sample-by-sample basis, the aircraft position error must be removed to obtain the Navigation System Error (NSE):

$$NSE = TotalError - PositionError$$

Removing the aircraft position error requires a position reference or "truth" system which is aware at all times of the 3-dimensional location of the aircraft's Nav receiver antenna location and how that location differs from the desired flight path. Truth systems range from radio-telemetering theodolites (RTT, manual or automatic optical tracking) to autonomous multi-sensor systems (typically Inertial Reference Units augmented by smoothed altimetry and micro-acceleration sensors), to recently, Differential GPS systems. [1,2]

For each type of truth system, the timing of raw data collection must be matched to the truth system timing to remove any latency between the two. This is especially challenging when high rates of position change occur. Also, the position difference between the Nav antenna and the truth system reference point must be accounted for. For example, if a DGPS antenna and the Glide Slope antenna are separated by a substantial distance, this can cause errors in the resultant NSE when the aircraft pitches up and down during the approach. The two antennas will be moved by differing amounts, and the corrections (Position Error) will not be appropriate for the Nav antenna location. This will result in residual evidence of the aircraft movement appearing in the (presumed) corrected data or plot of NSE.

Truth System Errors

A recent glide slope investigation, for which some conclusive work remains, provides examples of obvious truth system differences and inaccuracies. Figure 1 illustrates four raw data plots for glide slope approaches, all taken within a time frame of approximately 90 minutes. All have the same horizontal distance scale, with oscillatory errors noted in the last 1-2 miles prior to threshold. Close inspection reveals that the periods, amplitudes, and exact location of individual maxima and minima vary considerably from run to run. Unfortunately, simultaneously-plotted data from the truth system are not available. The varying raw data characteristics strongly suggest with a very high probability that these oscillatory errors are due to aircraft pitching movements, and are not characteristics of the radiated glide slope signal. If the truth system is effective, the errors are expected to be removed.

Contrasting Two Truth Systems

Figure 2 shows repeated raw data from two of the runs at the top of the figure, with the corresponding corrected data using two different truth systems at bottom. The RTT truth system at bottom left has removed nearly all of the oscillatory errors, while the DGPS truth system at bottom right has decreased the magnitude of the errors only from approximately ± 20 µA to ± 7 µA.

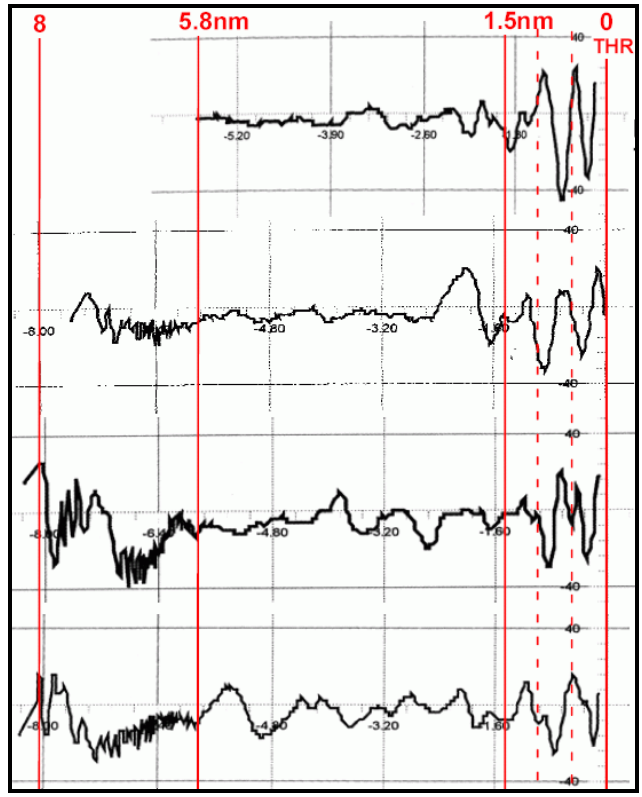

Figure 1. Four GS Approaches, Raw Data, 1.5 Hour Time Period.

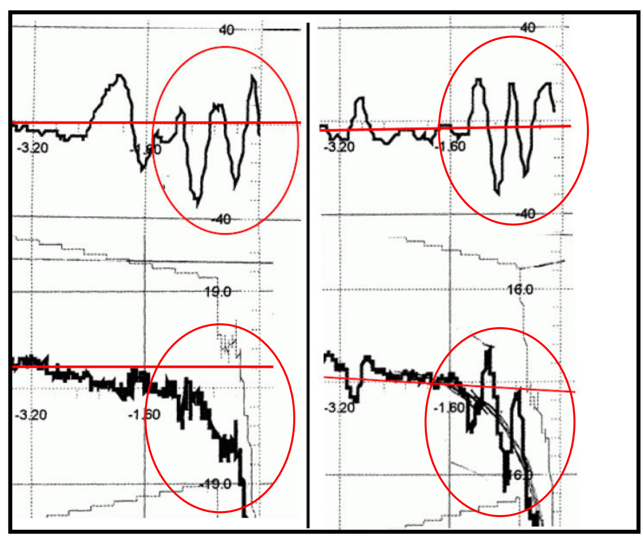

Figure 2. Raw Data (top), with Corrected Data from RTT (bottom left) and DGPS (bottom right).

Raw Data and Truth System Latencies

Figure 3 shows the DGPS portion of Figure 2, enlarged to show the relative timing between the raw data errors and the claimed NSE errors. Average GS position in Zone 2 (4 NM to 3500' prior to threshold) is shown with a straight line left to right. Since the DGPS-corrected trace at bottom has an increasing bias near threshold, a "best-fit" line has been sketched through the oscillatory errors.

The vertical dashed lines are positioned at several of the maxima and minima on the raw data measurements at the top of figure. In each case, they intersect the corrected trace at its zero baseline (i.e., the straight or curved trend lines). This is indicative of an uncorrected latency between the raw data collection system, and the DGPS truth system – i.e., the corrections from the truth system are not applied to the proper raw data sample, resulting in a partially-removed, time-shifted (90 degrees) residual error that might be mistakenly considered as GS NSE.

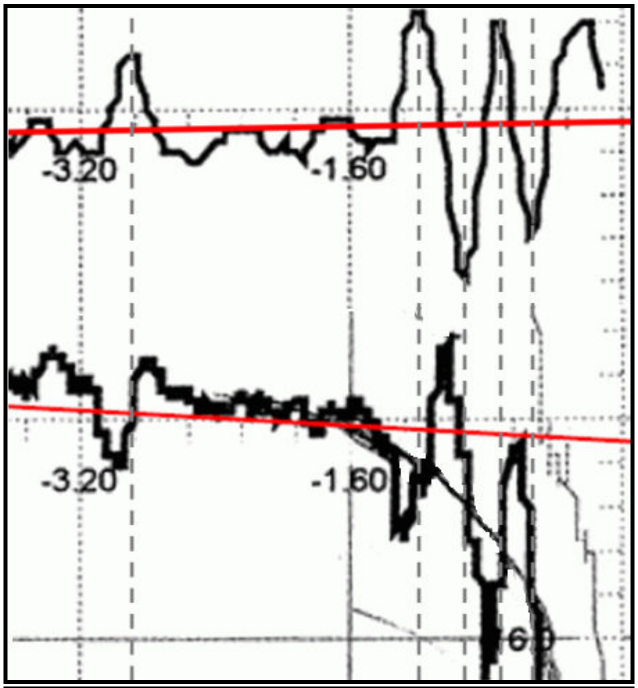

Figure 3. Time Correlation between Raw and Corrected Data for DGPS Truth System.

LARGE ANGULAR OFFSET APPROACHES

Terrain Avoidance – Offset LLZ

Frequently, an offset approach is desired to a point in space from which a turn to a visual landing can be made. An example is shown in Figure 4, with an airport for which the approach path must be separated from large hills. This necessitates offsetting the localizer (LLZ) by a large angle. The turn point is often considered (arbitrarily), for tolerance application purposes, to be Point B (e.g., middle marker area) on a straight-in approach.

The initially suspected engineering issue was whether a new relatively low power line, shown in Figure 4, was responsible for the out-of-tolerance structure. Figure 5 shows a sample flight measurement of the LLZ structure, with traditional CAT I tolerances shown in heavy dashed lines. The apparent out-of-tolerance segment outside 10 miles is due to positioning and LOC intercept of the aircraft, and should be ignored. However, the crosspointer near 4 miles exceeds Localizer tolerances.

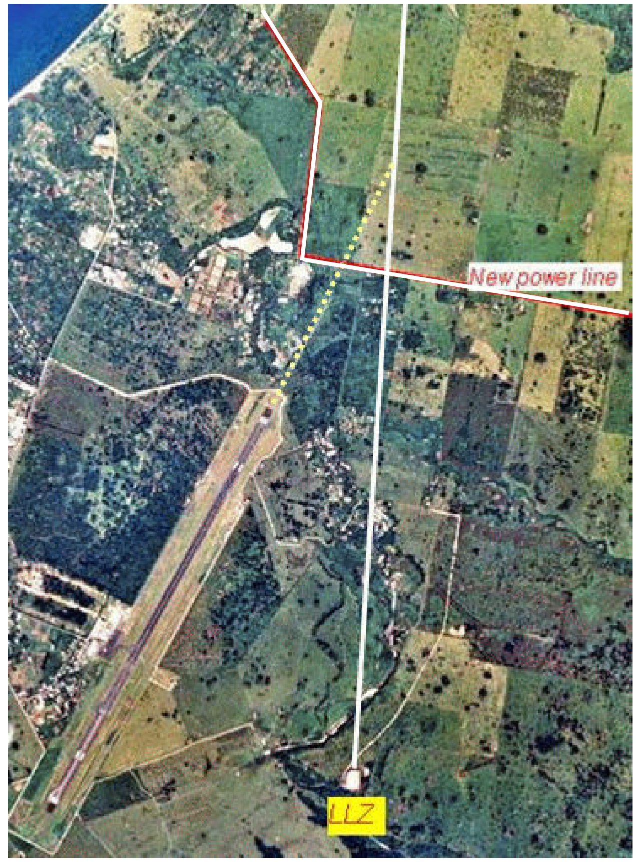

Figure 4. Terrain Avoidance Offset LLZ.

Figure 5 Out-of-Tolerance Results for Offset LLZ.

Some strands of the power line were taken down temporarily, with mixed results. One report showed a marked improvement, but removal of an additional strand in the same area was reported to make the structure worse, indicating possible random measurement results.

Initial assessment of the recordings shows that while the power line effects are visible as high-frequency scalloping in some segments of the approach, such as between 4 and 6 miles in Figure 5, the out-of-tolerance conditions do not exhibit power-line characteristics. This can be easily confirmed by appropriate numerical simulations.. Further, the recordings are not consistent in general nature, even for repeated flights separated by only several minutes.

For example, Figures 6 and 7 each show back-back structure measurements taken one year apart. Within each figure, the measurements are separated by only 7 and 11 minutes respectively. Only the recording segments inside Point A (4 nautical miles) are included, and they have been scaled to match in both axes for valid visual comparison. Category I and II tolerances are highlighted.

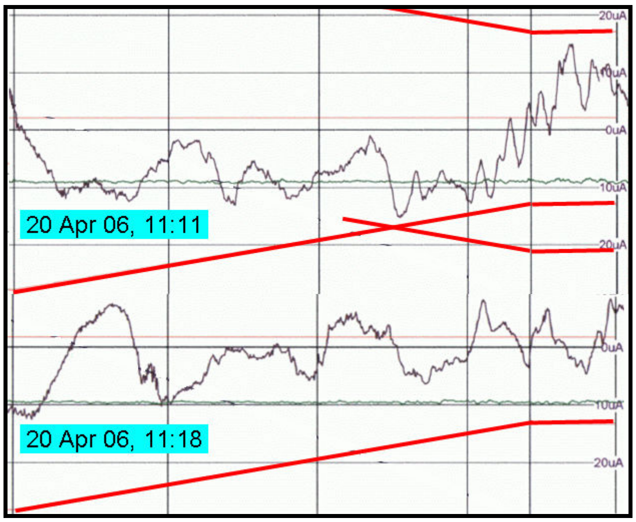

Figure 6. Structure Measurements from 2006.

Both runs in Figure 6 are in-tolerance, although the scalloping is clearly different. The run made at 11:11 is generally straight for the first 3 miles, but "turns" sharply during the final mile. However, the run made at 11:18 does not show the change in the final mile.

Figure 7 shows two runs made a year later but only 11 minutes apart. Both are out-of-tolerance during the approximate first mile of the recording segment, although the character of the errors is quite different from one run to the next. Further, at approximately 0.5 mile, the upper recording consumes only 50% of the tolerance, while the lower recording is out of tolerance at 110%. The variations in both Figures 6 and 7 over short time periods may explain the apparently contradictory results when lowering the lines. The uncertainties also raise potential questions about the positioning methods used and the truth system references when there is no runway with which to align during the runs.

While these actual measurement uncertainties are problematic, the larger conceptual issue is whether it is appropriate to apply international CAT I structure tolerances, intended for a precision approach (straight-in to a runway), to an LLZ being used for a non-precision, offset, terrain-separation application.

Since offset LLZ facilities rarely enjoy the protection from multipath sources afforded an on-airport environment, it will be common that structure tolerances are more difficult to meet for these facilities. From a procedures point of view, a non-directional beacon (NDB) or a VHF OmniRange (VOR) likely could meet the need. But these facilities often are not used because their omni-directional radiation makes meeting tolerances even more problematic.

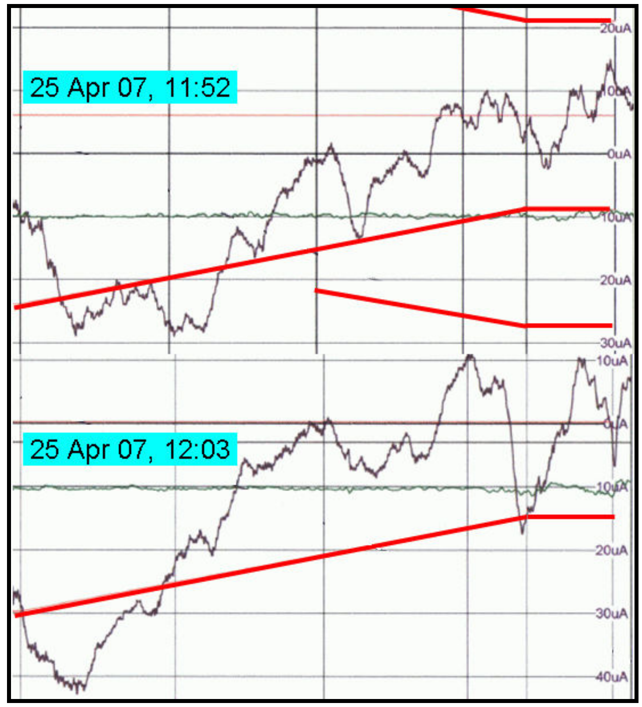

Figure 7. Structure Measurements from 2007.

The Standards in Annex 10 [1] and the Testing Practices in Document 8071 [2], both published by the International Civil Aviation Organization (ICAO), do not address offset facilities. As a result, flight inspection organizations typically apply straight-in precision tolerances to a non-precision application, which does not seem to be appropriate or recommended.

<u>Missed Approach – Offset LLZ</u>

Another example of the use of a LLZ, where procedurally an NDB or VOR would be sufficient if either could meet tolerances, is shown in Figure 8. Here, a dual-frequency localizer is installed at ~3350 meters in a very popular skiing area, to provide missed approach guidance away from the facility. The sensing is reversed so that it flies "normally" for an outbound flight.

On three sides of the LLZ, higher terrain at ~4300m requires a highly-directional antenna system, preventing the use of NDB or VOR. When the LLZ was initially flown as a straight-in facility, using precision approach tolerances, the structure requirements could not be met.

Fortunately, although no international standards existed for this application, the flight inspection organization was willing to compose new tolerances for this unique missed approach application.

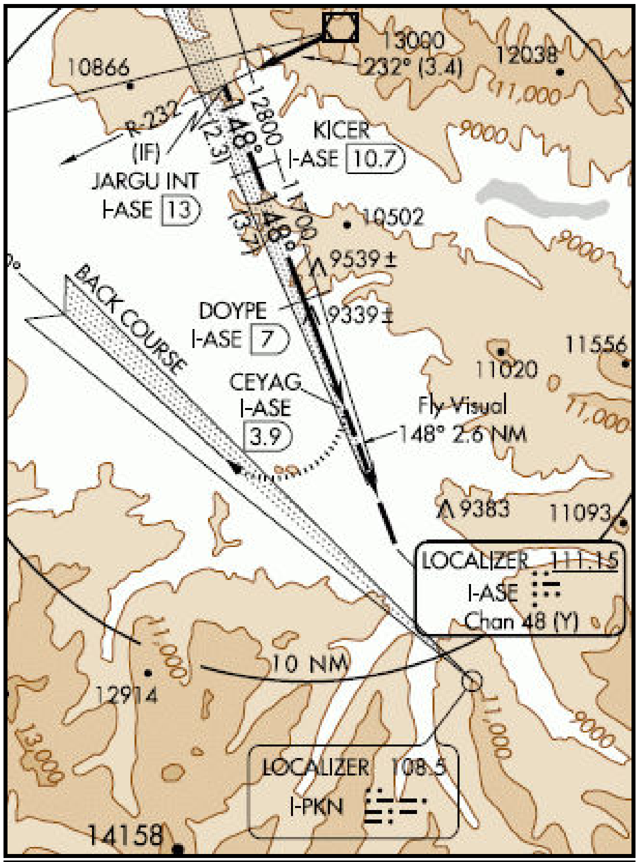

Figure 8. LLZ for Missed Approach Guidance.

Noise Reduction – Offset LLZ with GS

A new offset approach is being considered at a large airport, to reduce night-time noise effects over sensitive neighborhoods. The approach includes a 4-mile segment (offset LLZ with glide slope) prior to a turn to a straight-in visual segment about 1600m prior to the runway, as shown in Figure 9. The Decision Altitude would be relatively high for an ILS-type approach, perhaps 400'.

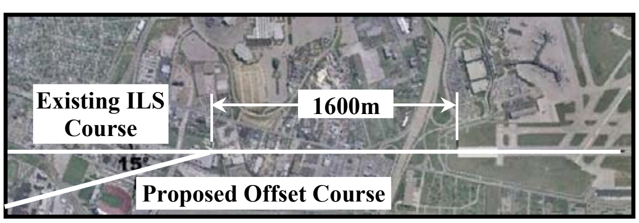

Figure 9. Overview, Noise Reduction Approach.

After all feasible Localizer locations on the offset course line were considered, the best overall site is one near the terminal, as shown in Figure 10. The potential site is circled and is located approximately 600m from the junction of the terminal concourses, on the side opposite the approaching aircraft. The rectangle depicts the approximate normally protected Critical/Sensitive area for a centerline-mounted Localizer. Clearly, the protected area includes a taxiway and some of the terminal ramp area, through which B-737-sized aircraft taxi throughout the day.

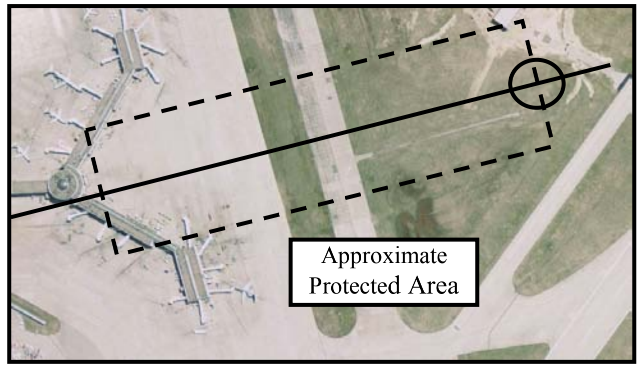

Figure 10. Localizer Siting Behind Terminal.

While this site provides a normal ground-mounted Localizer environment for the antenna array, the installation would be highly unusual in that the terminal is directly between the Localizer and the user aircraft on the offset approach, with the obvious expectation of taxiing and parking aircraft routinely penetrating its critical area. Figure 11 is a photograph from the approximate site location, looking in the direction of the approach.

Figure 11. View of Terminal from Localizer.

The estimated vertical angle to the top of the terminal/concourse structure is 0.7 degrees, while the approximate vertical angle to the user aircraft at the offset approach turn point (lowest use of the proposed localizer) is 2.5 degrees. Therefore the line of sight to the user aircraft is unobstructed, but the effect of the terminal structure on the signals must be determined by sufficiently advanced mathematical simulations and/or site testing [6].

In addition to the potential effects of the terminal structure on the Localizer signals, aircraft will be moving through and parking in/near the Localizer critical area. It is clear the use of the taxiway must be controlled while the offset approach is in use at night, and this may not be a significant issue.

However, aircraft transiting or parking on the ramp near the concourses cannot reasonably be restricted. Unfortunately, no known protected area criteria [1] address this unusual application. Due to the position of the terminal between the aircraft in the critical area and the user aircraft, the multipath from the aircraft on the ground and in the protected area would be blocked or substantially attenuated, compared to a normal end-of-runway localizer antenna installation. This suggests that this protected area violation, while serious in principle, may not be an operational issue. Although a waiver of protected area criteria for normal centerline-mounted arrays will be needed, it likely can be defended by mathematical simulations [6], and by a simple site test with temporary equipment if necessary.

ABNORMAL RECEIVER BEHAVIOR

Previous papers [3, 4, 5] have introduced examples of anomalous receiver crosspointer behavior which sometimes results in inappropriate ground facility restrictions. Here, two additional examples are given for Automatic Gain Control (AGC), or signal strength recordings, and additional examples for VOR crosspointer will be seen in the final section.

While AGC indications themselves seldom result in restrictions for other than insufficient signal strength, abnormal behavior of the AGC recording can often propagate to or cause abnormal behavior of other parameters, such as modulation percentage (SDM).

Level-Sensitive AGC Characteristics

During a commissioning flight inspection effort on a Doppler VOR, it was noted that even during orbital flight, the AGC recording was consistently noisy above a level of -60 dBm, and very smooth at levels below. This is the opposite of normal expectations, since larger signal strengths generally dominate any multipath-induced noise characteristics. The change in behavior was abrupt, and occurred whether the signal strength was increasing or decreasing.

Figure 12 shows four examples of this behavior, with the transition through the noisy/quite threshold level circled. For each segment, the -60 dBm level is shown, with stronger (but noisier) signals plotted above that threshold. In two of the segments, the VOR signal increases and decreases through the threshold. In the first three examples, it is noted that the change in signal levels appears much more compressed below the -60 dBm level than above. This might suggest that very small signal levels may not be displayed to the proper scale. [In this example, the unusual behavior did not cause any facility restrictions, but warrants further investigation.]

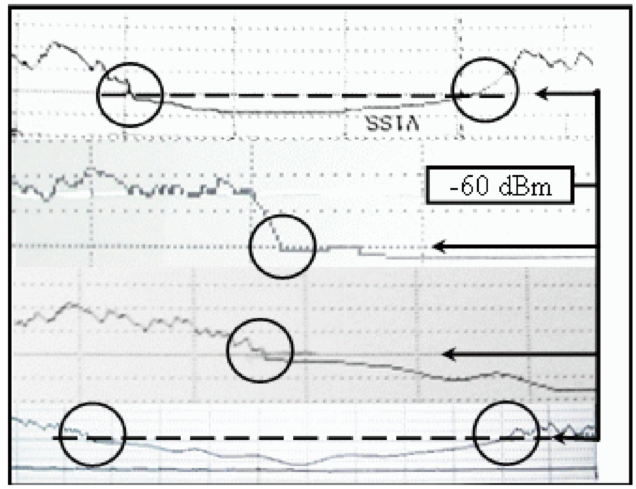

Figure 12. Unusual AGC Parameter Behavior.

Exponential AGC Attack and Decay Characteristics

A second example of abnormal AGC parameter behavior on flight inspection recordings is shown in Figure 13. Here, a glide slope signal is generally increasing in level (downward), from left to right in the figure. Several identified segments of the recording are observed to have exponential shapes where the normally noisy trace becomes very smooth. The two circled areas at left show exponential increases in signal strength, with each lasting approximately four seconds. Several smaller segments in the ellipse at right show exponential decreases.

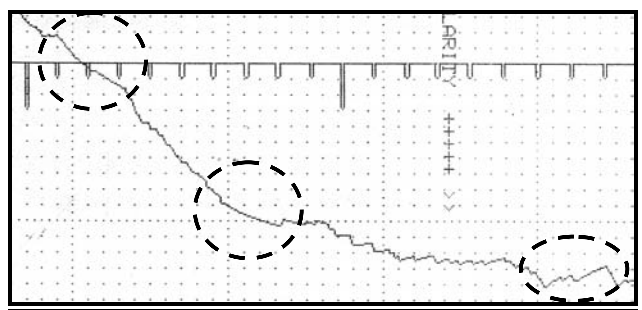

Figure 13. Exponential Increase/Decrease in AGC.

In general, these exponential segments appear on recordings when the rate of change of signal strength is high. This suggests that the AGC circuitry, its display circuitry, or even its software processing may have rate-limited characteristics. During flight inspection measurements, navaid modulation percentages are usually obtained by comparing detected audio levels against a (presumed constant) carrier level from the AGC circuits. The observed apparent rate-limited condition may contaminate response and calibration of the modulation percentage recordings for receivers using this technique.

UNUSUAL CAT III MULTIPATH ON RUNWAY

A recently installed Category III Localizer was mounted on a high platform, but failed to provide in-tolerance guidance in Zone 5 over the runway, as shown in Figure 14. Approximate mathematical modeling of various potential reflectors was conducted as part of the siting activities, and did not predict any appreciable Localizer roughness. The modeling tools used considered only lateral multipath on flat ground, and did not take into account terrain profiles (e.g., slopes and holes) and effective antenna mounting height above these features.

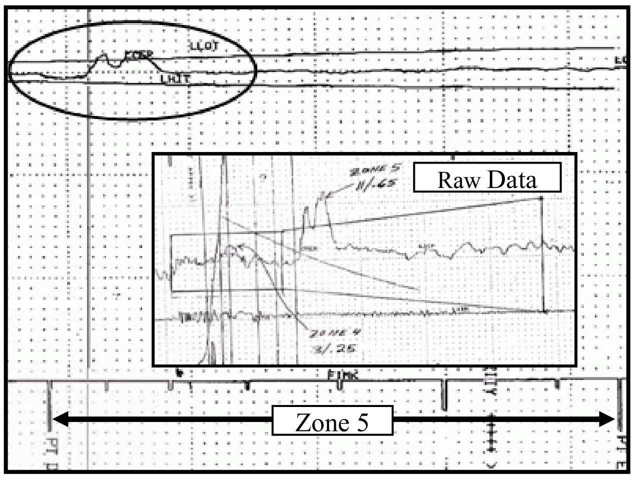

Figure 14. Zone 5 Structure Measurements.

The offending reflection is not in-beam multipath from the 14-element Course array, but rather a reflection from the 10-element Clearance array. The source of the offending reflection was confirmed to be on the pilot's left side of the runway by using a directional antenna while driving on the centerline. Geometric analysis of the reflection environment and the characteristics of the Zone 5 roughness suggest that the large hanger at 40-45 degrees from the Localizer is the source of the reflection, as shown in Figure 15.

Normally, a hanger outside 40 degrees and as distant as this one can be safely ignored for Localizer reflection purposes. However, several characteristics of this site combined destructively to produce the Zone 5 roughness.

- Although newly constructed on fill material, the runway has a 17' dip (below the approach threshold elevation) in its centerline profile, in the area where the Localizer structure is worst, reducing the desired signal level to the receiver in the rollout phase of the approach.
- The geometry for the hanger reflection matches the runway dip location and the measured bad structure location.
- Because the 14-element array is platform mounted on a 26 foot structure as shown in Figure 16, and the view from it to the hanger looks over an unfilled area, the antennas appear abnormally high from the hanger perspective. This tilts the vertical pattern downward, illuminating the hanger more strongly than if everything were on a more typical flat airport.

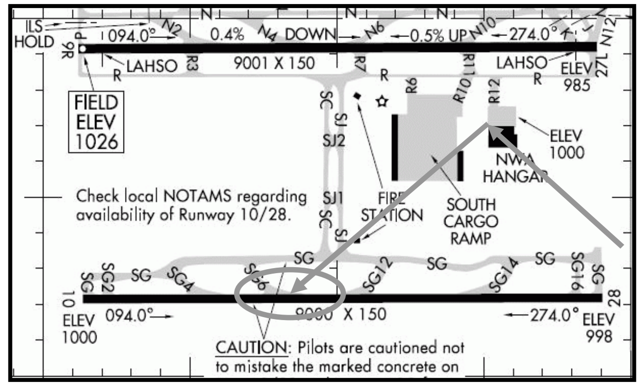

Figure 15. Zone 5 Localizer Multipath Geometry.

Figure 16. Platform-Mounted CAT III Localizer.

TESTING/SIMULATING NEAR-FIELD OBJECTS

Until recently, the capability to mathematically simulate near-field objects at a navigational aid, with sufficient fidelity that the simulations might replace the need for a flight inspection or might validate the flight inspection and completely explain the effects, has not been available. A recent site test of a conventional VOR with extremely close objects provided a validation of a new, completely general solution for VOR/DVOR/TACAN simulations, but also additional examples of potential measurement problems.

Figure 17 is a photo and Figure 18 a diagram of the very challenging flight test conditions, with an ILS marker antenna, shelter, GPS antenna, communications antenna, and a security camera, all within approximately 8-15 meters of the VOR (counterpoise: local height 3.2m, diameter 7.3m) just visible left. In addition, an airport security fence (height 2.5m) rings the test site on three sides, open to the east, at distances of approximately 20 to 80 meters. Due to the proximity of these objects, they have a large azimuthal extent and cannot be considered during simulations as point-like.

A flight test documented the sum of the multipath from all of these objects. Although siting conditions such as these are considered completely impractical for a permanent installation, the test was intended to get an idea about the effects of the close airport fence on the VOR performance and on a potential later Doppler VOR installation. Some detailed explanation and comparison of the new simulations and the flight test will be presented in a separate paper [6].

Figure 17. Site Test of Near-Field Objects.

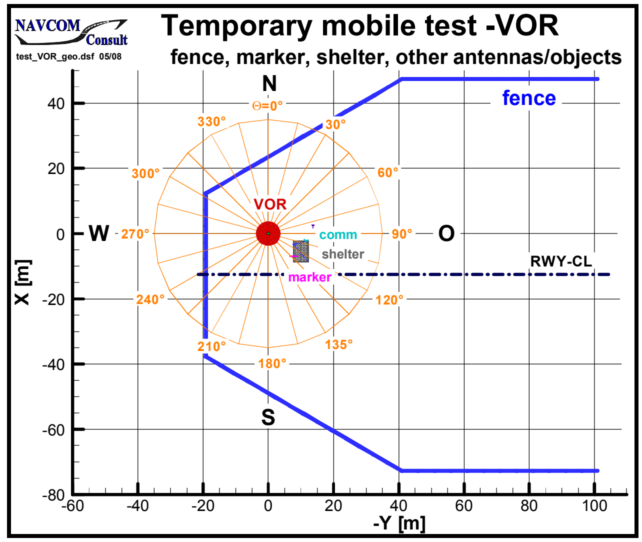

Figure 18. Geometry of the VOR-antenna, airport fence, marker and objects.

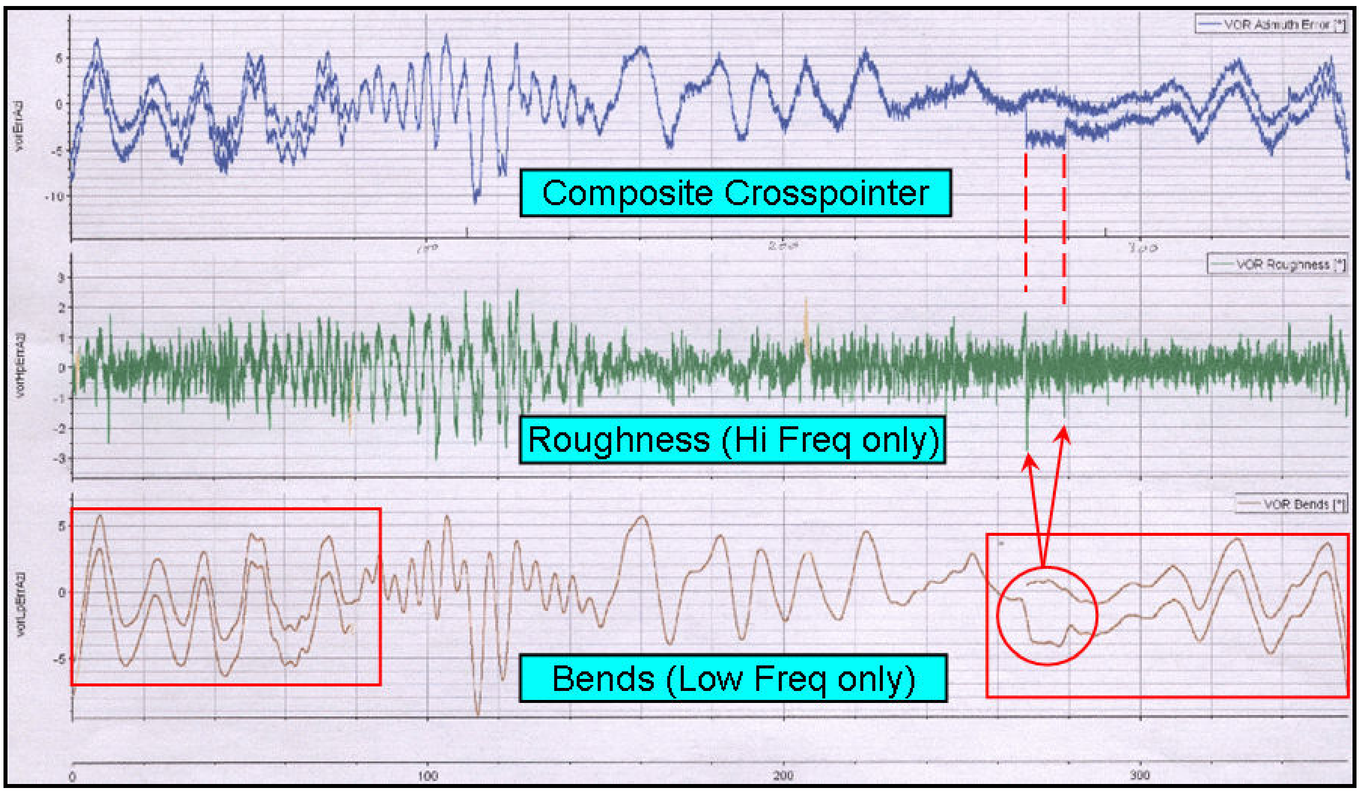

Figure 19. VOR Site Test Orbital Measurements.

Figure 19 depicts the orbital flight data – total error, roughness, and bends are plotted separately. Not surprisingly, the signals are well out of tolerance for much of the orbit. But several measurement or facility errors are also visible.

An apparent step function in the alignment occurs at approximately 270-280 degrees in the top trace. It is unknown whether this error occurred at the test facility, but it is considered highly unlikely. However, it can be receiver-caused, as previously found on other recordings at other locations. Regardless of the source, the error introduces instantaneous at-tolerance high-frequency content in the roughness trace (arrows), and a rounded step function in the bends trace (circle). In addition, an approximately 2-degree change in alignment over time is visible in those portions of the orbit for which an overlap in azimuth was flown. Again, this change in apparent alignment could be a drift in the test facility or a drift in the measurement system, and additional investigation would be required.

For this same VOR test, the new general simulation solution was used to predict the errors from the individual near-field objects, and from all of them together as a comparison against the flight measurements. This is a demanding but typical task for a capable, generalized numerical simulation.

The independent simulations confirm, for example, that the marker antenna is responsible for the ± 5° errors between 320 and 80 degrees. The frequency of these errors is sufficiently low (or almost zero due to the very close objects) that a flight along the affected radials will appear to have a constant alignment error.

It will be intuitive to siting engineers that the fence should produce the largest errors to the east, with smaller diffraction effects to the west. In addition, the error frequency should be much higher than for the marker antenna, due to the greater distance to the fence. As expected, the simulations shown in Figure 20 for the 000-180 degree azimuth segment match the expectations. In the figure, the simulations for all objects (red) and for the fence only (blue) almost perfectly match between 030 and 150 degrees azimuth. In addition, minor high-frequency diffraction errors are seen between 240 and 300 degrees azimuth in Figure 19. Except for detailed phasing of the individual scallops, which are expected to be improved when precise relative geometry is used, the simulations also match the flight measurements in Figure 19 very well.

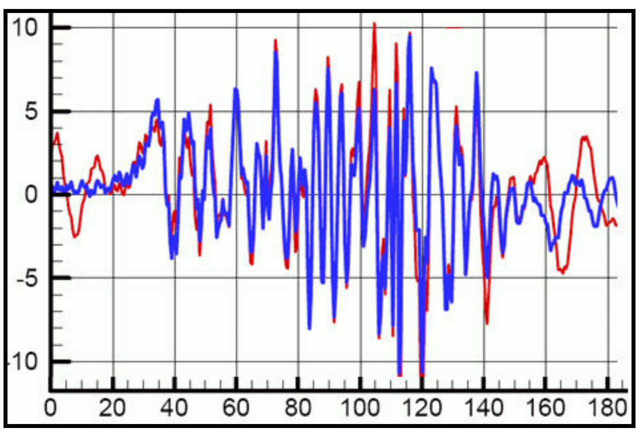

Figure 20. Security Fence Contribution to VOR Near-Field Simulations.

This actual siting test, with both flight measurements and advanced numerical simulations matching so well, shows that even for multiple near-field objects, flight test time may be reduced and eventually eliminated for known or proposed changes in the facility siting.

CONCLUSIONS

The various measurement issues discussed in this paper produce the following conclusions:

a. Flight inspection truth systems must be carefully characterized under both static and dynamic conditions, to ensure that they properly remove as much measurement error as possible. Residual errors must be thoroughly identified. The truth system data for aircraft position must be available.

b. Inappropriate flight inspection truth systems can directly and negatively affect the advertised status of navigation facilities.

c. Unusual applications of traditional ground-based navaids such as large angular offset azimuth systems will increase to cope with the increased demand for system throughput, as well as noise and flight time reductions.

d. It is unnecessarily restrictive to apply precision approach navaid tolerances to a precision approach navaid used in non-precision applications.

e. Additional criteria and more flexibility are needed in the definition and application of ILS antenna protected areas for navaids not sited traditionally with respect to the runway.

f. Navaid receivers designed for routine piloting applications, including those modified to provide discrete flight inspection outputs, frequently exhibit behavior that can mistakenly discredit the navaid being inspected.

g. The ICAO Standards define the signal-in-space of the ground based system, and do not include receiver errors and anomalies. Receiver effects must be identified and removed before facilities can be properly restricted.

h. Advanced modeling techniques that include ground terrain features and effective antenna height above the reflection surface are required for confident siting of low-visibility approach facilities.

i. Advanced and general solution numerical simulation techniques can faithfully predict flight performance of navaid facilities, including those with near-field reflecting objects.

RECOMMENDATIONS

a. Flight inspection mission specialists must be vigilant for these and other abnormal characteristics of flight inspection measurements, and should report each occurrence for further investigation and resolution.

b. When a flight inspection truth system is being initially qualified or questioned due to field experiences, a completely independent measurement system should be used to resolve the issue by contrasting measurements.

c. In the absence of international criteria, flight inspection organizations should consider carefully whether it is appropriate to apply precision approach tolerances to non-precision applications using a precision approach navaid, such as a large-offset localizer. Appropriate tolerances can be developed based on the operational need for terrain and obstacle clearance.

d. ICAO should provide fully coordinated Standards for non-precision applications of precision approach navaids, and more detailed Guidance Material for ILS protected areas when facilities are sited non-traditionally.

e. Flight inspection receivers that were not purpose-built for measurement of navaid parameters should be thoroughly tested under dynamic conditions before being qualified for flight inspection uses.

f. Siting activities for CAT III localizers should be sensitive to runway profiles that can compromise desired-to-undesired signal strength ratios and can result in out-of-tolerance performance over the runway.

g. As modeling techniques become more advanced, flight inspection organizations should consider substituting the reliable simulations in place of some flight tests, particularly engineering and special inspections dealing with defined reflecting objects.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions and assistance with the numerical calculations provided by Mr. W.-D. Biermann of NAVCOM Consult.

REFERENCES

[1] International Civil Aviation Organization, July, 2006, Annex 10, Aeronautical Telecommunications, Volume 1, Radio Navigation Aids

[2] International Civil Aviation Organization, 2000, Manual on Testing of Radio Navigation Aids [Doc 8071], Volume 1, Testing of Ground-Based Radio Navigation Systems (10/02 version)

[3] G. Greving and N. Spohnheimer, Recent Issues in Demanding ILS Ground and Flight Measurement Environments, International Flight Inspection Symposium, Toulouse, France, June, 2006

[4] G. Greving and N. Spohnheimer, Current Issues in Demanding ILS Ground and Flight Measurement Environments, International Flight Inspection Symposium, Montreal, Canada, June, 2004

[5] G. Greving and N. Spohnheimer, Problems and Solutions for Navaids Airborne and Ground Measurements – Focus on Receiver Sampling and TCH, International Flight Inspection Symposium, Rome, Italy, June 2002

[6] G. Greving, International Flight Inspection Symposium, Status and Progress of System Simulations for ATC Systems - Examples, Results and Consequences, Oklahoma City, Oklahoma, USA, June 2008