The Instrument Landing System: Replace it, or Repair it?

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The Instrument Landing System (ILS), in its present 90/150 Hz format, had its beginnings in the United States and England during the years 1939 to 1945. Since then, it has served the aviation community worldwide. There have been many improvements to cope with ever increasing traffic, crowded airports, and difficult siting problems. There are those who say that it's time to replace the system with newer technology; are they right?

1. INTRODUCTION. In 1939, the city of Indianapolis airport became the site of the first of four 109·9 MHz ILS localizers in the United States. The development of the system was described at the time by the four workers (Jackson *et al*., 1939) from the respective viewpoints of the government, and the developers of the antenna, transmitter, and receiver. A Boeing 247-D aircraft (Figure 1) was fitted with receivers and recorders to measure the system characteristics in flight. A few years later, a second 247-D was fitted by United Airlines, leased to Signal Corps, Wright Field, and used for testing the later SCS-51 portable system. A 247-D was similarly equipped and shipped to England (Moseley, 1945). All three aircraft had an electric autopilot and ILS coupler. The following year, an alarm flag was added to the pilot's cross-pointer (Moseley, 1946) to monitor the presence of adequate signal strength. Prior to introduction of the alarm flag, the pilot could only aurally monitor the localizer identification. The glide slope needle was biased to full fly-up in the absence of a signal.

The basic specification for the ILS had been prepared in 1937 at the sixth meeting of the Radio Technical Committee for Aeronautics, and is quoted here in part:

> 1. RUNWAY LOCALIZER.
> (a) The runway localizer shall operate on an ultra-high frequency, preferably in the band 92–96 megacycles, or, if the localizer transmitter is operated as a separate unit, in the band 108–112 megacycles.
> (b) Straight course, i.e., one which has no bends or multiple courses perceptible to a pilot flying in still air.

The choice of a frequency band for the localizer, at Item 1(a), was not taken lightly. The existing long-wave Radio Range had a serious problem with static just when it was most needed. Microwaves were available and considered, but the 110 MHz band was high enough to avoid the static. Its nine-foot wavelength permits diffraction around a large aircraft or over a hump in a runway. Comparative tests (Lee and Jackson, 1940) had shown horizontal polarization to be preferred over vertical. Item 1(b) above, relates to distortions of the radiated antenna patterns. This simple statement would become a subject of concern, and much further development, for many years to come.

Figure 1. Interior view of NC-11 showing work bench replacing passenger seats on the left side. Test instruments and panel operator's seat are forward of the wing spar. Aft, on the bench, is an auxiliary set of instruments for the visitors who would be seated on the couch along the right side. During 1946, ILS and other navigation facilities under development at CAA Experimental Station, Indianapolis were demonstrated to delegates from the Provisional International Civil Aviation Organization. Roscoe Turner flew this Boeing 247-D in the 1934 London–Melbourne air race. In 1952 it was flown to Washington, retired permanently, repainted, and hung from a ceiling in the Smithsonian Museum.

The glide slope component of the ILS, in the band 329–335 MHz, was not adopted until 1941. This step was taken after a joint CAA/military study of the ILS against competing microwave systems on 10 cm and 3 cm wavelengths. Flight tests were conducted at three different types of site: Indianapolis (flat), Cincinnati (sunken), and Pittsburgh (hilltop). In 1942, the CAA placed the first production orders for the ILS at 10 major cities. By 1946, there were 47 more ILS on order, and in 1947, scheduled airlines began using the ILS under reduced minima (Metz, 1959).

2. FINDING THE AIRPORT VERSUS LANDING ON THE RUNWAY.

The process of navigation to a completed landing by instruments, divides naturally into two quite different tasks. Task 1 comprises finding the airport: specifically, navigating to a region located suitably on the downwind extension of the intended runway, and turning inbound. Task 2 includes: responding to the localizer deviation signal; stabilizing the aircraft heading with due regard for cross-wind; intercepting the glide path; establishing a rate of descent; and following the cross-pointer deviations to the point of landing. It should be noted that task 1, navigating to the final approach fix and finding the localizer course, can be better accomplished today by the use of several systems that did not exist in 1939, such as satellite, omni-range, r-nav, Loran, or distance measuring equipment. In spite of this, the ILS is still expected to maintain standard characteristics outside of the linear course guidance sector. If this was not the case, automated airplane systems might execute a 'false capture' prior to arrival at the localizer course.

3. PROBLEMS AND CURES. It may be helpful to consider dividing the problems into the following categories: localizer multi-path in task 1; glide slope distortions in task 1; localizer multi-path in task 2; glide slope distortions in task 2; and FM broadcast interference to localizer transmissions.

3.1. *Localizer Multi-path in Task 1.* The radiation patterns of early localizers, such as shown in Figure 2, covered 360 degrees in azimuth and were used for finding the airport (task 1), as well as for landing (task 2). They included a back course capability. Such broad patterns are very vulnerable to multi-path re-radiation causing course bends. As airports, hangars and airplanes grew larger, these problems became worse. It was decided to take a step that tended to separate task 1 (finding the

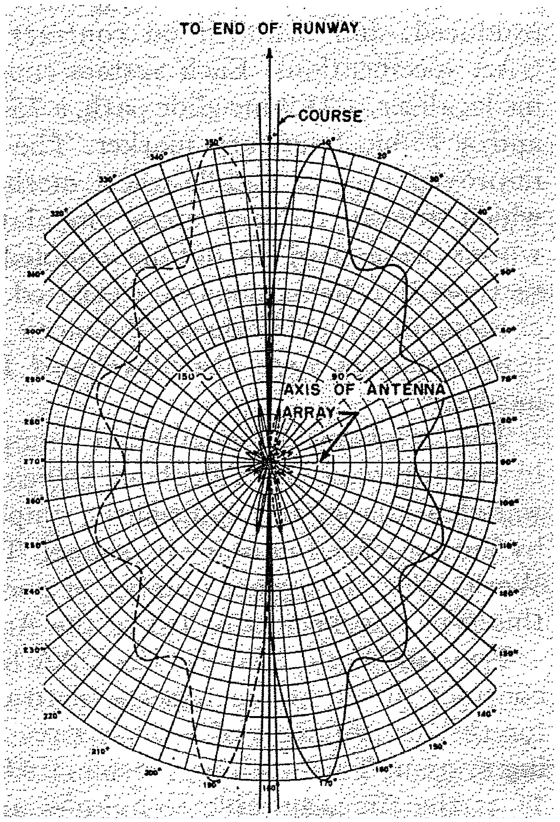

Figure 2. Alford eight-loop localizer polar plot showing the right and left 90/150 Hz beam patterns, plus/minus 180 degrees with equal strength front and rear courses. Before the introduction of the VHF omni-range, this type of ILS localizer antenna pattern was used, with basic flight instruments and orientation procedure, as the sole radio navigational means to find an airport and land.

localizer) from task 2 (approach and landing). The Air Navigation Development Board (Leas, 1950) approved a proposal by Andrew Alford, to employ a narrow guidance antenna pattern together with a broad clearance antenna pattern, as in Figure 3. Each antenna had its own RF carrier, closely spaced, so that both would be in the pass-band. The stronger of the two would tend to 'capture' the receiver detector (Butterworth, 1929). While somewhat dependent on receiver type, the capture effect produces, roughly, an audio ratio equal to twice the square of the RF ratio. Thus, there exists a very rapid transition from clearance signal to guidance signal as the azimuth angle changes through the point of equality. The development was followed quickly by a series of narrow beam antenna projects aimed at reducing the effects of reflections. These projects are summarized in a special IRE issue (Jackson, 1959). Metz, in the same issue, provides a detailed outline of the ILS history to the year 1959 (Metz, 1959).

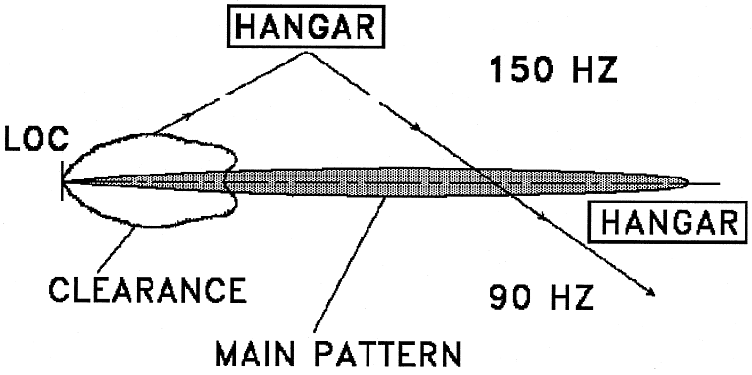

Figure 3. Polar field strength patterns of a directional localizer (2F). Note that the main guidance beam is made sharp enough to miss completely the closest hangar. The more distant hangar is in the clearance pattern, reflecting signal across the centerline. If strong enough, the reflection can cause bends in spite of capture effect.

The development of sharp guidance patterns followed the trends in other fields, where parabolic reflectors, linear dipole arrays, and slotted waveguides were being used. The clearance arrays had 360-degree coverage, providing a back course. However, availability of the two-frequency (2F) technology did not mean that it necessarily would be implemented. In the first place, in addition to having the two antennas, two transmitters and two monitors would be required, almost doubling the cost. In the second place, there was usually another new technology waiting in the wings, along with the philosophy 'newer is better.' In the mid 1960s, the 2F localizer received only moderate use. More effort was put into shaping the single-frequency patterns to be 'self-clearing.' In addition, the concept began to gain popularity that clearance coverage need be only plus and minus 35 degrees rather than 360 degrees. This idea was not quickly accepted overseas, as the author discovered personally, when he attempted to record 360-degree clearance on a V-ring localizer in Turkey in 1968. The flight inspection receiver recorded weak deflection at about 120 degrees from the front course, and acceptance was refused. When the disappointed author boarded a PanAm flight to return home, he persuaded the pilot to circle the airport once after takeoff. Keeping his eyes glued to the localizer needle, he did not see it leave the stop.

The change to plus/minus 35-degree coverage, with no back course requirement, allowed for the introduction of the LPD (log periodic dipole) as an element in localizer arrays. With reduced signal radiated beyond 35 degrees azimuth, single frequency LPD arrays became more immune to reflections from hangars.

In the late 1970s, two frequency (2F) systems started to become more popular and came in several configurations. In spite of the greater cost, they were considered very useful for runways having very large hangars nearby. Referring again to Figure 3, we see the ray reflected from a hangar, then crossing the runway centerline and continuing into the opposite side clearance sector. When crossing the main pattern, the reflected clearance signal is prevented from producing serious course bends by the 2F-capture effect. However, the 150 Hz reflected signal, continuing into the opposite sector could, if strong enough, make a hole in the 90 Hz clearance. Several workers have found that shifting the *audio* phase, clearance versus guidance modulations, can be quite beneficial in such a case. A more potent cure would be a 3F system, which places the 90 Hz clearance sector on its own RF carrier, so that capture effect will keep the 90 Hz deflection intact. To the author's knowledge, this cure using 3F has never been implemented, although it would not be very expensive. It would involve changing the clearance transmitter SBO output stage to a CSB stage modulated with 90 Hz only, and shifting its carrier frequency a small amount to F3. Also, the original clearance CSB stage 90/150 Hz modulation would need to be changed to 150 Hz only. A wiring change in the antenna feed network would then route the F2 and F3 signals to the appropriate sides of the runway.

The foregoing problem is much harder to cure if the reflected ray equals or exceeds the strength of the direct clearance signal. In this case, if it exists, the 3F cure will not work. In the opinion of the author, the best solution, other than modifying the hangar, is to convince the aviation community that they no longer need the task 1 function of the ILS. If this could be done, then the clearance transmitter 90/150 Hz modulation could be turned off, leaving pure F2 carrier. This would create what Alford called a 'swamper.' The un-modulated carrier captures the receiver, causing the alarm current to drop to zero, and the spring-loaded flag to cover the cross-pointer. Figure 4 shows a proposed plot of flag current versus azimuth. There is no safety issue involved, and the main course is left undisturbed.

3.2. *Glide Slope Distortions in Task 1.* One may wonder why glide slope should be involved at all with task 1 – finding the airport. The approach procedure should be to ignore glide slope deflections until after bracketing the localizer. In fact, if someone started following the glide slope outside localizer full-scale width, they could get into very serious trouble. With this in mind, pilots may tend to be upset if they see a fly-down indication before they have reached the edge of the localizer sector. Therefore, there is some justification for requiring glide slope coverage to be somewhat wider than the localizer full-scale width. The problem arises when an image-type glide slope antenna is placed on a ground plane of such limited extent that the required coverage cannot be obtained. The only cures were landfill, which could be very costly, or, a non-image broadside array requiring a very tall mast, with its own siting problems. In 1972, development resumed on the non-image end-fire glide slope antenna, resulting in the 1978 installation at Rock Springs, Wyoming. At the same time, however, another technique using microwave was having a revival in a very big

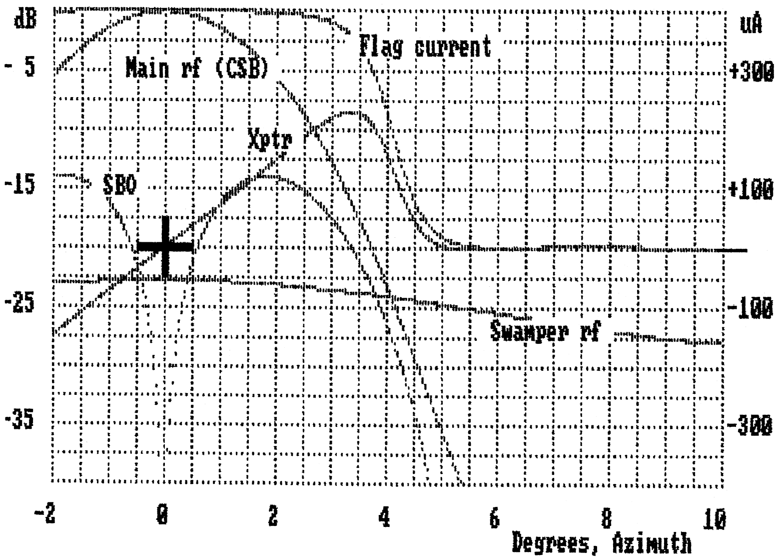

Figure 4. Showing author's proposal to substitute a wide coverage swamper antenna fed with F2 unmodulated carrier in place of the conventional clearance array and clearance transmitter. Note rapid flag current transition at four degrees azimuth.

way. Support for ILS development stopped almost completely. The pressure to scrap the ILS became country-wide, then worldwide. A major aviation magazine (Klass, 1982) was reporting the claim that the ILS cannot be used at small airports in mountainous areas; at that time, the author was fortunate enough to be installing an ILS End-Fire Glide Slope (EFGS) on a mountain top in Venezuela (Figure 5). That same magazine would not use the black and white, glossy print of the mountain-top EFGS, supplied at considerable effort. However, the cure remains, used or not.

3.3. *Localizer Multi-path in Task 2.* Precision lateral guidance from the outer marker down to landing and roll-out is the primary purpose of the ILS localizer. Over the years, as the reflection surface (hangar) became larger and closer, the localizer main beam needed to be made sharper. According to physical laws, this means wider antenna aperture. Fortunately, there should be plenty of room. For safety, a typical instrument runway is normally required to have a shoulder on each side, giving a rather wide clear strip. After Alford's 2F proposal, main antenna apertures were commonly in the range 80–110 ft. Antenna types were parabolic reflectors, linear dipole arrays and slotted-waveguides. A 300-foot waveguide was installed for a while at Atlantic City. Probably, the all-time record localizer aperture was 400 feet (Lemmon and Herd, 1967). Today, apertures of 130–165 ft have become popular. Most localizer antenna arrays have been supplied signals through a corporate or parallel feed network. The slotted waveguide and slotted cable are exceptions, employing serial feed. The difference in feed method is significant when considering increased apertures. Serial feed has the advantage in having fewer components when extended to large apertures.

To evaluate the benefits of increased localizer aperture, it is helpful to compare plots of the localizer SBO field strength versus azimuth. It is the SBO signal

Figure 5. Photograph taken through the windshield of a light twin-engine aircraft in March 1982, approaching the middle marker, at Aeropuerto de Caracas. The installation here of ILS with End Fire Glide Slope was proof that ILS could indeed be successfully installed at a small airport on a mountain-top.

component that accounts for the deflection of the cross-pointer needle. Figure 6 shows a comparison of several SBO patterns for different apertures. If these are plotted to the same zero-crossing slope, they can be used to predict a bend reduction factor. For example, suppose an existing localizer, 100 ft. aperture, is suffering course bends from a known reflector at 2·5 degrees azimuth. Reading from Figure 6, the SBO amplitude here is 0·80. At this same azimuth, the 278-foot aperture (slotted cable) shows an SBO amplitude of 0·35. The bend factor is therefore 0·35/0·80 or 44 percent of the original value. For a reflector at five degrees azimuth, the bends produced by the 278-foot antenna would be essentially zero amplitude in comparison with any of the others.

It should be mentioned, in connection with bend reduction using wide apertures, that some attention must be given to the distance between the localizer and the offending reflector. With an aperture as large as 278 ft, the radiation pattern becomes somewhat broader at closer distances on the airport due to near-field de-focussing. However, if, for example, the reflector is a large hangar at a distance of 7000 ft from the localizer, the antenna can be focussed at that distance by laying it out in a gentle curve with the ends brought forward 2·3 ft. Existence of a cure does not guarantee that the cure will be used. Shand (1995) has recorded the unfortunate tale of new hangar construction at Cardiff destroying the ILS localizer service there. It should not have happened.

The more difficult problem for the localizer relates to the complex matter of defining the *critical area*. Aircraft, and other vehicles on the ground, need to be kept

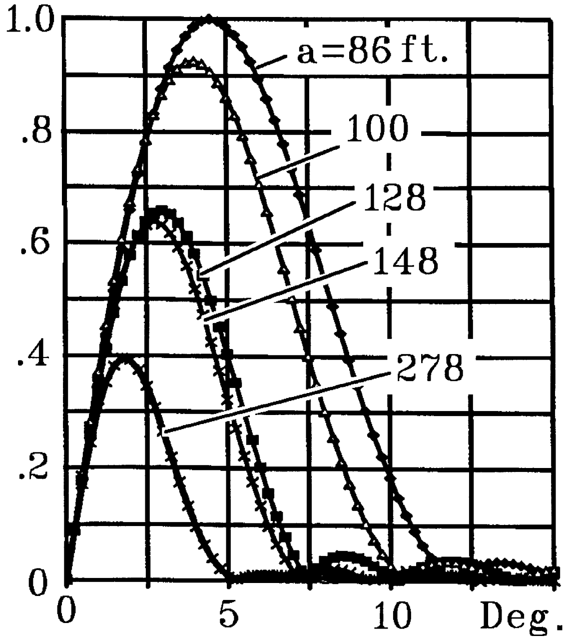

Figure 6. Comparison of SBO (deflection) localizer patterns, plotted to the same zero-crossing slope (course width), for different apertures. Note that the 278-foot aperture will produce essentially zero multi-path with reflectors at five degrees or beyond.

out of locations where they can reflect enough energy to have significant effect on the quality of the guidance signal being received by a landing aircraft. Computer modeling studies (Quinet, 1999) are currently on going toward revising the size of *critical areas*. The number of variables is large, including taxiing aircraft locations, types and orientation, as well as building locations and orientations. Without being very exact, one can conclude that the localizer radiation should be confined, in azimuth, as closely as possible to the runway served.

Figure 7 is intended to indicate how increased localizer aperture could reduce the *critical area* in an imaginary situation. Here, the movements on a parallel runway and taxiway may have to be curtailed, during weather requiring instrument approaches, to avoid interference with instrument landings. The figure shows two maps of the same airport, using localizers of different apertures. To improve clarity, the map scale is expanded in the transverse direction. The left view has localizer 'A' with a 148-foot aperture. Superimposed over runway 30L is a contour line of constant SBO field intensity, calculated at a fixed altitude of 50 ft over the runway. A reflection from an aircraft, in a particular orientation, located anywhere on the contour line could be expected to re-radiate with the same intensity. Thus, the contour should be a useful guide in evaluating the size and shape of the *critical area*. The right half of Figure 7 shows the same runway 30L, but has localizer 'B' with 278-foot aperture. The associated SBO contour line is plotted to the same zero crossing slope as with localizer 'A', allowing direct comparison of the two apertures. Figure 8 is a photograph of a 278-foot aperture localizer.

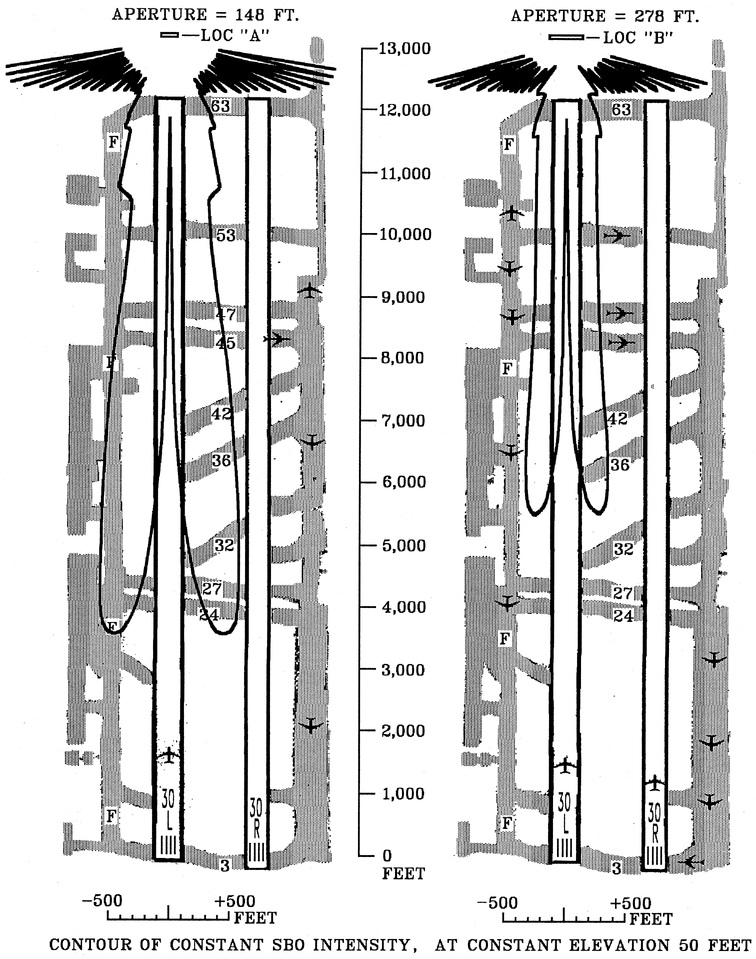

Figure 7. Indicating increased freedom of movement to be expected in parallel runway operation when using 278-foot versus 148-foot localizer aperture. For the comparison, both SBO (deflection) contours are plotted with the same power and course sharpness, crossing the runway edge around taxiway 36.

3.4. *Glide Slope Distortions in Task 2.* The glide slope coverage sector is required to be wider than the localizer guidance sector, mainly for the reason that the glide slope antenna must be offset from the runway centerline, unless buried in the pavement. As the aircraft follows the localizer, approaching the runway threshold, the angle subtended to the glide slope antenna increases more and more. The maximum angle, of course, will depend on the offset distance. This tends to define the minimum azimuth coverage requirement. A small antenna offset distance is a characteristic of EFGS.

Probably the most serious problem for glide slope antennas, of all kinds, has been the runway that has high terrain under the approach. An extended upslope can reflect enough energy into the path to produce out-of-tolerance distortion. The classic cure involves canceling out the radiated signal reaching the offending upslope, or reducing

Figure 8. Localizer antenna, 278-foot aperture, installed for testing. The radiating slotted cable is on frangible mounts, about head height. A corner reflector of copper tubes extends up behind the antenna. To the right, is an LPD 20 element array used for optional clearance.

its amplitude. This was done by Iden about 1958 with the M-array. Butts (1967) added below-path clearance creating Capture Effect Glide Slope (CEGS). In 1978, the first upslope version of EFGS was tested at Butte, Montana.

3.5. *FM Broadcast Interference to Localizers Transmissions.* If ever there were a preventable, man-made ILS problem, this is it. It was long after the ILS became well established that FM broadcasting invaded the radio spectrum. Picture a pilot on an ILS approach, about 7 miles out, flying above a thick layer of ground fog. Now, looking out a side window, he notices the top end of an FM broadcast tower projecting through the fog about one mile away. Next, the localizer needle starts to follow the drumbeat of a rock and roll band just before the autopilot disconnects. The FM station has, perhaps, 50000 watts at the top of the tower outside; the localizer has about 15 watts at ground level, at the far end of the runway ahead. This is a difficult problem, but there are possible solutions: 1. get the localizer moved to a different frequency (may be difficult); 2. get the FM station moved to a different frequency (still more difficult); 3. get all aircraft that might need this facility to change to a receiver with better RF selectivity (most difficult).

4. CONCLUSION.

Cures exist for the known problems with the ILS. Whether there will be motivation to apply the cures is uncertain. The most difficult problems seem to be associated with task 1, finding the airport. Delegating task 1 to a more modern system would cut ground equipment costs by a significant factor. This would also leave the ILS free for task 2, which it can do better than anything else, horizontal and vertical guidance to a safe landing on the runway.

Since the ILS began, the clearance requirement has dropped from plus/minus 180, to 35 degrees with some advocating 10 degrees. The author thinks it is time to eliminate the clearance requirement (task 1) altogether. The motivation for this could be the complete freedom to build larger hangars up to the point of physical limitation.

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KEY WORDS

1. Air. 2. Navaids. 3. ILS.