PREDICTING THE EFFECTS OF SHADOWING AND SCATTERING FROM
PLANAR SURFACES ON LOCALIZER COURSE STRUCTURE USING
GEOMETRICAL OPTICS AND THE UNIFORM THEORY OF DIFFRACTION
AS IMPLEMENTED IN THE NEAR ZONE BASIC SCATTERING CODE/

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Elliott C. "Rusty" Rushton
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I. SUMMARY

A new computer-based mathematical model has been designed to calculate the effects of scattering, signal blockage (or shadowing), and scatterer interactions on the course structure of the Instrument Landing System (ILS) localizer. This model uses the Ohio State University ElectroScience Laboratory Near Zone Basic Scattering Code (NZBSC) along with a pre-processor and a post-processor interface which were designed at Ohio University Avionics Engineering Center as a part of this work. No current localizer model has the capability to predict the effects on the localizer course structure produced by shadowing. This model using NZBSC has been developed for the purpose of evaluating the effects of scatterers such as hangars, closely spaced power lines, and vehicles on the localizer course structure. The theoretical bases of this model for calculation of the scattered fields are Geometrical Optics and the Uniform Theory of Diffraction. The pre-processor and post-processor were designed to implement the NZBSC appropriately for analyzing localizer course structures in a multipath environment where reflections, signal blockage, and scatterer interactions exist.
II. INTRODUCTION

Safety in air travel today is greatly enhanced by the presence and continuing development of more reliable navigational aids. The siting of navigational systems for aircraft is frequently challenging, many times because of construction taking place in the nearby environment. The use of computer technology permits the engineer to perform analytical tasks which permit ILS components to be sited efficiently. Calculations based on sophisticated mathematical models allow quantitative predictions of the effects of multipath on the quality of the radio navigation information.

Of all the systems used by aircraft for approach to landing, (Instrument Landing System, Microwave Landing System, Differential Global Positioning System\(^a\) [1]), the Instrument Landing System (ILS) is employed more than any other in the United States today. There are more than one thousand commissioned systems in service [2]. ILS was the first landing system used and was initially installed at Indianapolis in 1939 [3].

The ILS localizer is one of the functional parts of the ILS. The localizer is the ILS component that transmits left/right guidance signals to the airborne receiver, thus allowing the aircraft to align with the extended centerline of the runway. Using this

\(^a\) Today, DGPS is a proposed system [1].
lateral guidance information, a pilot is able to execute an approach even when weather conditions provide little or no visibility from the cockpit (a more detailed description of the localizer can be found in [4,5]). This enables aircraft to land more reliably with less regard for the visual conditions [6]. An important consequence is the directly affected reliability of flight schedules, which are crucial to the economics of air transportation.

Airport congestion, hangar construction, and other airport environment changes can generate multipath which degrades the performance of the ILS and prevents commissioning and operation. Since this factor also influences the availability of the landing system, these changes can impact economic issues surrounding air transportation. It is these reasons which motivate the avionics industry to find more effective means of analyzing the problems that occur in landing systems.

One of the main problems encountered when installing and operating reliable landing systems is signal multipath. The term "multipath" refers to signals with other than direct transmission paths to the airborne receiver. Multipath is produced by signals scattering from reflective objects in the environment [7]. Due to differences in characteristics of the magnitude and phase created by the different path lengths and the mechanism of the scattering, multipath creates interference patterns in space that translate into errors in the received signal. These errors affect the guidance information presented to the pilot through the course deviation indicator (CDI).
Mathematical modeling provides the chief analytical tool to allow quantitative assessments of the deleterious effects of multipath.

For over 20 years, computer modeling has helped make planning for ILS installations more efficient and assessment of the physical environment more precise. Information taken from construction drawings, topography maps, and airport layout plans provide source data for the mathematical model when it is used to predict the localizer course roughness. Using modeling tools, factors in the modeled environment can be specifically identified and perhaps subsequently altered to minimize error caused by multipath sources. Computer models are also used to plan changes in the environment of an ILS installation. Models are routinely used to predict the effects of proposed construction on the localizer course structure. These results may impact the size, placement, and orientation of the scatterer and the type of ILS antenna installation if significant problems are predicted. All of these possibilities can be explored through use of computer models, this being done, many times, with less expenditure of time and money required by performing experiments in the field.

In most practical situations, the localizer antenna array itself is changed since scatterers such as buildings causing the roughness cannot be changed. In some cases, however, parameter changes such as orientation of the scatterer and the localizer
antenna type are not available for changing to correct the multipath problem. In one such case at the San Jose Airport, a different type of solution was attempted.

During the time construction was to be performed on the stop end of the San Jose Runway 30L, it was essential to maintain use of the runway and its localizer. However, the construction vehicles, potential sources of multipath, would be penetrating "critical areas" which are to be free of such objects. Critical areas experiments using a jumbo jet in the proximity of the localizer array show changes to the localizer course structure that create out-of-tolerance conditions [8]. If critical areas penetration were totally prohibited, this would force the San Jose Authority to close the runway during construction. A possible solution was the introduction of a screen symmetrically placed on the extension of centerline of the runway between the localizer array and the construction vehicles. It has been shown, in the past, that symmetrical obstructions cause minimal disturbance of the localizer course structure when compared to non-symmetrical ones [9]. The hypothesis was that a stationary, symmetrical obstruction to the array would lessen the effects of the construction vehicles. Unfortunately, there were no computer models available to test this hypothesis. Existing models were designed to account only for the effects of reflections on the localizer course structure. This demand motivated research performed on the design and validation of a model to predict the effects of shadowing and signal blockage on the localizer course structure.
The development of the computer-based localizer shadowing model is described in this document. Initially, the possible choices of theoretical bases for the localizer shadowing model are discussed. Next, the selection of Geometrical Optics and the Uniform Theory of Diffraction for use is justified.

Validation and testing of the localizer model is an important subsequent step which calls for the use of data known to be accurate for use as a baseline comparison. Following these steps, the limitations discovered during the development process are identified and documented in detail.

This document describes the development of a mathematical model based on Geometrical Optics (GO) and the Uniform Theory of Diffraction (UTD) to predict effects of scatterers such as shadowing and reflections on the ILS localizer course structure. The theory on which the code is based, implemented in Ohio State University ElectroScience Laboratory Near Zone Basic Scattering Code, enables the model to predict accurately the fields in regions shadowed from the source by objects where current models are not valid. This improvement increases computational accuracy in these regions and broadens the capability to model various scenarios.
III. HISTORY OF MODELING AT THE OHIO UNIVERSITY AVIONICS ENGINEERING CENTER

The Ohio University Avionics Engineering Center has been involved with research and development of mathematical models for more than 20 years. In 1966, D. Luttermoser published a M.S.E.E. on the development of a model using Physical Optics (PO) and Huygens secondary sources to predict the effects of a layer of snow on the ground plane area in front of a null reference type glide slope array [10]. In that same time frame, D. Hill published documentation of a similar method applied to the effects of irregular ground terrain on imaging glide slope systems [11]. In 1969, R. Redlich and J. Gorman published a paper discussing the utilization of PO for use with ILS localizer modeling [12]. In 1972, Y. Kwon used Geometrical Optics to predict the effects of scattering from the fuselage and tail fin of a Boeing 747 onto the glide slope course structure [13]. Also in 1972, Chin, Jordan, Kahn, and Morin from the U. S. Department of Transportation, Volpe National Transportation Systems Center (VNTSC, formerly TSC), in Cambridge, Massachusetts, released results from efforts to use PO and the vector Green's Theorem to model airport environmental effects on the localizer course structure [14]. In 1974, Morin, Newsome, Kahn, and Jordan applied this same method to the ILS glide slope for irregular terrain [15]. The localizer model from VNTSC has been modified by Ohio University Avionics Engineering Center (OUAEC) for use with a graphical interface to facilitate its use. In 1973, R. Rondini published a technical memorandum on the application of Kirchoff's Diffraction Integral to
diffraction and shadowing caused by a Boeing 747 and its effect on the localizer course structure. Rondini also published documentation of this method applied towards the ILS glide slope in 1976 [16]. Later, in 1981, V. Ungvichian completed validation of a model using GO and the Uniform Theory of Diffraction (UTD) to predict the effects of irregular terrain on the glide slope structure [17].

Among the above models, the VNTSC PO localizer model is the most suitable model, if modifications are made, to obtain the desired result of a model usable for predicting the effects of shadowing on the localizer course structure. The PO model needs to be modified to include mathematics that allow more accurate predictions in the shadow regions. The suitability of this modification will be discussed later in more detail.
IV. CHOICE OF THEORETICAL APPROACH

Research was performed on selected electromagnetic theories and their suitability for predicting the effects of shadowing by scatterers in practical applications. The primary interest in these theories is validity in the shadowed regions behind scatterers, as illustrated in Figure 1.

![Diagram of shadowed region](image)

**Figure 1.** Illustration showing the incident shadow region, the primary region of interest for this modeling study.

Of the theories that can be used to calculate fields in this region, three were initially selected. These are the Method of Moments, Physical Optics with the Physical
Theory of Diffraction, and Geometrical Optics with the Uniform Theory of Diffraction. The selection of the theory on which to develop a mathematical model from these three choices was based on calculation efficiency, ease of implementation, reliability, and documentation available.
A. The Method of Moments

The Method of Moments (MoM) is the name given to a numerical technique used to solve integral equations [18,19,20,21]. In electromagnetics, integral equations describe the field incident on a surface to the currents induced on that surface. One such equation is known as the electric field integral equation (EFIE) [22]. MoM can be used to solve for the unknown current distribution on the scatterer, which can be used to determine the scattered field from that surface. The method enables one to approximate the solution of the EFIE which would otherwise be difficult or even impossible. The approximation is generally an accurate one and in some cases the result is the exact solution.

The process of solving a problem using MoM involves solving equations to fill in elements of a large matrix (dependent on the electrical size of the scatterer). This process is usually performed on a digital computer because of the number of mathematical manipulations involved. During this process, problems have surfaced. These problems are presently being researched. One problem is the vast amount of computer memory and speed necessary to evaluate the elements of the large matrix in modeling of practical applications unless an alternative matrix can be found. Another problem encountered using MoM is numerical instability which occurs due to the truncation of significant digits during the many calculations performed by the computer [23]. Due to the problems associated with this method, this theory was not selected.
B. Physical Optics and the Physical Theory of Diffraction

Using Physical Optics (PO), the magnitude of the current induced on the scatterer surface (from the EFIE) by the incident field is assumed instead of calculated directly. This assumption, though limiting in some cases, greatly increases calculation time while simplifying the complexity of the mathematics. To obtain the induced current, a Geometrical Optics (GO) approximation is used, and these currents are assumed to be the same magnitude as if the surface were infinitely large (greater than 10 wavelengths is sufficient for this assumption in most cases), which is typical for optical techniques [24]. This current is:

\[
J_{po} = \hat{n} \times H_{total}^{\text{illuminated region}} - \hat{n} \times H_{total}^{\text{shadowed region}}
\]

The fields radiated from these currents are calculated directly by evaluating the radiation integral over the surface of the scatterer. This equivalent source method allows PO solutions to give useful estimates of the scattered field in directions other than that of specular reflection. However, PO fields are not valid where the direct or specular reflection field is not dominant, as in shadow regions. This is because the GO current approximation which is used is not valid near edges or on shadowed surfaces. PO will give an accurate representation of the scattered fields emanating from a surface provided the assumed PO current is reasonably close to the true current [25]. This leads to imposing high frequency assumptions necessary when
using optical techniques such as PO. They require that the scatterer preferably be greater than 10 wavelengths in the smallest dimension. The wavelength for localizer frequencies is approximately 9 feet (108 - 118 MHz).

A localizer model based on PO has been implemented successfully by VNTSC [14]. It is used for evaluation of scattering onto the localizer course structure by large obstacles. Since the model is based on PO, its results are not valid if the observation point passes through a shadowed region. Without modification, the model cannot be used for evaluation of the effects of blockage due to the limitations of the theory on which it is based.

While PO alone does not provide accurate field solutions in the shadowed regions of scatterers, an extension of PO called the Physical Theory of Diffraction (PTD) has been developed for use with PO, helping to eliminate this limitation [26,27]. The PO/PTD fields together more closely represent the actual scattered fields in many practical situations. At the present time the PTD is developed only for edged bodies and is limited to those applications [28]. The calculation of the fields in PO and PTD involves timely numerical integration, which greatly increases the amount of CPU time the computer model requires to calculate the scattered fields. Scatterer interactions, such as coupling between two scatterers in close proximity to one other, are not calculated with PO/PTD. This is essential since many applications will have two scatterers, one of which shadows the other from the radiating source as in Figure 2.
PO and PTD were not chosen to be used in this model for three reasons. The first is the lack of considerations of scatterer interactions or coupling that would allow the effects of a shadowed scatterer to be calculated. The second is the large computing time needed to perform the numerical integrations that are necessary with PO and PTD. The third is the difficulty foreseen in implementing the complex mathematics of PTD with PO. Due to these reasons, PO and PTD are viewed as poor choices for this modeling exercise.
C. Geometrical Optics and the Uniform Theory of Diffraction

Geometrical Optics (GO) is a technique used to evaluate scattering by objects [29,30,31]. GO was originally developed to analyze the interaction of beams of light with objects. In that application, the wavelength of light is sufficiently high that the wave nature need not be considered as with lower frequency interaction. GO, frequently referred to as ray optics, uses rays to analyze the propagation of electromagnetic waves, approximating the direct and reflected field contributions at the observation point in space. This assumption is only valid where the wavelength of operation is small with respect to the size of the scatterer or antenna that is being analyzed and the observation point is not near a shadow boundary. Shadow boundaries divide regions of space where the different ray contributions (direct, reflected, diffracted, etc.) do and do not exist. An illustration of a canonical diffraction problem is shown in Figure 3 with the shadow boundaries between three regions of space labeled. Within these three regions, different ray components representing the total fields exist.

Figure 3 shows the GO ray contributions (solid lines) in three different regions of space for a scenario. The shadow boundaries (dashed lines) indicate the divisions between regions of space where the different rays exist.
Figure 3. Illustration showing location of shadow boundaries between the regions where different combinations of GO rays exist.

For practical applications, such as an aircraft on approach to a runway with hangars in the airport environment, the observation point passes through several of these shadow boundaries. The fields in these regions are not an accurate approximation of the actual fields in space and cannot be used to calculate the aircraft guidance information accurately. GO is insufficient to describe completely the scattered field in many of these practical applications due to the inaccuracies inherent to GO near the shadow boundaries.

The Uniform Theory of Diffraction (UTD), when used in conjunction with GO, gives the capability to solve for the scattered fields in a large number of practical problems.
that ordinarily would be difficult or even impossible [32]. Combining UTD with GO enables an accurate estimation to be obtained of the effects of the scattered fields coming from obstacles down to one-quarter of a wavelength in some cases [33]. High frequency methods such as GO/UTD are much more practical to use to solve for fields from large scatterers due to the poor rate of convergence of techniques such as MoM as previously mentioned. GO and UTD have been used to predict accurately scattering from a wide variety of complex structures that would normally be impossible to evaluate otherwise [34,35].
V. GEOMETRICAL OPTICS AND THE UNIFORM THEORY OF DIFFRACTION

Geometrical Optics (GO) is a high frequency approximation of how fields behave in the presence of some electrical or geometrical discontinuities, as discussed by Stutzman and Thiele [36]. GO is used to quantify fields from a source received at a point through direct, reflected, refracted, or other transmission by electrical discontinuities in terms of rays.

The rays of GO are perpendicular to the phase or wave fronts, extending in the direction of propagation. The ray paths are straight in a homogeneous medium, but can change direction at electrical interfaces according to Snell's Laws. Snell's Law of reflection states that the relationship between the incident and transmitted angles is determined by the optical characteristics of the two media which form the boundary [37]. The amplitude variation of a field represented by a ray is obtained through the method of stationary phase and requiring that the fields obey the law of conservation of energy within a ray pencil or flux tube [38]. This constraint leads to the development of spreading factors describing the dynamics of the wave front in space along the flux tube.

GO alone, however, yields fields that are discontinuous across the shadow boundaries created by the geometry of the problem. At points in space far from these shadow boundaries, GO is valid, but its validity decreases as the observation point gets closer
to a shadow boundary. Another technique, the Geometrical Theory of Diffraction (GTD), was developed by Keller in 1951 to allow more accurate calculation of fields close to the shadow boundaries [39]. Further improvements came with the Uniform Theory of Diffraction (UTD), which was developed for use in the transition regions (on shadow boundaries) where GTD failed [40]. This enables the fields scattered by a multitude of canonical shapes in all space to be calculated more accurately.

The diffracted rays of UTD, as well as for the original GTD, obey Fermat's Principle for propagation as do those of GO [41]. Fermat's Principle states that the trajectory taken by a ray is such that its optical path length is an extremum (local maximum or minimum), though not necessarily a minimum [42]. The different types of rays also have inherent constraints. For example, a direct ray must not pass through any scatterers in the scenario, otherwise the ray does not exist. Reflected rays must include a point on the surface of a scatterer where Snell's Law is satisfied, otherwise the reflected ray does not exist.

The total fields in space are a combination of the components, or mechanisms, of GO and UTD. Depending on the shapes and geometry of the scenario of interest, UTD can provide many diffraction mechanisms to increase the accuracy of the calculations (see Figure 4).
Figure 4. Examples of diffracted rays.

Figure 4. Examples of diffracted rays. Diffraction (a) by a curved edge, (b) at a discontinuity in surface impedance ($Z_{s1}$ and $Z_{s2}$), (c) at a discontinuity in surface curvature, (d) by a thin, curved wire, (e) by a smooth, convex surface, and (f) by a vertex in a plane screen. (Lo and Lee, p. 4-4)
The total field in space at a given observation point can be represented as:

\[
E_{\text{Total}} = E_{\text{Direct}} + E_{\text{Reflected}} + E_{\text{Diffracted}}
\]

\[
= E_{\text{GO}} + E_{\text{UTD}}
\]

where GO provides the direct and reflected field contributions and UTD provides the diffracted field contributions. The field is computed at a given observation point by summing vectorially the contribution of each ray that reaches that point.

Figure 5 shows a classic two-dimensional example for the field due to an infinite line source in the presence of a perfectly electrically conducting (PEC) infinite half plane (wedge angle parameter \( n = 2 \)) [43]. The fields produced by this geometry are shown in Figure 6. This figure shows the total fields calculated using GO and UTD combined, along with its individual components for this geometry. The previously mentioned discontinuities in the GO field are apparent at the shadow boundaries. This is the region of space where GO is most inaccurate.

This geometry is referred to as normal incidence (Figure 7), and creates two shadow boundaries: the incident shadow boundary and the reflected shadow boundary. These shadow boundaries represent the points in space where the discontinuities in the direct and reflected fields occur using GO. At these points, the diffraction coefficients are at a maximum, smoothing the fields as the observation point travels from one region of space to another (see Figure 6).
Figure 5. Two-dimensional electrical conducting wedge and field regions. [18, p. 505]

Figure 6. Normalized far-zone field distribution of a soft polarized cylindrical wave incident upon a conducting half-plane (n=2). [18, p. 506]
Figure 7. Two types of edge diffraction a) normal incidence and b) oblique incidence. [18, p. 507]
For the field components in space for this example, we have:

1) \( E_{\text{Direct}} \): The direct, unobstructed field.

\[
E_{\text{Direct}} = e^{jka}/\sqrt{\alpha}
\]

where \( \alpha \) is the distance from the source point to the observation point.

2) \( E_{\text{Reflected}} \): The field from the image of the source in the infinite half plane. This field exists only if the specular point (satisfying Snell's Law) falls on the half plane.

\[
E_{\text{Reflected}} = \Gamma e^{jkb}/\sqrt{\beta}
\]

where \( \beta \) is the distance from the image of the source to the observation point and \( \Gamma \) is the reflection coefficient for the polarization of the incident field with respect to the surface of the plate. \( |\Gamma| = +1 \) for hard, or perpendicular, polarization, while \( |\Gamma| = -1 \) for soft, or tangential, polarization.

3) \( E_{\text{Diffracted}} \): The field diffracted from the edge of the half plane. This field exists wherever the edge specular point \( Q \) falls on the edge. This is a trivial matter for this example, however, since the edge is infinite in extent.

\[
E_{\text{Diffracted}} = E_{\text{incident}} D A(s,s') e^{jks}
\]

where \( D \) is a tensor representing the diffraction coefficient; \( A(s,s') \) represents the spreading factor for the incident field wave front; \( s \) and \( s' \) represent the distance from the diffracting specular point \( Q \) and the observation point or source point, respectively.

For diffracted field calculations of the effects due to soft (tangential to the edge) polarization, it can be shown that the diffraction coefficient \( D \), for the equivalent electric line source in this example is given by [44]

\[
D_z(L,\beta^-,\beta^+,n) = D^l(L,\beta^-,n) - D^r(L,\beta^+,n)
\]
where

\[ D^i(L, \beta^-, n) = -\frac{e^{-j\frac{\pi}{4}}}{2n\sqrt{2\pi k}} \]
\[ \times (C^+(\beta^-, n)F[kLg^+(\beta^-)] + (C^-(\beta^-, n)F[kLg^-(\beta^-)]) \]
\[ D^f(L, \beta^+ , n) = -\frac{e^{-j\frac{\pi}{4}}}{2n\sqrt{2\pi k}} \]
\[ \times (C^- (\beta^+, n)F[kLg^+(\beta^+)] + (C^-(\beta^+, n)F[kLg^-(\beta^+)]) \]

\( D^i \) and \( D^f \) are referred to, respectively, as the incident and reflected diffraction coefficients.

The other functions and parameters are defined by

\[ C^+(\beta, n) = \cot\left(\frac{\pi + \beta}{2n}\right), \quad C^-(\beta, n) = \cot\left(\frac{\pi - \beta}{2n}\right) \]
\[ F[kLg(\beta)] = 2j\sqrt{kLg(\beta)}e^{jkLg(\beta)} \int_{\sqrt{kLg(\beta)}} e^{-j\tau^2} d\tau \]
\[ \beta^+ = \phi + \phi', \quad \beta^- = \phi - \phi' \]
\[ g^+ = 1 + \cos[(\phi + \phi') - 2\pi N'] \]
\[ g^- = 1 + \cos[(\phi + \phi') - 2\pi N'] \]

where the source and observation coordinates are defined by

Source location \((\rho', \phi')\)  Observation location \((\rho, \phi)\)  \(L = \rho'\)
with \( N^+ \) or \( N^- \) being a positive or negative integer or zero, whichever most closely satisfies the equation

\[
2n\pi N^+ - (\phi \pm \phi') = +\pi \quad \text{(for } g^+) \\
2n\pi N^- - (\phi \pm \phi') = -\pi \quad \text{(for } g^-)
\]

For calculations of the effects due to hard (perpendicular to the edge) polarization, the diffraction coefficient \( D_h \) (in terms of the incident and reflected diffraction coefficient) for an equivalent magnetic line source can be written as [45]

\[
D_h(L, \beta^-, \beta^+, n) = D^I(L, \beta^-, n) + D^I(L, \beta^+, n)
\]

While the two-dimensional assumptions are sufficient for many highly symmetric applications, oblique incidence is more commonly necessary for three-dimensional cases. For oblique incidence on the diffracting edge, there exists a slightly modified set of equations [46].

\[
E^d(s) = E^I(Q) \cdot D_0(\phi, \phi', \pi; \beta'_o) \sqrt{\frac{s'}{s(s+s')}} e^{-jks}
\]

where \( D(\Phi, \Phi', n; \beta'_o) \) is the dyadic diffraction coefficient for an obliquely illuminated canonical wedge by planar, cylindrical, conical, or spherical wave fronts. By employing an edge-fixed coordinated system, the representation of the diffraction coefficients is greatly simplified. The incident and diffracted fields are defined by
components tangential and perpendicular to the plane of incidence and diffraction, respectively.

$$(\phi', \hat{\beta}') \perp, \parallel to plane of incidence$$
$$(\phi, \hat{\beta}) \perp, \parallel to plane of diffraction$$

$$\hat{s}' = \hat{\phi} \times \hat{\beta}_o \quad \hat{s} = \hat{\phi} \times \hat{\beta}_o$$

Source $$(s', \beta_o, \phi')$$ Observation $$(s, \beta_o, \phi)$$

$$L = \frac{s \cdot s' \sin^2(\beta'_o)}{s + s'}$$

$$E_{p_o}^d = \frac{\sqrt{8\pi k}}{\eta k} D_s f_k e^{-jk(\phi + s')} \frac{e^{-jk(s' + s)}}{4\pi(s' + s)\sqrt{s'}} \times E^i_z \sin(\beta_o) L \sin(k\frac{L}{2}(\cos(\beta_o) - \cos(\beta'_o)))$$

$$H_{p_o}^d = \frac{\sqrt{8\pi k}}{k} \frac{\eta e^{-jk/4}}{\eta} D_H \frac{jk}{\eta} \frac{e^{-jk(s' + s)}}{4\pi(s' + s)\sqrt{s'}} \times \frac{-E^i_z}{\eta} \sin(\beta_o) L \sin(k\frac{L}{2}(\cos(\beta_o) - \cos(\beta'_o)))$$

$$E_{\phi}^d = -\eta H_{p_o}^d$$

A more detailed description of the mathematics involved with diffraction from an edge can be found in [47,48].

The edge-diffracted rays spread in a cone whose axis is parallel to the edge (see Figure 7). The half-angle $\beta$ of the diffracting cone equals the angle $\beta'$ between the ray incident on the edge and the vector in the direction of the edge (both $\beta$ & $\beta' =$...
90 degrees for normal incidence). This criterion is used to determine the specular point used for the diffraction calculations for the edge. For finite edges in the oblique incidence case, discontinuities are created where the edge ends (at a corner of a scatterer). In the same manner that edge diffraction contributions smooth the discontinuities of GO fields, another mechanism, corner diffraction, smooths the discontinuity in the edge diffracted fields caused by the finite edge’s end.

These mathematics are a summary of the single edge diffraction equations implemented in computer codes using GO/UTD to calculate scattered fields. In situations where planar scatterers are being analyzed, this is the most dominant of the different UTD mechanisms. These equations represent the theoretical bases implemented in mathematical models using GO and UTD to calculate scattered fields.
VI. NEAR ZONE BASIC SCATTERING CODE

Near Zone Basic Scattering Code (NZBSC) is the newest generation of software stemming from the Aircraft Code, developed by Ohio State University's ElectroScience Laboratory (OSUESL) for the U.S. Air Force in the 1970s. The Aircraft Code was used to analyze radiation patterns of antennas that were mounted on aircraft surfaces and structures. Later versions have been associated with many other contracting agencies. The latest version, NZBSC 3.3, was developed for use by the National Aeronautics and Space Administration (NASA) [49] for analysis of antennas mounted on space stations for use by NASA and completed in September, 1992. It was written to compute fields scattered from shapes such as polygonal plates and finite elliptical cylinders using the Geometrical Optics (GO) and the Uniform Theory of Diffraction (UTD). Implemented in NZBSC are single edge, double edge, curved edge, corner, and slope diffraction mechanisms; single, double, triple reflections between scatterers; and combinations of diffractions and reflections.

NZBSC is capable of modeling aperture, dipole, and loop antennas, as well as arrays of these antennas. NZBSC's documentation includes many situations with scattering used to validate the predictions of NZBSC (see Appendix I). The results show the correlation between the measured and modeled fields in the examples provided.
Based on NZBSC's documented accuracy and the breadth of practical problems that can be implemented with its command structure, NZBSC was chosen as the computational tool to be used as the heart of the localizer model. Ohio University purchased the latest version of the NZBSC source code (3.3) from Ohio State University ElectroScience in March, 1993.

Appendix I shows one of the 28 validation examples included with the NZBSC documentation. Listed with it are the required input file describing the scenario, the generated output file, and graphs of the calculated results versus the actual measured data.

NZBSC requires as input the geometry of the source, the scatterers, and the observation point flight path. The source geometry includes the source type (magnetic or electric), orientation, length, and excitation. Many sources may be arrayed together, with the maximum number of sources depending on array limits in the model's source code which can be set by the user upon compilation. Earlier versions had these array sizes fixed such that only 30 discrete radiating sources could be used at once [50]. A localizer with as many as 196 discrete sources was implemented by allowing only 30 or fewer sources to radiate at one time. The fields from each run with each set of 30 or fewer discrete sources were vectorially summed by an earlier generation post-processor. The newer version of NZBSC, with its
customized array sizes for a higher number of discrete sources, performs its calculations in about 2/3 of the time of earlier versions without sacrificing accuracy.

NZBSC presents the results of its calculations as listings of observation point positions in the reference coordinate system with the corresponding electric field, magnetic field, and the power intensity. These results are given in the directions of all three unit vectors of the coordinate system of choice.

During this investigation, some anomalies were discovered with the NZBSC computational tool. The first was a difficulty imaging the diffracted fields when a ground plane is used and the scatterer is near the ground plane. The second problem was associated with the method in which the doubly-diffracted ray is implemented. These problems limited the practical situations that could be modeled accurately using this code before special considerations were made. The details of the changes will be discussed in the next section.
A. Enhancements Made to NZBSC for this Application

The following sections discuss the enhancements made to NZBSC in order to produce valid results with the localizer model using NZBSC. The two major problems encountered with the code and their respective solutions are discussed in this section.

i. Overcoming the Ground Plane Problem With Imaging

The problem discussed in Section VI regarding the ground plane was investigated. This can be avoided by using image theory to image the sources and scatterers (within the input file previous to calculations) if a perfectly electrically conducting (PEC) and infinitely flat ground plane is assumed. This assumption is currently used when generating the input file. This assumption has shown to be limiting in many cases of imperfect terrain structures that could be modeled using this code.

To demonstrate the differences observed between the calculated fields with and without the ground plane included, some comparisons were made with a validated PO model. A pair of horizontally oriented dipoles were placed at the origin with a PEC scattering plate located in the far field (as indicated in Figure 8). The observation point approaches the array of dipoles from broadside in both models. Figures 9 and 10 show the comparisons of NZBSC field strengths versus the PO
model with and without the ground plane in the modeled scenario. The increased magnitude with the ground plane in Figure 9 was attributed to the error in diffracted field calculations over a ground plane. Figure 10 shows the improved correlation when the ground plane is removed and Image Theory is applied in generating the input file.
Figure 8. Geometry of scenario for PO and NZBSC comp. #1.

Figure 9. Comparison of PO and NZBSC with ground plane included.
Figure 10. Comparison of PO and NZBSC with no ground plane included.
The second problem is related to the implementation of the doubly-diffracted ray in the calculations. NZBSC approximates the coupling of 2 edges by allowing the diffracted field from one edge to illuminate another edge. The second edge consequently radiates a diffracted field of its own. Using this technique, a second scatterer that is shadowed by a scatterer can be illuminated by the diffracted field from the edges of the first scatterer. This type of ray is necessary to account for edge interactions such as in the screen experiments for San Jose Airport. In this case, a truck behind a shadowing screen was illuminated only by diffracted energy from the edges of the shadowing screen.

A perfected doubly-diffracted algorithm, however, is not available in the NZBSC at this time. The current algorithm does work under certain conditions, such as when the two edges are parallel and the far-zone radiation pattern is desired. However, the application of this program to the fields present on an aircraft approach path requires that calculations be performed at specified points in space and not for a far-zone orbit. The mathematics are not implemented correctly in the algorithm used to calculate the fields at varying observation points in space. These implementation errors found during this study have been brought to the attention of OSUESL.
VII. BUILDING OF THE LOCALIZER MODEL USING NZBSC

After eliminating the problems associated with the ground plane through the use of image theory, programs were created to generate an input file containing discrete sources that represent a localizer array. This input file is used by NZBSC to model the effects of scatterers along a defined observation point on the flight path.

The localizer model utilizes NZBSC for field calculations, along with a customized front and back end for pre-processing and post-processing of the data. The model consists of three functional steps: input file processing, field calculations, and output file processing. The pre-processor and post-processor are written using Borland C++. The field calculation processing section consists of NZBSC.
A. Description of the Pre-processor

The pre-processor performs the task of setting up the input file in a format usable by NZBSC. To do this, it is necessary to have information available in data files for the compilation of the input data. The modeled localizer array element is constructed of dipoles in the current input processor arrangement. This limits the type of antennas to those that can be accurately modeled using dipoles, such as the log-periodic dipole antenna (LPD). The LPD is an array of seven dipoles whose lengths and spacings are each related through logarithmic functions (see Figure 11) [51]. LPDs are the antennas commonly used today in localizer arrays. It is possible that with modifications to the pre-processor, other elements may be approximated by using a combination of dipoles, magnetic loops, constant current loops, apertures or interpolated sources for modeling of other more complicated antennas.

The pre-processor requires that three data files be supplied. The first provides the geometry and excitation of the dipoles used to build the localizer array element. The second is the element feeds and spacings for the particular localizer array being modeled. The third file provides the description of the observation point flight path. An optional fourth data file describes the scatterer placement and orientation.
Figure 11. Wilcox FA-9759 Log-Periodic Dipole antenna [51] used in many localizer arrays.
The first data file contains the dipoles' relative excitation magnitude, phase, length, and position that make up the modeled array element. This information will be used whenever this element is used in an array. This data file is provided from the results obtained using NEC for the LPD, as previously mentioned. The data is organized into 4 columns: magnitude, phase (deg), dipole length (m), and offset along the x-axis (m). There are seven dipoles for the LPD element, each with four columns of this information. The current excitation file for the LPD is listed in Appendix II.

The second data file is the array excitation information, which varies from one array to the next and is independent of the element used. It is needed by the pre-processor to calculate the feeds for the array elements. The first row has the height (in meters) of the elements from the ground below the array. The next section of this data file is grouped into five columns: offset, sidebands-only (SBO) magnitude, SBO phase, carrier-plus-sidebands (CSB) magnitude, and CSB phase. The CSB and SBO are the two signals transmitted that contain the guidance information in the modulation. The offset is the distance in wavelengths along the y-axis from the center of the array (which is the origin) to that particular element. The phases of the SBO are in quadrature to the CSB, with the elements on the 90-Hz (negative y-axis) side being advanced 90 degrees (and vice versa on the +y-axis elements). The array distribution file for the eight-element self-clearing array is shown in Appendix III.
The third file contains the information describing the observation point flight path through space. It contains the orientation of the pattern coordinate system, the location of the origin of the pattern coordinate system, the starting point, the incremental step values, and the number of points to be taken.

Two types of standard Ohio University data-gathering flight patterns are implemented in data files. The first is the Pattern A approach. Pattern A starts at ILS point A and flies down the glide path to the threshold, then continues along the runway at a constant elevation as illustrated in Figure 12. The second type of flight pattern is a Pattern D orbit. Pattern D is flown at approximately 5 nautical miles from the array on an arc that extends 35 degrees both sides of the runway centerline as illustrated in Figure 13.

There are two data files representing two sections of a Pattern A observation point approach. The first starts beyond 4 nautical miles (nmi) from the threshold (ILS point A) and travels down a 3.0-degree approach to cross the threshold at the specified crossing height. The second portion of the Pattern A travels down the runway at a specified height from the threshold towards the stop end of the runway. The Pattern D observation point orbit is performed at a specified range and elevation angle. Example pattern information data files are listed in Appendix IV.
The fourth file, if present, provides the position, orientation, and characteristics of the scatterer(s) to be modeled. This file, however, is not required to be present if a scatterer-free environment is desired. A sample plate data file is shown in Appendix IV.
Figure 12. Illustration of a Pattern A approach path.

Figure 13. Illustration of a Pattern D orbit path.
B. **Description of the Post-processor**

The post-processor reads the data provided by the calculations performed in NZBSC. From these calculations, the SBO electric field levels are corrected to adjust the course width to the desired value. The field data are needed by the algorithm that calculates the course deviation indicator (CDI) current. The CDI is an instrument display in the cockpit used to communicate to the pilot the direction to fly during an instrument approach. The aircraft's ILS receiver feeds a current to the CDI display depending on the signals received from the ILS component to which the receiver is tuned, such as the localizer frequency for the runway on which the aircraft is approaching. The calculated CDI current from the localizer modeling can be filtered to simulate the damping that occurs in the meter display for a velocity of 200 knots. Full-scale deflection for the CDI current for the ILS localizer is ±150 uA.

The fields calculated from the scenario are extracted from the output file, adjusted for proper course width, and listed in a five-column format in a specified output file. There are four groups of needed field data. The first two are the complex CSB and SBO fields at the localizer course width point. These fields are used to calculate the CDI current at the edge of the existing course and calculate the necessary scalar change in the SBO field strength to adjust the course width with no scatterers according to:
\[ CDI_{\text{no adjust}} = \frac{(a_{dm}) (CDI_{\text{edge}})}{DDM_{\text{edge}}} \frac{|SBO|}{|CSB|} \cos(\angle SBO - \angle CSB) \]

\[ SBO_{\text{adjustment}} = \frac{CDI_{\text{no adjust}}}{CDI_{\text{edge}}} \]

where

\[ a_{dm} = 0.4 \]
\[ CDI_{\text{edge}} = 150 \mu A \]
\[ DDM_{\text{edge}} = 0.155 \]

The first column of the fields file generated by the post-processor is the position parameter. The values in this column depend on the type of observation point path that is flown. The position parameter is used as a reference for the point in space at which the corresponding fields are calculated. The next four columns are the real and imaginary parts of the complex CSB field at that observation point, followed by that for the complex SBO. This file is in the format used by the receiver algorithm.

The receiver algorithm produces an unfiltered CDI output versus the position parameter from the fields file generated by the post-processor. This output is in two columns, with the first being the position parameter followed by the CDI data. This CDI information can be filtered to represent the damping that occurs in the meter display. The filter used is a low-pass with a one-second time constant. The sample points are taken at 50-foot increments along the flight path.
VIII. MODEL VALIDATION

The following sections discuss validation tests performed with the localizer model using NZBSC. These sections discuss results from modeling of the LPD element, an eight element localizer array, some practical applications complete with field measurements, and additional examples showing correlation with a validated PO localizer model.
A. Validation of the Modeled LPD Localizer Array Element

The LPD geometry was modeled using the Numerical Electromagnetics Code (NEC) [52]. NEC implements MoM to solve for the current segments that make up an antenna based on the geometry and excitations. The results of modeling gave a discrete current segment representation of the LPD. This information was used to determine the relative magnitude and phase of the 7 dipoles that represent the LPD element in the NZBSC localizer model. The implemented antenna element pattern is shown in Figure 14 versus the actual measured pattern obtained from field measurements of the LPD element [53]. Minor discrepancies between the measured and modeled results are attributed to difficulties in modeling the structure and actual environment (such as buildings, tree lines, and other factors present) due to simplifying assumptions made when using NEC and measurement errors in the field environment.

B. Validation of a Modeled Localizer Array With No Scatterers Present

After the LPD element was implemented successfully by using the information from NEC, it was necessary to validate an array of LPDs with measured data. The array chosen for this task was the 8-element self-clearing (8SC) localizer array of LPDs. This was the array used with the shadowing experiments performed for San Jose at the Ohio University Avionics Engineering Center (OUAEC) Test Facility at the Kendall Tamiami Executive Airport (TMB) in Miami, Florida. It is necessary to show
Figure 14. Measured versus modeled radiation pattern for the LPD.

the correlation of the measured and modeled antenna patterns of this array before presenting the predicted effects of shadowing on the localizer structure.

A Pattern D orbit was flown to measure the field strength pattern of an 8SC localizer for the CSB portion of the radiated signal. The NZBSC localizer model was used to calculate the CSB field pattern from the 8SC. The results are shown in Figure 15. The data correlate well until approximately 50 degrees from centerline. Beyond this point, the modeled results show much deeper nulls than the measured data. As for the data obtained for the LPD comparisons, these discrepancies were attributed to difficulties in modeling the array structure and measurement
inaccuracies in the field environment. Due to limited phasing precision, parasitic coupling, and stray radiation in practical applications, the -60 dB nulls in the modeled environment are not obtainable with the localizer array.

![Diagram showing radiation pattern](image)

**Figure 15.** Measured versus modeled results for the CSB radiation pattern of the 8SC.
The differences in the signal levels of the side lobes may create inaccuracies in scenarios dependent upon the effects of these signals. The signal strength of the illumination of scatterers located in the azimuth angles between 50 degrees and 160 degrees from centerline is not modeled to be as large as it is measured to be. This leads to fields from these scatterers being lower in intensity than in the actual scenario and this is due to these lower modeled side lobes. The result will be less predicted roughness in the localizer course structure than what actually exists. Careful consideration of such factors must be made in the use of this and other models.

C. Validation of Some Modeled Scenarios

To validate the predictions of the NZBSC localizer model, it is necessary to model and predict correctly scenarios for which measured data are available. Several examples of localizer course structures were chosen to prove the usefulness of the GO/UTD localizer model. As an extension of the validation tests, predictions made using a previously validated PO localizer model were compared to results obtained using NZBSC for the same scenarios. For simplicity in these examples, single-frequency data are used.
i. Runway 17L at Tulsa, Oklahoma

Tulsa's Runway 17L was served by a 14-element self-clearing localizer array when the flight measurement in Figure 16 was taken. From the on-site inspection, two buildings were deemed the major contributors of measured course roughness. These buildings and their layout geometry are shown in Figure 17. Figure 18 shows that both the frequency and the magnitude of the scalloping in the course structure was well predicted by NZBSC. The phase differences can be attributed to unmodeled characteristics of the actual scenario such as measurement range errors and errors in determining scatterer position due to limited accuracy of maps, blueprints, etc. These unmodeled factors can change the path length difference between the direct and reflected signals significantly enough to affect the phase of the scalloping of the CDI current (a half-wavelength error, about 4.5 feet, between actual and modeled path length difference creates 180-degree phase difference between the total signal-in-space). These differences do not, however, significantly affect either the magnitude of the current or the rate of change of the path length difference, which determines the frequency of the scalloping rate of the CDI current. This CDI current scalloping frequency is a key element in determining a multipath source in a modeling study. Even with such unmodeled characteristics in an environment, modeling continues to give a good estimate of what measurements would be expected in an actual scenario.
Figure 16. Measured results from Tulsa Runway 17L.

Figure 17. Layout of buildings modeled at Tulsa Runway 17L.
Figure 18. Modeled results from Tulsa Runway 17L.
ii. **Runway 36L at Memphis, Tennessee**

At Memphis Airport, Runway 36L is served by a dual-frequency (14-6) 14-element localizer array of LPDs. Power lines run essentially parallel to Runway 36L (see Figure 19). Due to the limitations of the localizer shadowing model, wires cannot be directly represented. Their effects can be approximated in many cases by using a solid plate. This usually occurs when the spacing between the wires is less than 1/10 wavelength. However, it is apparent that for horizontal conductors combined with horizontal polarization, this spacing can be larger and still yield accurate results. When this site was investigated for the cause of the measured structure roughness using another model, plates were modeled in place of the wires and the results compared favorably. The measured results for the course-only data are shown in Figure 20. NZBSC proved to estimate accurately the course structure in the presence of this scatterer, as seen in Figure 21.

*Figure 19. Geometry of plate modeled giving approximate effect of section of power lines at Memphis.*
Figure 20. Measured data from Memphis Runway 36L.

Figure 21. Results from scenario modeled using NZBSC.
Vehicle and Screen Tests in Miami, Florida

To simulate the effects of vehicles in front of the localizer array on the localizer course structure, several experiments were performed at TMB. The experiments at TMB were motivated by proposed construction on Runway 30L at San Jose. The flight measurements from these experiments were used for comparison with the modeled results from the localizer shadowing model implemented using NZBSC.

A variety of sizes of trucks and vans were used in measurements of the effects of moving vehicles in front of the array. A large, flat mesh screen (64 feet x 16 feet) was also constructed. The screen was symmetrically-placed and perpendicular to the runway centerline between the localizer array and the vehicles. Scenarios with various combinations of the screen and vehicle positions were set up and flight measurements were taken. The sizes of the various vehicles used were:

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Dimensions (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Truck</td>
<td>8 x 23 x 8</td>
</tr>
<tr>
<td>Stretch Van</td>
<td>6.5 x 18.5 x 6.3</td>
</tr>
<tr>
<td>Budget Truck</td>
<td>10.7 x 22.75 x 8</td>
</tr>
<tr>
<td>Ford Tempo</td>
<td>4.6 x 14 x 5</td>
</tr>
<tr>
<td>Ryder</td>
<td>9.8 x 21.75 x 8</td>
</tr>
<tr>
<td>Large Truck</td>
<td>11 x 29 x 9</td>
</tr>
</tbody>
</table>

Due to the limitations of NZBSC regarding double diffraction, the effects of vehicles shadowed by a screen could not be modeled accurately. This is due to implementation errors of the doubly-diffracted ray algorithm, as explained previously.
Under these conditions, the only scenarios that can be used for validation are those where double diffraction is among the least dominant fields. This limits application to single scatterer scenarios, such as one vehicle in front of the array.

Two of the flight measurements performed with the vehicles in front of the 8SC localizer array at TMB are shown in this section for the purpose of validation. The first flight measurement was flown in a scenario containing a scatterer placed as in Figure 22. In the indicated position and orientation, the large truck (29 feet long by 11 feet high) caused a measured localizer course shift of 12 uA (CDI) as seen in Figure 23. The large oscillations seen in Figure 23 are caused by reflections from the wings and fuselage of a second aircraft flying over the localizer array during a flight measurement. The modeled scenario produced principally an alignment shift of approximately 18 uA as seen in Figure 24. The additional course shift of the modeled results was attributed to the overestimation of the diffracted fields from a scatterer of this size in this geometry. Measured data from electrically larger scatterers were not obtainable.

Flight measurements were obtained on a Pattern A approach while another large truck travelled across the front of the 8SC localizer array. This geometry is shown in Figure 25. An oscillation occurred in the approach profile while the truck passed in front of the localizer array, shown in Figure 26. Since the localizer model cannot model scatterers in motion, the effects of the scatterer were modeled for different
positions across the front of the array. The resulting modeled structure alignment shifts were compiled and plotted versus the scatterer's position. The position of the truck during the flight measurement was calculated for different points during this oscillation. The results of this comparison are shown in Figure 26. The discrepancies between the two plots are attributed to the small electrical size of the scatterer modeled, and errors associated in estimating the location of the truck. As previously mentioned, diffracted fields calculated from electrically small scatterers may be an accurate estimate in some simple geometries. However, due to the nature of the space modulation and the method in which the CDI is extracted from the signals in space, overestimations in field calculations may lead to an increase in the resulting CDI deflection resulting from those fields.
Figure 22. Scenario with large stationary truck in front of an 8SC localizer array.

Figure 23. Measured data from Tamiami scenario with a stationary truck in front of an 8SC array.
Figure 24. Modeled data from Tamiami scenario with a truck in front of an 8SC array.

Figure 25. Geometry of scenario with a large truck traveling in front of an 8SC array.
Figure 26. Comparison of modeled dynamic localizer alignment shift flight measurement with a moving truck traveling in front of an 8SC.
iv. Additional Examples Using Physical Optics Localizer Model

Additional validations tests were performed using the PO ILS model used by Ohio University Avionics Engineering Center (OUAEC). Since this model is not valid for shadowing effects, the tests performed had the observation point move in regions other than those shadowed by the scatterer. Figure 8 and Figure 27 show the geometries used for the comparisons between these two models. The localizer used was the 8-element self-clearing array at an operating frequency of 110 Mhz and 4.5-degree course width.

The results compare well for these scenarios, both in magnitude and scalloping frequency of the CDI trace for most areas along the flight profile. Figure 28 and Figure 29 show the comparisons of the results of modeling each scenario with the different models on a higher resolution scale to show more detail.
Figure 27. Geometry of scenario for PO and NZBSC comp. #2.

Comparison of PO and NZBSC
Scat 3000, −1000, 0 parallel 400x50'

Figure 28. Comparison #1 between PO and NZBSC.
Comparison of PO and NZBSC
Scat 1000, -1000, 0 (rot 150 deg) 400x50'

Figure 29. Comparison #2 between PO and NZBSC.
IX. RESULTS AND DISCUSSION OF COMPARISONS

Two problems with the NZBSC were uncovered during this study. One was related to the way in which imaging is performed in the field calculations. This error was avoided by imaging the sources and scatterers before the computations are performed. The second problem with the NZBSC was with the implementation of the doubly-diffracted ray. This problem was not corrected, but the authors of NZBSC at Ohio State University ElectroScience Laboratory were notified. This ray is excluded from calculations performed by this code. Scenarios where this doubly-diffracted ray would be needed to estimate accurately the total scattered fields should be avoided. Such scenarios include those having one scatterer in the shadowed region of another, such as the San Jose experiments performed at TMB using large vehicles and the reflective screen. Incidentally, the shadowing screen experiment was shown not to be effective. Not enough angular separation could be attained in that environment between the approaching aircraft and the multipath-causing vehicles. This led to an insignificant difference in the signal strengths of the desired and undesired signals, thus no separation and no significant change in error characteristics.

Comparing measured and modeled data showed two discrepancies that occurred when using the localizer model implementing NZBSC to predict results measured in practical applications.
The first difference that was noted was a change in side lobe levels for the 8SC localizer array when compared to measured data. The side lobes of the modeled arrays are more than 20 dB lower than those measured of an actual 8SC localizer array of LPDs. This occurs due to unmodeled factors in the LPD element using NEC such as parasitic coupling, stray radiation, and practical measurement limitations. Scatterers in azimuth angles greater than 50 degrees from centerline are illuminated with lower field intensities than those in actual measured scenarios. This leads to lower scattered fields from these objects and, in turn, less roughness on the localizer course structure.

The scenario at Tulsa has a large scatterer in the azimuth angle beyond 50 degrees. The modeled results from the validation tests for the scenario at Tulsa shows roughness that is approximately half of the roughness actually measured for that scenario.

This limitation does not affect the phase of the signal adversely. The scalloping rate of the roughness was shown to be the same as in measured data. The scalloping rate of the course roughness is frequently used to identify which scatterers are contributing to roughness in a practical application.

The localizer model implementing NZBSC can be used to identify accurately the scatterers even with the inaccuracies introduced by the lower side lobes in the
modeled array. The limitation of the lower modeled side lobes in the implemented localizer array must be kept in mind when applying this model to situations that have scatterers in azimuth angles greater than 50 degrees.

The second discrepancy occurred when comparing predicted results of shadowing to those measured at TMB. Tests show that for electrically small scatterers, a greater roughness is predicted when compared to measured data. This is due to the overestimation of the diffracted fields from scatterers that are electrically small (less than 10 wavelengths or approximately 90 feet at localizer frequencies). The increase in course roughness in the modeled scenarios is approximately double that of measured data according to the tests performed. However, the modeled alignment shift of the localizer course structure with a vehicle in front of the array was in the same direction as the alignment shifts measured in actual experiments.
X. CONCLUSIONS

A model for predicting the effects of scattering and shadowing onto the ILS localizer course structure has been developed and is presented. Presently no other model has the capability to predict the effects of shadowing on the localizer course structure. This model utilizes the Near Zone Basic Scattering Code, which implements Geometrical Optics and the Uniform Theory of Diffraction to calculate scattered fields.

Unmodeled characteristics of the LPD localizer element in NEC limit the accuracy of the calculated results in some scenarios. Due to decreased side lobe levels in the modeled array, predicted roughness from reflections at azimuth angles greater than 50 degrees from centerline is less than actual measurements show it to be. Validation comparisons of a scenario at Tulsa with a scatterer in this region result in modeled localizer course structure roughness that is approximately half of the roughness measured.

When using the localizer model to predict the effects of shadowing by electrically small scatterers, the magnitude of the predicted roughness is greater than the measured data show. This is attributed to an overestimation of the diffracted fields from objects that are electrically small (less than 10 wavelengths).
A model for use in the analysis of the ILS localizer course structure in the presence of planar scatterers has been successfully validated and documented. This model accounts for the effects of shadowing and signal blockage on the localizer course structure as shown by comparisons with flight measurements.
XI. RECOMMENDATIONS FOR IMPROVEMENT

Solving the problems that cause the errors introduced by the ground plane would be the most helpful improvements in the NZBSC. Based on the work performed, this improvement would enable use of the localizer shadowing model for analysis of the effects of irregular terrain on the localizer course structure and perhaps for the ILS glide slope array as well with some modifications. The authors of the code at Ohio State University ElectroScience Laboratory have been notified of the problems. Future versions hopefully will have this correction implemented.

The implementation of the doubly-diffracted ray would increase greatly the areas of application of the localizer model implementing NZBSC. Based on the experiments performed, this improvement should enable the prediction of effects of scatterers that are shadowed by other scatterers from direct illumination. Again, the authors of the code at Ohio State University ElectroScience Laboratory have been notified of the problems. Future versions hopefully will have this correction implemented as well.

Along with the pre-processor, several additional data files must be used in tandem to create the input file structure for the scenario to be modeled. This structure should be reorganized and a menu-driven interface written to create input files. This improvement would help to eliminate the human error factor that is introduced
when there are so many data files present to be edited and compiled. The more of
the process that is "automated", the fewer the errors that may occur due to misuse.

A graphical interface used to orient the scatterers should be more efficient to use
than the standard methods of entering complex geometries coordinate-by-coordinate.
Creating such an interface would be especially helpful when building three-
dimensional objects using standard shapes, such as boxes and cylinders, in a scenario.

Future work should also include validation of this model using scatterers other than
PEC plates. Shapes such as cylinders or polygons with imperfect electrical properties
could be useful for modeling characteristics of environments such as dense vegetation
on hillsides or upslopes.
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APPENDIX I - NZBSC Validation Example [33]

This example illustrates how to set up a data set to calculate the far zone pattern of an electric dipole in the presence of a finite perfectly conducting ground plane as shown in Figure 7.1. The input data for the $H$-plane pattern is given by

```
CE: FAR ZONE PLATE TEST, EXAMPLE 1A.
UN: UNITS IN INCHES
3
US: SOURCE UNITS IN WAVELENGTHS
0
FR: FREQUENCY IN GHZ
8.0
PF: PATTERN CUT
 0.,0.,90.,0.
  T,90.
  0.,1.,361
PG: PLATE GEOMETRY
  4,0
  0.,3.5,3.5
  0.,-3.5,3.5
  0.,-3.5,-3.5
  0.,3.5,-3.5
SG: SOURCE GEOMETRY
  5.12,0.,0.
  0.,0.,90.,0.
  -2,0.5,0.
  1.,0.
PP: PLOTTABLE OUTPUT
  T
  T,5.33,2.66
  0.,360.,36.
  -40.,0.,10.
XQ: EXECUTE CODE
EN: END CODE
```

The computer code prints out on the line printer, terminal, or disk file for later printing the information in Figure 7.2 pertaining to the input
data. This information can help the user decipher how the computer code interpreted the input data. It also provides messages to the user if the input data is found to be incorrect by the code.

The $E_\theta$ pattern is compared with the measured results in Figure 7.6. The $E_\phi$ pattern is not plotted because it is of negligible value.
Figure 7.2: Line printer output for the code's interpretation of the input data set of Example 1A. The figure is continued on the following pages.
FR: FREQUENCY IN GHz

FREQUENCY = 8.000 GIGAHERTZ
WAVELENGTH = 0.037474 METERS

PF: PATTERN CUT

PATTERN AXES ARE AS FOLLOWS:

VPC(1,1) = 1.00000 VPC(1,2) = 0.00000 VPC(1,3) = 0.00000
VPC(2,1) = 0.00000 VPC(2,2) = 1.00000 VPC(2,3) = 0.00000
VPC(3,1) = 0.00000 VPC(3,2) = 0.00000 VPC(3,3) = 1.00000
PHI IS BEING VARIED WITH THETA = 90.00000
START = 0.00000 STEP = 1.00000 NUMBER = 361

PG: PLATE GEOMETRY

THIS IS PLATE NO. 1 IN THIS SIMULATION.

METAL PLATE USED IN THIS SIMULATION

<table>
<thead>
<tr>
<th>PLATES</th>
<th>CORNERS</th>
<th>INPUT LOCATION IN INCHES</th>
<th>ACTUAL LOCATION IN METERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.000, 3.500, 3.500</td>
<td>0.000, 0.089, 0.089</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0.000, -3.500, 3.500</td>
<td>0.000, -0.089, 0.089</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.000, -3.500, -3.500</td>
<td>0.000, -0.089, -0.089</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0.000, 3.500, -3.500</td>
<td>0.000, 0.089, -0.089</td>
</tr>
</tbody>
</table>

Figure 7.3: Figure 7.2 continued.
SG: SOURCE GEOMETRY

THIS IS SOURCE NO. 1 IN THIS COMPUTATION.

THIS IS AN ELECTRIC SOURCE OF TYPE -2
SOURCE LENGTH = 0.60000 AND WIDTH = 0.00000 WAVELENGTHS
SOURCE LENGTH = 0.01674 AND WIDTH = 0.00000 METERS
THE SOURCE WEIGHT HAS MAGNITUDE = 1.00000 AND PHASE = 0.00000

<table>
<thead>
<tr>
<th>SOURCES</th>
<th>INPUT LOCATION IN INCHES</th>
<th>ACTUAL LOCATION IN METERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.120, 0.000, 0.000</td>
<td>0.130, 0.000, 0.000</td>
</tr>
</tbody>
</table>

THE FOLLOWING SOURCE ALIGNMENT IS USED:

VISS(1, 1) = 1.00000 VISS(1, 2, 1) = 0.00000 VISS(1, 3, 1) = 0.00000
VISS(2, 1) = 0.00000 VISS(2, 2, 1) = 1.00000 VISS(2, 3, 1) = 0.00000
VISS(3, 1) = 0.00000 VISS(3, 2, 1) = 0.00000 VISS(3, 3, 1) = 1.00000

Figure 7.4: Figure 7.2 continued.
Figure 7.5: Figure 7.2 continued.
Figure 7.6: Comparison of measured and calculated $H$-plane pattern ($E_{t_e}$) for a half-wave dipole located above a square plate. (VAX 8550 run time is 0.106 min and VAX 11/750 run time is 1.2 min.)
APPENDIX II - Assumptions and Limitations

Due to assumptions made in this modeling effort, limitations exist pertaining to the scenarios that may be modeled.

The ground plane in the modeled scenario is flat, perfectly electrically conducting, and infinite in extent. This is due to difficulties encountered in the proper imaging of diffracted fields from objects above some ground planes. Currently, the model interface performs the necessary imaging calculations needed for the radiating sources. These calculations are valid only for ground planes that are flat, perfectly conducting, and infinite in extent.

To complete this imaging process, the obstructions to be modeled must be reflected in the modeled ground plane during the input file creation. As illustrated in Figure 30, the user must place in the proper data file not only the obstruction to be modeled, but its image as well.

As explained in previous sections, the localizer model does not currently have the ability to calculate the effects of double diffraction. This limitation becomes meaningful when one wishes to model the effects of multiple scatterers when one is shadowed by another. Figure 31 shows two such scenarios where double diffraction would be necessary to account for the effects of the 2\textsuperscript{nd} and 4\textsuperscript{th} plates on the field.
Figure 30. Illustration of an example actual scenario (a) and its proper equivalent (b) to be modeled.
received at the observation

Plate 1

Plate 2

\[ \text{src} \]

\[ \text{obs} \]

Top View Scenario A

Plate 3

Plate 4

\[ \text{src} \]

\[ \text{obs} \]

Profile View Scenario B

Figure 31. Illustration showing two example scenarios that cannot currently be accurately modeled.

point. The only illumination that these plates receive is from the diffracted fields of the 1\textsuperscript{st} and 3\textsuperscript{rd} plates, which would in turn be diffracted to the observation point. The localizer model currently does not have the ability to account for these effects. Care must be taken by the user to be sure that these scenarios are approached with understanding of these limitations.
APPENDIX III - Description of Source Data File

The following data is used by the pre-processor to describe the dipole excitations, position, and length that make up the array element. The data columns are organized as follows:

- exc. mag., exc. phase, length, offset from y-axis

where:

- **exc. mag.** is the corresponding relative magnitude of the excitation for that dipole of the array element.
- **exc. phase** is the corresponding relative phase of the excitation for that dipole of the array element in degrees.
- **length** is the corresponding dipole length for that dipole of the array element in meters.
- **offset from y-axis** is the corresponding offset from the x=0 line to the center of the corresponding dipole on the array element in meters.

The pre-processor orients the dipoles horizontally with the prescribed offsets and dipole lengths. The following data file describes the seven dipoles that make up the LPD localizer array element. It is named LPD.CUR.

```
1.1003E-02  97.096  0.809244  0.0000
1.0963E-02 -166.178  0.870712 -0.3465
1.2974E-02  -86.396  0.936244 -0.7188
8.7451E-03  -2.630  1.007364 -1.1196
6.2949E-03  124.795  1.083056 -1.5504
4.1479E-03  115.658  1.317244 -2.0140
2.4336E-03  -115.658  1.384808 -2.5123
```
APPENDIX IV - Localizer Excitation Data File

The following data is used by the pre-processor to determine the feeds of the individual dipoles that make up the entire localizer array. The data file represents the localizer array feeds for the particular localizer being modeled. The first row contains a number representing the height of the elements from the ground in meters. Each row following this number corresponds to an element in the localizer array. The next section of data contains 5 columns of information on the placement of the element and its excitation in terms of the carrier-plus-sidebands (CSB) and sideband-only signals (SBO). The data columns are organized as follows:

- offset from x-axis, CSB mag., CSB phase, SBO mag., SBO phase

where:

- **offset from x-axis** is the distance from the line \( y=0 \) to the center of the array element along the \( y \)-axis in wavelengths.
- **CSB mag.** is the relative magnitude of the CSB excitation corresponding to that element of the localizer array.
- **CSB phase** is the relative phase of the CSB excitation corresponding to that element of the localizer array in degrees.
- **SBO mag.** is the relative magnitude of the SBO excitation corresponding to that element of the localizer array.
- **SBO phase** is the relative phase of the SBO excitation corresponding to that element of the localizer array in degrees.

The following data file is used by the pre-processor to calculate the dipole excitations for an 8-element self-clearing localizer array. These feeds are multiplied by the
dipole feeds on a per-element basis to properly scale and phase each element of the localizer array. The data file is named 8_SC.DIS.

<table>
<thead>
<tr>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.778</td>
<td>-2.550</td>
<td>0.05500</td>
<td>180.0</td>
<td>0.41600</td>
</tr>
<tr>
<td>2.550</td>
<td>0.05500</td>
<td>180.0</td>
<td>0.41600</td>
<td>-90.00000</td>
</tr>
<tr>
<td>-1.800</td>
<td>0.14300</td>
<td>0.0</td>
<td>0.70000</td>
<td>90.00000</td>
</tr>
<tr>
<td>1.800</td>
<td>0.14300</td>
<td>0.0</td>
<td>0.70000</td>
<td>-90.00000</td>
</tr>
<tr>
<td>-1.050</td>
<td>0.36300</td>
<td>0.0</td>
<td>0.89000</td>
<td>90.00000</td>
</tr>
<tr>
<td>1.050</td>
<td>0.36300</td>
<td>0.0</td>
<td>0.89000</td>
<td>-90.00000</td>
</tr>
<tr>
<td>-0.300</td>
<td>1.00000</td>
<td>0.0</td>
<td>1.00000</td>
<td>90.00000</td>
</tr>
<tr>
<td>0.300</td>
<td>1.00000</td>
<td>0.0</td>
<td>1.00000</td>
<td>-90.00000</td>
</tr>
</tbody>
</table>
APPENDIX V - Observation Point Path Data File

The following data file is used by the pre-processor to describe the observation point flight path. It is in a format that is directly recognizable by NZBSC in its input file. It describes the location of the origin of the pattern coordinate system, its orientation, the starting point, the incremental changes made to the current observation point to go to the next point, and the number of points to be used. This section is used exactly as the NZBSC structure specifies for observation point patterns. A more detailed description can be found in the NZBSC documentation.

The data file is organized into rows as follows:

PN: description
origin
orientation of z & x-axes
logical LRECT
starting point
incremental steps
number of points

where:

- **PN: description** is the command word for "near zone pattern" as read in the input file by NZBSC. The command word may be followed by a short description, if desired, to explain what this section of input is to represent.
- **origin** is the location of the origin of the pattern coordinate system origin in terms of the reference cartesian coordinate system in feet.
- **orientation of z & x-axes** describes the orientation of the pattern coordinate system origin. The orientation of the unit vector for each axis is described in terms of THETA and PHI from the reference coordinate system. These two unit vectors must be defined perpendicularly to each other. The standard orientation is with the z-axis located at (THETA,PHI) 0,0 and the x-axis at 90,0 in degrees.
logical LRECT is used to specify if the pattern coordinate system is cartesian or spherical. For a Pattern A approach, a cartesian system is chosen, while for a Pattern D orbit, a spherical system is used (T or F).

starting point describes the initial point at which the calculations are to be performed in terms of the pattern coordinate system (in feet and degrees).

incremental steps describe the changes added to the coordinates of the current observation point to get to the next one for calculation (in feet and degrees).

number of points describes the number of observation points to be used in the calculations as an integer.

The following data file is used by the pre-processor to create an input file that flies the observation point on a 3.0-degree approach towards the threshold of the runway.

The origin is set at the threshold, 10680 feet from the array and 55 feet off the ground. The orientation of the z \& x-axes is standard, with z pointing perpendicular to the ground, and x directed from the localizer array along the centerline of the runway. The pattern system is cartesian. The starting point is 25000 feet from the threshold up a 3.0-degree path. The increments along this 3.0-degree path bring the observation point 50 feet closer each successive step. 500 points are taken total, which ends the flight profile just above the threshold. This sample was used for part of the validation analysis performed for the scenarios at Tulsa, Oklahoma.

PN: Patt A - Approach to Threshold Crossing Pt.
10680.,0.,55.
0.,0.,90.,0.
T
24965.7384., 0., 1308.399
-49.93148, 0., -2.6168
500
APPENDIX VI - Plate Description Data File

The optional fourth file describes the scatterers to be used in the scenario. This section takes its structure from that needed in the NZBSC input file. Each scatterer uses one command word followed by a row for each corner plus another for other information. The organization of the data file is as follows for each scatterer:

PG: description
number of corners, PEC
corner 1 coordinates
corner 2 coordinates
...

where:

- **PG: description** is the command word for "plate geometry" from used in the NZBSC input file structure. This may be followed by a brief description of this plate for reference.
- **number of corners, PEC** describes the number of corners (integer) on the one scatterer being described in this section, followed by a 0 (integer) to describe the scatterer as PEC (perfectly electrically conducting).
- **corner 1** describes the location of the first corner \((x,y,z)\) of the scatterer in the reference cartesian coordinate system in feet. Which corner is designated as the first one is not relevant. The corners must be specified in either a clockwise or counterclockwise manner. Either method yields valid results. Each successive corner for this scatterer is specified in a successive row in the same manner.

- multiple scatterers are specified by repeating the process defined above for each scatterer. All scatterers must be kept in the same file, with no blanks rows above or within the file structure.

- each plate must be "imaged" in the infinite ground plane beneath it (see Figure 31). This means that for a scatterer coming in contact with the ground, its bottom edge is below the ground at points whose \(z\)-coordinates are equal and opposite to those ending points of its top edge.
The following data file was used to model 2 scatterers in the scenario used for validation of flight measurements from Tulsa, OK. Each scatterer is simulated as a plate with 4 corners.

PG: TULSA BUILDINGS IN FEET - McD. Doug. Bldg.
4,0
0,1040.,-66.7
0,1040.,66.7
3464.1016, 2040., 66.7
3464.1016, 2040.,-66.7
PG: JJ Hangar
4,0
6910.466, 1757.794,-113.5
6910.466, 1757.794, 113.5
7589.534, 1722.206, 113.5
7589.534, 1722.206,-113.5
APPENDIX VII - Modifications to NZBSC Code for Use in Localizer Model

In order to accommodate the application of NZBSC to the localizer modeling, three changes were made to the FORTRAN source code before compiling for use in the localizer shadowing model.

The first was to accommodate for a greater number of discrete sources radiating at one time. This was changed in the include file NZBSC33A.FIN where the integer NSX is initialized to 32. This assignment should be changed to 196 \{7 (dipoles/LPD) x 14 (LPDs/array) x 2 (arrays including image)\} before compiling for use in the localizer shadowing model.

In the file NZBSC33V.FOR in the subroutine GETCP, changes must be made dependent on the compiler used (Microsoft, NDP, VAX, etc.). The proper function for determining the current time must be selected. The others should be commented in the source code. The comment marks in columns 1 through 4 indicate which lines are for which compilers.

In the original code, the output data was broken every ten lines by a space. The data must be in one complete block for the post-processor to function properly as it is currently organized. In the file NZBSC33O.FOR, lines containing conditionals between I and IMAX with a write statement should be examined for their effect on
the output file. These lines must be removed for proper operation of the data extraction from the output file to transpire.
APPENDIX VIII - Localizer Model Operating Manual

The model is made up of three parts: pre-processor, NZBSC calculational segment, and post-processor. The pre-processor assembles the input file for the computation segment (NZBSC) from separate files describing the scenario and measurement path. The computational segment, NZBSC, operates on the input file and produces one output file describing the interpreted commands and the calculated results. The post-processor extracts from the output file the four sections of data necessary to compute the resulting CDI current.

The preprocessor is named MAKE.EXE. This program takes five command line arguments. They are:

1) INPUT FILE: This is the file to be created by MAKE. This will hold all scenario and observer path information necessary for NZBSC to estimate the resulting fields.

2) PATTERN FILE: This file contains the observation point path through space. It includes the coordinate system type (cartesian or spherical), orientation of the observation point coordinate system, starting point coordinates, and incremental step sizes.

3) ARRAY FILE: This file contains the array distribution information. It requires SBO and CSB magnitude and phase information, array elevation, and a normalizing factor for SBO. The excitation feeds are polar (degrees).

4) ELEMENT FILE: This file contains the dipole information that makes up the array element. This includes the dipole offset from the array axis, its length, and the dipole feed (magnitude and phase).
5) PLATE FILE: This file is optional. It contains information on the scatterer(s) to be included in the scenario. Currently, this indicates the plate type (PEC or imperfect dielectric) and the positions of each of the vertices of the plate. Each plate should be imaged in this file due to the problems encountered with the ground plane effects.

Once executed with these command line arguments, the program prompts the user for some information about the ILS installation. This includes the operating frequency, the desired course width, and the distance from the localizer to the threshold for tailored widths. For non-tailored installations, this distance should be to the point at which the course width is 700 feet across in accordance with FAA Flight Inspection paragraph no. 217.3206 [54].

The post-processor is straightforward to operate. The program name is SPLIT.EXE. The arguments needed by SPLIT are the data file name, the data column code, and the desired output file name. SPLIT assumes that the data is in the format output by NZBSC after operating on the input file provided by MAKE.

Four sets of data are retrieved from the output file. Two contain the carrier-plus-sideband (CSB) complex field information and sibebands-only (SBO) complex field information. Two contain samples for each field made at the localizer edge point used for setting the proper course width.

For an observer point path of an approach towards the array along centerline, the "data column" or "path type" code is 1. For a constant radius orbit of the array, the code is a 3.
This number is used to reference the columns of the output data and determine the proper coordinate system in which the fields are expressed.

The output file contains two sets of fields as real and imaginary parts in five columns. The first column is the position parameter. This would correspond to a range or an angle, depending on the path taken by the observer path. The second and third columns contain the CSB fields. The fourth and fifth columns contain the SBO field, adjusted for the proper course width.

Another file is created during this process called ORIG.FLD. This file contains the calculated fields without the adjustment to the SBO power for course width for debugging purposes. The process currently sets the desired course width without the scatterers, then calculates the fields for this setting with the scatterers present. This may not be appropriate for some scenarios. For these cases, one may use the raw fields to determine the proper course width with the scatterers present. The CDI current may be calculated using these fields instead following the adjustment.

These fields are subsequently used by a digital receiver algorithm to compute the CDI current (LOCDI). LOCDI takes two arguments: the first is the file containing the fields in the 5-column format created by SPLIT and the second is the name of the output file to contain the CDI current versus position data.
The CDI current file may be filtered again to simulate the damping that occurs in the meter used to display CDI current to a pilot using FLTR. This program also takes two arguments: the first is the CDI current file to be filtered (from the receiver algorithm) and the second is the name of the output file. This filtering algorithm assumes an approach speed of 200 knots and a sample spacing of 50 feet. It is crucial to maintain this spacing of 50 feet for this filtering process to yield valid results. Due to this factor, the constant-radius orbits should not be filtered since their spacing is typically too large (for 0.5 degree increments and 5 nmi radius, the spacing is approx. 265 feet).

A batch file was created to simplify to process of decoding the fields from the output files. It saves many keystrokes.

```batch
@echo off
split %1.out %2 %1.fld
locdi %1.fld %1.cds
fltr %1.cds %1.cdi
```

It would be called in this fashion:

```
DAT2CDI sample 1
```

where SAMPLE.OUT was the name of the file created by NZBSC containing the field data. The observer path was a standard approach to the threshold, so the "path type" code was a 1. For an orbit, the data are organized differently and a 3 must be used for the path type.

The resulting CDI current is filtered and presented in SAMPLE.CDI for plotting versus its position parameter. For an orbit, as mentioned previously, the file SAMPLE.CDS should be used for evaluation of the modeled installation. The file SAMPLE.CDI should not be
used for orbits because it passes through the filter that is valid only for the modeled approaches (due to sample spacing).