OPERATIONAL VIABILITY OF A DIRECTIVE DISTANCE MEASURING EQUIPMENT (DME) ANTENNA IN A NATIONAL AIRSPACE SYSTEM (NAS) APPROACH AND LANDING ENVIRONMENT

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Master of Science

by

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<tr>
<td>AZ</td>
<td>Azimuth</td>
</tr>
<tr>
<td>BAZ</td>
<td>Back Azimuth</td>
</tr>
<tr>
<td>D</td>
<td>Desired</td>
</tr>
<tr>
<td>DME</td>
<td>Distance Measuring Equipment</td>
</tr>
<tr>
<td>DME/N</td>
<td>Narrow-Spectrum Distance Measuring Equipment</td>
</tr>
<tr>
<td>DME/P</td>
<td>Precision Distance Measuring Equipment</td>
</tr>
<tr>
<td>DME/W</td>
<td>Wide-Spectrum Distance Measuring Equipment</td>
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<tr>
<td>D/U</td>
<td>Desired-to-Undesired Ratio</td>
</tr>
<tr>
<td>EL</td>
<td>Elevation</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
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<tr>
<td>FPSV</td>
<td>Frequency Protected Service Volume</td>
</tr>
<tr>
<td>GS</td>
<td>Glide Slope</td>
</tr>
<tr>
<td>H</td>
<td>High Altitude (FPSV)</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>ILS</td>
<td>Instrument Landing System</td>
</tr>
<tr>
<td>ITS</td>
<td>Institute for Telecommunications</td>
</tr>
<tr>
<td>L</td>
<td>Low Altitude (FPSV)</td>
</tr>
<tr>
<td>LOC</td>
<td>Localizer</td>
</tr>
<tr>
<td>MLS</td>
<td>Microwave Landing System</td>
</tr>
<tr>
<td>NAS</td>
<td>National Airspace System</td>
</tr>
<tr>
<td>OSMP</td>
<td>Office of Spectrum Management and Policy (FAA)</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PCH</td>
<td>Phase Center Height</td>
</tr>
<tr>
<td>PWR</td>
<td>Power</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
</tr>
<tr>
<td>TACAN</td>
<td>Tactical Air Navigation</td>
</tr>
<tr>
<td>TL</td>
<td>Transmission Loss</td>
</tr>
<tr>
<td>TRSB</td>
<td>Time Reference Scanning Beam</td>
</tr>
<tr>
<td>U</td>
<td>Undesired</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>VOR</td>
<td>Very High Frequency Omnidirectional Radio Range</td>
</tr>
</tbody>
</table>
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I. INTRODUCTION

Rapid growth of aviation during the 1920’s intensified the demand for all-weather and night operations. As a result, such equipment as the radio range, direction finders, and instrument landing systems were researched and developed. It was not until 1938 that the first form of radio navigation became common within the United States, which was equivalent to today’s non-directional ground beacon [19].

The Distance Measuring Equipment (DME) was developed from the radar beacon concept during World War II. Its creation was used to satisfy the navigation needs of both the civilian and military aviation community [12]. The all-weather DME used in association with additional navigational systems provides navigational guidance in each phase of flight (i.e., departure, enroute, and approach and landing). Associating the DME with a Very-high-frequency Omnidirectional Range navigation aid (VOR), referred to as VOR/DME, the facility can provide direction (radial / bearing) and distance (slant range) from the known facility location, and thus guidance for enroute flight. The term ‘enroute,’ is in reference to the straight flight paths to adjoining facility coverage areas. Like the enroute phase, approach and departure phases use the VOR/DME facility to ensure proper terminal area procedures. The approach phase of flight can use a DME in combination with a guidance system for approach and landing operations, such as the Instrument Landing System (ILS) or the Microwave Landing System (MLS).

The DME is an omni-directional range measurement system that is comprised of
an airborne interrogator and a ground based transponder. When associated with a VOR, DME coverage equals that of the VOR to the extent practical. When associated with either an ILS or an MLS, DME coverage is at least equal to the respective ILS or of the MLS azimuth angle guidance coverage sectors [10].

In reference to the ILS-DME association, the protected service volume is that of the ILS. The remaining coverage that is outside the ILS service volume but within the DME service volume is labeled as unnecessarily limits installation of an additional ILS-DME, particularly a co-channel DME. The plan view radiation coverage of the DME compared to that of the ILS is shown in Figure 1. The reference in Figure 1 to sector DME coverage is developed in the following section.

The purpose of this thesis is to provide an assessment of the benefit of a sector-directional DME antenna over that of the omni-directional antenna. It will be shown that with the use of the sector-directional antenna, additional DME facilities could be introduced into the National Airspace System (NAS) without conflicting with existing DME facilities.
Figure 1. Example Application of a Horizontally- Directive DME Transponder Antenna. (FPSV: Frequency Protected Service Volume)
II. BACKGROUND

The DME supplies the user with the line-of-sight distance between the aircraft and the ground transponder, also known as the "slant range." The DME (as with radar) is based upon the principle of time measurement. For conventional radar, the time measurement is the elapsed time between the transmission of the signal and the receipt of the signal echo. Therefore, the slant range $R$ for a radar system is given by

$$R = \frac{\Delta t \cdot c}{2}$$

where $\Delta t = t_r - t_i$

where $\Delta t$ is the elapsed time between $t_i$, the initial transmission, and $t_r$, the reception of the reflected signal, and $c$ is the propagation velocity. The received signal consists of reflections of the transmitted signal by targets of different sizes. This reflection occurs regardless of the individual target's importance to the radar user [12]. Furthermore, echoes from the desired target may be masked by stronger echoes from buildings or terrestrial features, such as mountains. In such cases, the radar beacon is useful as a navigational aid in locating specific targets. The radar beacon, upon reception of the pulses, responds with its own transmitter to radiate a signal which is easily distinguishable from the weaker echoes from surrounding objects [12].

The concept of the DME is identical to that of the radar beacon. The slant range
is calculated by the total time between transmission of the interrogation signal and reception of the reply signal transmitted from the ground based transponder. The interrogator is located in the aircraft and transmits a signal suitable to trigger the transponder which continuously waits for interrogation. The transponder delays its reply for a predetermined fixed time period and then transmits. The interrogator receives the reply, computes the total time, and then calculates the range from the aircraft to the ground facility.

Computation of the DME slant range requires that the additional delay introduced by the transponder be subtracted from the elapsed time. This time period allows the transponder to process and respond with a reply. The additional delay, also labeled the transponder dead time or zero-mile delay, accounts for the limitations on the instantaneous reply to the interrogation due to electronic devices. Under standard operation, the transponder delay time is predetermined for a specific operating mode and channel suffix, between 50 and 62 microseconds [10]. Figure 2 illustrates the principle of range measurement. The slant range $R$ is given by

$$R = \frac{(\Delta t - \tau) * c}{2}$$

where $\Delta t = t_r - t_i$

where $\Delta t$ is the elapsed time between $t_i$ at which the down-link signal is transmitted and at the time $t_r$ at which the up-link signal is received, $c$ is the propagation velocity of the
Figure 2. DME Range-Measurement Concept.
signal, and $\tau$ is the fixed delay introduced by the transponder.

A. Approach and Landing Aids

Slant range is one of three values needed to provide accurate guidance for approach procedures. Navigational aids which provide the lateral, vertical, and optional range guidance for final centerline approach procedures, under low-visibility conditions, are referred to as "precision" landing aids [13]. The DME plays an important role in supplying such systems as the ILS or MLS with the range measurement needed in the precision instrument approach.

1. Instrument Landing System (ILS)

The ILS consists of such elements as the localizer (LOC) and the glide slope (GS). Typical LOC and GS ground element locations are shown in Figure 3. The LOC forms a single course path, generally aligned with runway centerline. The GS provides vertical guidance along a fixed approach angle of about $3^\circ$. These two beams define a sloping approach path with which the pilot aligns the aircraft, starting at a point 4-7 miles from the runway [12]. To best describe the two elements, directions and guidance will be in reference to an approaching aircraft's pilot point of view.

Lateral guidance is, provided by the localizer, typically located 1,000 feet beyond
Figure 3. Typical ILS Ground Element Locations.
the far end of the runway. Two lobes, the left modulated by 90 Hz and the right by 150 Hz, are provided, as shown in Figure 4a. The localizer needle of the airborne display is driven right by the 90 Hz signal and left by the 150 Hz signal, and centers when the aircraft is on course [12].

Vertical guidance, generated by the glide slope antenna, is located at the side of the approach end of the runway, approximately 1,000 feet behind threshold. A 150 Hz modulated signal is provided below course and 90 Hz modulation is provided above course, Figure 4b. The horizontal needle of airborne display is driven up when the amplitude of the 150 Hz signal exceeds that of the 90 Hz signal and is driven down when the reverse occurs. The needle is centered when the aircraft is on course [12].

The third part of the ILS is the marker beacons. The marker beacon is a Very-High Frequency (VHF) radio transmitter which propagates an elliptically-shaped (fan) vertical radiation pattern on an assigned frequency of 75 MHz. Placed at critical locations below the glide path, their function is to mark points in space along the localizer and glide slope beams. The locations of the markers are shown in Figure 3 and Figure 5. As the aircraft passes over the markers, the airborne marker receiver indicates a blue, amber, or white light indicating appearance of the outer, middle, or inner marker, respectively [9]. The outer marker is placed about 5 nmi out from the threshold and modulated at 400 Hz, two dashes per second. The middle marker is placed
Figure 4. Principles of ILS.
where the glide slope is 200 feet above the runway, approximately 3,500 feet from the threshold. The middle marker is modulated at 1300 Hz, with one dash-dot each ¾ second. When present, the inner marker is placed where the glide slope is 100 feet above the runway, approximately 1,000 feet before the threshold. The inner marker is modulated at 3000 Hz, with six dots per second [10,12].

The required location of the marker beacons, in reference to the projected centerline of the runway, requires substantial areas of off-airport land. Largely populated cities, mountainous terrain, and bodies of water limit the operation of the marker beacons due to obstructions at the proper marker beacon locations. For these reasons and others, the DME has been accepted by International Civil Aviation Organization (ICAO) as an acceptable alternative to part or all of the marker beacon components of the ILS [10].

2. Microwave Landing System (MLS)

The MLS consists of the azimuth (AZ), elevation (EL), and precision distance measuring equipment (DME/P) elements. An optional back azimuth (BAZ) element can be installed to provide missed approach and departure guidance. Typical AZ, EL, BAZ, and DME/P ground element locations are shown in Figure 6. The MLS operates on the time reference scanning beam (TRSB) concept, where the signals are radiated from ground antennas in a standard format and then processed in the airborne MLS receiver.
Figure 6. Typical MLS Layout and Landing Operation.
The angle information is derived by measuring the time difference between the successive passes of highly directive narrow fan-shaped beams, as shown in Figure 7 and Figure 8 [12].

Narrow fan-shaped beams are generated by the ground equipment and scanned electronically to fill the coverage volume. The azimuth subsystem provides the lateral position of an approaching aircraft relative to the antenna, located beyond the stop end of the runway on the extended centerline. The azimuth and elevation subsystems operate in the microwave C-band, between 5.031 and 5.0904 GHz. The azimuth equipment generates a very narrow vertical fan shaped beams shown in Figure 7. The azimuth beam scans the coverage area which can extend to about ± 62° about the centerline, in a "TO-FRO" pattern [17].

The elevation subsystem provides vertical guidance to the approaching aircraft and is sited at a distance of 800-900 feet from the runway threshold with an offset of 250-400 feet from runway centerline. The elevation subsystem generates a narrow horizontal fan shaped beam. This beam scans the coverage area vertically from 0.9° to at least 15° above horizontal, Figure 8 [17].

The AZ and EL subsystems are commonly designated as the angle portion of the MLS since they provide angular guidance information. The angular position, either azimuth or elevation, is determined by measuring the time difference between the TO-
Figure 7. MLS Signal Coverage, Indicating Azimuth Scanning Beam.
Figure 8. Elevation Scanning Beam.
and FRO-pulses received in the aircraft. The angle measurement concept is illustrated in Figure 9.

The DME/P subsystem which typically is collocated with the azimuth subsystem provides line-of-sight range information to the aircraft [17]. Later in this chapter, section C provides a detailed discussion on the technical characteristics of the DME/P system.

B. Conventional DME System

Three types of DME ground facilities were developed, two of which have been standardized by the ICAO. The most common is the DME/N, standardized in 1952 and in use for the past 50 years. The three types of DME ground facilities are the DME/N (Narrow-band), DME/W (Wide-band), and the DME/P (Precision), each operating in the L band between 960 and 1215 MHz. Except for the spectrum, DME/N and DME/W are identical. The DME/W has a less restrictive spectrum constraint on the transmitted waveform. This rarely used system was intended to serve as an inexpensive means of providing DME service in isolated regions where frequency protection of the service volume was not a concern [12,16].

In the discussion of the DME system, there are several considerations that need to be mentioned. One is accuracy. The methodology used to derive the slant range of the DME/N involves using a fixed reference point within the transmitted and received
Figure 9. MLS Angle Measurement Concept.
signal that is standard for all DME/N systems. As required by ICAO, the accuracy of the derived range information is on the order of ±0.2 nmi [10]. Each signal is comprised of two pulses (referred to as a pulse-pair) with specific characteristics. The DME/N transmitted pulse specifications are shown in Figure 10. The half amplitude point of the pulse leading edge serves as the reference point. The airborne interrogator uses this reference point, of the first pulse, to declare the departure time of the interrogation pulse-pair as well as the arrival time of the reply pulse-pair, in turn, accurately calculating the overall elapsed time. The transponder uses this reference point of the first pulse to declare the arrival time of the interrogation pulse-pair and the departure time of the reply pulse-pair, to accurately calculate a delay which will coincide with the predetermined fixed time delay (zero-mile delay). A graphical representation of the reference point usage is shown in Figure 11. The usefulness of the second pulse, in the pulse-pair, is discussed below.

Another consideration is in reference to the DME channel plan. The frequency range for the DME is between 960-1215 MHz. The actual operating frequencies are defined on 1 MHz increments between 962-1213 MHz, leaving 2 MHz guard bands at both ends of the band [68]. An additional requirement is a frequency separation of 63 MHz between the interrogation and the reply frequency. This accommodates the pulse-pair shaping and signal processing bandwidth necessary to achieve individual system integrity [68]. This procedure leaves only 126 possible frequency pairs. As of August 2, 1995, there were a total of 686 operational DMEs in the NAS [15]. Therefore, to
Pulse envelope: Measured with a wideband linear detector.

Note: The characteristics of the DME pulse (shape and spectrum) are defined with respect to the radiated signal-in-space and do not include the effects of receiver filtering.

Leading edge @ 0.5A: Reference point for all ranging and delay measurements.

Pulse Amplitude (A): Peak amplitude of pulse envelope.

Pulse duration (h-a): Pulse duration utilized in determination of average transmitted power.

\[ P_{AV} = \frac{A^2}{2 (h-a)} \int_{a}^{h} p^2(t) \, dt \]

Pulse rise time (d-b): Rise time as measured between the 10% and 90% amplitude points on the pulse leading edge.

(d-b) \leq 3\mu s

Pulse width (f-c): Time interval between the 50% amplitude points on the leading and trailing edges.

(f-c) = 3.5 \pm 0.5\mu s

Pulse decay time (g-e): Decay time as measured between the 90% and 10% amplitude points on the pulse trailing edge.

(g-e) \leq 3.5\mu s

**Figure 10.** DME/N Transmitted Pulse Specifications (reference [12]).
Range \( (\text{nmi}) = \frac{\text{Total Round Trip Delay} - \text{Transponder Delay}}{12.36 \mu\text{s/nmi}} \)

- The \( \frac{1}{2} \) amplitude point (i.e., 6dB below the pulse peak) on the pulse leading edge is the reference point for all time measurements: range, transponder delay, and code. Hence, range measurements are independent of pulse shape.

- Range measurements are based on first pulse timing.

- Transmitted RF interrogation pulse pair is processed by interrogator receiver to begin range timing. Bias errors due to delays in the processing path are minimized since the received reply pulse pair is processed by the same receiver path.

- The transponder begins transmission of the reply pair such that the desired delay results between the \( \frac{1}{2} \) amplitude point on the leading edge of the first interrogation pulse received and the same point on the first pulse of the reply pair.

Figure 11. DME/N Calibration and Range Coding (reference [12]).
ensure the proper operation of DME facilities with the limited frequency pairs, a few processes need to be followed.

The first process includes increasing the number of DME frequency pairs. This is done by creating different modes of operation. Each frequency pair (referred to as a channel) consists of an up-link and down-link frequency which corresponds to an interrogation and a reply. In addition, each channel has a mode W, X, Y, and Z. The mode indicates the time spacing, in reference to the half amplitude reference points, between the two pulses in the pulse-pair. This creates a method of coding the DME transmissions by time spacing of a pulse pair, so that each frequency can be used more than once. These time spaces also are known as interrogation and reply codes.

Utilizing only the X and Y modes for the DME/N creates channels one through 126X and one through 126Y, totaling 252 possible channels. A brief summary of the frequency pairing is shown in Table I. The interrogation and reply code for the X channel is 12 microseconds. For the Y channels, the interrogation code is 36 microseconds where the reply code is 30 microseconds. The graphical representation of the DME channel plan with interrogation and reply frequency pairing, including modes W and Z, is shown in Figure 12. The additional modes, W and Z, are utilized exclusively by the DME/P final approach procedures, discussed later in this chapter, section C. Also shown in Figure 12, are the overlapping of Y channel frequencies due to the difference in interrogation and reply codes.
<table>
<thead>
<tr>
<th></th>
<th>Interrogation</th>
<th>Reply</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X - Channel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-63X</td>
<td>1025-1087 MHz</td>
<td>962-1024 MHz</td>
</tr>
<tr>
<td>64-126X</td>
<td>1151-1213 MHz</td>
<td>1088-1150 MHz</td>
</tr>
<tr>
<td>pulse spacing</td>
<td>12 µsec.</td>
<td>12 µsec.</td>
</tr>
<tr>
<td><strong>Y - Channel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-63Y</td>
<td>1025-1087 MHz</td>
<td>1088-1150 MHz</td>
</tr>
<tr>
<td>64-126Y</td>
<td>1088-1150 MHz</td>
<td>1025-1087 MHz</td>
</tr>
<tr>
<td>pulse spacing</td>
<td>36 µsec.</td>
<td>30 µsec.</td>
</tr>
</tbody>
</table>
**Figure 12.** DME Channel Plan with Interrogation Reply Frequency Codes, and Transponder Delays (reference [12]).
The second process involves establishing the maximum acceptable interference, within the desired service volume, between two facilities. This defines the “D/U Ratio”, where D is the signal strength of the desired facility and U is the signal strength of the undesired facility. As stated in the introduction, the DME can be associated with different navigation aids. The coverage volume of the DME must conform to at least that of the associated navigation aid. Therefore, for the particular coverage area at hand, the D/U ratio must hold for the entire area. As in reference [8], the D/U ratio for two co-channel DME facilities is +11 dB. ‘Co-channel’ means that the two facilities are on the same channel. The 1\textsuperscript{ST} and 2\textsuperscript{ND} adjacent channels indicate ±1 MHz and ±2 MHz frequency separation, respectively. Below are the D/U ratios as listed in reference [8].

<table>
<thead>
<tr>
<th>TABLE II. DME D/U Criteria.</th>
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<tbody>
<tr>
<td>Co-channel</td>
</tr>
<tr>
<td>+11 dB</td>
</tr>
<tr>
<td></td>
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<td></td>
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</tbody>
</table>
An additional consideration is that the interrogator should only communicate with the desired transponder, and likewise, the transponder only communicate with the desired interrogators. The interrogator will receive its own reply as well as be susceptible to erroneous replies from other transponders located within the radio line-of-sight. To accommodate for this, the interrogator is equipped with a process known as Search and Track. This process allows the interrogator to sort out the reply to its own interrogation and track the time windows that encompass the desired reply pulse-pair. It does so by searching through the replies until it finds a pulse-pair that is consistently synchronous with its own interrogation. The time window is then tracked for the duration of the usage of the DME facility [2].

As required by ICAO, a single DME transponder must have the capacity to service 100 aircraft, providing a minimal 70 percent reply efficiency [10,12]. The reply efficiency is seen as the ratio of the replies to interrogations [2]. To ensure that the transponder will supply unambiguous replies, it must have the capability of determining which interrogations are fitting and which are mistaken. It does so by using a Ferris discriminator. The Ferris discriminator consists of a narrow-band and wide-band filter. The narrow-band filter is used to determine and pass the on-frequency signals and attenuate the off-frequency signals. The wide-band filter is used to preserve the information contained in the leading edge of the pulse. Only if the signal is an on-frequency signal will it be processed [2,12].
This introduces a faint possibility of the interrogator speaking to the wrong ground facility. Typically for any ground facility (i.e., DME, VOR, ILS, or MLS), a three to four character identifier in Morse code is used. The DME identification signal consists of on-channel pulse-pairs sent at a periodic rate of 1350 pulse pairs per second. The airborne unit converts the periodic train of decodable pulse pairs into an audible tone. The periodic signal is keyed on and off in order to form the dots and dashes of the Morse code identification signal [12].

C. Precision DME System

The precision DME, DME/P, was standardized by ICAO in 1985 and was developed to conform with the approach and landing procedures of the MLS [12]. Like the conventional DME system, the DME/P is based on time measurement principles, which provides the user with the slant range value from the ground based transponder to the airborne interrogator. As stated earlier, the range is computed from the total elapsed time between the initial interrogation from the airborne unit and the response from the ground based facility.

During the development of the DME/P, the operational requirements defined by ICAO stated that the manner of achieving higher accuracy must be compatible with the existing DME/N systems. One aspect includes reducing the effects of multipath in the form of reflections, scattering, and diffraction from obstacles (e.g., aircraft, hangars, light
poles, etc) in the airport environment during landing operations [17]. In reference to the DME/N, multipath from obstacles, such as those stated above, cause error in the elapsed time measurement. Since DME multipath rays always arrive ‘late’ with respect to the direct signal, the resulting errors are minimized in the DME/P by referencing the received pulse at a point early in the waveform which has not been corrupted significantly by multipath [12]. The shape of the pulse, known as the cos/cos² waveform (shown in Figure 13), satisfies the required quick rise time as well as the pulse shape specifications of the DME/N system. The reference point for the approach and landing was determined to be within the first 5-30% of the leading edge and within the first 300ns [12]. This would achieve the early reference point.

Another aspect of the DME/P is the technique used to determine the time of arrival of the pulse. Due to stipulations such as loss of phase information, the envelope detection used by the DME/N is not acceptable for the DME/P. Therefore, the delay-attenuate-compare procedure, Figure 14, is used to determine the pulse arrival time. This procedure compares a delayed version of the pulse to an attenuated version of the same pulse. Pulse arrival is declared when the delayed signal exceeds the attenuated signal [12].

As stated earlier, the main stipulation on the development of the DME/P was the
Figure 13. The DME/P Pulse: FA Mode Requirements and the \( \cos/\cos^2 \) waveform (reference [12]).
Table 1: Definitions:
- P(t) = RECEIVED PULSE
- T = DELAY
- A = ATTENUATION
- TR = 100% RISE TIME OF LINEAR LEADING EDGE PULSE
- TD = DAC DECODE TIME

Figure 14. Delay-Attenuate-Compare Design Relations (reference [12]).
compatibility with the conventional DME. Unfortunately, the technique discussed above is not compatible. Therefore, the two-pulse/two-mode technique was adopted as the procedure for the DME/P system. The two modes are the Initial Approach mode (IA) and the Final Approach mode (FA), illustrated in Figure 15. The initial approach mode conforms to the requirements and methods used in the DME/N system and the final approach mode incorporates the procedures of the DME/P. The FA mode utilizes the early referencing technique in both the interrogator and the transponder for the range up to 7 nmi from the transponder. The region between 7-8 nautical miles is known as the transition region and beyond the 8 nautical miles, the IA mode is used and its operations are identical to that of the DME/N [12]. The interrogator selects the mode according to the measured range from the ground facility. The appropriate approach mode is indicated by the present interrogation mode, described by the pulse code, pulse-pair spacing (channel X, Y, W, or Z). The X and Y channels indicate the IA, thus operating as a DME/N. The W and Z channels indicate the FA, and therefore utilizing the procedures of the DME/P. The transponder reply delay timing is then based on the proper reference point for the type of interrogation received[12].
Figure 15. DME/P Two-Pulse / Two-Mode System Operation, Explained Using X Channel Code (reference [12]).
III. DME FACILITY ASSIGNMENT PROCESS

A. Frequency Congestion

One aspect of installing a DME is assigning its channel or frequency such that it does not interfere with neighboring DME facilities. When a DME is installed as an element of an approach and landing system in a DME facility congested region, its omni-directional, radiation pattern complicates the frequency-assignment process. This complication has seriously limited the use of DME in such areas, and such a limitation may not be necessary when the DME is intended only to support an approach and landing operation. As illustrated by the example shown in Figure 1, when the DME is used in place of the outer-marker beacon for an ILS, the DME readily could satisfy the operational requirements with its coverage restricted to the ILS localizer Frequency Protected Service Volume (FPSV). The resulting reduction in DME signal radiation into those regions outside the localizer FPSV should significantly alleviate the frequency-assignment limitations discussed above.

B. Sector-Directional DME Transponder Antenna

Since many of the current approach and landing installations without DME are sited in terminal areas with heavy frequency-assignment demands, it is highly probable that their DME frequency assignments were hindered, if not prohibited, due to the omni-
directional, horizontal radiation pattern provided by the current DME transponder antenna. Therefore, it is expected that the availability of a horizontally-directive DME transponder antenna will aid in mitigating the DME frequency-assignment limitation, thus providing benefit to the NAS approach and landing environment. Thus, in order to gain insight into the operational viability of a directive or “sector” DME antenna, a channel-assignment analysis is desired to investigate the implementation benefits which may occur when utilizing a sector DME antenna.
IV. ASSESSING THE BENEFIT OF A SECTOR DME ANTENNA

A. Overview

Due to the finite number of available channels, many ILS facilities are required to use the same channel. Radio-frequency (RF) interference among these co-channel facilities is prevented by requiring a minimum geographical separation. The minimum separation is determined based on consideration of the required localizer, glide slope and DME separations, as appropriate for the facility. Since all elements must be free of RF interference, the largest separation is used as the facility separation. In many cases, the separation required for the DME with its omni-directional lateral pattern is the driving factor in establishing the required facility separation. This separation is based on the requirement that the signal ratio between the desired DME facility and the undesired DME facility (i.e., D/U ratio) be at least +11dB anywhere in the desired facility’s FPSV. Generally, the outer coverage limits of the FPSV are the most susceptible to RF interference; thus they are referred to as critical points. The two desired-facility critical points closest to the undesired facility (i.e., in the plan view) will be used for determining the required separation which provides at least a +11 dB D/U ratio.
B. Methodology

For the channel-assignment analysis, the following equation, obtained from Appendix 3 of reference [8], will be used for estimating the D/U ratio for a given desired-undesired facility geometry:

\[
\frac{D}{U} = (P_{WR_D} - P_{WR_U}) + (Gain_D - Gain_U) + (Lateral_D - Lateral_U) + (TL_U - TL_D)
\]

Where:

- the subscript D (U) indicate a desired (undesired) facility parameter
- PWR is the carrier power, dBW
- Gain is the antenna gain, dBi
- Lateral is the relative lateral pattern gain, dB
- TL is the basic transmission loss, dB

For the channel assignment analysis, the carrier power, cables losses, and monitor tolerances of the desired and undesired facilities are taken to be equal. The antenna gain for eight DME models given in reference [8], ranges from +9 dBi through +11 dBi. To incorporate the worst case scenarios, the antenna gain will be directly dependent upon the omni antenna being either the desired facility or the undesired facility. Acting as the desired facility, the antenna gain is taken to be +9 dBi. Acting as the undesired facility, the antenna gain is taken to be +11 dBi. For the sector DME antenna, candidate antenna
manufacturers have calculated the antenna gain to be +17.5 dBi using their antenna model. For the channel-assignment analysis, this value will be used.

For an omni facility, an ideal omni-directional lateral pattern is assumed (i.e., a relative gain of 0 dB in any direction). For the sector facility, the relative lateral pattern gain as calculated by the manufacturer's antenna model is used.

The basic transmission loss accounts for signal reduction due to propagation between either the desired or undesired facility and the critical point. Two possible methods for obtaining the transmission losses were researched. The first was an atlas of loss curves for the desired frequency range. The second was the propagation model used to supply the atlas with the loss curves.

1. An Atlas of Basic Transmission Loss

Estimates of the basic transmission loss were taken from Report No. FAA-RD-80-1, 'An Atlas of Basic Transmission Loss For 0.125 to 15.5 GHz'[5]. The report provides transmission-loss estimates at the following frequencies: 0.125, 0.3, 1.2, 5.1, 9.4, and 15.5 GHz. The loss calculations are in reference to the distance between two antennas, 'H₁' and 'H₂'. For this analysis, 'H₁' will represent the ground based antenna and 'H₂' will represent the airborne antenna. These losses were developed by taking into account free-space loss, signal reflection, terrain effects (i.e., diffraction by 4/3 radius earth), and
atmospheric absorption. For each frequency, several sets of basic transmission loss estimates are provided and the format for a particular data set is shown in Figure 16. Each set (i.e., one figure in the atlas) is for a specified antenna height ‘H₁’, and is comprised of three data plots. These three data plots correspond to 5, 50, and 95-percent time availability (more on this later). Within each plot are the transmission loss curves, calculated for the particular ‘H₁’ and ‘H₂’ antenna height combination, as a function of separation. The values of ‘H₂’ are illustrated as letters ‘A’ through ‘I’. Unfortunately, the transmission-loss curves do not account for the particular geometries (antenna height combinations) needed for the purpose of the channel-assignment analysis. However, adequate loss curves were obtained from the atlas as described below.

The loss curves were earlier indicated to provide 5, 50, and 95 percent time availability predictions. These predictions are based upon a probability distribution curve, which incorporates the inconsistencies involving atmospheric absorption. The IF-77 model obtains estimates for atmospheric absorption by interpolating between values taken from an earlier study [6].

The effectiveness of the time availability is useful to determine the appropriate loss curves. For example, using the 95% time availability curve, means that the basic transmission loss would be no less than that, 95% of the time. Using the 5% time availability curve means the basic transmission loss would be no more than that, 5% of
Figure 16. Transmission Loss Versus Distance Curves.
the time. Therefore, the basic transmission loss curves generated from the 95% time availability curves are used for estimating the loss for the desired facility. The curves generated from the 5% time availability curves are used for estimating the undesired facility transmission loss.

The first aspect to be considered in generating the loss curves is the actual DME frequencies. The DME transponder operates on frequencies between 0.962 and 1.213 GHz, and for the case where a DME is paired with a precision approach and landing aid, specific transponder frequencies between 0.979 and 1.143 GHz may be used.

Using the interpolation technique provided in the atlas, several test points were selected and interpolations were performed for 0.979 and 1.143 GHz, using the 0.3 GHz and the 1.2 GHz curves. The results are presented in Table III and indicate that errors up to 2.716 dB (i.e., approximately 3 dB) could result if interpolation for frequency were not performed. Before determining whether interpolation for frequency is required it should be realized that there is a distinct objective to be achieved in regard to the channel assignment analysis. The objective is the generalized assessment of the benefit of a directional DME in terms of channel-assignment in the NAS approach and landing environment. This assessment will investigate how much the separation for co-channel facilities can be reduced given the availability of a sector DME and under what conditions. Since the sector antenna to be analyzed is expected to have a front-to-back
# TABLE III. Test Points for Frequency Interpolation.

<table>
<thead>
<tr>
<th></th>
<th>Loss(_{\text{A}}) @ (x = 0.3) GHz</th>
<th>Loss(_{\text{B}}) @ (x = 1.2) GHz</th>
<th>Interpolated Loss @ (x = 0.979) GHz from 1.2 GHz</th>
<th>Difference</th>
<th>Interpolated Loss @ (x = 1.437) GHz from 1.2 GHz</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve A</td>
<td>50 km</td>
<td>131.3</td>
<td>129.9</td>
<td>0.206</td>
<td>129.949</td>
<td>0.049</td>
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<td></td>
<td>70 km</td>
<td>137.9</td>
<td>139.8</td>
<td>0.279</td>
<td>139.733</td>
<td>0.067</td>
</tr>
<tr>
<td></td>
<td>90 km</td>
<td>146.4</td>
<td>152.0</td>
<td>0.822</td>
<td>151.803</td>
<td>0.197</td>
</tr>
<tr>
<td></td>
<td>100 km</td>
<td>150.9</td>
<td>160.0</td>
<td>1.336</td>
<td>159.868</td>
<td>0.319</td>
</tr>
<tr>
<td>Curve C</td>
<td>50 km</td>
<td>119.3</td>
<td>123.0</td>
<td>0.543</td>
<td>122.87</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>70 km</td>
<td>124.4</td>
<td>127.2</td>
<td>0.411</td>
<td>127.102</td>
<td>0.098</td>
</tr>
<tr>
<td></td>
<td>90 km</td>
<td>129.6</td>
<td>128.6</td>
<td>0.147</td>
<td>128.635</td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>100 km</td>
<td>132.0</td>
<td>131.3</td>
<td>0.103</td>
<td>131.325</td>
<td>0.025</td>
</tr>
<tr>
<td>Curve D</td>
<td>50 km</td>
<td>111.1</td>
<td>122.5</td>
<td>1.674</td>
<td>122.1</td>
<td>0.4</td>
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<tr>
<td></td>
<td>70 km</td>
<td>114.7</td>
<td>125.7</td>
<td>1.615</td>
<td>125.314</td>
<td>0.386</td>
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<tr>
<td></td>
<td>90 km</td>
<td>118.2</td>
<td>128.1</td>
<td>1.454</td>
<td>127.752</td>
<td>0.348</td>
</tr>
<tr>
<td></td>
<td>100 km</td>
<td>119.9</td>
<td>129.0</td>
<td>1.336</td>
<td>128.681</td>
<td>0.319</td>
</tr>
<tr>
<td>95%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve A</td>
<td>50 km</td>
<td>136.8</td>
<td>136.1</td>
<td>0.103</td>
<td>136.125</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>70 km</td>
<td>148.6</td>
<td>150.8</td>
<td>0.323</td>
<td>150.723</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td>90 km</td>
<td>162.3</td>
<td>171.0</td>
<td>1.277</td>
<td>170.695</td>
<td>0.305</td>
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<tr>
<td></td>
<td>100 km</td>
<td>170.9</td>
<td>182.6</td>
<td>1.718</td>
<td>182.189</td>
<td>0.411</td>
</tr>
<tr>
<td>Curve C</td>
<td>50 km</td>
<td>122.1</td>
<td>137.4</td>
<td>2.246</td>
<td>136.863</td>
<td>0.537</td>
</tr>
<tr>
<td></td>
<td>70 km</td>
<td>139.7</td>
<td>134.1</td>
<td>0.646</td>
<td>133.946</td>
<td>0.154</td>
</tr>
<tr>
<td></td>
<td>90 km</td>
<td>137.8</td>
<td>138.3</td>
<td>0.073</td>
<td>138.282</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td>100 km</td>
<td>141.7</td>
<td>142.5</td>
<td>0.117</td>
<td>142.472</td>
<td>0.028</td>
</tr>
<tr>
<td>Curve D</td>
<td>50 km</td>
<td>127.2</td>
<td>138.1</td>
<td>1.6</td>
<td>137.717</td>
<td>0.383</td>
</tr>
<tr>
<td></td>
<td>70 km</td>
<td>128.8</td>
<td>141.1</td>
<td>2.2</td>
<td>140.688</td>
<td>0.432</td>
</tr>
<tr>
<td></td>
<td>90 km</td>
<td>126.5</td>
<td>143.2</td>
<td>2.452</td>
<td>142.614</td>
<td>0.586</td>
</tr>
<tr>
<td></td>
<td>100 km</td>
<td>125.7</td>
<td>144.2</td>
<td>2.716</td>
<td>143.551</td>
<td>0.649</td>
</tr>
</tbody>
</table>

**Interpolation Equation Between Curves**

\[ Loss = Loss_{kl} + \frac{Loss_{k2} - Loss_{kl}}{\log \frac{x_2}{x_1}} \log \frac{x}{x_1} \]
ratio of 65 dB, the 3 dB variation which occurs across the relevant portion of the DME band for the transmission loss for a specific distance will not notably influence this assessment work. Therefore, the general analysis will best be analyzed with the transmission loss at 1.2 GHz since the loss curves are readily available.

The next aspect to be considered is the Phase Center Height (PCH) of the DME transponder antenna, which is generally about 8 to 10 feet above ground level. Since transmission loss curves are available from reference [5] for a height of 3 meters (‘H₁’), these curves are used directly.

Finally, the lower and upper heights of the FPSV for the ‘standard’ ILS and the associated DME FPSV are 1,000 feet and 4,500 feet, respectively (Figure 17). These heights represent the critical points of the sector facility. Since curves are available for H₂=300 meters (i.e., 984 feet) these curves are acceptable for the 1,000 foot height. For the upper limit, the curves for H₂=1,000 meters (3,278 feet) and H₂=5,000 meters (16,393 feet) are acceptable for interpolation to 1,371.6 meters (4,500 feet). Unlike the frequency interpolation as before, this is the interpolation of the antenna height to match that of the upper limit of the ILS FPSV.
Figure 17. Standard ILS Frequency Protected Service Volume (FPSV).
For the channel-assignment analysis, the omni facility is viewed as an existing DME associated with an ILS, having the appropriate terminal FPSV. Thus, the critical point is not the same as those for the sector facility. The critical point for the omni facility, indicated in Figure 18, is the point at which the line between the two facilities intersect the FPSV of the omni facility. The sector DME will incorporate the FPSV of the standard ILS and the critical points are as shown in Figure 17.

2. IF-77 Propagation Model

In the process of researching the transmission loss curves that correspond to those illustrated in the atlas, the model which was used to create those transmission loss curves became available. The model is known as the IF-77 model. The propagation model was developed in 1977 by the Institute for Telecommunications (ITS) for the Federal Aviation Administration (FAA). It includes allowance for terrain and atmospheric effects to be used to develop the basic transmission loss curves illustrated in the atlas, mentioned earlier [5]. Obtaining the IF-77 model has removed the limitations set by the atlas, limited by the frequency and the antenna height combinations.

Using the model parameters stated in the atlas, the loss curves were closely regenerated. Comparison testing was done to measure the differences among the recently generated curves and those digitally replicated from the atlas. The comparison verifies the proper operation of the model.
Critical Points
For Sector Facility

### Equations

- **D**: Desired distance from Omni Facility to critical point
- **D_s**: Desired distance from Sector Facility to critical point
- **U**: Undesired distance from Omni Facility to critical point
- **U_s**: Undesired distance from Sector Facility to critical point

---

**Figure 18.** Typical Geometry For an Omni-Sector Scenario.
The verification of the model made it possible to generate the loss curves at any frequency, within the limitations of the model, and any antenna height combination. Additional efforts were performed to compare the loss curves from the model with those that were previously available only through interpolation. The results displayed a difference in magnitude of at least 10 dB existing within the portion of the curve that is of interest. This difference is in the form of interpolation error and is indicated in Figure 19 and 20, shown for the 5 and 95 percent curves, respectively. Figures 19 and 20 indicate the two curves that were used for the interpolation, labeled curve C and D as labeled in the atlas. An interpolation error was anticipated, but the magnitude was not expected to be very large. Hence, the values obtained by interpolation should be used with caution. This effort provided further support to incorporate the output from the IF-77 into the channel-assignment analysis.

The initial frequency used in the analysis, prior to the verification of the propagation model, was selected from a list of six supplied by the atlas. Subsequent to verifying the propagation model, the frequency was selected to be within the ILS-DME frequency band. This frequency band is from 0.979 GHz to 1.143 GHz, thus 1.080 GHz was used throughout the analysis.
Figure 19. The Curve Interpolated Using 5% Curves C & D From The Atlas Versus The Curve Generated From The IF-77 Model.
Figure 20. The Curve Interpolated Using 95% Curves C & D From The Atlas Versus The Curves Generated From The IF-77 Model.
C. Channel-Assignment Analysis Tool

No current mathematical model exists that completely performs the needed analysis to satisfy the requirements of channel assignment. Thus, a tool has been developed to assist in the analysis. This included solving the D/U equation for preferred geometries of the desired and undesired facilities.

1. MathCad® Technique

The initial tool was produced using the software package MathCad® 6.0 Plus. MathCad® is a graphically oriented program that allows the user to view the actual equations and formulas as would be seen in standard textbooks. The tool that was created is listed in Appendix A.

The purpose of the MathCad® software package was to create a platform that would contain the algorithms used to assist in the analysis. Developed as a validation approach, it was used as a reference platform to reproduce the tool in the C/C++ language, more compatible with standard personal computers (PCs) and not requiring the MathCad® software package.
The tool performs D/U calculations for particular facility geometries. The initial algorithms required the facility separation to be supplied by the user. The variables not set by the user included values such as the relative lateral pattern gain for the sector-directional antenna (dBi), the 95% basic transmission loss curve (dB), and the 5% basic antenna loss curve (dB). These values are stored into arrays and when needed, are retrieved using a search routine to choose a value closest to that needed for the analysis. The other variables needed for the D/U equation, such as the gain of the desired and undesired facility’s are preset values depending on the scenario. For example, if the omni-directional antenna is labeled as the desired facility, the gain of the omni antenna will have a value of +9 dBi, as explained in the previous section.

The first part, part A, of the MathCad® document considers the omni-directional antenna as the desired facility, with the user input as the separation value of the two facilities. This part of the document returns all possible orientations of the sector-directional facility that pass the minimal +11 D/U ratio, at the specific distance between the two facilities. The orientation of the sector-directional facility, ranging from 0 - 359 degrees, is defined as the angular displacement between the relative lateral antenna pattern beam peak (equivalent to the extended runway centerline) and the imaginary line created between the location of the desired facility and location of the undesired facility (Figure 21). The tool computes the appropriate transmission losses using the distances computed between the desired facility and the critical point and between the undesired facility and the critical point. These distances are used by a search routines to return the
Orientation of the sector directional facility

"Sector Alignment Angle"

Extended runway center line

This part of the analysis is finished once the "Sector Alignment Angle" has incremented to 360 degrees about the fixed base.

Figure 21. Method Used Within The Analysis Tool To Determine The Separation For The Desired Omni Facility.
appropriate transmission losses. Returning all possible orientations of the sector-directional facility, the sector facility is rotated in small increments about its fixed location, a total of 360 degrees, computing the D/U ratio at each increment. The results are stored and used by an additional function to flag the values that are greater or equal to +11 dB, indicating an allowable orientation of the sector facility that satisfies the minimal D/U ratio for co-channel DME. The output is plotted in polar form and indicates the possible orientations of a sector facility, given the separation distance used in the calculations. For the results of part A, shown in Appendix A, page A-9, the separation value was set to 64 nautical miles. The thick dotted line indicates the allowable orientation of the sector facility. The thin dotted line indicates the relative lateral antenna pattern of the sector-direction DME and the thick solid line indicates the FPSV associated with the sector facility.

Part B of the MathCad® document considers the sector-directional antenna as the desired facility, using the same separation of the two facilities as in part A. This part of the document returns all possible locations of the omni-directional facility, with the specified separation, that pass the minimal +11 dB D/U ratio. The orientation of the omni-directional facility is defined as the angular displacement between the relative
lateral antenna pattern beam peak of the sector antenna (the extended runway centerline for the sector facility) and the imaginary line created between the location of the desired facility and location of the undesired facility. This orientation angle is identical to the orientation angle described for part A (more on this later). An easier explanation would be to visualize the omni facility as rotating about the sector facility with a fixed radius (Figure 22), the radius being the facility separation. To compute the appropriate transmission losses, the distances are computed between the desired facility and the critical point and between the undesired facility and the critical point. Mentioned earlier (Figure 17), the sector facility as the desired facility has a total of four candidate critical points. Therefore, at each angular increment of the omni facility’s location, the distances from each facility to each critical point is computed, the corresponding transmission losses are computed, and the relative lateral pattern gain of the sector facility corresponding to the angular location of the omni facility is computed. These computations are used to compute the D/U ratio at each angular increment of the omni facility’s location. The results are stored and used by an additional function to flag the values that are greater or equal to +11 dB, indicating an allowable orientation that satisfies the minimal D/U ratio for co-channel DME. The output indicates the possible locations of an omni facility, given the facility separation distance used in the calculations.
Figure 22. Method Used Within The Analysis Tool To Determine The Separation Distance For The Desired Sector Facility.
The results of part B are as shown in Appendix A, page A - 16. For this particular example with a facility separation of 64 nautical miles, indicated with the thick dotted line, that every location of the omni facility along the radius of the specified separation created a D/U ratio less than +11 dB. It follows, therefore, that the facility separation must be greater than 64 nautical miles to satisfy the D/U ratio of co-channel DME. The thin dotted line indicates the relative lateral antenna pattern of the sector-directional DME and the thick solid line indicates the FPSV associated with the sector facility. The circles on each corner of the FPSV indicate the critical points that were analyzed.

The first two parts of the MathCad® document were used as preliminaries for Part C. Part C was developed to satisfy the requirements specified for a channel-assignment analysis tool. Developed to assist in the analysis, the output indicates the minimal separation between the two co-channel DME facilities for a given sector facility orientation (indicated in the results as the ‘Sector Alignment Angle’), as described in both part A and part B. The program combines the algorithms of segments A and B and replaces the user input with a decrementing facility separation, starting at 190 km. Therefore, unlike results from part A and B, part C returns the separation value needed at a particular orientation. Computed for the omni facility as the desired facility and for the sector facility as the desired facility, the minimal separation values are obtained that satisfy the +11 dB for every orientation. The results are as shown in Appendix A, pages A - 20 through A - 24. In order to reduce the computation time, the incrementing value of the orientation angle as well as the decrementing value of the separation distance were...
set large, thus creating the 'stair step' effect in the output. The first graph, Appendix A, page A - 20, indicates the required separation with the omni facility as the desired facility. The second graph, Appendix A, page A - 23, indicates the required separation with the sector facility as the desired facility. Combining the two graphs creates a chart that supplies the facility separation for any orientation, satisfying the D/U requirements for both facilities. This is shown in Appendix A, page A - 24.

Once the algorithms for the MathCad® platform were validated, the actual analysis tool was developed in the C/C++ language. This language made the tool more compatible with other PCs and also greatly decreased the computation time. Thus, the incrementing and decrementing could be reduced for finer resolution.

2. Analysis Tool

The analysis tool was formed directly from the development platform of the MathCad® document. The algorithms are identical to those used in part C and therefore required minimal validation work. Graphed using Excel® 7.0, the output is shown in Figure 23. As indicated, the 100 nautical miles separation for two co-channel DME facilities can be reduced to a minimum of 70 nautical miles, under specific geometries.
Figure 23. The Output Of The Analysis Tool Used To Assist In The Channel-Assignment Analysis For The 1080 MHz Co-channel Frequency.
V. CHANNEL-ASSIGNMENT ANALYSIS

For the case where the desired and undesired facilities both have an omni-directional DME antenna, the separation provided in FAA Order 6050.32 (reference [8]) will be taken as the minimum required separation, which is 100 nmi for the standard FPSV. This separation is the basis for assessing the benefit of a sector DME antenna.

Performing the channel assignment analysis involved using the results of the analysis tool with sector aeronautical charts for the central Ohio region. In addition to using the topographical charts, the Airport/Facility Directory provided regional airports that use ILS as an approach and landing aid. The theoretical testing used a circular area with 100 nautical mile radius centered at the Zanesville, Ohio airport, (ZZV).

The analysis was completed two separate ways. The first analysis considered ZZV as a site location to install an ILS-DME approach and landing aid. This analysis illustrates the benefit of applying the sector-directional DME antenna in an area not acceptable for the omni-directional DME antenna. For this analysis, the facilities surrounding ZZV exist as omni-directional ILS-DME facilities. The second analysis considered ZZV as the site location of an existing ILS-DME approach and landing aid. This analysis illustrates the possibilities of installing candidate ILS-DME facilities within the FPSV of the omni-directional ILS-DME facility, considered to be ZZV.
A. Installation of a Sector-Directional DME Antenna

This analysis considered ZZV as the candidate for the installation of an ILS-DME approach and landing aid. The analysis was broken into two sections, the first performed the channel-assignment analysis with the omni-directional DME antenna. The second, performed the channel-assignment analysis with the sector-directional DME antenna, with the identical scenario as the first test.

First, the typical channel-assignment analysis was applied for the omni-directional DME antenna. These procedures include assigning an ILS-DME to a channel that is unused by another ILS-DME facility within a 100 nautical mile radius. Because the channel plan of the ILS-DME collocation is limited to channels 18-56 (even values of the X and Y channels), only 40 sites have the possibility to be an ILS-DME. Therefore, within the 100 nautical mile radius, if at least 40 ILS-DME channels have already been assigned, a channel would therefore not be available for the ZZV ILS-DME. Thus the installation of the collocated DME must be canceled, reverting to marker beacons if geographically capable. For this analysis, 23 instrument approach airports are within the 100 nautical mile radius of ZZV, with a total of 41 runways equipped with ILS. For this particular analysis, it is assumed that only 40 runways are ILS-DME. Therefore, installing an ILS-DME will use a channel already existing.

The second test applied the channel-assignment analysis for a sector-directional
DME antenna with the identical scenario above. These results will indicate which existing ILS-DME facilities are geographically located to permit a co-channel existence with ZZV. Using Figure 23 (the analysis tool), the specific geometries were indicated that can reduce the required facility separation. The benefit of a sector-directional DME antenna is the allowance of an ILS-DME installation at ZZV. Therefore, indicating only one geometry that exist between ZZV and a surrounding ILS-DME that is also shown to operate using Figure 23, thus has provided a benefit.

The geometries are established using the location of the two facilities and the extended runway centerline of the sector facility. The ‘Sector Alignment Angle’ is the angle between the extended runway centerline of the sector facility and line connecting the two ILS-DME facilities. This is identical to that illustrated in Figures 21 and 22.

The results identified 11 runways with acceptable geometries that allowed for the addition of the sector-directional DME antenna to be installed at ZZV. These 11 runways provide a candidate channel that can co-exist with ZZV.

B. Possible Locations for Use of a Sector-Directional DME Antenna

This analysis uses ZZV as the ‘pre-existing’ omni-directional DME facility, collocated with ILS. The surrounding ILS facilities act as the ‘to be installed’ sector-directional DME facilities. Noting that the analysis tool only calculates the facility
separation for two facilities, it will be assumed that the two facilities involved in the analysis are the only facilities of interest. Therefore, each facility, within the 100 nautical mile radius, paired with the ZZV facility will be analyzed independently. It is easily seen that with the addition of a single DME in the NAS, a cascading effect results with respect to RFI on the surrounding DME facilities. Thus, the final results provide the list of candidate facilities that could use the sector-directional DME antenna.

Because the channel plan of the ILS-DME collocation is limited to channels 18-56 (even values of the X and Y channels), only 40 sites have the possibility to be an ILS-DME. If there are more than 40 ILS-DME collocations in the same region, some facilities will have identical channels. For this analysis, a total of 23 airports are within the 100 nautical mile radius, each with at least one ILS facility (total of 41 ILS equipped runways).

To use Figure 23 (analysis tool), each sector facility was given an extended runway centerline in the direction of runway heading. In addition, a straight line was drawn from ZZV, the ‘pre-existing omni facility,’ to each sector facility. The angle between the two lines would indicate the ‘Sector Alignment Angle,’ which is the x-axis as shown by the output of the analysis tool. Matching the angle computed between the two lines with the sector alignment angle of the analysis tool output, indicates the minimal separation values needed to obtain the required +11 D/U ratio. Comparing the minimal separation value with distance computed from the map, indicates if a possible
candidate for a sector facility.

For this analysis, the sector-directional DME antenna provided a benefit for 10 of the 41 ILS runways.
VI. CONCLUSIONS

This thesis has examined the operational viability of sector-directional distance measuring equipment. When used to support ILS precision approaches, the usual omni-directional lateral pattern of the DME is grossly inefficient and precludes the installation of additional co-channel facilities within a 100 nautical mile radius.

Although the sector-directional DME antenna provided a benefit over the omni-directional antenna, the improvement was not as great as was expected. With the parameters of the sector-directional antenna (i.e., relative antenna gain, front-to-back ratio), it was expected that the separation would be much less than the minimum of 70 nautical miles computed by the analysis tool. Using Figure 24, the performance can be explained.

The separation of two omni-directional facilities must be a minimum of 100 nautical miles, 82 nautical miles between the undesired facility and the desired facility’s critical point. For the sector facility, the minimal separation is computed at the critical point most susceptible to the undesired facility, typically the one closest to the undesired facility. In Figure 24, these susceptible critical points are indicated to be approximately 27 nautical miles from the omni-omni critical point. At the sector critical point, the relative antenna gain is approximately +11dBi, which is identical to that of the omni-directional facility. This limits the desired sector facility to a minimal 73 nautical miles.
Approximately -7.5 dB below Omni DME FPSV antenna beam peak

Separation Distance 100 nautical miles

Omni-Directional Antenna Pattern, Gain=11 dBi

Approximately 27 nautical miles

Generalized Sector-Directional Antenna Pattern, Gain=17.5 dBi

Figure 24. Explanation Of Poor Facility Separation Results.
of facility separation. This could be eliminated by improving the relative antenna pattern beam width to better cover the outer critical points of the ILS FPSV.

The overall performance of the sector-directional DME antenna supplied a benefit in the predicted areas as shown in Figure 25. Use of the sector-directional antenna will allow for additional DME installations in areas where omni facilities currently are prohibited.

It is recommended that future work focus on the field testing of candidate sector-directional equipment. Any deviations in actual performance with respect to that which was expected should then be fed back into the analysis tool described herein.
Figure 25. Possible Sector Facility Orientations For Nearby Runways.
VII. REFERENCES


APPENDIX A: MathCad® Document
**User Input:**

A. **Omni antenna labeled as the Desired Facility**

The separation distance between the desired facility and the undesired facility.

\[ d_{\text{Separation}} = 64 \text{ nmi} \]

---

B. **Sector antenna labeled as the Desired Facility**

The following are the angles at which the sector DME critical points are located and their distance from the facility.

\[
\begin{align*}
\Phi_{FPSV_0} &= 35 \\
\Phi_{FPSV_1} &= 10 \\
\Phi_{FPSV_2} &= 350 \\
\Phi_{FPSV_3} &= 325 \\
A_{B_0} &= 10 \\
A_{B_1} &= 18 \\
A_{B_2} &= 18 \\
A_{B_3} &= 10
\end{align*}
\]
Constant: Angular location of the Undesired Facility in terms of the Desired Facility.
\[ \beta = 137 \text{ degrees} \]

Constant: Identified critical point of the Desired Facility.
\[ d_{FPSV} = 18 \text{ nmi} \quad \text{Alt}_{FPSV} = 1372 \text{ meters} \]
\[ \phi_{FPSV} = 137 \text{ degrees} \quad \text{Top:} \ 1372 \text{ meters} \]
\[ \text{Bottom:} \ 305 \text{ meters} \]

Antenna Pattern Data file:
\[ \text{azimuth} := \text{READPRN}(\text{dme_azm}) \]

Using user input data to find the distance from the undesired facility to the critical point of the desired facility.

Law of Cosines:
\[ A = d_{FPSV} \quad a = |\beta - \phi_{FPSV}| \]
\[ C^2 = A^2 + B^2 - 2AB\cos\theta \quad B = d_{\text{Separation}} \quad a = 0 \]
\[ C = 46 \]
\[ d_{\text{Undesired}} = C \]

Calculates the angle between Beta and Phi.
\[ a = d_{\text{Separation}} \quad b = C \quad c = d_{FPSV} \]
\[ \eta = \arccos\left(\frac{a^2 + b^2 - c^2}{2ab}\right) \quad \eta = 0^\circ \text{deg} \]
\[ \psi(\beta, \eta) = \begin{cases} \eta & \text{if } \beta > 180 \\ \eta & \text{otherwise} \end{cases} \]
\[ \psi(\beta, \eta) = 0^\circ \text{deg} \]

Changing the distance from 'nmi' to 'km' for use in the 'Free Space Loss Equation'.
\[ d_{\text{Undesired}} = 46 \text{ nmi} \quad 1\text{nmi} = 1.852 \text{ km} \]
\[ d_{FPSV} = 18 \text{ nmi} \]
\[ d_{U} = d_{\text{Undesired}} \times 1.852 \text{ km} \]
\[ d_{D} = d_{FPSV} \times 1.852 \text{ km} \]
Transmission Loss Values.

**Top: 1372 meters**

1. Depending on the altitude, either A or E will be used. Column '0' for the E matrix does not contain distance values. Because all curves have the same Column '0' values, the A matrix was used as a substitute.

2. Depending on the facility, either 95% or 5% curve will be used.

*Default frequency is 1200 MHz.*

---

**Bottom: 305 meters**

A 300 \textunderscore 5 = \text{READPRN}(\text{three\_a\_5})

A 300 \textunderscore 95 = \text{READPRN}(\text{three\_a\_95})

A 1200 \textunderscore 5 = \text{READPRN}(\text{twelve\_a\_5})

A 1200 \textunderscore 95 = \text{READPRN}(\text{twelve\_a\_95})
Desired Losses incorporate 95% curves.

Loss from the Desired Facility:

\[ \text{TL}_{\text{Desired}}(R) := \begin{cases} \text{for } j \in 1..1499 \quad & \text{if } \text{Alt}_{FPSY} = 1372 \\ \text{if } A_{1200-95,j,0} \leq R & \begin{cases} \text{if } A_{1200-95,j+1,0} - R \text{ } & \text{after} \quad \text{answer} \rightarrow E_{1200-95,j,1} \text{ if before<after} \\
\text{if } A_{1200-95,j,1} - R \text{ } & \text{before} \quad \text{answer} \rightarrow E_{1200-95,j+1,1} \text{ otherwise} \\
\text{if } A_{1200-95,j,1} - R \text{ } & \text{answer} \\
\text{otherwise} \quad \text{answer} \\
\text{otherwise} \quad \text{answer} \\
\end{cases} \\
\end{cases} \]

Searching routine that uses; the calculated distances from the critical point, and the transmission loss data files. The distances are matched with the closest corresponding distances in the transmission loss files. Thus indicating the appropriate loss.

\[ \text{TL}_{\text{Desired}}(d_{D}) = 134.5 \]

**Revisited:** Calculated distance from the desired facility to the critical point, used to find the appropriate transmission loss.

\[ d_{D} = 33.336 \text{ km} \]
**Undesired Losses incorporate 5% curves.**

Loss from the Undesired Facility:

\[
TL_{Undesired}(R) = \begin{cases} 
\text{for } j \in 1..1499 \\
\text{if } Alt_{FPSV}=1372 \\
\text{if } A_{1200-5j,0} \leq R \\
\text{after} \rightarrow A_{1200-5j+1,0} - R \\
\text{before} \rightarrow A_{1200-5j,0} - R \\
\text{answer} \rightarrow E_{1200-5j,1} \text{ if before}<after \\
\text{answer} \rightarrow E_{1200-5j+1,1} \text{ otherwise} \\
\text{answer} \\
\text{answer} \\
\text{otherwise} \\
\text{if } A_{1200-5j,0} > R \\
\text{after} \rightarrow A_{1200-5j+1,0} - R \\
\text{before} \rightarrow A_{1200-5j,0} - R \\
\text{answer} \rightarrow A_{1200-5j,1} \text{ if before}<after \\
\text{answer} \rightarrow A_{1200-5j+1,1} \text{ otherwise} \\
\text{answer} \\
\text{answer} \\
\text{answer} \\
\end{cases}
\]

\[TL_{Undesired}(d_U) = 128\]

**Revisited:** Calculated distance from the undesired facility to the critical point, used to find the appropriate transmission loss.

\[d_U = 85.192 \text{ km}\]
Basic Transmission Loss values:

\[ d_D = 33.336 \quad d_U = 85.192 \]

**Loss for the desired facility:**

\[ TL_{\text{Desired}}(d_D) = 134.5 \quad \text{dB} \]

\[ TL_D = TL_{\text{Desired}}(d_D) \]

**Loss for the undesired facility:**

\[ TL_{\text{Undesired}}(d_U) = 128 \quad \text{dB} \]

\[ TL_U = TL_{\text{Undesired}}(d_U) \]

Most recent azimuth data (11/15/95).

*Searches the data "dme_azm.dat" to find the relative power that closely matches the desired angle, \( \phi \) & \( \theta \).*

**Azimuth:**

\[
\text{RelativePower Lateral}(\phi) =
\begin{align*}
\text{inc} & \leftarrow 0 \\
\text{for } j & \in 1.. \text{last(azimuth)} \\
\text{answer} & \leftarrow \text{azimuth}_{j, 1} \text{ if azimuth}_j, 0 \leq \phi \\
\text{answer}
\end{align*}
\]

RelativePower Lateral(\( \phi \) FPSV) = -60.5

Lateral \( D = 0 \) The '0' represent the omni relative power gain (dB) for the desired facility.

**Current values calculated for the 'D/U' Ratio Equation.**

\( \phi : 1, 4 .. 360 \quad \text{Gain}_U = 17.5 \quad \text{Gain}_D = 9 \)

\[ TL_{\text{Undesired}}(d_U) = 128 \quad \text{TL Desired}(d_D) = 134.5 \]

\[ \text{Lateral}_U(\phi) = \text{RelativePower Lateral}(\phi) \quad \text{Lateral}_D = 0 \]

**Equation used to determine the overall 'D/U' Ratio.**

\[ \text{Ratio}(\phi) = (TL_U - TL_D) + \text{(Gain}_D - \text{Gain}_U) + (\text{Lateral}_D - \text{Lateral}_U(\phi)) \]

An 'if, then' statement used to create a graphical representation of the allowable degrees of orientation of the undesired facility.

\[ \text{Pass}(\phi) =
\begin{align*}
\text{a} & \leftarrow 1 \text{ if Ratio}(\phi) < 11 \\
\text{a} & \leftarrow 11 \text{ otherwise}
\end{align*}
\]
Angular orientation of undesired facility

Current 'Pass / Fail' plot does not take into consideration the angular shift due to the difference between the desired facility location and the location of the critical point, if any at all.
angle_{\text{az}_i} := \frac{\pi}{180} \cdot \text{azimuth}_{i,0}

\min(\text{azimuth}^{<1>}) = -76.6

r_{\text{az}_i} := -\min(\text{azimuth}^{<1>}) + \text{azimuth}_{i,1}

\text{round}(x) := \text{if}(x - \text{floor}(x) < .5, \text{floor}(x), \text{ceil}(x)) \text{'Rounding routine.'} \\
\psi(\beta, \eta) = 0 \cdot \text{deg}

\Delta := \text{round}\left(\frac{\psi(\beta, \eta) \cdot 180}{\pi}\right)

\Delta = 0 \\

\theta := 0 \ldots 360

\text{FPSV} :=
\begin{cases} 
\text{for i} & 0 \ldots 10 \\
\text{r}_i & 11 \\
\text{for i} & 11 \ldots 35 \\
\text{r}_i & 6.11 \\
\text{for i} & 36 \ldots 324 \\
\text{r}_i & 0 \\
\text{for i} & 325 \ldots 349 \\
\text{r}_i & 6.11 \\
\text{for i} & 350 \ldots 360 \\
\text{r}_i & 11 \\
\end{cases}

\phi := 1 \ldots 360

\text{Pass}_{\phi} := \text{Pass}(\phi)

r_{\text{az}_i} := \frac{\max(r_{\text{az}})}{\max(\text{Pass})} \cdot \max(\text{Pass})

\text{Normalized Sector antenna pattern, scaled for "Pass / Fail" Area plot.}

r_{\text{az}_i} := \frac{11}{-\min(\text{azimuth}^{<1>})} \cdot r_{\text{az}_i}
**User Input:**

The separation distance between the desired facility and the undesired facility.

\[ d \text{ Separation} = 64 \text{ nmi} \]

\[ d_{FPSV} = 18 \text{ nmi} \]

\[ \phi_{FPSV} = 137 \text{ degrees} \]

\[ \text{Alt}_{FPSV} = 1.372 \times 10^3 \text{ meters} \]

*Top: 1372 meters*

*Bottom: 305 meters*

---

**Undesired Facility:** The "Pass / Fail" Region is placed with the undesired facility and indicates the allowable locations of the desired facility.
Onmi Facility with indications of the critical point and the direction of the undesired facility.

\[ \text{omni}_i := 11 \quad \text{Undesired Facility} \quad \text{udf}_i := 0 \quad \text{Critical Point} \quad \text{udf}_\beta := 11 \quad \text{cp}_{\text{FPSV}} := 11 \quad \text{d FPSV} \]

Desired Facility:

![Desired Facility Diagram]

- Critical Point
- FPSV
- Antenna Pattern
- Direction of Undesired Facility
Part B:

Renaming the Sector Facility as the Desired and the Omni Facility as the Undesired.
The following are the angles at which the sector DME critical points are located.

\[ \Phi_{\text{FPSV}_0} = 35 \quad \Phi_{\text{FPSV}_1} = 10 \quad \Phi_{\text{FPSV}_2} = 350 \quad \Phi_{\text{FPSV}_3} = 325 \quad \beta = 1..360 \]

Critical Point '0': Calculations for the critical point located at 35 degrees.

\[ A_B = 10 \quad \alpha_0 = |\beta - \Phi_{\text{FPSV}_0}| \quad \Phi_{\text{FPSV}_0} = 35 \]

B = Separation

\[ C_0 = \sqrt{(A_B)^2 + B^2 - 2 \cdot A_B \cdot B \cdot \cos(\alpha_0 \cdot \frac{\pi}{180})} \]

Default values:

- Lateral \( U = 0 \)
- Gain \( D = 17.5 \)
- Gain \( U = 11 \)

Critical Point '1': Calculations for the critical point located at 10 degrees.

\[ A_B = 18 \quad \alpha_1 = |\beta - \Phi_{\text{FPSV}_1}| \quad \Phi_{\text{FPSV}_1} = 10 \]

B = Separation

\[ C_1 = \sqrt{(A_B)^2 + B^2 - 2 \cdot A_B \cdot B \cdot \cos(\alpha_1 \cdot \frac{\pi}{180})} \]

Sector_Loss_0 = TL Desired \( (A_B \cdot 1.852) \)

Omni_Loss_0_\( \beta \) = TL Undesired \( (C_0 \cdot 1.852) \)

Lateral_0D = RelativePower \( \text{Lateral}(\Phi_{\text{FPSV}_0}) \)
Critical Point '2': Calculations for the critical point located at 350 degrees.

\[ A_B = 18 \quad \alpha_\beta = \left| \beta - \Phi_{FPSV_2} \right| \quad \Phi_{FPSV_2} = 350 \]

\[ B = \text{Separation} \]

\[ C_\beta = \sqrt{(A_B)^2 + B^2 - 2 \cdot A_B \cdot B \cdot \cos(\alpha_\beta \frac{\pi}{180})} \]

\[ \text{Sector Loss}_2 = \text{TL Desired}(A_B \cdot 1.852) \]

\[ \text{Omni Loss}_2 = \text{TL Undesired}(C_\beta \cdot 1.852) \]

\[ \text{Lateral}_2 = \text{Relative Power Lateral}(\Phi_{FPSV_2}) \]

Critical Point '3': Calculations for the critical point located at 35 degrees.

\[ A_B = 10 \quad \alpha_\beta = \left| \beta - \Phi_{FPSV_3} \right| \quad \Phi_{FPSV_3} = 325 \]

\[ B = \text{Separation} \]

\[ C_\beta = \sqrt{(A_B)^2 + B^2 - 2 \cdot A_B \cdot B \cdot \cos(\alpha_\beta \frac{\pi}{180})} \]

\[ \text{Sector Loss}_3 = \text{TL Desired}(A_B \cdot 1.852) \]

\[ \text{Omni Loss}_3 = \text{TL Undesired}(C_\beta \cdot 1.852) \]

\[ \text{Lateral}_3 = \text{Relative Power Lateral}(\Phi_{FPSV_3}) \]
Default values for the 'D/U' Ratio Equation.

Gain U = 11  Gain D = 17.5
Lateral U = 0

Equations used to determine the overall 'D/U' Ratio for each critical point.

\[
\text{Ratio}_0 = \left(\text{Omni}_0 - \text{Sector}_0\right) + \left(\text{Gain}_D - \text{Gain}_U\right) + \left(\text{Lateral}_D - \text{Lateral}_U\right)
\]

\[
\text{Ratio}_1 = \left(\text{Omni}_1 - \text{Sector}_1\right) + \left(\text{Gain}_D - \text{Gain}_U\right) + \left(\text{Lateral}_D - \text{Lateral}_U\right)
\]

\[
\text{Ratio}_2 = \left(\text{Omni}_2 - \text{Sector}_2\right) + \left(\text{Gain}_D - \text{Gain}_U\right) + \left(\text{Lateral}_D - \text{Lateral}_U\right)
\]

\[
\text{Ratio}_3 = \left(\text{Omni}_3 - \text{Sector}_3\right) + \left(\text{Gain}_D - \text{Gain}_U\right) + \left(\text{Lateral}_D - \text{Lateral}_U\right)
\]

An 'if, then' statement used to create a graphical representation of the allowable degrees of orientation of the undesired facility.

\[
\text{Pass}_0 = \begin{cases} a-1 & \text{if } \text{Ratio}_0 < 11 \\ a-11 & \text{otherwise} \end{cases} \quad \text{Pass}_1 = \begin{cases} a-1 & \text{if } \text{Ratio}_1 < 11 \\ a-11 & \text{otherwise} \end{cases}
\]

\[
\text{Pass}_2 = \begin{cases} a-1 & \text{if } \text{Ratio}_2 < 11 \\ a-11 & \text{otherwise} \end{cases} \quad \text{Pass}_3 = \begin{cases} a-1 & \text{if } \text{Ratio}_3 < 11 \\ a-11 & \text{otherwise} \end{cases}
\]

\[
\text{test} := \begin{cases} \text{for } \beta \in 1..360 \\ \text{answer}_0 := 11 \text{ if } (\text{Pass}_0 = 11) \cdot (\text{Pass}_1 = 11) \cdot (\text{Pass}_2 = 11) \cdot (\text{Pass}_3 = 11) \\ \text{answer}_0 := 1 \text{ otherwise} \\ \text{answer} \end{cases}
\]
D/U for all locations of Omni Facility

angular location of undesired facility

"Pass / Fail" Areas
**User Input:**

The separation distance between the desired facility and the undesired facility.

\[ d_{\text{separation}} = 64 \text{ nmi} \]

\[ \text{Alt FPSV} = 1.372 \times 10^3 \text{ meters} \]

*Top: 1372 meters*

*Bottom: 305 meters*

**Undesired Facility:** The "Pass / Fail" Region is placed with the undesired facility and indicates the allowable locations of the desired facility.
The following are the remaining "Basic Transmission Loss Curves"

\[ \begin{align*}
\text{low-mid:} & \\
1000 \text{ meters} & \\
C_{300 \_5} &= \text{READPRN(c300 \_5)} \\
C_{300 \_95} &= \text{READPRN(c300 \_95)} \\
C_{1200 \_5} &= \text{READPRN(c1200 \_5)} \\
C_{1200 \_95} &= \text{READPRN(c1200 \_95)} \\
\end{align*} \]

\[ \begin{align*}
\text{high-mid:} & \\
5000 \text{ meters} & \\
D_{300 \_5} &= \text{READPRN(d300 \_5)} \\
D_{300 \_95} &= \text{READPRN(d300 \_95)} \\
D_{1200 \_5} &= \text{READPRN(d1200 \_5)} \\
D_{1200 \_95} &= \text{READPRN(d1200 \_95)} \\
\end{align*} \]
Part C:

This section provides the minimal separation for all orientations of the omni and sector antennas.

- The first analysis has the omni antenna as the desired facility.

- The second analysis has the sector antenna as the desired facility.
FIRST ANALYSIS: Omni antenna facility is labeled as the desired location.

Range :=
  for beta ∈ 10, 20..360
    for distance ∈ 190, 180..5
      if \[ (\text{TL Undesired}(\text{distance}) - \text{TL Desired}(33.336)) + (9 - 17.5) + 0 - \text{RelativePower} L \]
        \[ \text{answer}_{\text{beta}} \leftarrow (\text{distance} + 10) + 33.336 \]
        break
    end
  end
end

if \text{distance} < 33
  \text{answer}_{\text{beta}} \leftarrow 33 + 33.336
end

\text{answer}
Required Separation, Omni as Desired

- Range Data
- Minimal Omni-Sector Separation Range
SECOND ANALYSIS: Sector antenna facility is labeled as the desired location.

NOTE: Listed below are external values used in the following function. Values were removed from the function to decrease processing time.

\[ \theta_0 = 35 \]
\[ A_0 = 18.52 \]
\[ \text{double}A_0 = 2 \cdot A_0 \]
\[ \text{square}A_0 = \left( A_0 \right)^2 \]
\[ \text{DesiredLoss}_0 = \text{TL Desired}(A_0) \]
\[ \text{LateralGain}_0 = \text{RelativePower Lateral}(\theta_0) \]
\[ \theta_2 = 350 \]
\[ A_2 = 33.336 \]
\[ \text{double}A_2 = 2 \cdot A_2 \]
\[ \text{square}A_2 = \left( A_2 \right)^2 \]
\[ \text{DesiredLoss}_2 = \text{TL Desired}(A_2) \]
\[ \text{LateralGain}_2 = \text{RelativePower Lateral}(\theta_2) \]

\[ \theta_1 = 10 \]
\[ A_1 = 33.336 \]
\[ \text{double}A_1 = 2 \cdot A_1 \]
\[ \text{square}A_1 = \left( A_1 \right)^2 \]
\[ \text{DesiredLoss}_1 = \text{TL Desired}(A_1) \]
\[ \text{LateralGain}_1 = \text{RelativePower Lateral}(\theta_1) \]
\[ \theta_3 = 325 \]
\[ A_3 = 18.52 \]
\[ \text{double}A_3 = 2 \cdot A_3 \]
\[ \text{square}A_3 = \left( A_3 \right)^2 \]
\[ \text{DesiredLoss}_3 = \text{TL Desired}(A_3) \]
\[ \text{LateralGain}_3 = \text{RelativePower Lateral}(\theta_3) \]
RangeII = \{ \text{for } \beta \in 10, 20..360 \}
\begin{align*}
\phi_0 &= \cos(\beta - 35 \cdot \text{deg}) \\
\phi_1 &= \cos(\beta - 10 \cdot \text{deg}) \\
\phi_2 &= \cos(\beta - 350 \cdot \text{deg}) \\
\phi_3 &= \cos(\beta - 325 \cdot \text{deg})
\end{align*}
\text{for distance } \in 190, 180..5

\text{SquareDistance} \leftarrow \text{distance}^2
\begin{align*}
C_0 &\leftarrow \sqrt{\text{squareA}_0 + \text{SquareDistance} - \text{doubleA}_0 \cdot \text{distance} \cdot \phi_0} \\
C_1 &\leftarrow \sqrt{\text{squareA}_1 + \text{SquareDistance} - \text{doubleA}_1 \cdot \text{distance} \cdot \phi_1} \\
C_2 &\leftarrow \sqrt{\text{squareA}_2 + \text{SquareDistance} - \text{doubleA}_2 \cdot \text{distance} \cdot \phi_2} \\
C_3 &\leftarrow \sqrt{\text{squareA}_3 + \text{SquareDistance} - \text{doubleA}_3 \cdot \text{distance} \cdot \phi_3}
\end{align*}

\text{ratio}_0 \leftarrow (\text{TL Undesired}(C_0) - \text{DesiredLoss}_0) + \text{gain} + \text{LateralGain}_0 \\
\text{ratio}_1 \leftarrow (\text{TL Undesired}(C_1) - \text{DesiredLoss}_1) + \text{gain} + \text{LateralGain}_1 \\
\text{ratio}_2 \leftarrow (\text{TL Undesired}(C_2) - \text{DesiredLoss}_2) + \text{gain} + \text{LateralGain}_2 \\
\text{ratio}_3 \leftarrow (\text{TL Undesired}(C_3) - \text{DesiredLoss}_3) + \text{gain} + \text{LateralGain}_3

\text{smallest} \leftarrow \min(\text{ratio})
\text{if smallest} < 11
\begin{align*}
\text{for } y \in 0..3 \\
\text{if } \text{ratio}_{y \text{ smallest}} \\
\text{answer}_{\beta, 0} \leftarrow \text{distance} + 5 \\
\text{answer}_{\beta, 1} \leftarrow y \\
\text{break}
\end{align*}
\text{if } \min(C) < 74.08
\begin{align*}
\text{answer}_{\beta, 0} &\leftarrow 74.08 \\
\text{answer}_{\beta, 1} &\leftarrow 8 \\
\text{break}
\end{align*}
\text{answer}
Sector Alignment Angle, degrees

Required Separation, Sector as Desired

-  Rangell Data
-  Minimal Sector-Omni Separation Range

Most Susceptible Critical Point

-  Critical Point Most Susceptible to Interference
Required Separation

Distance of Separation, nmi

Sector Alignment Angle, degrees

Range II Data

Minimal Sector-Omni Separation Range

Range Data

Minimal Omni-Sector Separation Range
APPENDIX B:  Analysis Tool Source Code
DME Channel Assignment Analysis

Created By: Jeff Haubeil

6/25/96

Created to compute the D/U ratio for an omni-sector DME configuration.
Used as a time saver for the computation. Initial work done in
MathCad 6.0.

#include <stdio.h>
#include <math.h>
#include <stdlib.h>
#include <graph.h>
#include <process.h>
#include <string.h>
#include <conio.h>

void OpenDataFiles(void);
void OpenData1080_5(void);
void OpenData1080_95(void);
void OpenDME_AZM(void);
float TLDesired(float R);
float TLUndesired(float R);

void OmniAsDesired(void);
void SectorAsDesired(void);
int MinimumIndex(float Y[4]);

float data1080_5[2][100], data1080_95[2][100], DME_AZM[360]
float omni[361], sector[2][361];

void main(void)
{
    FILE *fpr;
    int j=0;

    printf("\n\nAvionics Engineer Center\tOhio University\n\nTask Order 7, Sector-Directional DME Antenna\n\nCreated By: Jeff Haubeil\n\nAnalysis for 1080 MHz Co-Channel Separation.\n\nCreated Data File: data1080.txt\n\n");
    OpenDataFiles();

    // ** Analysis for Omni as desired Facility **
    OmniAsDesired();
    // ** Analysis for Sector as desired Facility **
    SectorAsDesired();

    fpr=fopen("data1080.TXT","w+");
    fprintf(fpr,"Angle, Omni Separation(km), Sector Separation(km), Sector Critical Point, ");
    fprintf(fpr,"Omni Separation(nmi), Sector Separation(nmi)\n");
    // For plotting reasons, the number of data points were reduced to 72
    for(j=0;j<3600;j=j+5)
    {
        fprintf(fpr,"%i, %f, %f, %f, %f, %f, j, omni[j], sector[0][j], ");
    }
}
sector[1][j]);
    fprintf(fpr, "%f, %f\n", omni[j]/1.852, sector[0][j]/1.852);
}
  fcloseall();

// Function : OpenDataFiles
//
// Arguments : void
// Purpose : Function used to open files containing digitized transmission loss curves and horizontal DME antenna pattern.
//
// Return : void
//
// Author : J. Jeffrey Haubeil
// Date : 07-12-96

void OpenDataFiles(void)
{
    Opendata1080_5();
    Opendata1080-95();
    OpenDME_AZM();
}

// Function : Opendata1080_5
//
// Arguments : void
// Purpose : Places data contained in the digitized transmission loss curve into an 2X100 array call data1080_5.
// Included in the file name (data1080_5) is the frequency (1080 MHz) and the time-availability (5%).
//
// Return : void
//
// Author : J. Jeffrey Haubeil
// Date : 07-12-96

void Opendata1080_5(void)
{
    int counter=0, status=0, j=0;
    FILE *fp;

    fp=fopen("1080_5.csv", "r");
    do
    {
        status=fscanf(fp, "%f,%f\n", &data1080_5[0][counter],
                      &data1080_5[1][counter]);
        counter++;
    }
    while(counter <= 99 && status != EOF);

    fclose(fp);

// Function : Opendata1080_95
void Opendata1080_95(void)
{
    int counter=0, status=0;
    FILE *fp;

    fp=fopen("1080_95.csv", "r");
    do
    {
        status=fscanf(fp,"%f,%f
\n", &data1080_95[0][counter],
                      &data1080_95[1][counter]);
        counter++;
    }
    while(counter <= 99 && status != EOF);

    fclose(fp);
}

void OpenDME_AZM(void)
{
    int counter=0, status=0;
    float temp=0.0f;
    FILE *fp;

    fp=fopen("DME_AZM.csv", "r");
    do
    {
        status=fscanf(fp,"%f,%f
\n", &temp, &DME_AZM[counter]);
        counter++;
    }
    while(counter <= 370 && status != EOF);

    fclose(fp);
}
// Function : TLDesired
//
// Arguments : float R
// Purpose : This function is pasted a range value, in kilometers,
// and returns the corresponding loss value, in dB.
// The array data1080_95[] contains the range from
// 2-800km in the first column and the corresponding
// transmission loss in the second column, for a 95%
// time availability (indicated in the array name).
// Because the input range value may not exactly
// match a value in the first column, "before" and
// "after" are used to select the closest one.
// Return : float
//____________________________________________
// Author : J. Jeffrey Haubeil
// Date : 07-12-96
//____________________________________________

float TLDesired(float R)
{
    float res=0.0f, after=0.0f, before=0.0f;
    int j=0;
    float Y=0.0f, m=0.0f, X=0.0f, b=0.0f;

    // Scan through the range column, starting at 2km,
    // stopping at the first range greater than the input
    // range. Leaving an index to evaluate the bfore and
    // after values.
    while(data1080_95[0][j]<=R && j<101)j++;

    // Interpolation Equation. Y=mx+b
    m = (data1080_95[1][j] - data1080_95[1][j-1])/(data1080_95[0][j] -
    data1080_95[0][j-1]);
    X = R - data1080_95[0][j-1];
    b = data1080_95[1][j-1];
    Y = m*X+b;

    return(Y);
}

// Function : TLUndesired
//
// Arguments : float R
// Purpose : This function is pasted a range value, in kilometers,
// and returns the corresponding loss value, in dB.
// The array data1080_5[] contains the range from
// 2-800km in the first column and the corresponding
// transmission loss in the second column, for a 5%
// time availability (indicated in the array name).
// Because the input range value may not exactly
// match a value in the first column, "before" and
// "after" are used to select the closest one.
// Return : float
//____________________________________________
float TLUndesired(float R)  
{
    float res=0.0f, after=0.0f, before=0.0f;
    int j=0;
    float Y=0.0f, m=0.0f, X=0.0f, b=0.0f;

    // Scan through the range column, starting at 2km,
    // stopping at the first range greater than the input
    // range. Leaving an index to evaluate the before and
    // after values.
    while(data1080_5[0][j]<=R && j<101)j++;

    // Interpolation Equation. Y=mX+b
    m = (data1080_5[1][j] - data1080_5[1][j-1]) / (data1080_5[0][j] -
        data1080_5[0][j-1]);
    X = R - data1080_5[0][j-1];
    b = data1080_5[1][j-1];

    Y = m*X+b;
    return(Y);
}

// Function : OmniAsDesired
//
// Arguments : void
// Purpose : This function is part one of a two part program.
// This function computes the separation(km) of two
// facilities (omni-sector scenario) needed to satisfy
// the +11dB D/U ratio for every degree (0-360).
// For this function, the omni facility is desired and
// the sector facility is undesired.
// Return : void

void OmniAsDesired(void)
{
    int beta=0;
    float distance=0.0f;

    printf("Calculating Omni-Sector separations:\n");
    // beta: the orientation of the sector facility with respect to the
    // straight line between the two facilities.
    for(beta=0;beta<=360;beta++)
    {
        if (fmod(beta,30)==0.0)printf("\n");
        printf(".");
    }
    // distance: starts at 190km and decreases in increments of 0.5km
    for(distance=190;distance>=0;distance-=.5f)
{
    if((abs(TLUndesired(distance)-TLDesired(33.336f))+(9.0f-17.5f)+(0.0f-DME_AZM[beta]))<11.0f)
    {
        omni[beta]=distance+0.5f+33.336f;
        distance=0;
    }
    else if(distance<=0)
    {
        omni[beta]=33.336f;
    }
}
printf("\nFinished Omni Calculations\n");

// Function : SectorAsDesired
//
// Arguments : void
//
// Purpose : This function is part one of a two part program.
// This function computes the separation(km) of two
// facilities (sector-omni scenario) needed to satisfy
// the +11dB D/U ratio for every degree (0-360).
// For this function, the sector facility is desired
// and the omni facility is undesired.
//
// Return : void
//
void SectorAsDesired(void)
{
    int beta=0;
    double pi=3.141592654;
    int i=0, SmallestIndex=0;
    float distance=0.0f, gain=(17.5f-11.0f);
    float SquareDistance;
    int theta[4];
    float A[4];
    float doubleA[4];
    float squareA[4];
    float DesiredLoss[4];
    float LateralGain[4];
    float phi[4], C[4], ratio[4];

    theta[0]=35;
    theta[1]=10;
    theta[2]=350;
    theta[3]=325;
    A[0]=18.52f;
double A[0] = (2*A[0]);
square A[0] = A[0] * A[0];

DesiredLoss[0] = TLDesired(A[0]);
LateralGain[0] = DME_AZM[theta[0]];
LateralGain[1] = DME_AZM[theta[1]];

printf("Calculating Sector-Omni separations: \n");

// beta: the orientation of the sector facility with respect to the
// straight line between the two facilities.
for (beta = 0; beta <= 360; beta++)
{
    phi[0] = (float) cos((double)((beta-35)*pi/180.0f));
    phi[1] = (float) cos((double)((beta-10)*pi/180.0f));
    phi[2] = (float) cos((double)((beta-350)*pi/180.0f));
    phi[3] = (float) cos((double)((beta-325)*pi/180.0f));

    if (fmod(beta, 30) == 0.0) printf("\n");
    printf(".");
}

// distance: starts at 190km and decreases in increments of 0.5km
for (distance = 190; distance >= 0; distance -= 0.5f)
{
    SquareDistance = distance * distance;

    for (i = 0; i < 4; i++)
    {
        C[i] = (float)sqrt(squareA[i] + SquareDistance -
                    doubleA[i]*distance*phi[i]);

        ratio[i] = TLUndesired(C[i]) - DesiredLoss[i] + gain +
                    LateralGain[i];
    }

    SmallestIndex = MinimumIndex(ratio);

    if (ratio[SmallestIndex] < 11.0f)
    {
        sector[0][beta] = distance + 0.5f;
        sector[1][beta] = (float)SmallestIndex;
        distance = 0.0f;
    }
    else if (distance <= 0)
    {
        sector[0][beta] = 0.0f;
    }
\[ \text{sector}[1][\beta] = 8; \]

}\}

\text{printf(\"\nFinished Sector Calculations\n\")};

\text{// Function : MinimumIndex}
\text{//}
\text{// Arguments : float Y[4]}
\text{// Purpose : This function returns the index pointing to the}
\text{// minimal value within the array. This function is}
\text{// limited to an array of only four elements. Which}
\text{// satisfies the problem at hand (Only four critical}
\text{// points). The values passed are the D/U values}
\text{// for each critical point.}
\text{// Return : int}
\text{//---------------------------------------------}
\text{// Author : J. Jeffrey Haubeil}
\text{// Date : 07-12-96}
\text{//---------------------------------------------}

\text{int MinimumIndex(float Y[4])}
\{\n  int j=0, answer=0;
  int temp[2];

  \text{// First test}
  if(Y[0]<Y[1])
  "
          \text{temp[0]=0;}
  \} \text{else}
\text{  temp[0]=1;}
\text{  else}
\text{  temp[0]=1;}

  \text{// Second test}
  if(Y[2]<Y[3])
  \{ \text{temp[1]=2;}
  \} \text{else}
  \{ \text{temp[1]=3;}
  \}

  \text{// Final test}
  if(Y[temp[0]]<Y[temp[1]])
  \{ \text{answer=temp[0];}
  \} \text{else}
  \{ \text{answer=temp[1];}
  \}

  \text{return(answer);}