Dale M. Rhoads, Avionics Engineer
Federal Aviation Administration
Office of Aviation System Standards
PO Box 25082, AVN-343
Oklahoma City, Ok 73125
Email: dale.rhoads@faa.gov
Phone (405).954-6694
Fax (405).954-4740

UNITED STATES AERONAUTICAL RADIO SPECTRUM INTERFERENCE INVESTIGATIONS, SUSTAINING AIR TRAVEL SAFETY, PRESENT AND FUTURE

ABSTRACT

Advances in wireless radio frequency technology, airport wireless services, and wireless internet services, have made the aeronautical radio spectrum more and more vulnerable to interferences to these technologies and services as time goes on. Large increases in the number of wireless technology users has led to an increase in the potential for these users interfering with one another, ultimately impacting aeronautical navigation and communication services.

Combining this trend with the aviation community's growing dependence on radio signals has created a more complicated radio spectrum environment with possible severe safety risk implications. Although avionics equipment can usually detect such problems, radio frequency interference (RFI) can render a navigational aid unusable for long periods of time. Not only is this a problem, it can also create a costly airspace environment to the users, dangerous circumstances, and impact the safety of the flying public. With this in mind, the demand for methods of quickly identifying and locating sources of interference is growing, and the flight inspection community has recognized this important need.

Within the United States Federal Aviation Administration (FAA), the Office of Aviation Systems Standards (AVN) recently began equipping its flight inspection aircraft fleet with a system known as the Airborne Interference Monitoring and Detection system (AIMDS). This added a key component to the FAA's already existing ground mobile capabilities in RFI detection and mitigation developed by the Office of Spectrum Policy and Management (ASR). Equipping aircraft with this airborne system addressed some unique problems that the ground-fixed, portable, and mobile systems, already in existence did not and presented some engineering challenges that needed to be overcome to achieve the functionality and performance desired.

The purpose of this paper is twofold. **Part I** presents the problems, issues, and solutions involved with implementing the AIMDS capability. **Part II** presents the future plans for a seamless airborne and ground Interference Monitoring and Detection System (IMDS) network working together to further improve the response and mitigation of RFI affecting the aeronautical radio spectrum. Ultimately, this joint capability will sustain the high level of air travel safety required by the flying public.

PART I: IMPLEMENTING THE AIRBORNE INTERFERENCE MONITORING AND DETECTION SYSTEM (AIMDS)

INTRODUCTION

To understand some of the issues and problems associated with implementing AIMDS, a basic understanding of the principles of RFI detection and radio direction finding (DF) techniques is required. This paper will begin with a discussion of RFI DF principles and continue with a discussion of the issues, problems, and solutions involved in implementing an AIMDS.

PRINCIPLES OF RFI DETECTION AND MITIGATION

After determining that a navigational aid is being affected by interference from another radio frequency (RF) source, the frequency of that source has to be found. In attempting to determine the frequency of the interference, a spectrum analyzer can be a very useful tool. The spectrum analyzer gives a visual indication, in an amplitude vs. frequency format, of RF signals that are being transmitted "over the air" at a particular instance in time. In addition to the frequency of the interference, an experienced user can identify the type of modulation and bandwidth of the interfering signal -- both of which can be valuable in locating the source of the interference. Even prior to AIMDS implementation, all FAA flight inspection aircraft had been equipped with a spectrum analyzer and a variety of antennas to be used for this purpose.

Figure 1. DF Receiver/Processor

After establishing the frequency of the interference, the next step is to locate it. This can be accomplished using one of the many DF techniques. In FAA flight inspection aircraft with AIMDS, the DF receiver/processor, shown in figure 1, works in combination with a four-element antenna array, shown in figure 2a, to give a visual indication of the relative direction to the interference source. Once the DF receiver/processor is tuned to the interfering frequency obtained from the spectrum analyzer, it automatically computes the relative bearing to the source and displays this on its front panel.

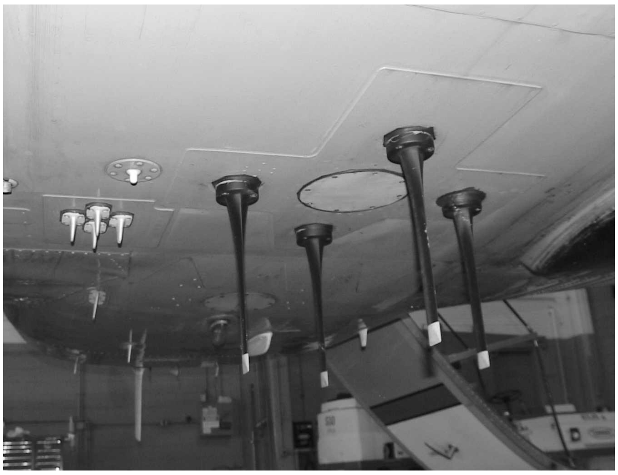

Figure 2a. DF Antenna Arrays

After the relative bearing to the interference is known, the location of the interference can be determined. This is accomplished by one of two methods. First, if the position and heading of the DF receiver/processor is known, the relative bearing to the interference can be plotted on a map. Once two lines-of-bearing (LOB) from two different locations are plotted, their intersection will indicate the location of the interference source. This is known as triangulation. The second method of locating the interference is to turn towards the interference (indicated by a relative bearing of zero degrees on the DF receiver/processor) and travel in that direction until the relative bearing changes to 180 degrees. The point where the bearing changed is the location of the interference. This method is what gives the AIMDS an advantage over a fixed or ground-based mobile IMDS. Aircraft are not limited to travel over roadways and have the added advantage of being above natural and man-made obstructions that make ground-based DF more difficult.

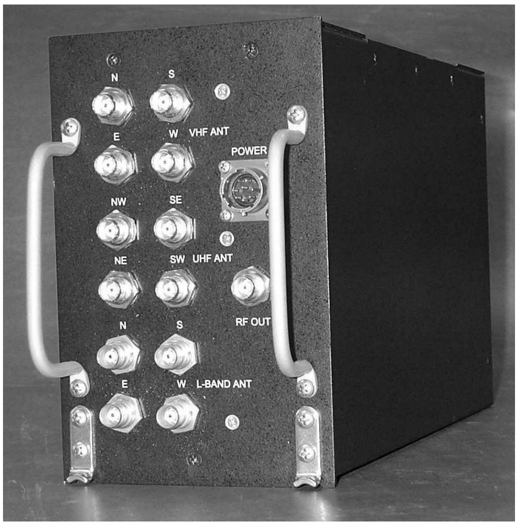

Figure 2b. DF Antenna Combiner

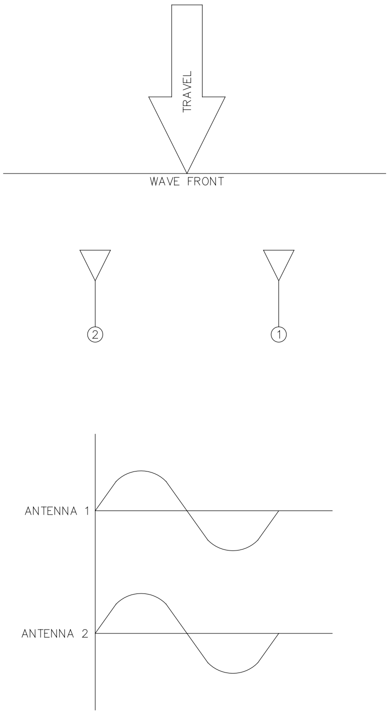

Figure 3. Simple 2-Element Array

Focusing now on the hardware and how it operates, the DF receiver/processor uses the Watson-Watt method of radio DF. Basically, the Watson-Watt method uses differences in time-of-arrival of a signal being received at the different elements in the antenna array. This is shown using a simple two-element antenna array made up of antenna-1 and antenna-2 shown in figure 3. A signal arriving from a relative bearing of zero degrees, will arrive at both antennas at the same time resulting in a zero-degree phase relationship between the signals received by the two antennas. The same phase relationship would also exist for a signal source with a relative bearing of 180 degrees.

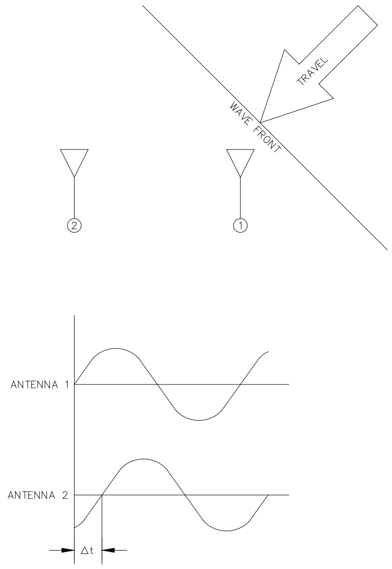

Figure 4. Simple 2-Element Array

Next, consider a signal with a bearing, relative to the antenna array, of 45 degrees as shown in figure 4. From this source, signals received by the two antennas have a phase difference between them, as shown. This is due to the different times-of-arrival of the signal at the two antennas. This same phase relationship would also be true for an incoming signal with a relative bearing of 135 degrees. To eliminate the ambiguity, a second pair of antennas is required. This antenna pair is made up of antenna-3 and antenna-4 shown in figure 5. The 45 degree relative bearing signal being received by this second set of antennas will cause the phase relationship shown, as would a signal with a relative bearing of 315 degrees. Both antenna pairs have the 45 degree relative bearing in common which causes the DF receiver/processor to ignore the 135 and 315 degree ambiguities. The use of differences in time-of-arrival, corresponding to a phase difference of the signals being received by the different elements in the antenna array, is the key concept in the Watson-Watt method.[1]

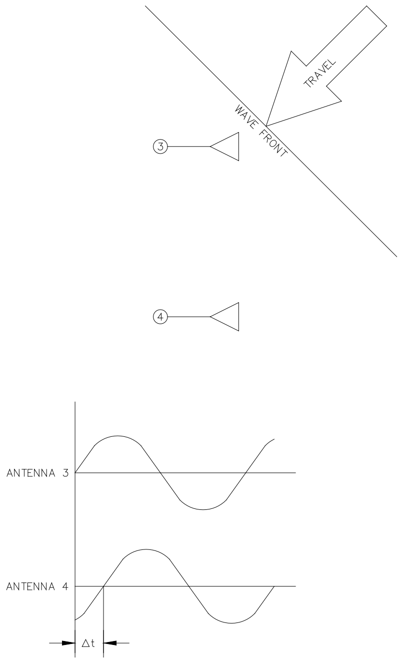

Figure 5. Simple 2-Element Array

EQUIPMENT SELECTION

The process of selecting AIMDS equipment is virtually the same as the selection process of any equipment required to perform a task -- balancing equipment costs against performance. The equipment selection process for the AIMDS was made somewhat easier by the fact that the Office of Spectrum Policy and Management (ASR) was already using RFI DF equipment in their fixed and mobile IMDS systems. ASR had even begun designing and using their own AIMDS with a high degree of success. In an effort to standardize equipment inventories, the decision was made to use this same equipment in FAA flight inspection aircraft. In addition, availability problems were overcome by using commercial off-the-shelf equipment whenever possible.

The AIMDS does differ from the fixed and mobile IMDS with regard to the antenna elements. The first AIMDS installed in a flight inspection aircraft used an antenna already proven for RFI DF by the FAA Technical Center. It was installed on the Beech model 300 Super King-Air and is the straight, black, blade antenna shown in figure 2a. Although the antenna performed well on the Beech 300, it is inadequate for use on high-speed jet aircraft.

EQUIPMENT LOCATION

As previously mentioned, the AIMDS consists of a DF receiver/processor, shown in figure 1; antenna arrays, like the those on the flight inspection Beech 300, shown in figure 2a; and the antenna electronics (referred to as the antenna combiner), shown in figure 2b. It was necessary to install the

DF receiver/processor in the cabin near the flight inspection console. The antennas are mounted on the bottom of the aircraft, presuming that all RF interference will be from ground-based sources, and the antenna combiner is installed in an avionics equipment rack inside the aircraft. The only other major consideration for laying out the equipment is the routing of the antenna cables from the antenna combiner to the antennas in the array. For this, careful consideration was given to ensure that the cables did not go through any disconnects. The antenna cables for the antenna array require that they be phase-matched to each other. Any disconnects could have made this difficult to achieve. As will be shown, small variations in cable lengths can cause large bearing errors.

ACCURACY AND SOURCES OF ERROR

No matter what the cost, how easy it is to install and maintain, or how simple or complex it is, the bottom line is, “How well does the system work?” If it does not work, it is of little value. For the AIMDS, understanding how it works and applying those principles during installation will ensure proper system performance. As mentioned earlier, the key concept to how the equipment operates is the difference in time-of-arrival of a signal being received by the different elements in the antenna array. Anything that varies the arrival time (phase) of a signal being received by an element in the DF array can potentially degrade system performance. Any phase shifting of the RF signal by the antenna system must be the same for all elements of the array to eliminate degradation in performance. The following is a discussion of antenna considerations followed by a discussion of antenna cabling considerations.

Antennas vary in size usually according to their operating frequency -- the higher the frequency, the smaller the antenna. This is due to the wavelength of the signals. Lower frequencies have longer wavelengths than higher frequencies.

wavelength (m): $\lambda = \frac{c}{f}$ (1)

(in free space)

where:
f is frequency of the signal (in Hz)
c is the velocity of signals in space (in m/s)
(c = 300,000,000 m/s)

At 108 MHz, the wavelength is a little less than 3 meters (in free space) and at 150 MHz the wavelength is 2 meters. By and large, antenna performance is typically defined in terms of a low standing-wave ratio in order to reduce the likelihood of damaging a radio transmitter. In this regard, for an antenna to work well across the aeronautical VHF band and keep its size reasonably small, it is necessary to employ some method of tuning. Unfortunately, this tuning results in phase shifts of received signals. Although the antenna performs well for VHF communications, it performs poorly as part of a DF antenna array unless the phase shift is the same among all antennas in the array.

FREQUENCY	STD DEV
65.5000 MHz	5.01
66.5000 MHz	4.17
71.5000 MHz	13.05
77.7000 MHz	33.84
87.3500 MHz	9.69
104.7700 MHz	2.57
113.9000 MHz	2.12
129.3500 MHz	24.60
131.0300 MHz	28.21
142.6000 MHz	180.97
148.2300 MHz	26.65
155.4000 MHz	8.74
162.8000 MHz	3.38
165.7000 MHz	3.45
173.7600 MHz	6.06
180.2900 MHz	6.17
191.3400 MHz	56.01
199.8100 MHz	13.36

Table 1. Bearing Errors (CI 108)

To demonstrate this, DF performance data was gathered on a DF array using off-the-shelf VHF antennas. Bearing measurements were made every 30 degrees at different frequencies in the VHF band. The standard deviation of the bearing errors is recorded in table 1.[2] A phase plot, shown in figure 6,[3] of one of the antennas in the array was made using a network analyzer. A comparison of the bearing error to the phase plot shows the largest errors occurring at the frequencies where the slope of the phase plot is greatest (maximum rate of change in degrees/MHz). To understand the significance of this, the sections of the plot where the slope is large are the sections where the phase differences among antennas are likely to be the greatest. Unless the phase plots of all antennas in the array are the same, frequencies will exist where the bearing error may be too large for DF use. Unfortunately, this is true for most VHF aircraft antennas. One solution is to hand-select antennas with identical phase plots. Another is to have an antenna designed specifically for DF applications.

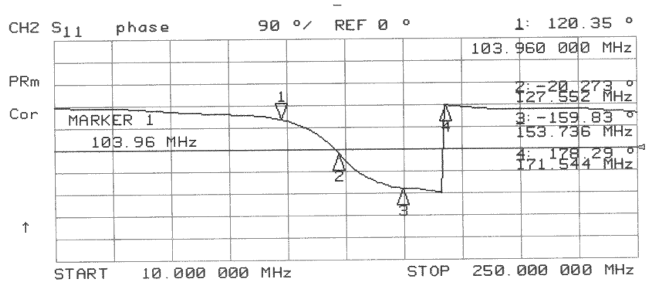

Figure 6. Phase-Plot (CI 108)

For higher frequencies, such as UHF and L-band, wavelengths of the signals are smaller. Many antennas designed for these frequencies do not employ tuning networks. They are quarter-wave monopoles, or similar, and will often work for DF applications without further considerations. The GPS-band DF array, shown in figure 2a, is made up of L-band antennas that demonstrate this. Variations in these antennas due to manufacturing are small and selecting a matched set is not necessary. The test results of this array are recorded in table 2.[4] Additionally, the test data for the VHF array, also shown in figure 2a, is recorded in table 3.[5] This particular antenna works well as a VHF or UHF (not shown) DF antenna. This is supported by the data in table 4.[6] Unfortunately, this is not a high-speed antenna.

FREQUENCY	STD DEV
1175.1000 MHz	3.66
1201.0000 MHz	5.72
1225.1000 MHz	5.86
1250.1000 MHz	4.55
1265.1000 MHz	4.74
1285.5000 MHz	5.72
1300.1000 MHz	2.91
1315.1000 MHz	3.14
1325.1000 MHz	5.98
1345.1000 MHz	5.42
1360.1000 MHz	4.71
1410.0000 MHz	6.17
1480.0000 MHz	3.07
1564.5000 MHz	3.35
1586.1000 MHz	3.03
1599.9000 MHz	3.07

Table 2. Bearing Errors (S65-5366-4S)

In addition to antenna delay errors, antenna cable delays can also cause bearing errors. Ultimately, the goal is to match the phase delay among all cables and all antenna elements. As mentioned earlier, signals of lower frequencies have longer wavelengths than signals of higher frequencies. For that reason, the distance between elements in DF arrays designed to operate at lower frequencies is greater than the distance between those designed for higher frequencies. The spacing between the elements in the VHF array in figure 2a is 38.74 cm (15.25 in) while the spacing between elements in the L-band array in figure 2a is 7.62 cm (3 in). As will be shown, the error introduced by the differences in cable lengths is directly related to the geometry of the array.

FREQUENCY	STD DEV
65.5000 MHz	6.86
66.5000 MHz	7.07
71.5000 MHz	3.34
77.7000 MHz	2.86
87.3500 MHz	2.12
104.7700 MHz	2.51
113.9000 MHz	6.47
129.3500 MHz	2.93
131.0300 MHz	2.90
142.6000 MHz	1.99
148.2300 MHz	2.60
155.4000 MHz	1.40
162.8000 MHz	1.97
165.7000 MHz	2.10
173.7600 MHz	1.76
180.2900 MHz	1.84
191.3400 MHz	2.84
199.8100 MHz	1.55

Table 3. Bearing Errors (DA100-001 VHF Configuration)

FREQUENCY	STD DEV
201.1000 MHz	3.82
211.1000 MHz	3.27
235.5000 MHz	3.55
260.9800 MHz	2.60
278.8000 MHz	2.37
296.5000 MHz	2.44
307.5000 MHz	3.74
320.3000 MHz	2.57
327.5000 MHz	3.02
337.5000 MHz	3.01
348.5000 MHz	3.40
361.4000 MHz	4.46
378.5000 MHz	3.61
389.5000 MHz	4.19
410.5000 MHz	3.25
421.5250 MHz	6.77
430.5250 MHz	4.74
450.5000 MHz	3.80
471.5000 MHz	4.44
494.5000 MHz	8.95
501.5000 MHz	4.27
519.9250 MHz	2.59

Table 4. Bearing Errors (DA100-001 UHF Configuration)

Again consider the simple two-element DF array made up of antenna-1 and antenna-2 as shown in figure 7. The spacing between the elements is d, and the error budget for bearing is θ. Distance L is the additional distance required for a signal to travel if it was arriving from a source with a relative bearing of θ.

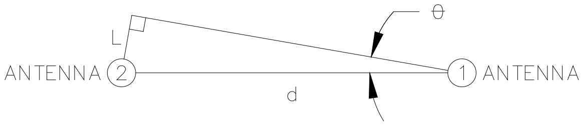

Figure 7. Simple 2-Element Array

length (m): $L = d \sin\theta$ (2)
(in free space)

where:
d is the antenna element spacing (in meters)
θ is the bearing error budget (in degrees)

If antenna-2 had a cable that was longer than that of antenna-1 by length L, a signal arriving from a source with a relative bearing of zero-degrees would appear to have a relative bearing of θ. When specifying cable lengths, a tolerance of ± L/2 is necessary to remain within the error budget. This is because one cable could be longer by L/2 and one could be shorter by L/2 resulting in a maximum bearing error of θ. Lastly, transmission line velocity factors further complicate matters. A signal travelling in free space will travel distance L in a shorter time than a signal traveling in a transmission line. Therefore, the equivalent L in terms of cable length requires that L be multiplied by the transmission line velocity factor Vp, thus making L' smaller.

length (m): $L' = L \times V_p$ (3)
(in transmission lines)

where:
Vp is the velocity factor of the transmission line

To determine the allowable phase delay of a cable, simply multiply L' by the phase constant β'. This is necessary for verifying cables with a network analyzer.

phase constant (deg/m): $\beta = \dfrac{360f}{c}$ (4)
(in free space)

phase constant (deg/m): $\beta' = \dfrac{360f}{V_p c}$ (5)
(in transmission lines)

It is interesting to note that equation (4) is the phase constant, β, for signals travelling in free-space and equation (5) is the phase constant,β', for signals travelling in a transmission line. When multiplying β' by L' the velocity factor , Vp, cancels out as shown in equation (6). Also, multiplying L, from equation (2), by β, from equation (4), results in equation (7), which is the same as equation (6).

phase delay (deg): $\beta' L' = \dfrac{360f}{c} \times d \sin\theta$ (6)

phase delay (deg): $\beta L = \dfrac{360f}{c} \times d \sin\theta$ (7)

For example, a VHF antenna array with a spacing of d = 38.74 cm (15.25 in) and an error budget of θ = 5 degrees yields a value of L = 3.376 cm (1.329 in). Multiplying by a velocity factor of Vp = 0.69 (the velocity factor of RG-142) produces L' = 2.329 cm (0.9171 in). Half of L' is 1.165 cm (0.4585 in), which is a reasonable tolerance for building RF cables. On the other hand, consider an L-band antenna array with a spacing of d = 7.62 cm (3 in) and an error budget of θ = 5 degrees. This results in L = 0.6641 cm (0.2615 in). Again, multiplying by a velocity factor of Vp = 0.69, produces L' = 0.4582 cm (0.1804 in). Half of L' is 0.2291 cm (0.0902 in) which corresponds to a 6.2 degree phase delay at 1575 MHz.[7] This is a much more difficult tolerance to meet. The solution is to purchase phase-matched cables if installing a GPS-band DF array. Building phase-matched cables, although not impossible, is a trial-and-error process that produces many cables that are not usable for L-band DF arrays. Although they are not usable for L-band DF, they are probably acceptable for VHF DF use.

It is also important to remember that the above example assumed no error introduced by antenna elements. To maintain an error budget of 5 degrees, the antenna cable tolerances will be smaller than those in the example due to any additional error introduced by the antenna elements.

PLANNED UPGRADE FOR THE AIMDS

In its present state, the AIMDS is virtually a stand-alone system independent of all other systems in the flight inspection aircraft. As result, it is operated manually from the front panel of the DF receiver/processor. This requires the operator to relay bearing information to the pilot in order to track down interference. Additionally, there is no heading information sent to the DF receiver/processor, and position information is obtained from a stand-alone GPS receiver. Not knowing aircraft heading, the DF receiver/processor can only be operated in a "relative" mode and all bearing measurements are relative to aircraft heading and not magnetic north. This makes it impossible to overlay stored LOB's on a map. To make the system more convenient to operate, some improvements are being planned. A simplified block diagram is provided in figure 8.

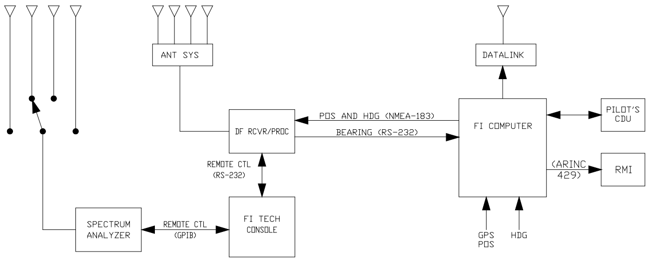

Figure 8. RFI System Block Diagram

First, the aircraft's flight inspection computer will be reprogrammed to provide heading and GPS-derived position to the DF receiver/processor. This data will be provided in NMEA 183 (National Maritime Electronics Association) format for compatibility with the DF receiver/processor. This will eliminate the need for a stand-alone GPS receiver and allow for overlaying stored LOB's on a map. Second, the flight inspection computer will be reprogrammed to accept LOB's from the DF receiver/processor and display this information in the cockpit. Eventually this data could be downlinked to a ground-based station. Third, software for the flight inspection technician's console will provide remote control of the DF receiver/processor and the spectrum analyzer. This will allow the flight inspection technician to remain seated during an RFI investigation, and eliminate any need for a second technician.

CONCLUSIONS

Given the need for a method of locating sources of RFI, an AIMDS has many advantages over a ground-based or fixed IMDS. The advantages include speed, unobstructed reception of interfering signals, and the ability to go directly to the interference source.

On the other hand, an AIMDS has some disadvantages. The main disadvantage is the space requirement for an antenna system. Lower frequency antenna systems require more space than higher frequency systems. Because lower frequency antennas are larger, some tradeoffs are made. Antennas are designed with tuning networks to make them reasonably small while at the same time rendering them incompatible for DF use by introducing a phase shift. To overcome this, antennas must be matched specifically for DF use. This increases their costs. The same is true for antenna cables used for higher frequency DF arrays. Small variations in cable lengths can cause large bearing errors. This can be overcome by purchasing expensive phase-matched cables.

Finally, enhancements that make it easier to operate and add functionality should be considered. Much can be said about making a system user-friendly. These types of enhancements can save time, eliminate complexity, reduce operator stress, and increase the likelihood of a successful RFI investigation.

ABOUT THE AUTHOR

Dale Rhoads is an Avionics Engineer in the Engineering Branch of the Office of Aviation Systems Standards. Mr. Rhoads has been with the FAA since 1988 and since that time has held the positions of Avionics Technician, Avionics Instructor, and Lead Avionics Technician. Mr. Rhoads holds an Associates Degree in Pre-Engineering and is currently a Senior at the University of Oklahoma where he is studying to earn a Bachelors degree in Electrical Engineering.

REFERENCES

[1] Jenkins, Herndon H.: "Small-Aperture Radio Direction-Finding," Artech House, Boston, 1991.

[2] Results of antenna testing performed by Cubic Communications at their antenna test range.

[3] Results of antenna testing performed by Cubic Communications in their engineering laboratory.

[4] Cubic Communications, "FAQT Test Report for AAC-1575G VHF/UHF/GPS Antenna Combiner," 2002.

[5] Cubic, "FAQT Test Report...," 2002.

[6] Cubic, "FAQT Test Report...," 2002.

[7] Hayt, William H. and John A. Buck: "Engineering Electromagnetics," 6th ed., McGraw-Hill, New York, 2001. Equations are from this book.