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Propagation Modeling in a Manufacturing Environment[1]

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Abstract

Wireless sensors which utilize low power spread spectrum data transmission have significant potential in industrial environments due to low cabling and installation costs. In addition, this technology imposes fewer constraints upon placement due to cable routing, allowing sensors to be installed in areas with poor access. Limitations are imposed on sensor and receiver placement by electromagnetic propagation effects in the industrial environment, including multipath and the presence of absorbing media. This paper explores the electromagnetic analysis of potential wireless sensor applications using commercially available finite element software. In addition, since the applications environment is often at least partially specified in electronic form using computer-aided drafting software, the importation of information from this software is discussed. Both three-dimensional and two-dimensional examples are presented which demonstrate the utility and limitations of the method.

Introduction

This paper provides an evaluation of the effectiveness of software tools used to analyze low power wireless technology for industrial process sensing and control. Low power radio frequency (RF) transmitters or transceivers collocated with process sensors, perhaps even at the level of a single

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hybrid circuit or integrated circuit element, have the potential to dramatically lower instrumentation costs and measure previously inaccessible process characteristics. Because of their low power, however, and because of the geometrically complex and metallic (RF-reflective) environment where these devices are likely to be used, there are significant questions regarding range, noise immunity, and data error rate. Answers to these questions may preclude or constrain the use of wireless sensor technology; generation of these answers is a computationally intensive task which may often be quite sensitive to modeling assumptions.

Software tools exist which allow specification of industrial environments; it is likely that the most widespread tool is AutoCAD from Autodesk. AutoCAD is normally used for drafting in either two or three dimensions and for storing mechanical designs in electronic form. Tools also exist for electromagnetic analysis in two, two and one-half, and three dimensions. These tools fall in two categories: particle-in-cell (PIC) algorithms, which assume a population of charged particles and calculate their behavior as a function of time, and finite element algorithms, which discretize and solve approximations to Maxwell's equations. Perhaps the most capable of the commercial electromagnetic analysis tools are Magic, which is a particle-in-cell simulator, and the Electro-Magnetic Analysis Software (EMAS), available from MacNeil-Schwendler Corporation (MSC), which utilizes a finite element analysis. This paper specifically addresses the feasibility of using the finite element electromagnetic analysis code EMAS to analyze the RF properties of three dimensional process environments modeled using AutoCAD.

We found that although this approach is conceptually straightforward, in practice there are many implementation issues which can limit the method's utility. Specifically, for three dimensional models, analysis using EMAS requires very large computational resources. Using a Sun SPARCstation 10 and two 1,000 Mbyte disk drives, execution times commonly required 5 to 10 hours. The computations also put a severe stress on networked resources, such as remotely mounted file systems, implying that to effectively use EMAS for these analysis problems one needs computational power on the order of 10 times faster than the SPARCstation 10 with several gigabytes of locally mounted file storage. This is not infeasible; the IBM RS/6000 high-end workstations, for example, can deliver this level of performance. It does, however, impact cost.

The second significant problem we encountered with analysis of three dimensional environments is sensitivity of the analysis to small inconsistencies in the models. For example, unless the grid spacing is less than the distance between two objects in the model, or the objects are touching, gaps in the Finite Element Model, FEM, will result in the solutions not converging. Unfortunately the ARIES interface to EMAS may not catch these gaps or may produce an ill conditioned FEM grid. This can result in one not finding this modeling error until many hours of computation are performed with no results, since the impact is to cause EMAS to fail to converge to a solution.

Finally, even when an environment is modeled completely in AutoCAD, a significant amount of preplanning is required using the MSC modeling tool, ARIES, to adjust this model into a form which can be correctly described to the EMAS code. For example, unlike structural modeling and analysis codes, not only the mechanical structures must be modeled; modeling of air spaces is also required. Since air spaces are typically described only by the absence of solid objects in an AutoCAD model, these gaps must be filled in before EMAS can be applied.

From our experience, we have found that the AutoCAD/EMAS approach to analysis of industrial environments for possible wireless applications can be used, but a significant front end investment is required to purchase the proper hardware and gain expertise. We can easily identify the need: multipath is a significant problem even in outdoor applications such as cellular telephony; this problem is greatly magnified by the highly RF-reflective surfaces and short line-of-sight distances in indoor industrial applications. AutoCAD/EMAS is a viable method for analysis of the multipath, or cavity resonance, problem; it is, however, an expensive remedy.

Wireless Sensors using Spread Spectrum

The focus of this report is not an overview of spread spectrum communications methods, which are adequately covered in digital communications textbooks, but rather the characteristics of spread spectrum communications which impinge upon its capability to implement low power wireless sensor and actuator technology. Therefore, only a brief discussion of spread spectrum methods is provided to form a common foundation for discussion. Spread spectrum communications methods have one common characteristic: They all trade off bandwidth for power, achieving equivalent communications error rates at lower average power per unit bandwidth while utilizing a broader portion of the RF spectrum.

A regulatory constraint also impacts the application of spread spectrum technology in industrial environments: The FCC has defined three frequency bands within which low power spread spectrum may be used without a licensing requirement, provided that transmission characteristics meet certain requirements. These three frequency bands are at 902-928 MHz, 2.4000-2.4835 GHz, and 5.725-5.850 GHz, with total bandwidths of 26 MHz, 83.5 MHz, and 125 MHz, respectively. Within the allocated frequency bands, frequency hopping methods must change carrier frequencies at least 2.5 times per second, and at most 1W power may be transmitted. The maximum bandwidth and minimum number of hops for frequency hopping radios depends upon the frequency band; these requirements are summarized in Table 1.

Table 1. Maximum allowable bandwidth and minimum number of hops required for each unlicensed band.

Frequency Band	Maximum Bandwidth	Min. # of Hops
902-928 MHz	500 kHz	50
2.4000-2.4835 MHz	1.0 MHz	75
5.725-5.850 GHz	1.0 MHz	75

A complication of unlicensed spread spectrum applications which we note in passing is the proximity of the two lower frequency bands to RF sources. The 900 MHz band is located between the cellular telephone band and a paging band, and the 2.4 GHz band overlaps the power spectrum of the RF field generated by microwave ovens. Therefore, in most industrial and office environments, interference from these sources must be considered in design of the transmitter and receiver.

In a typical industrial environment, there are many complex surfaces which are highly reflective to RF energy; for example, steel and aluminum components reflect most of the RF energy which impacts them without absorption. For continuous (approximately steady-state relative to the dwell time) waveforms, this environment causes significant standing wave effects, and the industrial environment can be analyzed as a cavity resonator. This can be done using the MSC/EMAS (Electro-Magnetic Analysis Software) package using finite elements and eigenvalue analysis. For transient signals, such as are typical of direct sequence spread spectrum, there are multiple paths from transmitter to receiver, each with a different time delay and many with little attenuation; this effect is called multipath, and is the time-domain equivalent of standing waves.

Cavity resonance, or multipath, impacts both frequency hopping and direct sequence methods of spread spectrum communications, but in different ways. Since the locations of resonant modes have a strong dependence upon frequency, and at specific frequencies a spread spectrum receiver may be at a location corresponding to a local minimum of field magnitude, the effect of cavity resonance will be to cause significantly higher communications error rates in some frequency bins. In the extreme case, some frequency bins may not be sufficiently error-free to allow error correction algorithms to remove transmission errors.

In contrast, multipath imposes a minimum rate at which the pseudo-random direct sequence code must change values (chip rate), corresponding to a maximum time allowed at a given carrier frequency. For outdoor direct sequence spread spectrum systems, this constraint is not normally binding since path lengths, and hence propagation delays, are much longer. For indoor (industrial) applications, however, this constraint become effective. A mitigating factor is the receiver's detection and averaging method, since a single data bit is normally detected at several frequencies. Thus, one must examine the overall design's immunity to transmission errors rather than the impact at a given frequency.

Frequency Hopping Method

Spread spectrum communications can be implemented utilizing frequency hopping, whereby the carrier frequency is randomly changed over the transmission band at regular intervals. In a frequency hopping transmitter, the rate at which the carrier frequencies are switched is small relative to the data (information transfer) rate. Thus, a typical system will broadcast a data packet at each of several frequencies. One way to mitigate the effects of cavity resonance is to utilize error correcting codes; another is to rebroadcast data packets at multiple frequencies. If two-way communications is implemented, an adaptive frequency hopping strategy can be used whereby frequencies which are strongly affected by cavity resonance can be avoided, and errors can be detected and corrected by rebroadcasting the packet which was incorrectly received.

Direct Sequence Method

Direct sequence spread spectrum modulates a carrier by both a data signal and a pseudo-random code signal, which typically has a much higher data rate. The effect is to broadcast the same data value at a multiplicity of frequencies and to average the information received at these frequencies to determine the data value.

Code Division Multiple Access

A typical industrial or process application of spread spectrum communications would deploy not one but many wireless sensors and possibly actuators. These transmitters would all utilize the same frequency band; thus, a method is required which minimizes or eliminates interference between data channels. The method which provides the greatest bandwidth utilization is code division multiple access, where an orthogonal set of direct sequence codes are used to eliminate interference between channels.

This method was pioneered by Qualcomm in its satellite communications system for shipping applications, and more recently in cellular telephony. The method requires time synchronization between transmitters so that direct sequence codes are aligned to guarantee orthogonality. Multipath can be a problem because differential delays in the receipt of signals from two or more transmitters can cause violation of orthogonality and corruption of data. In the cellular telephone system proposed by Qualcomm, this characteristic is utilized to determine the cell site used for a specific communications circuit; however, in an industrial or other indoor environment, differential delay times can be much smaller and impose a requirement for greater accuracy in transmitter synchronization.

Software Configuration

The results we report in this paper were generated using two computers: A 90 MHz Pentium running under the Windows NT 3.5 operating system, and a Sun SPARCstation 10 running under the SunSoft Solaris 2.4 operating system. Autodesk's AutoCAD Release 13 was used under Windows NT to model the three-dimensional environments, and the resulting files were moved to the Sun workstation using FTP, the standard Internet File Transfer Protocol. The MSC ARIES three dimensional modeling environment was used to import the AutoCAD-defined models and convert them to the proper input format for MSC/EMAS package. EMAS was used to perform a steady-state (eigenvalue) analysis to determine the mode shapes of the electromagnetic field generated by transmitters located at various positions in the applications environment.

AutoCAD Release 13 rather than Release 12 was used because it will export 3D models in the ACIS file format which is a format that ARIES will import. AutoCAD Release 12 AME provides export file formats, but none that work seamlessly with ARIES. 3D models can be constructed using Release 12 AME then switching to Release 13 which provides a function for converting Release 12 AME solid objects to Release 13 solid objects. The conversion function works well on simple objects such as solids created by the extrude and revolve operators. However, we encountered problems with the conversion function producing extraneous objects when using it on complex objects such as ones created by solid intersection and union.

Modeling and Analysis of 3D Environments

Three typical industrial applications were selected as analysis scenarios for testing the analysis methodology. Each application model contains specific features that address possible problems for wireless communications such as multipath, fading, and interference. Multipath signals result from multiple signal pathways due to signal reflections from various objects and surfaces in the manufacturing environment. Two applications were designed to present particular sets of commonly occurring surfaces; planar surfaces with abrupt angular edges, and curved surfaces with smooth rounded edges and relatively large curvature radii. The Robotic Arm application provides planar surfaces, and the Chemical Process application is typical of a environment with smooth features. A third application, the Hybrid Circuit, provides a scenario for investigating several forms of interference. The small features found in the Hybrid Circuit model are in the dimensional range of the wavelength of a wireless signal in the 2.4 GHz band, and two interference effects may occur; radiation from the wireless transmitter can be picked up by circuit elements and interfere with analog and digital signals in the circuit, and radiation may be absorbed and re-radiated by circuit elements causing a type of multipath signal that is different from signals that are reflected from surfaces many wavelengths in size.

Only the Robotic Arm application model is presented in this paper to illustrate the modeling and analysis method.

Robotic Arm

The Robotic Arm application is designed to provide an analysis scenario for a manufacturing cell environment. The application model, shown in Figure 1, shows a robotic arm positioned over a work table and suspended from a rail that allows the arm to move the length of the manufacturing cell. On one side of the work area are two equipment cabinets, one with a flat unbroken surface and a second with wiring conduits extending inside the front face of the cabinet. The wiring conduits run above the work area. The robotic arm model consists of 8 individual objects; the arm, the work table, the rail, two equipment cabinets, and three wiring conduits. Each object in the model can have a different material specification. The material specification can be used by AutoCAD to calculate various design parameters such as object mass and center of gravity, and all objects in this model have a material specification of mild steel. AutoCAD material properties do not include the ability to allow the electrical characteristics of the material to be included in the material specification. Material electrical and magnetic parameters are specified after the model has been transferred to ARIES.

Each object provides a reflective surface with varying characteristics for a wireless transmitted signal. The robotic arm consists of small or narrow surfaces with many edges and corners of various angles. The arm support rail is similar and provides several surfaces with very large length-to-width ratios. The primary surface of the work table is the top surface which is square and in close proximity to the robotic arm gripper. The electrical equipment cabinets provide two types of surfaces; an unbroken and one with pipes (conduits) extending perpendicular to the surface. The conduits are the only objects in the model with smooth, non-planar surfaces.

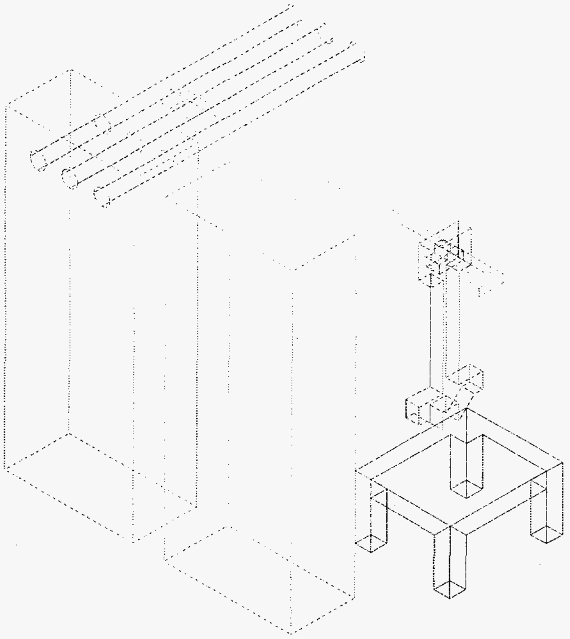


Figure 1 : Robotic Arm application model.

The next section provides details on using AutoCAD Release 13 to construct the Robotic Arm application model.

Constructing the Robotic Arm model

The Robotic Arm model is composed of five basic parts: robotic arm, support rail, work table, equipment cabinet, and conduit. Each part was constructed in AutoCAD Release 13 using solid modeling commands. Although Release 13 provides a set of solid object primitives that includes box, sphere, cylinder, cone, wedge, and torus objects, the objects in the manufacturing cell were constructed by first drawing a 2D shape (polyline) then extruding the shape in the third dimension. This approach of making 3D objects, *i.e.* using extrusion, is the method typically used in the Advanced Modeling Extension of Release 12 for generating solid objects. The isometric view in Figure 1 gives a good 3D perspective, but actual construction of the model is better handled by switching to a different frame of reference. The basic reference frame chosen for the model is the World Coordinate System (WCS); this coordinate system is oriented such that the view is looking down on the cell with the cabinets towards the bottom of the layout. The specific steps for producing each object will now be discussed.

The simplest object in the manufacturing cell is the equipment cabinet without the conduits. This object is constructed by drawing a 2D rectangle using a polyline then extruding the rectangle to a height of 5 meters to form the cabinet.

The next object is a conduit. The construction of this object is similar to the cabinet, but the base 2D object in this case is a circle that is then extruded to form the conduit. However, the conduit is perpendicular to the face of the cabinet, so the reference frame must be changed to a plane that is parallel to the cabinet face: the command **ucs** is used to rotate the coordinate system 90° about the X axis.

To make the equipment cabinet with the 3 conduits extending from the face, the following steps are required:

1. The right end of the conduit is in the plane of the back face of the cabinet. Shift the UCS to the WCS (looking down) and move the conduit such that the left end is in the plane of back face of the cabinet.

2. Make a copy of the cabinet in the position to the left of the original.

3. Make 3 copies of the conduit in the correct positions on the left cabinet, then select the 3 conduits and make a copy positioned off to the side of the other parts.

4. Use the solid subtract function to subtract the conduits from the cabinet thereby removing the volume occupied by the conduits from the cabinet.

5. Solid subtraction also deletes the conduit (hence the reason for the extra set of conduit copies). Move the remaining set into the correct position.

The robotic arm and rail are also constructed using solid subtraction. A 2D drawing of the arm is created then extruded to form the solid arm. The UCS for the 2D drawing of the arm is produced by first rotating about the Z axis by 90° (starting in the WCS) and then rotating about the X axis by 90°.

The last object to add to the model is the work table. Its construction differs from the previous cabinets and arm by the use of the solid union operator. The table surface is drawn in the WCS as a 2D rectangle then extruded 0.25 meters. Next a table leg is drawn at one corner of the table top and extruded 0.75 meters. Copies of the leg are then made at the other three corners. Two final steps are to move the table top to the top of the legs and then use the solid union command to make one object out of the five components (one table top and four legs).

The Robotic Arm model is now complete. The last step is to export the model as an ACIS file with a .SAT extension. This model file can now be imported into ARIES. The Robotic Arm model as rendered by ARIES is shown in Figure 2.

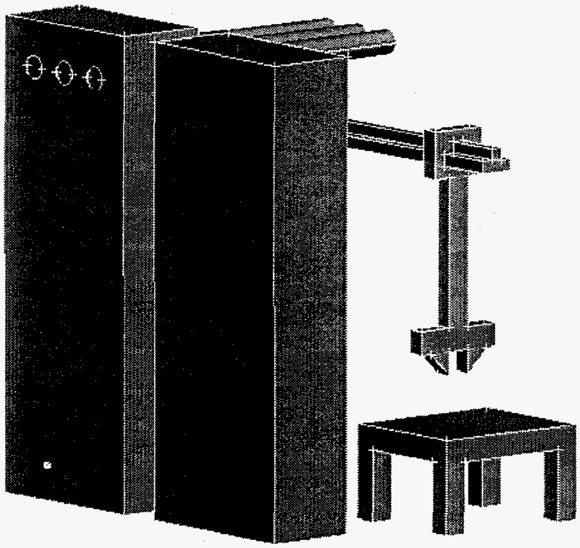


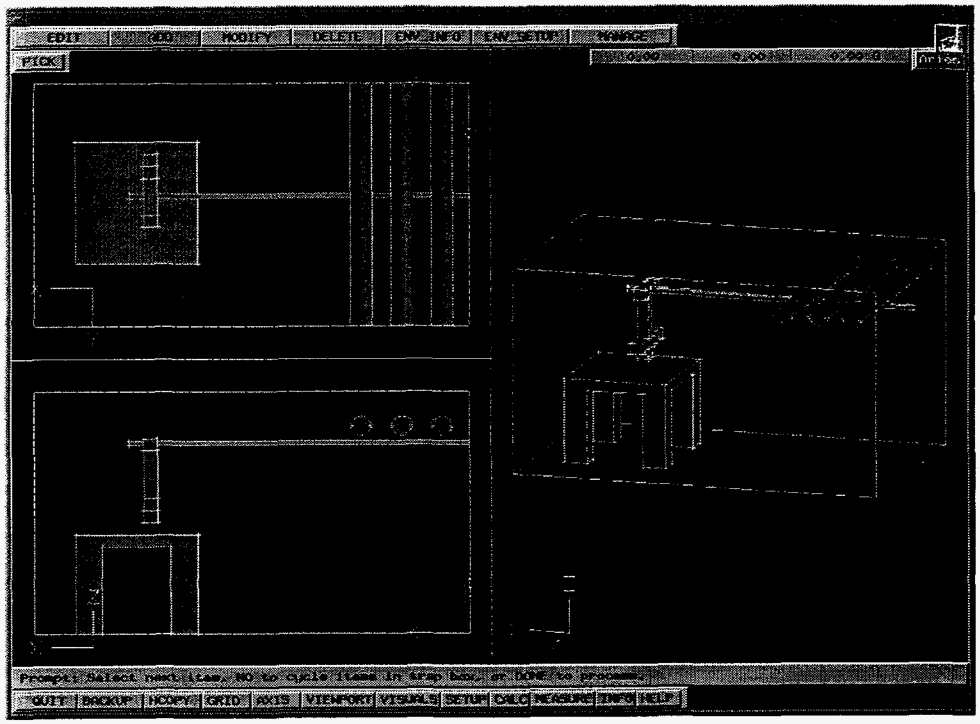
Figure 2: Robotic Arm model rendered in ARIES.

ARIES Importation and EMAS Analysis

The ARIES environment has proven to be very useful in the modeling of three dimensional electromagnetic problems but at the price of computer speed and control over mesh surfaces. In its native form ARIES is very simple to use and incorporates many of the functions of advanced high end CAD packages. It also has a very useful importation of CAD data via either the DXF or ASIS format. Both formats are useful. Creation of a model in ARIES is a deceptively simple process but contains numerous pitfalls for the inexperienced user.

A model must consist of a single 2 or 3 dimensional region, which includes all air space modeled as a solid block. To accomplish this, the parts are modeled and then "regioned" into the airspace using the region tool. The next step is to create the air space in the form of the rectangular volume which is either larger than or smaller than the objects enclosed, as shown in This space is then sectioned using the region command using the air space as the "stock" and the parts as the "tool".

Figure 3 shows the solid model with the boundary conditions added and prepared for mesh generation. At this point a finite element mesh is prepared and used to define the analysis problem to EMAS for processing. This model represents approximately 50,000 finite elements with 10,000 grid points.



Prompt: Select next item, NO to cycle items in trap box, or DONE to proceed.

Figure 3. Model with boundary conditions.

Figure 4 is a representative intensity plot from the three dimensional EMAS analysis showing the field strength in air from a transmitter located on the top of the robotic arm. The figure graphs the field strength over a two-dimensional slice through the environment. It can be noted that the greatest field intensity is at the transmitter point with the field falling off rapidly. More information can be gained about the far field and reflection pattern by scaling the intensity plots or using vector arrows to represent the data values. EMAS also provides information about penetration of the field within objects in the environment. From the same analysis run, Figure 5 shows the field strength on the surface of the robotic arm's support structure.

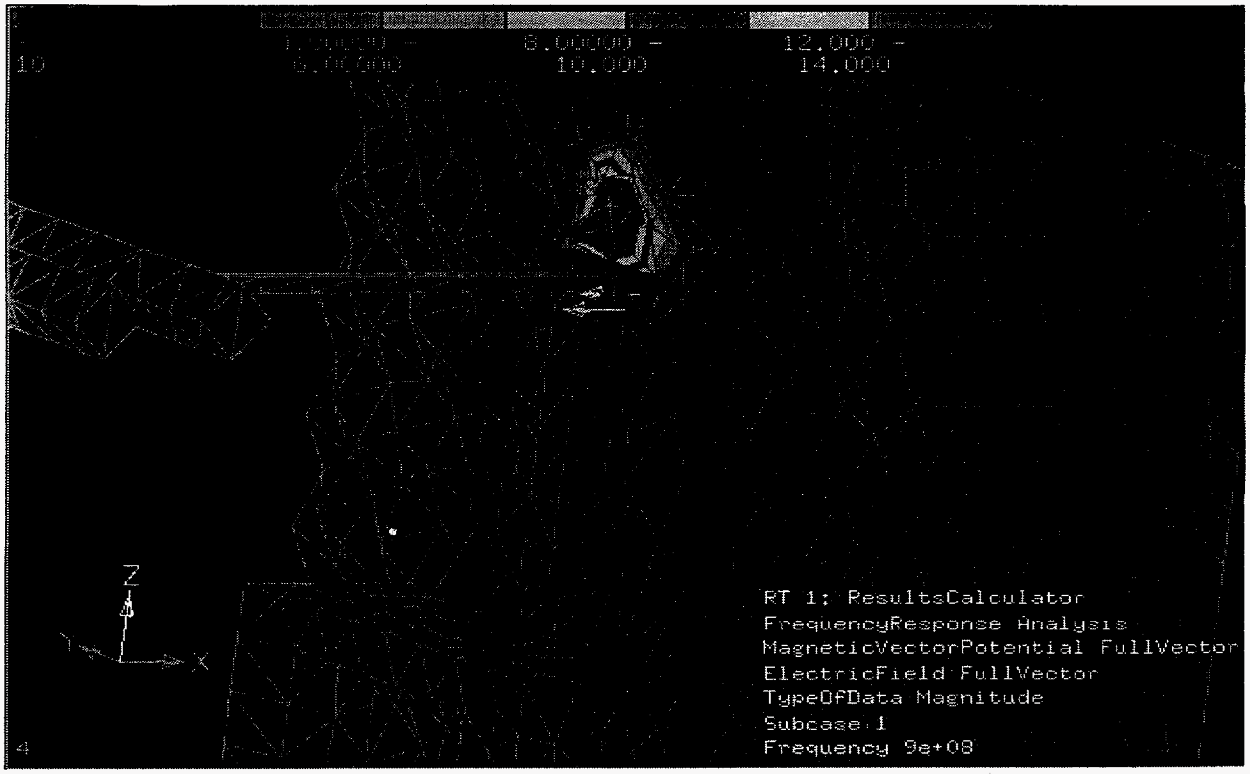


Figure 4. Field intensity in air space.

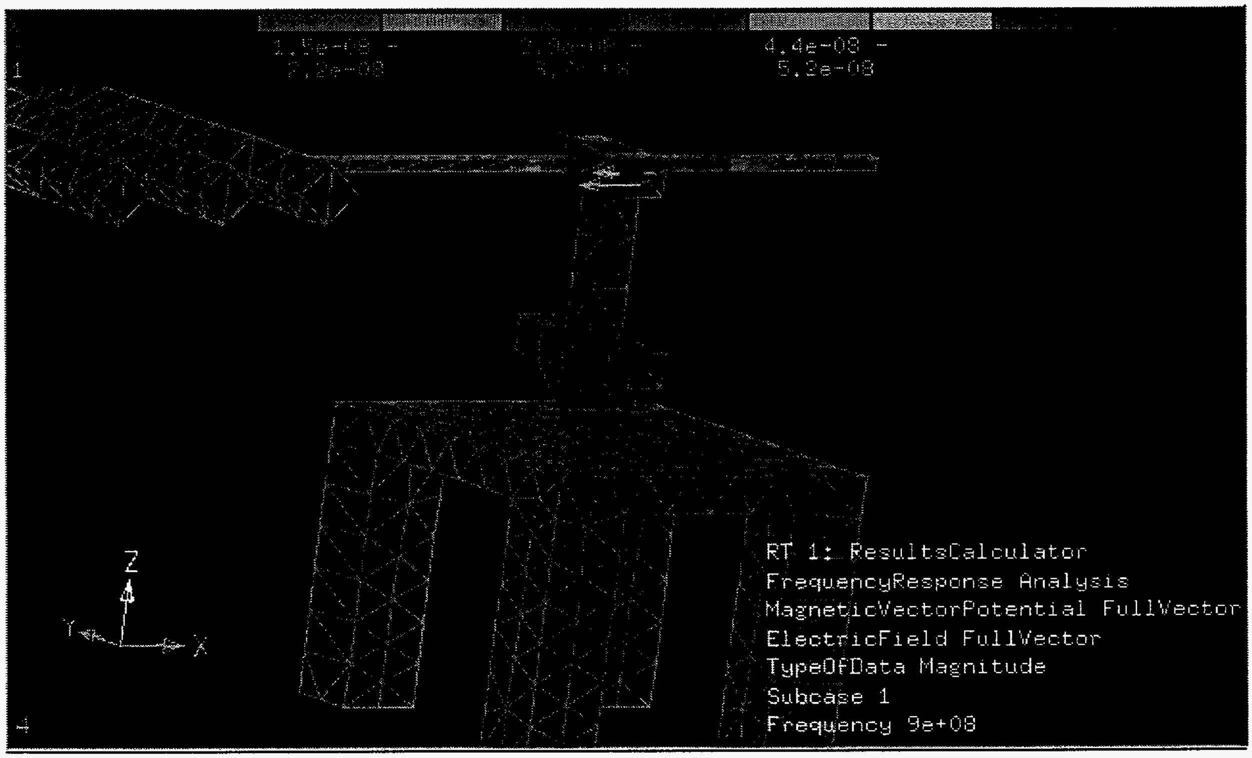
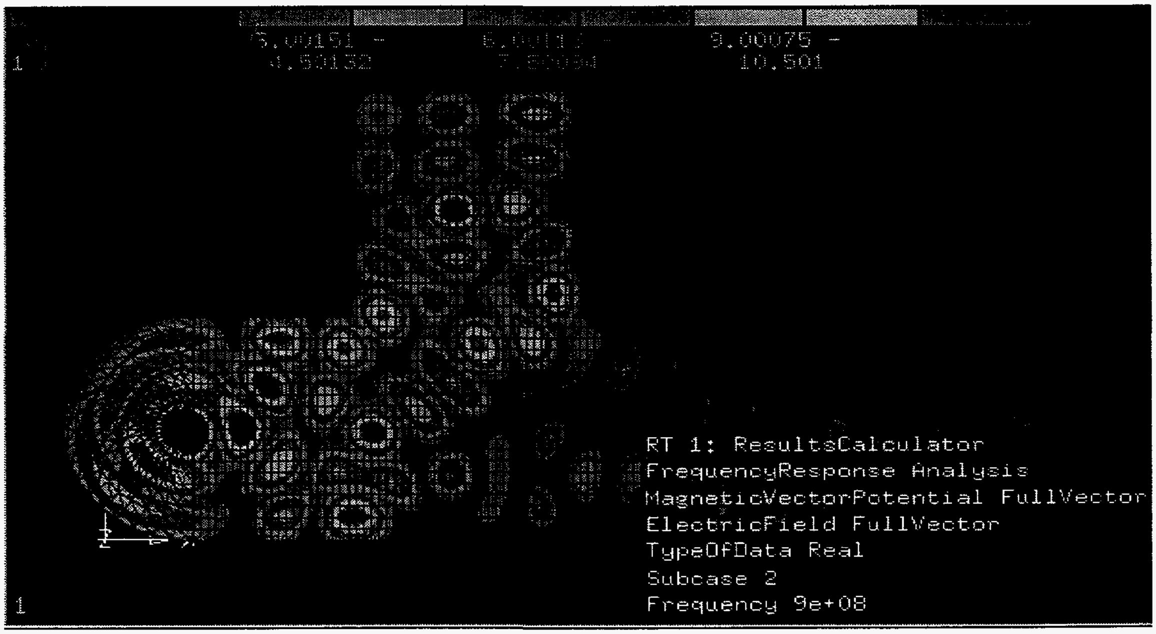


Figure 5. Field intensity on metal surface.

A 2D Example

We have modeled a cylindrically shaped room that was 3 meters end to end with a .9 meter rectangular annex on the upper side to demonstrate the strong dependence of the field intensity pattern upon both frequency and objects within the environment. These results are calculated in two dimensions rather that three in order to reduce the computation and data reduction that would otherwise be involved; it is expected that analogous results could be calculated in three dimensions. A source was modeled near the center radius of the left side semi circle to allow the field to experience a focusing effect. Test cases were run at multiple frequencies to observe the effects of frequency on the standing wave pattern. The air is a conductive media at 377Ω/meter with perfectly conducting walls. There is considerable degradation of the signal at the far end of the room. As the frequency increases to 930 MHz the signal quality degrades noticeably. The signal inside the side chamber is also severely degraded in areas that are not in the line of sight from the transmitter.

Figure 6 illustrates the same physical situation with two sources at 900 MHz. One source is located at the original position with the second source added in the annex. These two sources constructively and destructively interfere to produce the observed radiation pattern. Compared to the single source case, the field is significantly increased in the annex, but the field pattern is marginally aided in the right hand zone. This gives a strong indication that the field will be heavily influenced by line of sight. Figure 7 illustrates the field strength for a transmitter operating at 930 MHz. Comparing these two figures, note the significant attenuation in field strength with increasing frequency. The locations of resonance peaks in field intensity are also quite dependent upon frequency; note especially the change in the pattern in the middle section. This effect should be considered when receiver sites are selected.



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RT 1: ResultsCalculator
FrequencyResponse Analysis
MagneticVectorPotential FullVector
ElectricField FullVector
TypeOfData Real
Subcase 2
Frequency 9e+08
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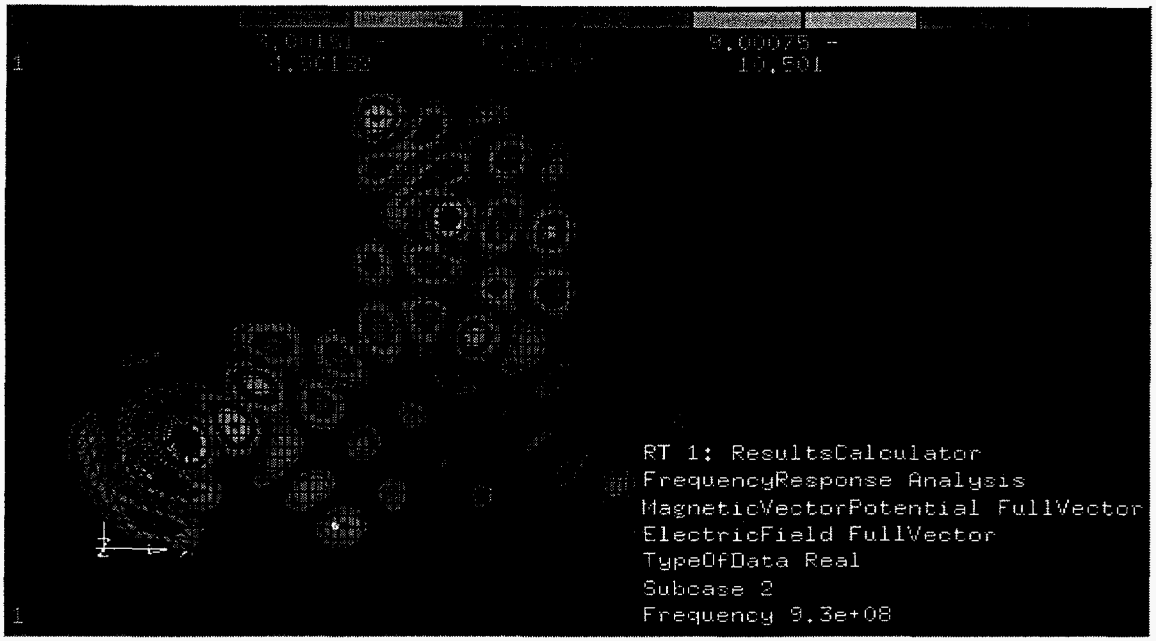
Figure 6. 900 MHz results with 2 sources.



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RT 1: ResultsCalculator
FrequencyResponse Analysis
MagneticVectorPotential FullVector
ElectricField FullVector
TypeOfData Real
Subcase 2
Frequency 9.3e+08
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Figure 7. 930 MHz results with 2 sources.

A second example was analyzed where the left curved surface is coated with two layers of conductive material. The first layer was specified with the electrical characteristics of sea water and the second layer with characteristics typical of conductive polystyrene. A conductivity gradient was specified to reduce wall reflections. Figure 8 illustrates the field intensity for a transmitter frequency of 930 MHz. Comparing Figure 7 and Figure 8, note that the field strength is significantly increased in the right hand region with the presence of the conductive surfaces.

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RT 1: ResultsCalculator
FrequencyResponse Analysis
MagneticVectorPotential FullVect
ElectricField FullVector
TypeOfData Real
Subcase 2
Frequency 9.3e+08
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Figure 8. 930 MHz results with conducting layers.

A potentially significant problem with wireless sensor technology is the random effects upon field strength introduced by uncontrolled changes in the electromagnetic properties of the environment. At the frequencies in use, the presence of metallic objects the size of an adjustable wrench can be significant. The presence of humans in the environment can be significant, since to the electromagnetic field a person is essentially a fairly large volume of conductive salt water. To illustrate this effect, Figure 9 shows the field pattern without (top) and with (bottom) the presence of a randomly placed absorber with the approximate size and electromagnetic properties of a human at 900 MHz. It can be seen that the worker distorts both the far and near field radiation patterns.

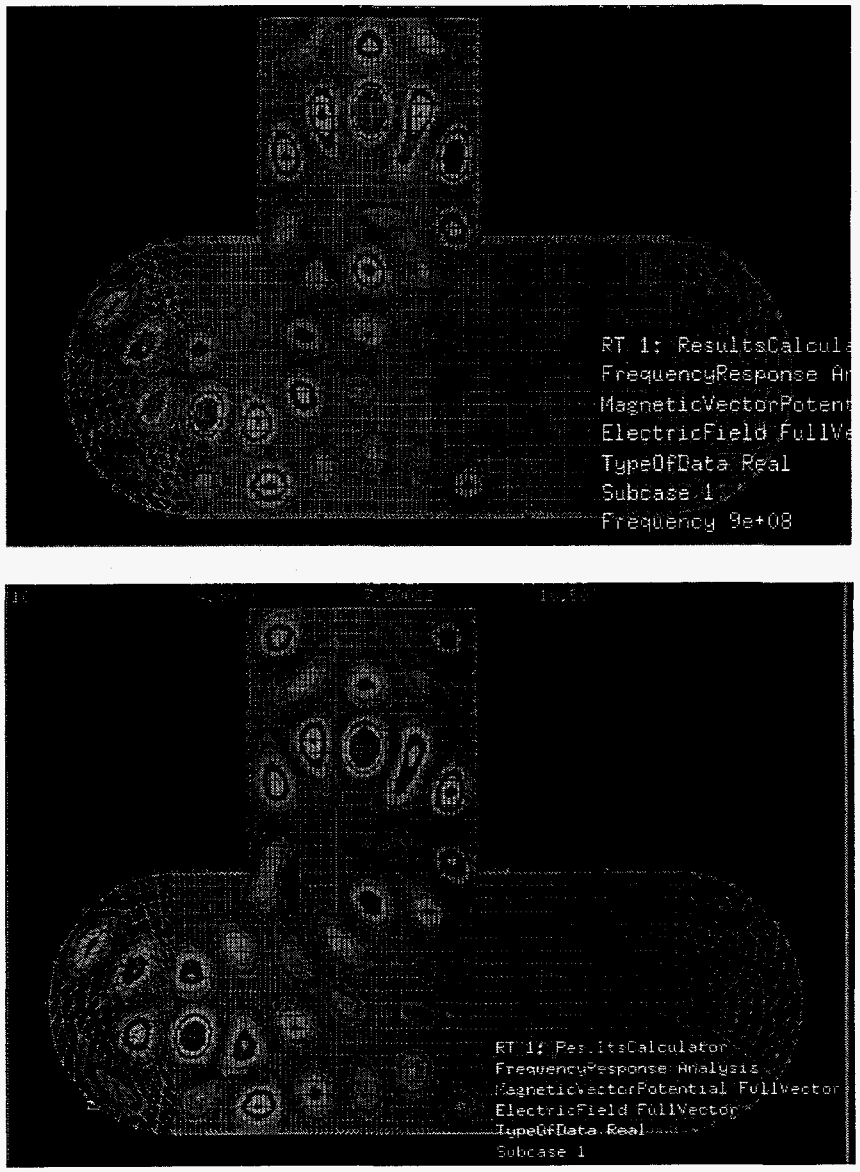

Figure 9. Electric field pattern without (top) and with (bottom) worker

The EMAS analysis results can be used to compute attenuation from the transmitter to an arbitrary location within the environment. To illustrate this, we define three points (labeled "1", "2", and "3") within the example two dimensional region, as shown in Figure 10. The attenuation from the source to these three points is graphed, as a function of frequency, in Figure 11 (magnitude) and Figure 12 (phase). As a further illustration of the sensitivity of RF transmission characteristics to sensor and receiver placement and frequency, note the significant variability of these attenuation characteristics over the three candidate points for the receiver's location.

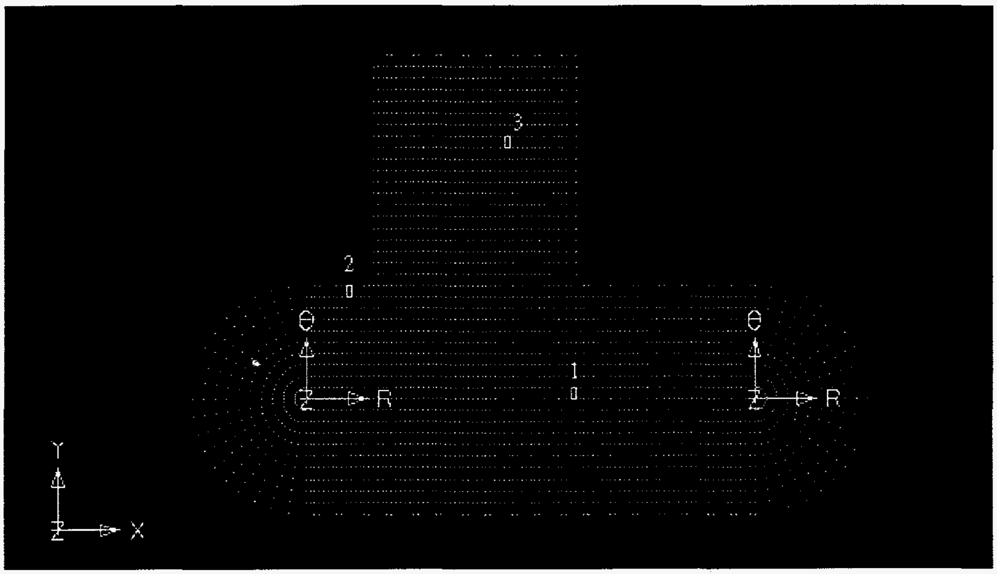

Figure 10. Locations of three points within region.

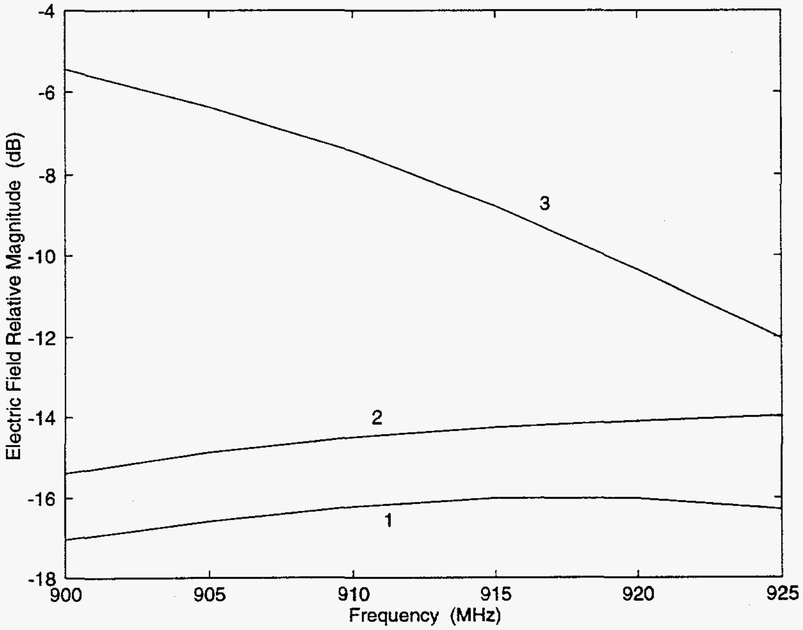

Figure 11. Far field attenuation (magnitude) relative to source (dB).

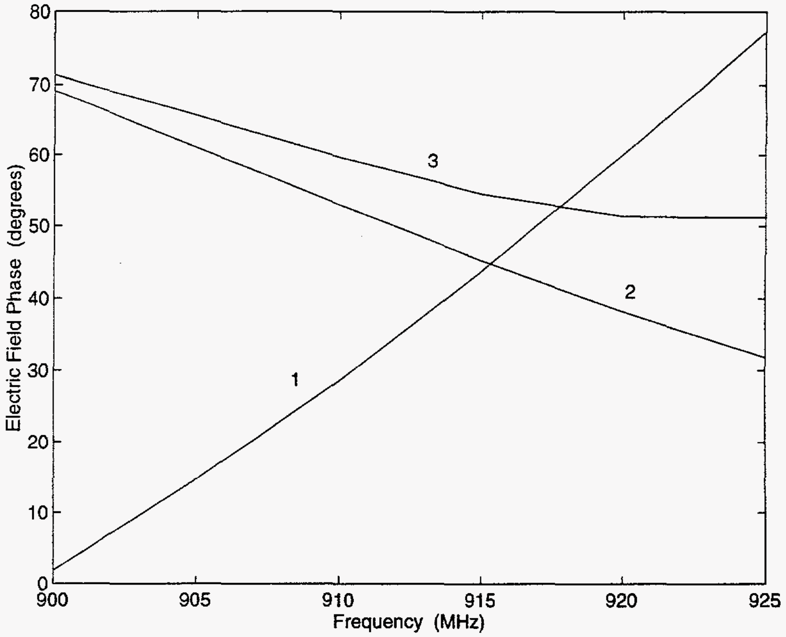

Figure 12. Far field attenuation (phase) relative to source (degrees).

Summary

Typical industrial sites contain many electrically conductive surfaces which reflect RF radiation, causing significant and highly complex standing wave patterns in steady-state, and multipath transient signals. The impact of these cavity resonance modes can be analyzed using available two- and three-dimensional electromagnetic analysis software, such as MSC/EMAS, and the results can be used to predict signal attenuation of an arbitrarily selected transmission path. Analysis of several fairly simple examples, however, illustrates the sensitivity of the results to both frequency and possibly unknown and random effects such as a human presence in the environment. Siting strategies for sensor and transceiver placement rely at present upon line of sight rules; however, because of multipath effects this may not be adequate. The addition of dampening materials within the environment may be useful in mitigating the undesirables effects of cavity resonance.

Environment component dimensions and compositions are likely to be available in electronic form from standard CAD packages such as AutoCAD. Therefore, one aspect of this work was to assess the feasibility of importing this information into the MSC/ARIES and MSC/EMAS software packages for electromagnetic modeling and analysis. While we did demonstrate feasibility, we found that the importation process was not typically easy, and that a fairly significant effort was required to learn the features and limitations of the various software packages. Electromagnetic analysis of potential application environments for wireless sensor technology prior to equipment acquisition and installation is recommended were multipath effects are likely to present a problem; however, the analyses should not be undertaken without adequate training and computational resources.