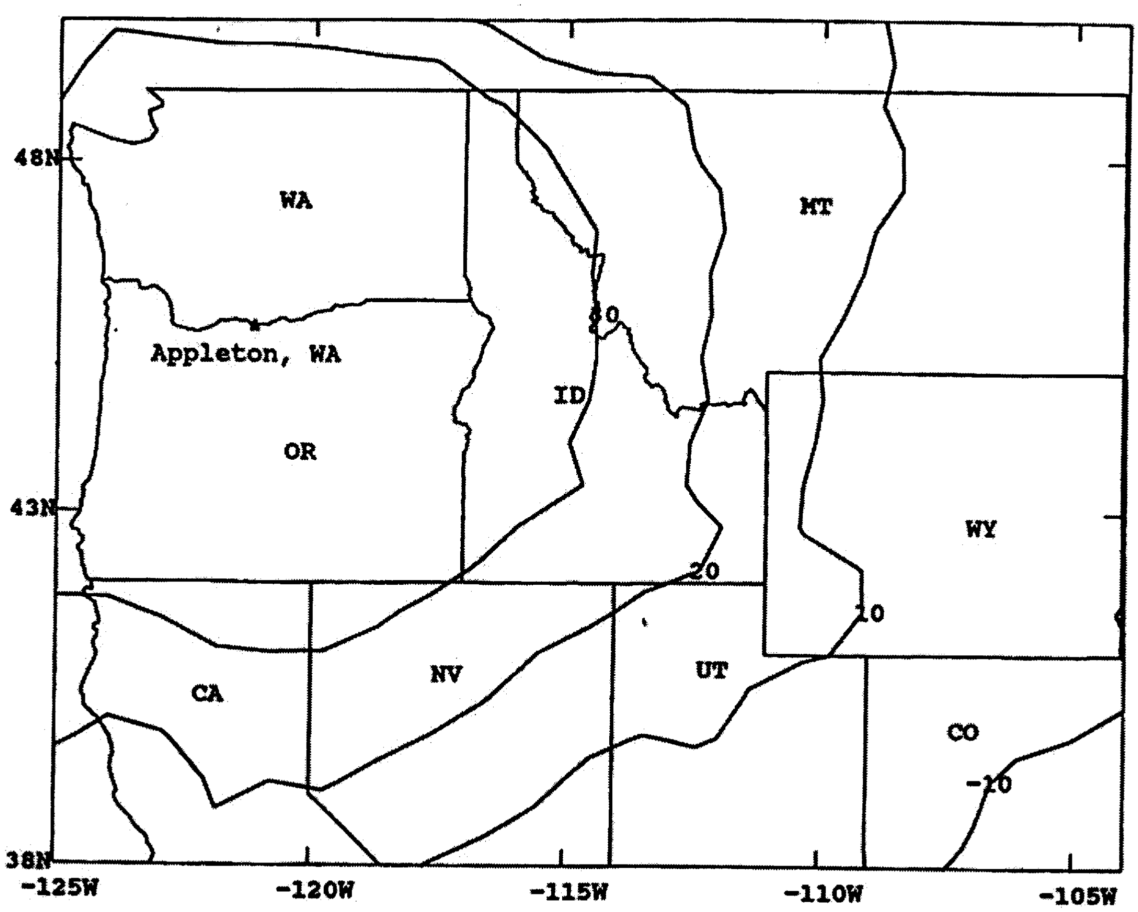

Figure 30. Contours of electric-field strength in dBuV/m from the Appleton, WA DGPS site at daytime (f=300 kHz).

7. CONCLUSION

This paper covered the basic aspects of radio-wave propagation and antenna modeling in the MF band. The MF band covers the frequencies of 300 to 3000 kHz. The sky wave models described in this paper are valid from 150 kHz to 1705 kHz. The ground wave models described in this paper are valid from 10 kHz to 30 MHz. In this paper the propagation models and antenna modeling techniques were shown to be quite different than those at other radio frequency bands. The propagation of radio waves in this band depends on both a ground wave and a sky wave and their interaction with the environment. The antennas are strongly influenced by the presence of ground and require numerical analysis techniques more sophisticated than free space techniques used in higher frequency bands. This paper describes radio wave propagation together with antenna modeling in this frequency band so that a better understanding of the phenomena can be obtained for use in design and application of ITS subsystems. The models described here can be used for designing systems and making performance predictions for both of these ITS applications and any other systems that operate in this band.

The radio-wave propagation loss computed using these models is a basic transmission loss and not free-space transmission loss. Free-space is a highly idealized environment and is not the environment encountered in actual propagation situations. The ground wave includes the direct line-of-sight space wave, the ground-reflected wave, and the surface wave that diffracts around the curved Earth. Propagation of the ground wave depends on the relative geometry of the transmitter and receiver location and antenna heights in addition to the presence of a conductive Earth. The radio wave propagates as a surface wave when both the transmitter and the receiver are near the Earth in wavelengths, because the direct and ground-reflected waves in the space wave cancel each other out, and as a result the surface wave is the only wave that is left. The surface wave propagates along and is guided by the Earth's surface. As the surface wave passes over the surface of the Earth, it is attenuated as result of the energy absorbed by the Earth due to the power loss resulting from the current flowing through the Earth's resistance. Energy is taken from the surface wave to supply the losses in the ground and the attenuation of this wave is directly affected by the ground constants of the Earth along which it travels. This cancellation is a result of the fact that the elevation angle is near zero and the two ground waves (direct and reflected) are equal in amplitude and opposite in phase. This is the condition that exists for the MF band and lower frequencies. The surface wave is predominantly vertically polarized, since the ground conductivity effectively shorts out most of the horizontal electric field component. What is left of the horizontal field component is attenuated at a rate many times the vertical component of field strength. When one or both of the antennas are elevated above the ground to a significant height with respect to a wavelength, the space wave predominates.

The exact equations derived by Norton [10] can be used for analysis, or some simpler equations also by Norton [9,10] can be used to describe the flat-Earth attenuation function when the geometry is such that the flat-Earth attenuation function is appropriate. When the geometry is such that the flat-Earth attenuation function is not appropriate, then smooth-Earth, smooth-Earth mixed-path, and irregular-Earth mixed path models such as those described in this paper should be used to take into account non-zero antenna heights, mixed-path ground conditions, and terrain.

A medium frequency sky wave will be returned back to Earth by the ionosphere if the degree of ionization in the appropriate regions is sufficient to refract and reflect the incident electromagnetic wave. Ionospheric propagation models for medium frequencies can predict this degree of ionization in the different layers to determine the amount of signal that is refracted and reflected and hence the system performance. The two regions that are responsible for the refraction and reflection of medium frequencies are the D region and the E region. The first region encountered by the sky wave is the D region and the E region is located above it. The D region is a region of low electron density whose degree of ionization is determined primarily by solar photoionization. This region usually exists during the daytime and absorbs the energy in the MF radio waves that pass through it during the daytime hours. The MF sky wave is therefore highly attenuated as it passes through the D layer during the daytime. Reflection and refraction of the sky wave by the E region does not usually occur, because of the large amount of attenuation experienced in the D region. At night the solar photoionization in the D region is reduced and hence the attenuation of the sky wave in this region is much less, so the sky wave travels on to the E region where it is refracted and reflected back to Earth. The D region of the ionosphere is characterized as having a strong dependence on frequency, but this is present only during the daytime. The E layer is the dominant contributor to LF and MF propagation at night and is only mildly dependent on frequency, so the effects of frequency on radio-wave propagation of this E layer can be neglected for most practical purposes. Three sky-wave propagation models were described in this paper and their relative merits were discussed. The ITU method is the only one that accounts for the variation of sky-wave propagation with frequency, but it has a frequency-dependent term that reduces the predicted field strength with increasing frequency. One reference, [47], notes that measurements in the United States show a frequency dependence that is exactly the opposite of what the ITU method predicts. Rather than adding the error that is incurred when using the ITU model [47], the effects of frequency for the sky wave are generally neglected. The frequency dependence over the range of 500 kHz to 1600 kHz is small, so it is often ignored and the field strength at 1000 kHz is taken as representive of the entire band [44]. The ITU method makes predictions that depend on both frequency and geomagnetic latitude. The field strength values are not symmetrical about the geomagnetic latitude equal to 0 degrees. The ITU notes that this field strength expression predicts lower field strength values as the frequency is increased in the MF band [43], but measurements performed in the United States show that the field strengths are higher at the higher frequencies in the MF band when compared to those measurements at the lower frequencies. Because of this discrepancy, the ITU method has not found wide acceptance as a worldwide prediction method. Davies [43] also refers to measurements and gives an equation that is a function of frequency. He recommends the use of predictions at 1000 kHz to represent the entire MF band. In an effort to create a valid model that would give reasonably accurate predictions in Region 2, Wang [47] developed an MF sky-wave model after examining all of the available MF methods. When compared to the ITU expression, Wang's expression is symmetrical about zero degrees latitude and is not dependent on frequency.

Accurate antenna modeling is necessary to determine the elevation and azimuth gain variability for prediction of the actual gain to be used in launching the sky wave at the appropriate take-off angles, and the ground-wave gain at the horizon angle. The performance of an antenna on or near the surface of the Earth is very dependent on the interaction with the lossy Earth. This is especially true for antennas at MF. Currently available techniques for analyzing antennas over ground with computer algorithms are time consuming and require conversion or normalization for use in system computations. This process was described in the propagation section. The gain of the antenna is a function of the antenna geometry, materials used, ground conductivity, ground dielectric constant, frequency, elevation angle, and azimuth angle. The gain required for systems performance analysis is usually calculated with respect to an isotropic radiator in free space or some other reference antenna such as a dipole. Conventional methods such as free space analysis could not be used due to the close proximity of the antennas to a lossy Earth. Antenna modeling techniques at medium frequencies must account for the actual gain that launches the ground wave. The end result for the antenna gain described in this paper has been transformed to be referenced to an isotropic radiator in free space.

There are several methods for modeling antennas that are in close proximity to a lossy Earth. Some of these are not valid for an antenna located right on the surface and require that the antenna be 0.2 wavelengths above the surface or the algorithm used in the calculation will not be valid. These algorithms that assume free-space conditions or negligible ground effects should not be used to model antennas that are too close to the Earth, because the results are poor. The model selected for analyzing antennas makes use of extensive method-of moments calculations and is implemented in a computer program titled the Numerical Electromagnetics Code (NEC) [50]. It is an accurate method for analyzing antennas at these low and medium frequencies where the antennas are small or comparable to a wavelength in size. Numerical methods are required to solve this problem and NEC is a good algorithm to use. The NEC program operates using a computation mode that implements a Sommerfeld integral computation for the determination of electromagnetic fields for antenna structures that are buried or penetrate the ground-air interface. This computation technique includes the reflected field below the interface, the field transmitted across the interface, and the fields above the ground-air interface. The algorithms used are also valid for antennas very close to the interface. The NEC program can also model near fields of the antenna very close to the antenna structure, in addition to being able to model the far field and compute antenna gain.

A different antenna gain phenomenon occurs with antennas at medium frequencies as compared to antennas at VHF, UHF and higher frequencies. The antenna principles are the same, but the surface wave becomes more signficant at MF. This is important because it is the surface wave that accounts for practically all of the energy transmitted and received at these frequencies. The concepts of gain and efficiency for antennas close to the surface of the Earth at MF are difficult to comprehend, since a major portion of the power launched by the antenna is absorbed by the lossy Earth. A method for calculating antenna gain of MF antennas including the normalization process to interface with the propagation models has been discussed in this paper. Agreement with measurements has been shown.

The propagation and antenna models described here can be used for performance prediction of ITS applications in the roadway environment to determine design criteria and parameters for building and testing these systems. The models can also be used to resolve measurement problems. These models can also be used for performance prediction in an interference environment, and aid in the resolution of interference problems. Propagation models that are used to analyze radio communication systems require sound engineering judgement in their use for a particular analysis.