3. DESCRIPTION OF THE MEASUREMENT SYSTEM FOR DTV E-FIELD STRENGTH MEASUREMENTS

In this section, the measurement system is explained, and measured results are presented and discussed. The transmitter systems on each mountaintop and the receiver measurement system in the van were configured as shown in the block diagram of figure 7. The transmitter consisted of two signal generators coupled into a single power amplifier via a combiner. The amplifier output incorporated a low-pass filter to reduce harmonic emissions. Figure 8 is an annotated photograph of the transmitter system used on both mountaintops. The signal was radiated from the first mountaintop (Eldorado Mountain) near Boulder (see the map in figure 9) via an omni-azimuthal directional antenna (with 1.9 dBi gain), mounted 3.66 m (12.0 ft) high at the edge of a cliff that overlooks the Boulder–Denver metro area. The second mountaintop (Squaw Mountain) is located significantly farther from Boulder (also shown in the map in figure 9), giving little line-of-sight coverage over the measurement area. The transmitter at this site was similar to that at Eldorado, but a different transmitter antenna was used. The transmitter antenna was a log periodic array with 6.5 dBi gain and was mounted 8.2 m (26.91 ft) above the ground. This array had a 3 dB beamwidth of 90 deg, and the beam was centered on the measurement area.

The transmitted signals were continuous, sinusoidal waves. This allowed the measurement bandwidths in the receivers to be set at sufficiently narrow values to observe the transmitted signals with nominal signal-to-noise ratios of 10 dB or more. The EIRP levels transmitted from the Eldorado Mountain site were 22.5 dBm and 30.5 dBm for the 533 MHz and 772 MHz systems, respectively. The EIRP levels transmitted from the Squaw Mountain site were 35.1 dBm and 43.5 dBm for the 533 MHz and 772 MHz systems, respectively.

The mobile measurement system, shown in figure 5, used a 1.9 dBi gain omni-azimuthal directional antenna mounted on a vehicle rooftop at 2.95 m (9.68 ft) above the ground. As shown in figure 7, the antenna line was routed to a splitter, and from there the received signal was coupled to a pair of receivers. Each receiver was dedicated to a single frequency (533 MHz or 772 MHz). Each receiver included a pre-selector (a varactor bandpass filter to reject strong adjacent-frequency signals) and a low-noise preamplifier (affording a noise figure of approximately 10 dB for the measurement system).

The preselector outputs were routed to spectrum analyzers. Each spectrum analyzer was tuned to the applicable frequency, with a zero Hertz frequency span. The IF bandwidth was set to 10 kHz, and the lowpass video bandwidth was set slightly wider. Positive peak detection was used. The sweep time was set to 60 s, so that each spectrum analyzer would record the received signal strength at the applicable frequency for 1 min at a time.

Each spectrum analyzer was controlled via a laptop PC-compatible computer. The computer downloaded each minute's-worth of data to data files, and then automatically reconfigured the spectrum analyzers and preselectors for the next minute of data. These systems were set to run continuously. Thus, received signal strength was continuously measured at each frequency. Seventeen peak amplitude strengths were measured and recorded per second at each frequency during data acquisition runs.

As the mobile measurement system was driven throughout the Boulder area, a global positioning system (GPS) receiver was used to track the vehicle's position. Notes were also kept on the vehicle's location as a function of local landmarks (e.g., road intersections). The routes driven for this study are shown in figures 10a, 10b, and 10c. The measurements for each mountaintop were performed on separate days during the week of January 22, 2001.

3.1 Calibration of System

The transmitter signal strengths coupled to the antennas were verified directly using calibrated spectrum analyzers. Antenna gain characteristics were taken from manufacturers' data sheets for the individual antennas used in the study.

The receiver system was calibrated at the antenna output using a noise diode and a standard Y-factor excess noise ratio calibration technique in which power is measured in the receiver system with the diode alternately turned on and then off. The complete system path of RF line, splitter, preselectors, and spectrum analyzers was calibrated with this technique. System noise figure was typically about 10 dB, and the correction factor between spectrum analyzer output and true power level was typically about 20 dB. These numbers were obtained from a noise diode calibration. The noise diode output levels are traceable to NIST.

Noise diode calibration data were stored in computer look-up tables, and were added automatically to all measured power levels. All stored data were corrected at the time of collection. Antenna factor data were not incorporated into these stored data; field strengths were computed after the measurements were completed, by adding antenna factor data to the measured power levels in the measurement system circuitry. A conservative estimate of the measurement uncertainty is ± 2 dB.

3.2 Data Analysis: Measured E-field Strengths

Recorded data were reduced from noise-diode-corrected measurement units in the receiver system circuitry (dBm) to peak received field strength in free space. This was accomplished by adding the appropriate antenna correction factors. Four different sets of data were collected for the two measured frequencies (533 MHz and 772 MHz) at the two different transmitting sites (Eldorado Mountain and Squaw Mountain). For each frequency and transmitter location, data were collected at various locations around the Boulder area. Appendix B presents the actual measured power levels for all the various locations, frequencies, and transmitter sites. From the Eldorado Mountain location the input power to the antenna was 0.115 W (20.6 dBm) and 0.724 W (28.6 dBm) for the 533 MHz and 772 MHz systems, respectively. The gain of the transmitting antenna at the Eldorado Mountain site was 1.9 dBi. From the Squaw Mountain location the input power to the antenna was 0.724 W (28.6 dBm) and 5.0 W (37 dBm) for the 533 MHz and

772 MHz systems, respectively. The gain of the transmitting antenna at the Squaw Mountain site was 6.5 dBi.

In this analysis, we are interested in the field strengths for 1 MW power radiating out of the transmitter (i.e., 1 MW EIRP). In lieu of transmitting 1 MW in this experiment, the measured power level in Appendix B can easily be transformed to any desired transmitter power level. Since Maxwell's equations are linear, it can be shown that by using the measured power level presented in Appendix B, received power levels for any given transmitter power in dBm can be obtained. For a given frequency, gain, and distance, received power is proportional to transmitted power (hence logarithms add) and the results for an arbitrary transmitter power can be obtained by scaling the measurements

$$P = P_{mes} - P_t + P_{eff} \quad \text{[dBm]} . \tag{8}$$

Here, P_{mes} is the measured power level given in Appendix B, P_t is the power level at the input to the antenna for the different systems (defined below), and P_{eff} is the input power level to the antenna that would correspond to 1 MW (90 dBm) EIRP, and is given by the following

$$P_{eff} = \text{EIRP} - G_t = 90 - G_t \quad \text{[dBm]} , \tag{9}$$

where G_t is the transmitter antenna gain. Recall that for the Eldorado Mountain site the transmitting antenna gain was 1.9 dBi, and for the Squaw Mountain site the transmitting antenna gain was 6.5 dBi. Therefore, for the Eldorado Mountain site

$$P_{eff} = 88.1 \quad \text{[dBm]}, \tag{10}$$

and for the Squaw Mountain site

$$P_{eff} = 83.5 \quad \text{[dBm]}. \tag{11}$$

P_t is different for the different sites and the different frequencies used. For the Eldorado Mountain site

$$P_t = 20.6 \quad \text{[dBm] for 533 MHz} \tag{12}$$

$$P_t = 28.6 \quad \text{[dBm] for 772 MHz} \tag{13}$$

and for the Squaw Mountain site

$$P_t = 28.6 \quad \text{[dBm] for 533 MHz} \tag{14}$$

$$P_t = 37.0 \quad \text{[dBm] for 772 MHz.} \tag{15}$$

With these various values of P_t and P_{eff}, the following expressions can be used to transform the measured power levels to the power level that would be received assuming 1 MW EIRP. For the Eldorado Mountain site

$$P = P_{mes} - 20.6 + 88.1 \quad \text{[dBm]} \quad \text{for 533 MHz} \tag{16}$$

$$P = P_{mes} - 28.6 + 88.1 \quad \text{[dBm]} \quad \text{for 772 MHz,} \tag{17}$$

and for the Squaw Mountain site

$$P = P_{mes} - 28.6 + 83.5 \quad \text{[dBm]} \quad \text{for 533 MHz} \tag{18}$$

$$P = P_{mes} - 37.0 + 83.5 \quad \text{[dBm]} \quad \text{for 772 MHz .} \tag{19}$$

In order to obtain the E-field strengths, the transformed power levels given in equations (16) through (19) need to be converted to power densities. Given the power in dBm, the power density is given by the following:

$$\mathscr{P} = \frac{1}{A_{eff}} \frac{10^{(P/10)}}{1000} \quad \text{[W/m}^2\text{],} \tag{20}$$

where A_{eff} is the effective area of the receiving antenna, which is a function of wavelength and the receiving antenna's gain [11]:

$$A_{eff} = \frac{\lambda^2 \, 10^{(G_r/10)}}{4\,\pi} \quad \text{[m}^2\text{] ,} \tag{21}$$

where G_r is the receiving antenna gain and is 1.9 dBi (1.55) for all the measurements. λ is the wavelength, which is equal to 0.563 m (1.85 ft) and 0.389 m (1.27 ft) for a frequency of 533 MHz and 772 MHz, respectively. Thus, the effective areas for the two different frequencies are:

$$A_{eff} = 0.0391 \quad \text{[m}^2\text{],} \quad \text{for 533 MHz, and} \tag{22}$$

$$A_{eff} = 0.0186 \quad \text{[m}^2\text{],} \quad \text{for 772 MHz.} \tag{23}$$

Once the power density is obtained, the E-field can be calculated from equation (2) given in Section 1.

Figures 11 through 48 show the measured E-field scaled to 1 MW EIRP for the two proposed sites and the two different frequencies. Figures 11 through 20 are the measured E-field strengths for a transmitter on Eldorado Mountain operating at 533 MHz. Figures 11 and 12 are the measured data for the DOC Laboratories and the Table Mountain NRQZ, respectively, while figures 13 through 20 show the measured E-field strengths for various other locations throughout the Boulder area. It was necessary to perform measurements over a broader geographic area than just the DOC properties to validate the area-specific propagation models that formed the basis of this assessment.

Figures 21 through 30 are the measured E-field strengths for a transmitter on Eldorado Mountain operating at 772 MHz. Figures 21 and 22 are the measured data for the DOC Laboratories and the Table Mountain NRQZ, respectively, while figures 23 through 30 show the measured E-field strengths for various other locations throughout the Boulder area.

Figures 31 through 38 are the measured E-field strengths for a transmitter on Squaw Mountain operating at 533 MHz. Figures 31 and 32 illustrate the measured data for the DOC Laboratories and the Table Mountain NRQZ, respectively, while figures 33 through 38 illustrate measured data for an area outside of Boulder and an area outside of Golden, Colorado.

Figures 39 through 46 are the measured E-field strengths for a transmitter on Squaw Mountain operating at 772 MHz. Figures 39 and 40 illustrate the measured data for the DOC Laboratories and for the Table Mountain NRQZ, respectively, while figures 41 through 46 illustrate measured data for an area outside of Boulder and an area outside of Golden, Colorado.

The rapid variation in the measured data is due to the multiple signal (multipath) reflections that arrive at the receiving antenna as the measurement vehicle is in motion. Some other interesting features present themselves in these data. For example, for the case when the transmitter is located on Eldorado Mountain, the results for the Table Mountain NRQZ location exhibit much less variability than the other measured locations. This is explained by the fact that the Table Mountain NRQZ site has, virtually, a LOS path from the Eldorado Mountain transmitter and, hence, there are very few objects (excluding the ground reflection) at the Table Mountain NRQZ that would cause multipath effects.

Figures 17 and 27 show results for the Eldorado Canyon route for a transmitter on Eldorado Mountain. Notice how the E-field strengths increase dramatically as the measurement vehicle emerged out of the canyon onto Highway 93. It should be noted that the field strengths in the canyon will most likely be higher than the measured results, if the Eldorado transmitter is raised to its proposed height of 115.5 m (380 ft), see Section 5. This is because shadowing in the canyon would be less. Figures 19 and 29 show results for the Greenbriar loop for a transmitter on Eldorado Mountain. These figures show measured data for both LOS and non-LOS paths. For the LOS path (on top of Shanahan Hill at Shanahan Ridge Park, around Fairview High School, and Southern Hills Junior High), field strengths of 1 V/m and higher are observed. For the non-LOS portion of the loop, the field strengths drop to about 0.3 V/m.

The effects of moving automobiles are seen in figures 47 and 48. These figures show measured data obtained at the intersection of Highway 93 and Highway 72, south of Boulder, for frequencies of 533 MHz and 772 MHz, respectively. Notice the change in the variation of the measured E-field when the measurement vehicle and/or other vehicles on the road were either in motion or were stopped. In particular, note that when the measurement vehicle was parked or stopped at the light, the higher frequency data (figure

48) exhibit more variation in the E-field strengths than do the lower frequency data. This is expected since scattering from automobiles would be more pronounced for shorter wavelengths (i.e., higher frequencies). These differences in the field variation are also due to the fact that higher frequency signals experience more rapid phase variation, which can alter how the multipath reflections add.

Propagation effects due to terrain features (LOS and non-LOS or shadowing) for a transmitter on Eldorado Mountain can readily be seen for the data collected for the 28th Street route, the Broadway route, and the McCaslin loop (see figures 13 through 16 and figures 23 through 26). For example, on the 28th Street route (figures 13 and 23) notice the very strong signal strength until the intersection of 28th (Highway 36) and Broadway is reached. At that point the road dips into a valley and no LOS path is present (i.e., the road dips into a terrain shadowed region). Similar results for the Broadway route are observed (see figures 14 and 24). For this route we see strong signal strengths at the top of the Table Mountain NRQZ, but the signal decreases as the measurement vehicle drove off the top of Table Mountain. The field strengths stay low throughout the northern part of Boulder on Broadway (this part of the route is shadowed from Eldorado Mountain), and as the measurement vehicle approached Arapahoe Avenue, the field strengths increase. The trend of increasing field strengths continues as the vehicle emerged into a LOS situation on south Broadway. Finally, the McCaslin loop results are shown in figures 15, 16, 25, and 26. The variation in the E-field due to the terrain features was observed for this route as well. In particular, notice how the field strengths increase to about 1 V/m when the measurement vehicle drove through NCAR's parking lot on the top of Table Mesa.

The measured E-field strengths at both the DOC Laboratories and at the Table Mountain NRQZ facility are examined next. Figures 12 and 22 show the measured E-field strengths at the Table Mountain NRQZ for a transmitter located on Eldorado Mountain for frequencies of 533 MHz and 772 MHz, respectively. From these figures it is seen that the measured E-field strengths exceed the FCC's regulatory requirements, which is unacceptable for research applications at the Table Mountain NRQZ. Figures 11 and 21 show the E-field strengths measured at the DOC Laboratories for frequencies of 533 MHz and 772 MHz, respectively. From these two figures, it is seen that the measured E-field strengths range from 0.1 V/m to as high as 1 V/m. These high field strengths at the Broadway site could possibly have an adverse effect on the sensitive measurements that are performed on a routine basis at the DOC Laboratories, as discussed in Section 8.

Figures 32 and 40 show the measured E-field strengths at the Table Mountain NRQZ for a transmitter located on Squaw Mountain for frequencies of 533 MHz and 772 MHz, respectively. From these figures it is seen that the measured E-field strengths do not exceed the FCC limits for the Table Mountain NRQZ.

The measured E-field strengths at the DOC Laboratories for a transmitter on Squaw Mountain are shown in figures 31 and 39. It is interesting to observe that data in these figures resemble a Rayleigh type of fading propagation channel, which is indicative of a non-LOS, multipath mobile environment [27, 28].

The data presented in this section are for an EIRP of 1 MW. Some of the DTV channels have maximum power allocations of 1.64 MW EIRP. The E-fields presented here can be transformed to a 1.64 MW EIRP by multiplying the results in all the figures by a factor of 1.3, resulting in even higher E-field strengths than those presented here.

4. COMPARISON OF MEASURED AND PREDICTED E-FIELD STRENGTHS

The data in the last section show measured E-field strengths for the two proposed DTV tower sites at 1 MW EIRP. The data were collected for a transmitter height of 3.66 m (12.0 ft) on the cliff edge of Eldorado Mountain (not the proposed 116 m (380 ft) height), and for a transmitter height of 8.2 m (27 ft) at Squaw Mountain (not the proposed 60.96 m (200 ft) height). In order to verify any calculated E-field strengths at the proposed tower locations and heights, comparisons to measured data for the lower antenna heights are needed. In this section, calculated E-fields obtained from the ITM (Longley-Rice model) are compared to the measured data in the above section.

Using a 1 MW EIRP and the same transmitter and receiver antenna heights as were used in the measurements, the E-field strengths for a transmitter located on Eldorado Mountain were calculated using the ITM. Contour plots of E-field strengths for the Boulder–Denver area at 533 MHz, for both a horizontally and vertically polarized transmitting antenna, are shown in figures 49 and 50, respectively. Figures 51 and 52 show the contour plots of E-field strengths for the Boulder–Denver area at 772 MHz for both a horizontally and vertically polarized transmitting antenna, respectively. The different colors on these contour plots indicate different E-field strengths.

Using the results shown in figures 49 through 52, specific locations can be directly compared to the routes that the measurement vehicle drove to collect the data in the previous section. Figure 53 shows the calculated E-field strengths for the 28th Street route in Boulder for 533 MHz. These results were calculated using receiver latitudes/longitudes obtained from the GPS data set collected during the measurements. Upon comparing the measured (see figure 13) and predicted (or modeled) E-field strengths, excellent agreement is demonstrated. Both the measured and predicted field strengths are about 0.7 V/m on the LOS portion of the route (before the Highway 36 intersection). It is also seen that both the measured and the predicted field strengths are about 0.02 V/m on the non-LOS path portion of the route (Highway 36 to the Table Mountain NRQZ).

Notice, however, that the measured data have much more variability than the predicted field strengths. As mentioned above, the variability in the measured data is due to the vehicle's motion and the motion of the local objects relative to the measurement vehicle, as well as the fact that the measured data contain three-dimensional multipath effects. Reflections reaching the receiver from all directions are indicative of a true three-dimensional multipath environment. Keep in mind that the predicted E-field strengths do not have local scatterers (i.e., buildings, cars, people, etc.) in the model. Only the terrain profile is taken into account. Also, the ITM uses only profile data on the bearing from