Drone Measurements Validate the Accuracy of Simulation for FM Pattern Verification

John L. Schadler
Dielectric LLC
Raymond, Maine, United States

Jason Schreiber
Sixarms
Gold Coast, Australia

Abstract – An extensive amount of experience has been gained in both drone measurement techniques of television broadcast antennas and data analysis using electromagnetic simulation. Through comparison, drone measurements and simulation predictions have time and time again validated that the techniques provide accurate measurements and predictions at UHF and VHF frequencies. Now that the FCC television channel Repack has passed, extending what has been learned to the FM market will provide new opportunities for FM broadcasters. Understanding the limitations of “old school” FM pattern range measurements and the power of computer simulation will be discussed in this paper. It will also include case studies, one of which would be impractical for any far field range and can only be realized using simulation and validation using drone-based measurements.

INTRODUCTION

Historically, field measurements have been performed to ensure that broadcast antennas are operating as designed, reaching the intended audience and installed correctly. For decades, this was done using ground-based measurements following the procedure specified in the “Field Strength Measurements” section 73.314 of the FCC rules. The rules are detailed. They specify a method for selecting measurement locations and require the field strength recordings to be recorded over a mobile run of at least 30 meters with the receive antenna at least 9 meters above the ground. The median field strength of the run is considered the field strength at this location.

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FIGURE 1: FIELD MEASUREMENT TRUCK AND DRONE MEASURING BROADCAST ANTENNA PATTERNS, COURTESY SIXARMS.

This cumbersome process took weeks and was based on the statistical averaging of a massive amount of data. Today, the use of unmanned aerial vehicles or “drone” technology has proven to be an accurate and cost-effective solution to pattern verification of broadcast antennas in the field. During the FCC channel Repack, many VHF and UHF stations took advantage of the government-reimbursable opportunity to do field pattern verification studies. During this time an extensive amount of knowledge was gained in both drone measurement techniques as well as subsequent data analysis. Near field pattern predictions using HFSS computer simulation provided a justification for the drones to measure within the 400’ “shielded airspace” of the tower while not being burdened with extensive paperwork required to obtain FAA waivers to fly [1]. Through comparison, drone measurements and simulations have repeatedly validated that the techniques provide both accurate measurements and accurate predictions [2].

Since FM stations were generally not affected by the Repack, these measurement and simulation techniques focused on VHF and UHF television frequencies. Now that Repack has passed, extending what has been learned to the FM market will provide a means to better understand the limitations of “old school” FM pattern range measurements and how computer simulation can overcome those shortfalls. Drone measurements provide a basis to evaluate the significance that detailed modeling can have on real world FM antennas by comparing simulations using basic tower models vs. detailed models inclusive of the features such as transmission lines, ladders, and other structures in the aperture, etc.

FCC RULE CHANGE

In June of 2021, Dielectric LLC and four other entities filed a joint PRM, Petition for Rule Making, with the FCC to allow the use of computer simulation to verify the performance of directional FM antennas. In November of 2021, the FCC showed very strong support of the proposal by unanimously deciding to move forward with a NPRM, a Notice of Proposed Rule Making to allow such simulation for pattern verification. In May of 2022, the new rules were adopted which gave FM license applicants the option of submitting computer generated proofs of FM directional antenna patterns from the antenna's manufacturer, in lieu of measured pattern plots and tabulations [3]. The strong support and quick adoption stems from the benefits and evident accuracy that simulation has over traditional range measurements.

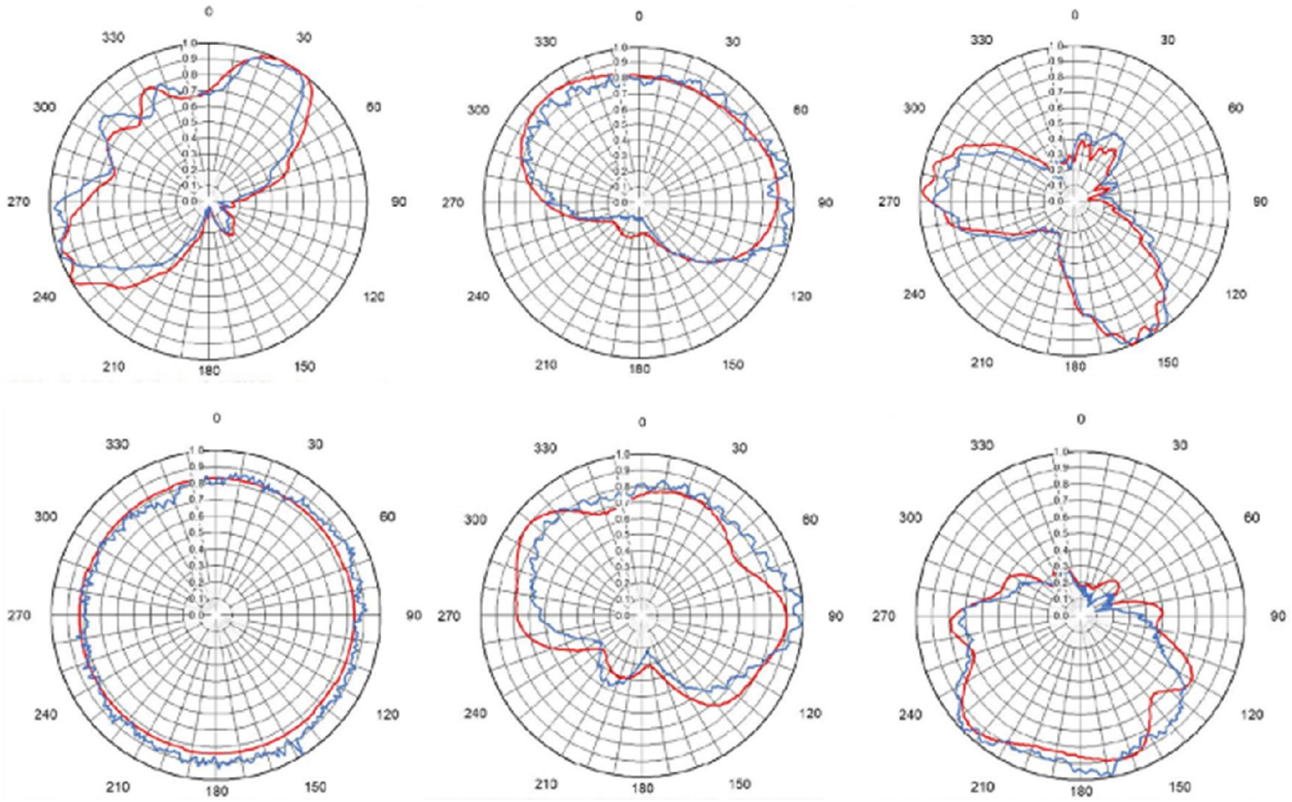


FIGURE 2: EXAMPLES OF THE 53 CASE COMPARISONS FILED WITH THE FCC IN SUPPORT OF ALLOWING HFSS COMPUTER SIMULATION AS AN ACCEPTABLE METHOD OF PROOF OF PATTERN PERFORMANCE ON FM DIRECTIONAL ANTENNAS. RED ARE HFSS COMPUTER SIMULATION PREDICTIONS. BLUE ARE DRONE MEASUREMENTS MADE AFTER ANTENNA INSTALLATION.

THE BENEFIT OF SIMULATION

Historically, FM directional pattern studies have been performed on full scale or quarter scaled ranges.

FIGURE 3: LEFT: FAR FIELD RANGE DIELECTRIC / HARRIS, PALMYRA, MO. RIGHT: QUARTER SCALE MODELING IN ANECHOIC CHAMBER – DIELECTRIC, RAYMOND, ME.

The benefits of computer simulation include:

- **Cost advantage** – No physical models need to be manufactured and handled.
- **Reflection free environment** – No range is truly reflection or interference free.
- **Mechanical tolerance** – Simulations are not limited by availability of materials or dependent on bore siting for directional calibration.
- **Human error** – Simulation does not rely on a human to measure the locations of parasitic elements in space or transferring information into CAD drawings.
- **Complete optimization** – Simulation is not constrained by time. A project need not settle for “close enough, we are out of time”.
- **Reproducibility** – Simulation provides the same exact calculation every time and is not set up tolerance dependent.
- **Standardization** – Since all measurement ranges are unique, there is no standard. With simulation, the CAD file from which the calculations are performed is the standard.

FM ANTENNA CASE STUDIES

Recently, two Dielectric side mounted ring style FM antennas were installed on towers in Bridgeport and Lubbock, Texas, and both were measured by a Sixarms drone in August of 2023. The purpose was to validate the drone measurement technique at FM as well as showcase the importance, power and accuracy of modeling using computer simulation. The Lubbock installation is a DCRM12DC50(SP) antenna servicing KLBB-FM (93.7 MHz), KTTU-FM (97.3 MHz) and KXTQ-FM (106.5 MHz). Refer to Figure 4. The antenna is leg mounted to a 6’ face tower with multiple transmission lines running through the aperture.

FIGURE 4: DCRM12DC50(SP) ANTENNA INSTALLED FOR KLBB-FM, KTTU-FM AND KXTQ-FM IN LUBBOCK, TEXAS.

The second site that was measured by a Sixarms drone is in Bridgeport, Texas, where a new Dielectric DCRS10DC ring style FM antenna for KBOC-FM (98.3 MHz), KYDA-FM (101.7 MHz), and KZZA-FM (106.7 MHz) was installed. The antenna is face mounted to a simple 6’ face tower that includes a ladder inside. However, this is a unique installation since the tower the antenna is mounted on comprises one leg of a candelabra. A second identical 6’ face tower is located 20.8’ away on the opposite leg of the candelabra in the FM antenna’s aperture. Because of the large structures involved, this site represents a situation that would be impractical for any far field test range to replicate. See Figures 5 & 6.

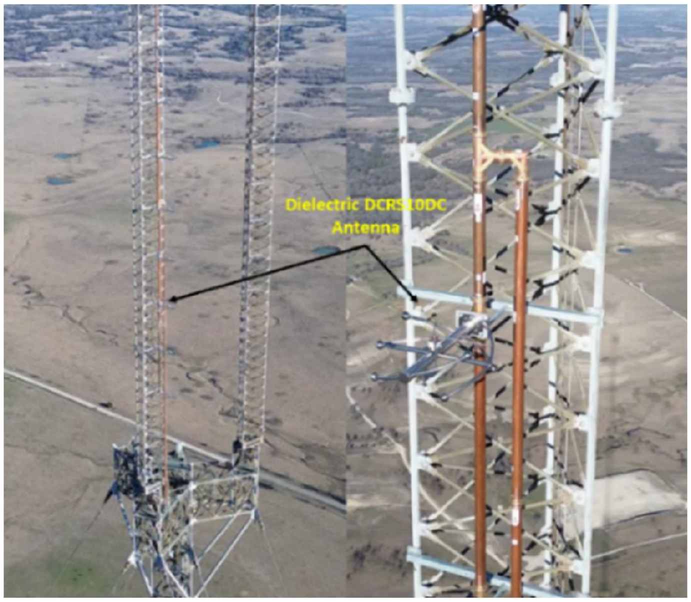


FIGURE 5: DIELECTRIC DCRS10DC FM ANTENNA SERVICING KBOC-FM, KYDA-FM AND KZZA-FM IN BRIDGEPORT, TEXAS.

Referring to Figure 6, a closer look at the candelabra shows a second FM antenna mounted on the opposing lattice arm and in the aperture of the Dielectric DCRS10DC FM antenna, causing even more distortion which cannot be replicated using a single bay on a physical mockup tower.

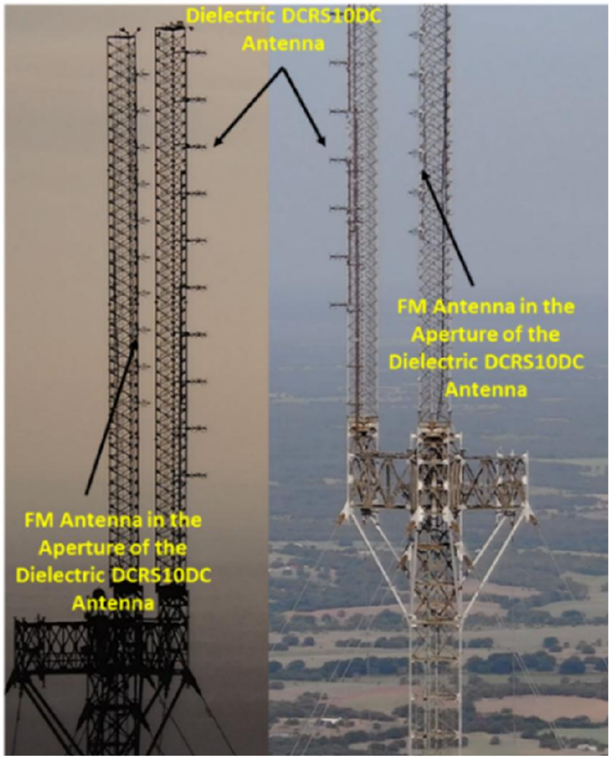


FIGURE 6: FM ANTENNA MOUNTED ON THE OPPOSING LATTICE ARM OF THE CANDELABRA AND IN THE APERTURE OF THE DIELECTRIC DCRS10DC FM ANTENNA IN BRIDGEPORT, TEXAS.

HISTORICAL METHODS OF EVALUATING ANTENNA PERFORMANCE ON A CANDELABRA

In the early days of community antenna sites, scale modeling of full antenna arrays was the only way to evaluate antenna performance in the presence of other complex apertures.

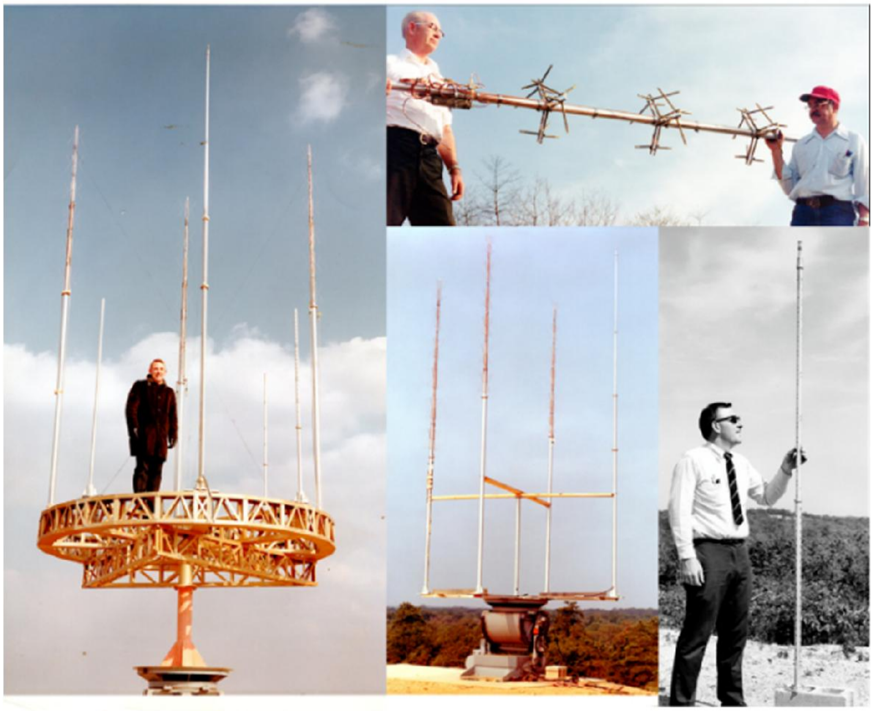


FIGURE 7: SCALE MODEL TESTING OF THE RADIATION CHARACTERISTICS OF ANTENNAS IN THE PRESENCE OF OTHER ANTENNAS. (SOURCE: RCA 1970'S).

To study the effects of radiation pattern distortion using full scaled aperture antennas today would be time and cost prohibitive. In the 1980's, mathematics and computer techniques were introduced to provide approximations for the effect that towers, and other structures had on the radiating antenna's performance when placed in its aperture. The equations were based on the diffraction of cylindrical reflecting objects such as pylon antennas, tower legs and transmission lines and vectorially summed with the radiating free space pattern. However, any geometry other than a cylinder had to be approximated by an effective cylinder [4]. The technique was much more cost effective than scaled model range testing but came with limited accuracy. It will be obvious in the following discussion that technology has come a long way since then with advancements in full 3-D electromagnetic solvers.

DRONE MEASUREMENT PROCESS

Due to recent (last 10 years) advances in commercial drone technology and the miniaturization of portable spectrum analyzers, the ability to accurately and efficiently measure broadcast antenna patterns using small drone aircraft has been realized. Over the last decade, the process of drone-based pattern measurements has vastly matured and is now capable of measuring antenna patterns for MF (AM Radio), VHF (FM Radio, Digital Radio and TV) and UHF (TV) [5].

The equipment needed can be summarized as:

- Capable commercial drone with precision GPS system
- Portable, integrated Spectrum Analyzer

- Appropriate calibrated Receiving Antenna
- Controlling Embedded PC connected to drone
- Data Coordination, Visualization and Flight Waypoint Generation Software

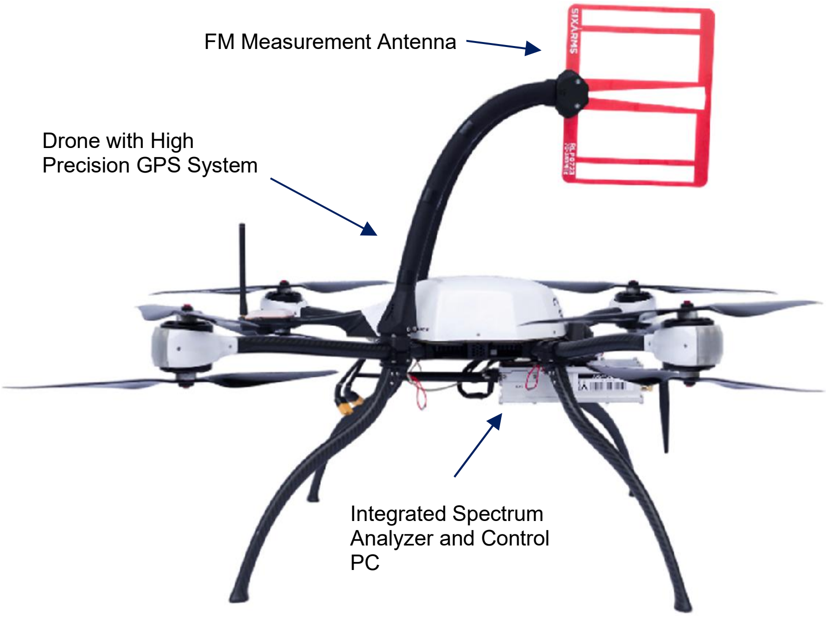


FIGURE 8: TYPICAL DRONE-BASED ANTENNA PATTERN MEASUREMENT SYSTEM EQUIPPED WITH AN FM MEASUREMENT ANTENNA.

The main difference in configuration between measuring AM vs FM vs Digital TV is simply:

- The Measurement Antenna appropriate for the frequency band.
- The sampling technique – How the field strength or Channel Power is derived.

The overall process of getting accurate antenna pattern data is similar between most broadcast technologies and is based on ITU-R Report SM.- 2056-1, "Airborne Verification of Antenna Patterns of Broadcast Stations" [6]. The main process involves two flight types. Elevation flights, which determine the elevation pattern and beam tilt of the main beam of the antenna and are performed at specific azimuth points around the antenna, and Azimuth flights which determine the direction and intensity of radiation in the azimuth plane.

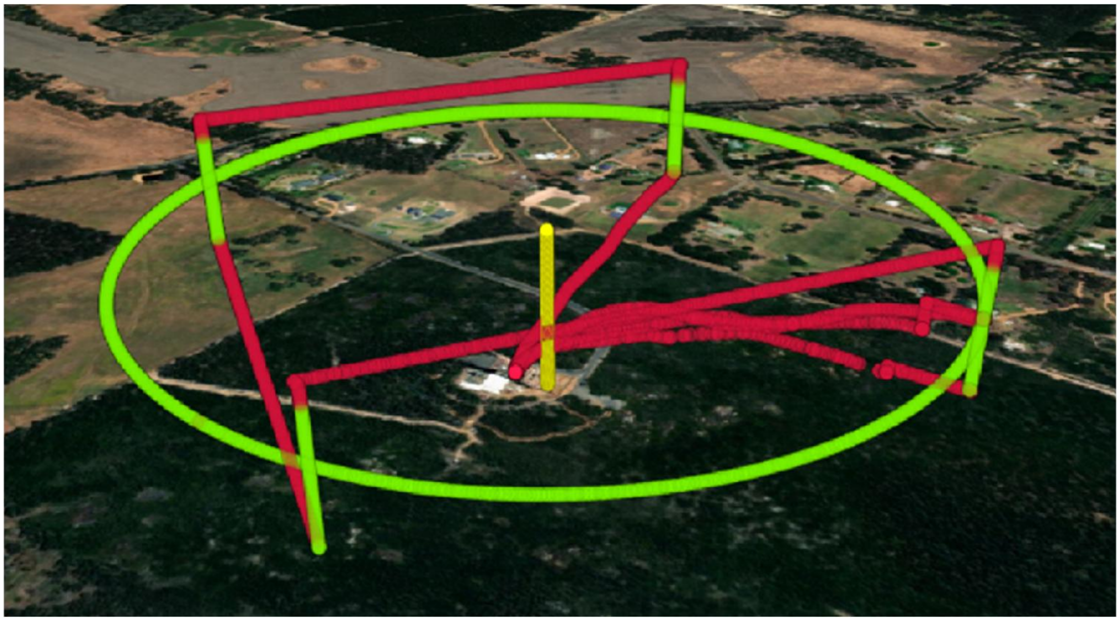


FIGURE 9: ACTUAL FLIGHTS PATHS TO GATHER FOUR ELEVATION SLICES AND ONE AZIMUTH PATTERN DATASET.

Both the azimuth flights and the elevation flights should ideally be conducted in the far-field (or Fraunhofer region) the antenna. This is usually calculated using (1) below:

$$R = \frac{2D^2}{\lambda} \tag{1}$$

Where:

$R = Far\ Field\ Distance$
$D = Aperture\ of\ antenna$
$\lambda = Wavelength$

Generally, it is acceptable to perform the azimuth flights at a closer distance than the elevation flights and still maintain the accuracy needed to measure the relative pattern shape. However, to measure the Effective Radiated Power (ERP) or absolute powers, it is best to fly as close as practical to the far field distance.

Results from the measurements can be compared against the theoretical patterns to determine if any installation, manufacture, or surrounding structure effects are present. The maximum ERP as well as the elevation and azimuth plots can be displayed for comparison.

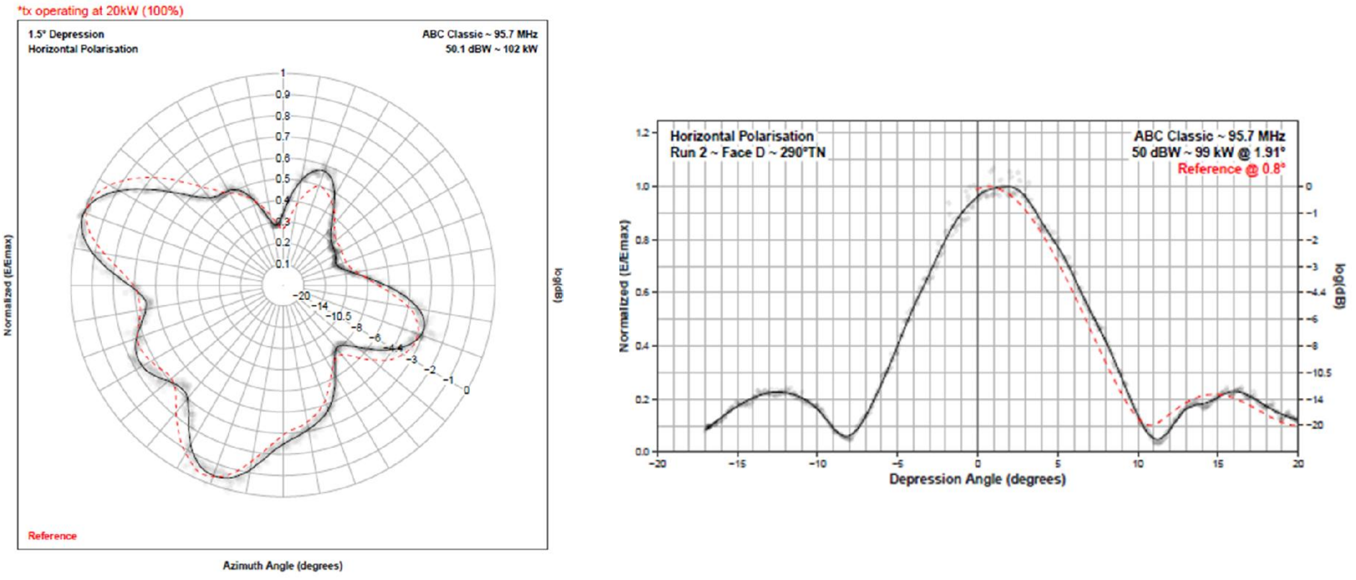


FIGURE 10: DISPLAY OF MEASURED ERP, ELEVATION PATTERNS AND AZIMUTH PATTERNS (BLACK SOLID) COMPARED TO THEORETICAL PATTERNS (RED DASHED).

DRONE MEASUREMENT UNCERTAINTY

Since drone data are from measurements, they have a degree of uncertainty regardless of the reported precision. Limitations on the measuring equipment and process can be combined and quantified as relative uncertainty. Relative uncertainty describes how much the actual value could be above or below the measured value or the range within the true values lies.

The uncertainty system model used is based on applicable international standards and more specifically follows the International Standards Organisation "Guide to the Expression of Uncertainty in Measurements".

The measurement uncertainty is a result of the measurement uncertainty of all input parameters. Typical input parameters are:

- Drone Positional Accuracy
- Scattering Effects
- Spectrum Analyser Level Variation
- Receive Coaxial Loss Variation
- Receive Antenna Alignment
- Receive Antenna Gain Variation

The calculation of the total measurement uncertainty for these FM pattern measurements is shown in Figure 11 below.

Source of uncertainty	Unit	Uncertainty				
		Probability distribution	Semi span a or σ	Divisor d	$u_i = a/d$	u_i^2
Positional Accuracy	dB	Triangular	0.2	√6	0.082	0.007
Scattering Effects	dB	Rectangular	1.5	√3	0.866	0.750
Spectrum Analyser Sampling	dB	Normal	0.5	2	0.250	0.063
Feeder Loss Variation	dB	Rectangular	0.05	√3	0.029	0.001
Azimuth Alignment	dB	Triangular	0.2	√6	0.082	0.007
Antenna Gain Variation	dB	Rectangular	0.1	√3	0.058	0.003
SUMS						0.830
Combined standard uncertainty, uc = √Σ(ui²)						0.911
Coverage factor, k						2 (95% CI)
Expanded Uncertainty, U = k × uc						**1.822**

Figure 11: Typical Relative Uncertainty Calculation for drone-based FM Radio antenna pattern measurements is ±1.8dB.

Improvements in the overall absolute uncertainty (ERP) and relative uncertainty (patterns, beam tilt) can be made by improving the following parameters:

- Absolute uncertainty of the spectrum analyzer through local on-site calibration
- Absolute and relative uncertainty in FM by using a Carrier Wave transmit signal instead of a modulated signal (requires radio program interruption), OR
- Measurement of the HD Radio channels, and the FM modulated signal (vastly improve channel power deviation).
- Use of more directive receive antennas to minimize multipath and scattering effects.

The drone-based pattern measurement system is currently the most accurate and efficient way of measuring large in-situ broadcast arrays in the most efficient way.

COMPUTER MODELING COMPARISION – SIMULARITY FIGURE OF MERIT

In many cases, you can visually look at two azimuth patterns and conclude which is closer to the expected pattern. But how can you mathematically quantify similarity? This can be achieved by calculating the mean pattern variance from the expected pattern. In this case the expected pattern must include all points that lie within the region of relative uncertainty. If the azimuth point lies within this range, then obviously that is to be expected. The variance from the expected pattern would then be the points that lie outside of relative uncertainty bounds. To quantify similarity, the mean distance of all points lying outside of the relative uncertainly bounds can be compared. The mean pattern variance is given by (2).

$$\bar{V} = \frac{\sum_1^N |f(\theta)-E(\theta)|}{N} \tag{2}$$

Where:

$$f(\theta) = E(\theta)\ for\ \mu_L(\theta) \le f(\theta) \le \mu_u(\theta)$$
$$E(\theta) = \mu_u\ for\ f(\theta) > \mu_u$$
$$E(\theta) = \mu_L\ for\ f(\theta) > \mu_L$$

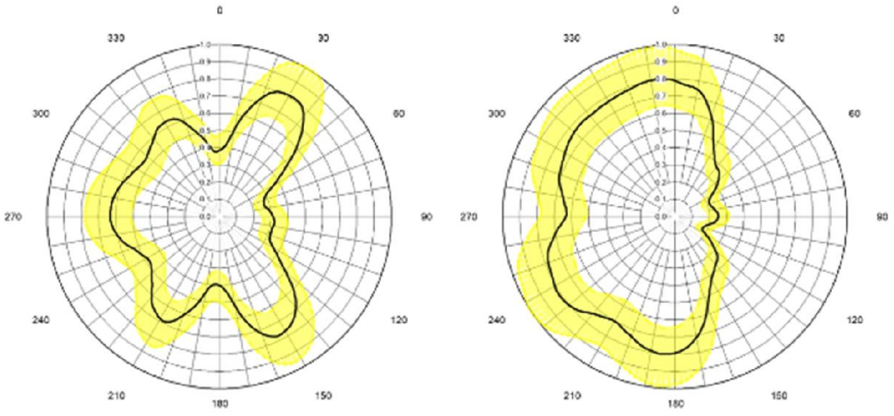
$f(\theta)$ is the simulated pattern
$E(\theta)$ is the expected drone pattern
$\mu_L(\theta)$ and $\mu_u(\theta)$ are the upper and lower bounds of the relative uncertainty

If the simulated pattern lies completely inside of the relative uncertainty bounds, the mean variance, $\bar{V} = 0$. The more points that lie outside of the bounds and the farther away they are from the upper or lower bound, the larger $\bar{V}$ becomes.

CASE STUDY 1 – LUBBOCK, TEXAS, DRONE MEASURMENT RESULTS

The azimuth pattern measurement results for KLBB-FM (93.7 MHz), KTTU-FM (97.3 MHz) and KXTQ-FM (106.5 MHz) are shown in Figure 12. The shaded yellow envelope represents the region of uncertainty, (+/- 1.8 dB).

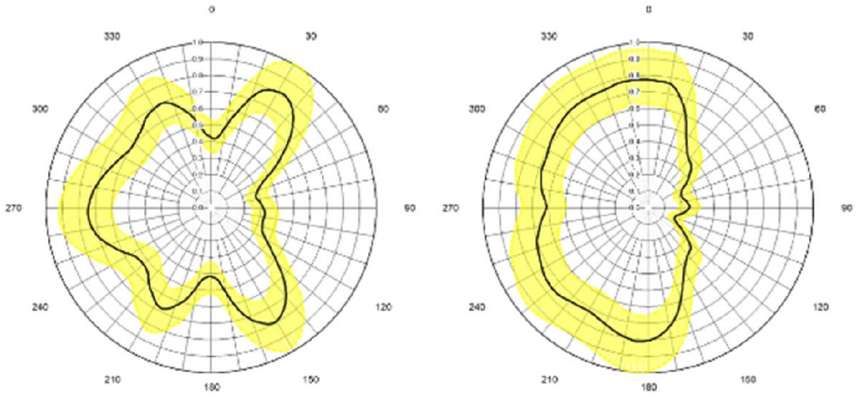
KLBB – 93.7 MHz



Horizontal Polarization

Vertical Polarization

KTTU – 97.3 MHz



Horizontal Polarization

Vertical Polarization

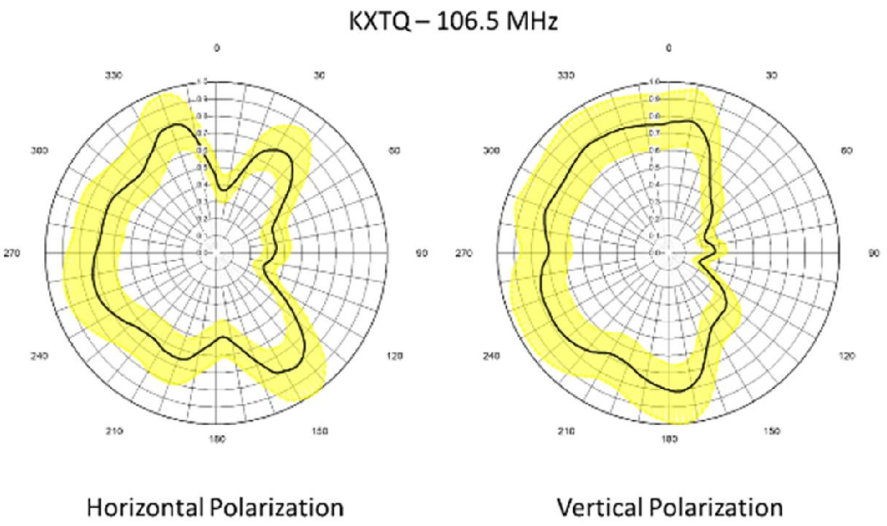


FIGURE 12: DRONE AZIMUTH PATTERN MEASUREMENT RESULTS OF KLBB-FM, KTTU-FM AND KXTQ-FM LOCATED IN LUBBOCK, TEXAS. THE SHADED YELLOW REGION REPRESENTS THE REGION OF RELATIVE UNCERTAINTY.

CASE STUDY 1 – LUBBOCK, TEXAS, COMPUTER MODELING AND SIMULATION

For the computer modeling at the Lubbock, Texas site, a single bay is used for simulation on a tower with all known features as shown in Figure 13. The performance is simulated in ANSYS HFSS software and overlaid with the drone data in Figure 14.

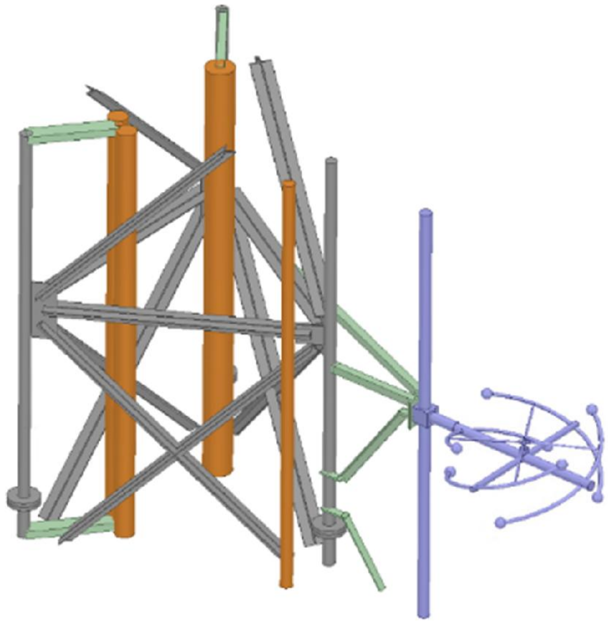


FIGURE 13: LUBBOCK, TEXAS, SINGLE FM BAY LEG MOUNTED TO TOWER.

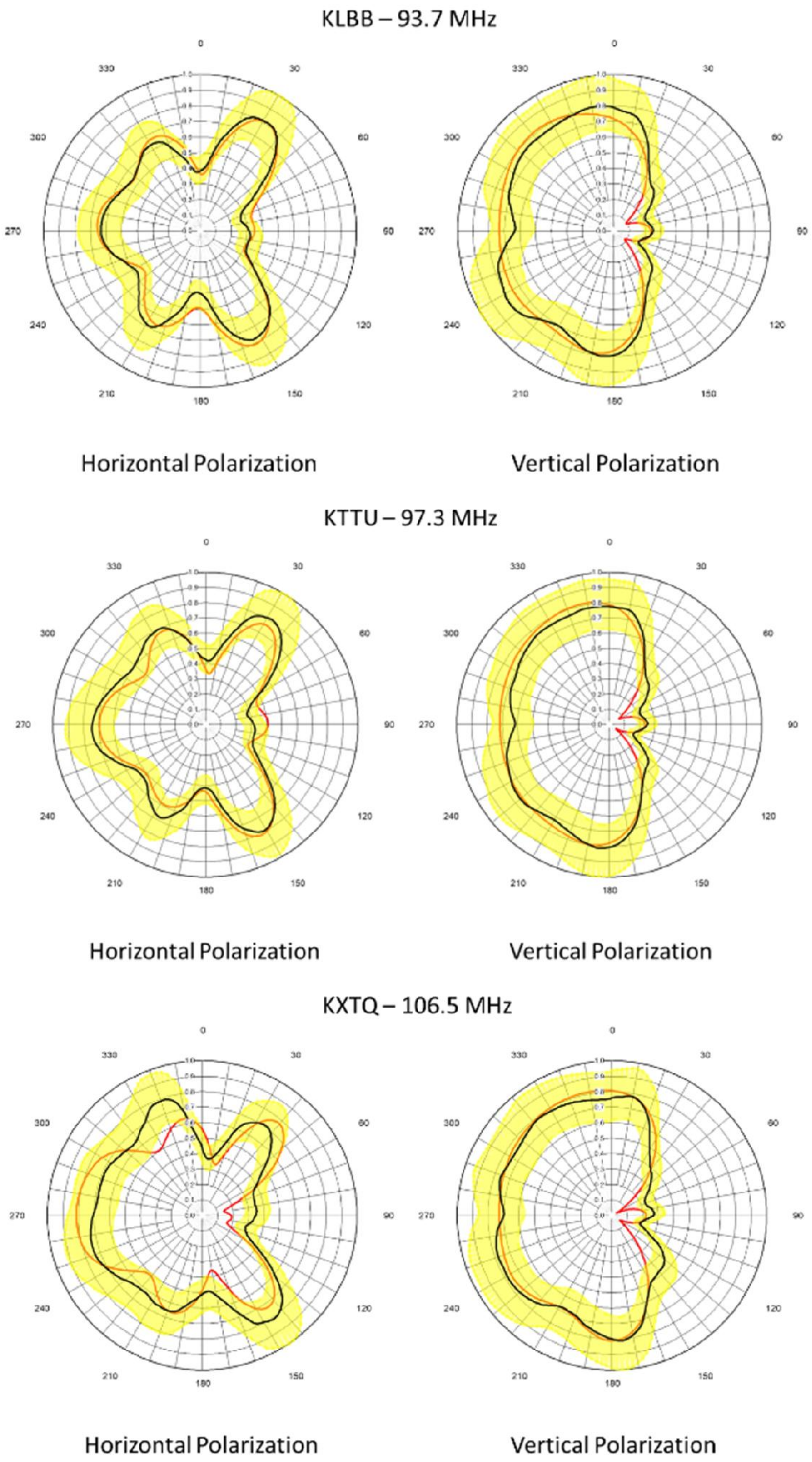


Figure 14: Lubbock, Texas, single FM bay leg mounted to tower. Black – Drone measurement. Red – HFSS computer simulation of the model shown in Figure 13. Yellow – Drone measurement region of relative uncertainty.

The corresponding mean pattern variance between the drone measurements and the HFSS computer model simulations for each frequency are shown in Figure 15.

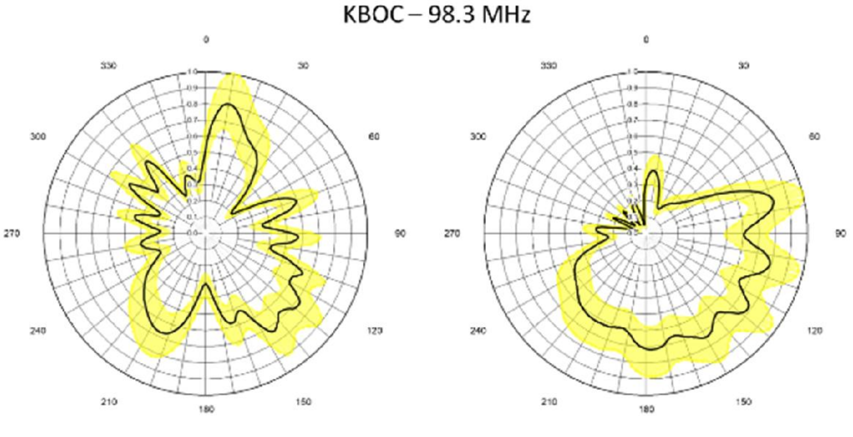
Frequency	HPOL $\overline{V}$	VPOL $\overline{V}$
93.7	0	0.016
97.3	0.001	0.017
106.5	0.019	0.024

FIGURE 15: LUBBOCK, TEXAS, SITE SIMILARITY SUMMARY FOR PLOTS SHOWN IN FIGURE 14. SINGLE FM BAY LEG MOUNTED TO TOWER.

The mean pattern variance numbers are small, reflecting close similarity between the drone measurements and the HFSS simulated patterns. Note that in the case of the HPOL (horizontal polarization) comparison at 93.7 MHz, the simulated pattern lies completely inside of the relative uncertainty bounds and $\bar{V} = 0$. The predicted and measured patterns are considered to be matches.

CASE STUDY 2 – BRIDGEPORT, TEXAS, DRONE MEASURMENT RESULTS

The azimuth pattern measurement results for KBOC-FM (98.3 MHz), KYDA-FM (101.7 MHz) and KZZA-FM (106.7 MHz) are shown in Figure 16. The shaded yellow envelope again represents the region of relative uncertainty.


KBOC – 98.3 MHz

Horizontal Polarization

Vertical Polarization

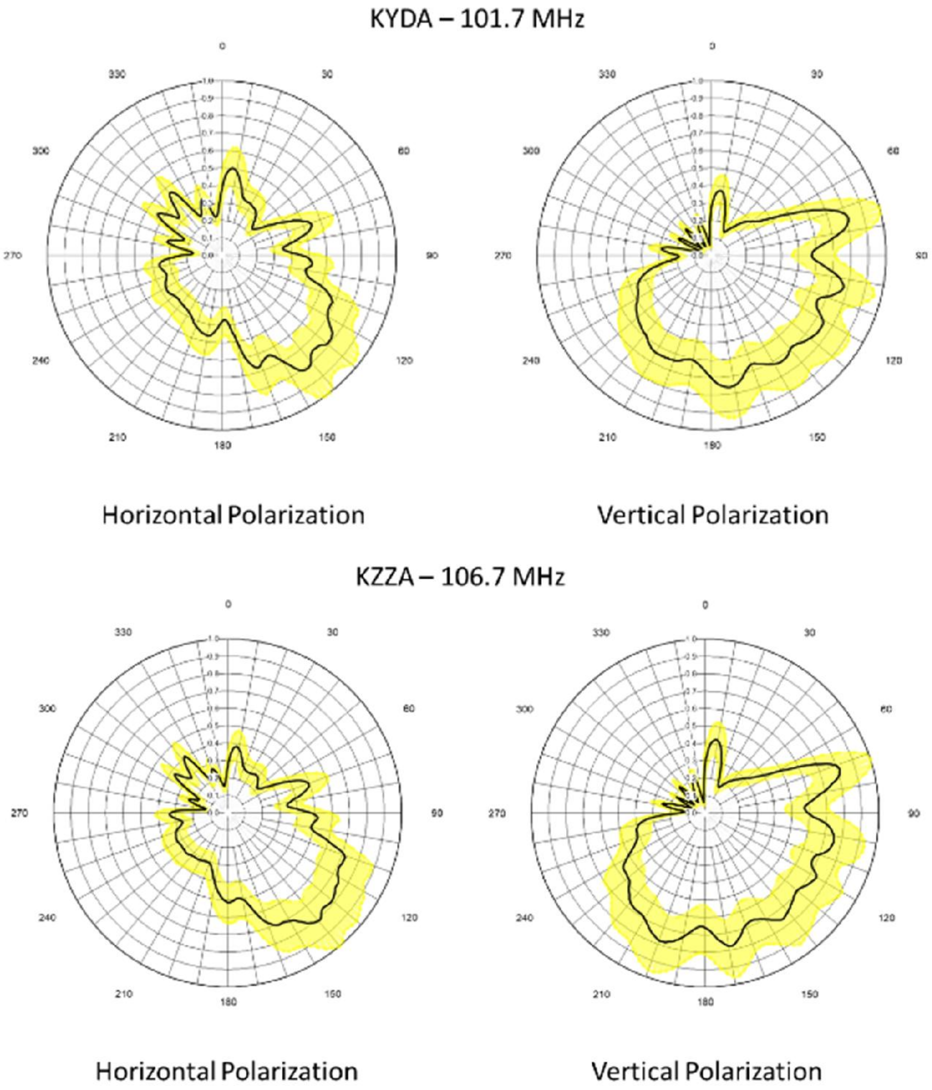


FIGURE 16: DRONE AZIMUTH PATTERN MEASUREMENT RESULTS OF KBOC-FM, KYDA-FM AND KZZA-FM LOCATED IN BRIDGEPORT, TEXAS. THE SHADED YELLOW REGION REPRESENTS THE REGION OF RELATIVE UNCERTAINTY.

CASE STUDY 2 – BRIDGEPORT, TEXAS, COMPUTER MODELING AND SIMULATION

A real-world antenna model is created using ANSYS HFSS software to include all objects in the aperture of the antenna (i.e.: tower, mounts, transmission lines, ladders, conduits, etc.). This is accomplished utilizing manufacturing, installation, and tower drawings in combination with photos and videos of the site. A single FM bay mounted to the tower, (Figure 17), is compared to the drone measurements taken by Sixarms.

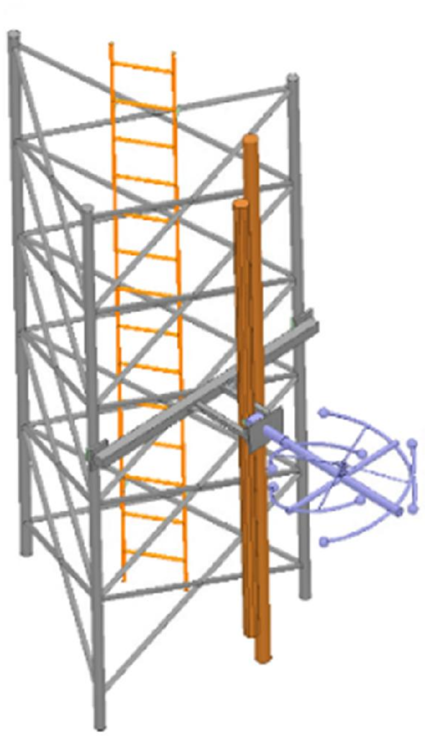
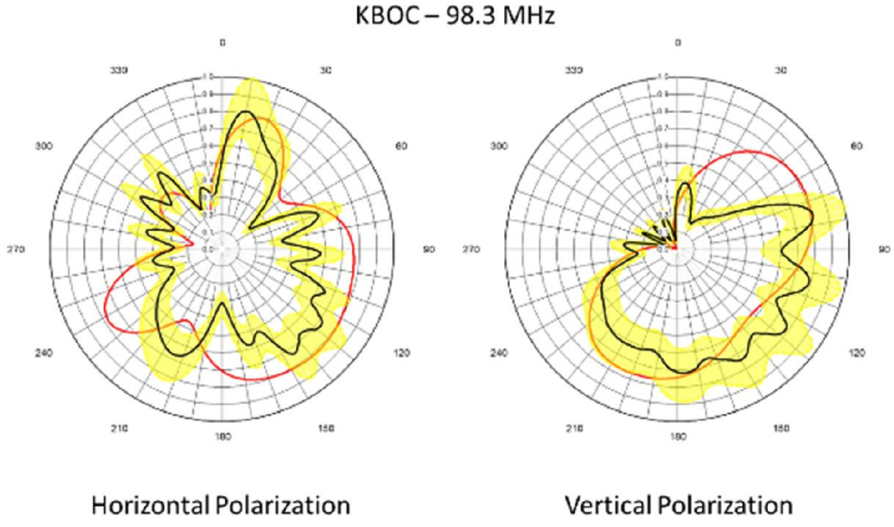


FIGURE 17: BRIDGEPORT, TEXAS, SITE SINGLE FM BAY FACE MOUNTED TO TOWER.

The simulation results for each station at the Bridgeport site are shown in Figure 18. In each case, the black trace is the drone measurement with the shaded yellow representing the region of relative uncertainty and the red trace is the HFSS computer simulation.



KBOC – 98.3 MHz

Horizontal Polarization

Vertical Polarization

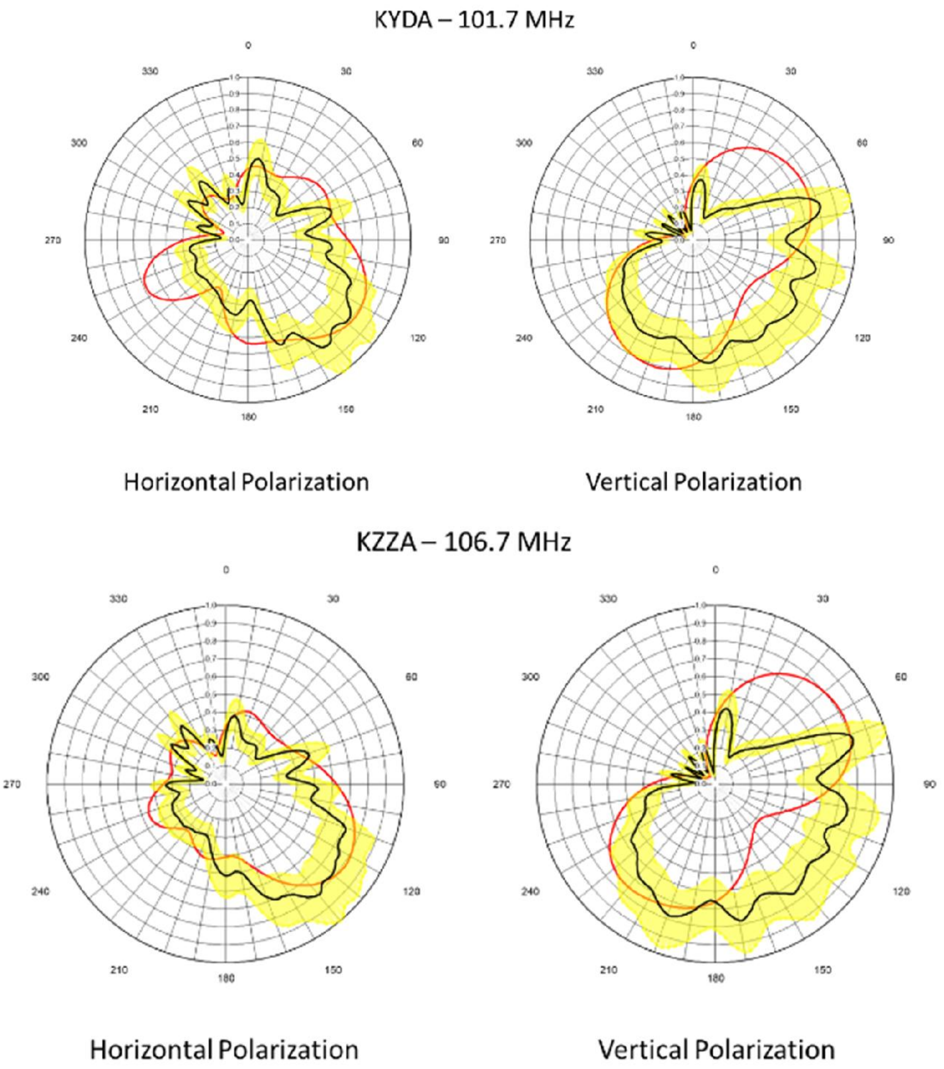


FIGURE 18: BRIDGEPORT, TEXAS, SINGLE FM BAY FACE MOUNTED TO TOWER. BLACK – DRONE MEASUREMENT. RED – HFSS COMPUTER SIMULATION OF THE MODEL SHOWN IN FIGURE 17. YELLOW – DRONE MEASUREMENT REGION OF RELATIVE UNCERTAINTY.

The corresponding mean pattern variance between the drone measurements and the HFSS computer model simulations for each frequency are shown in Figure 19.

Frequency	**HPOL $\overline{V}$**	**VPOL $\overline{V}$**
98.3	**0.078**	**0.064**
101.7	**0.055**	**0.078**
106.7	**0.031**	**0.107**

FIGURE 19: BRIDGEPORT, TEXAS, SITE SIMILARITY SUMMARY FOR PLOTS SHOWN IN FIGURE 18. SINGLE FM BAY FACE MOUNTED TO TOWER.

As can be seen, the basic pattern shape of the HFSS computer simulations match the drone measurements, but it is obvious that the effect of the second tower plus other features such as the other antenna in the aperture play a major role in the overall performance when comparing the data. When adding the second tower into the model as shown in Figure 20, the new simulation results are shown in Figure 21.

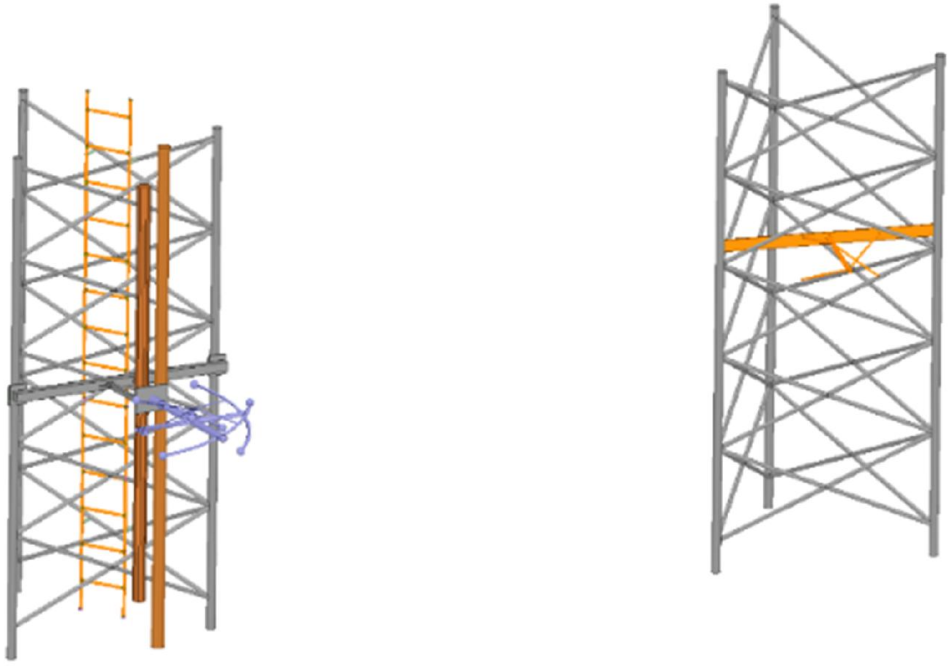
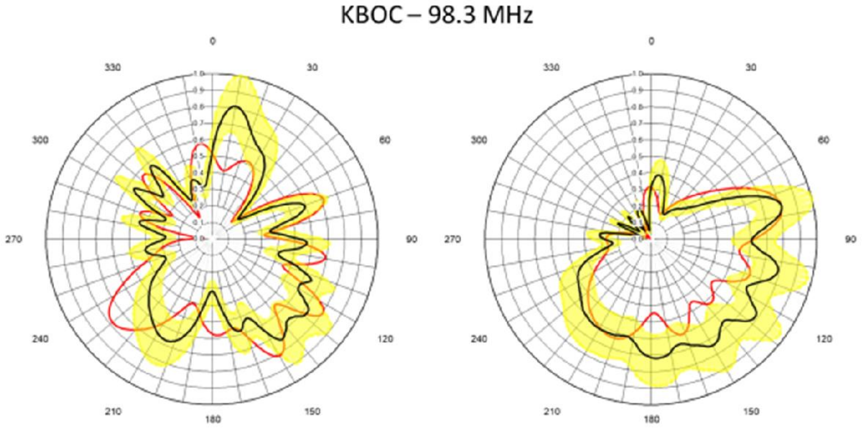


FIGURE 20: BRIDGEPORT, TEXAS, SITE WITH THE SECOND TOWER ON THE CANDELABRA ADDED INTO THE HFSS MODEL. NOTE THE SECOND TOWER ALSO INCLUDES ANOTHER ANTENNA ELEMENT IN THE APERTURE.



Horizontal Polarization

Vertical Polarization

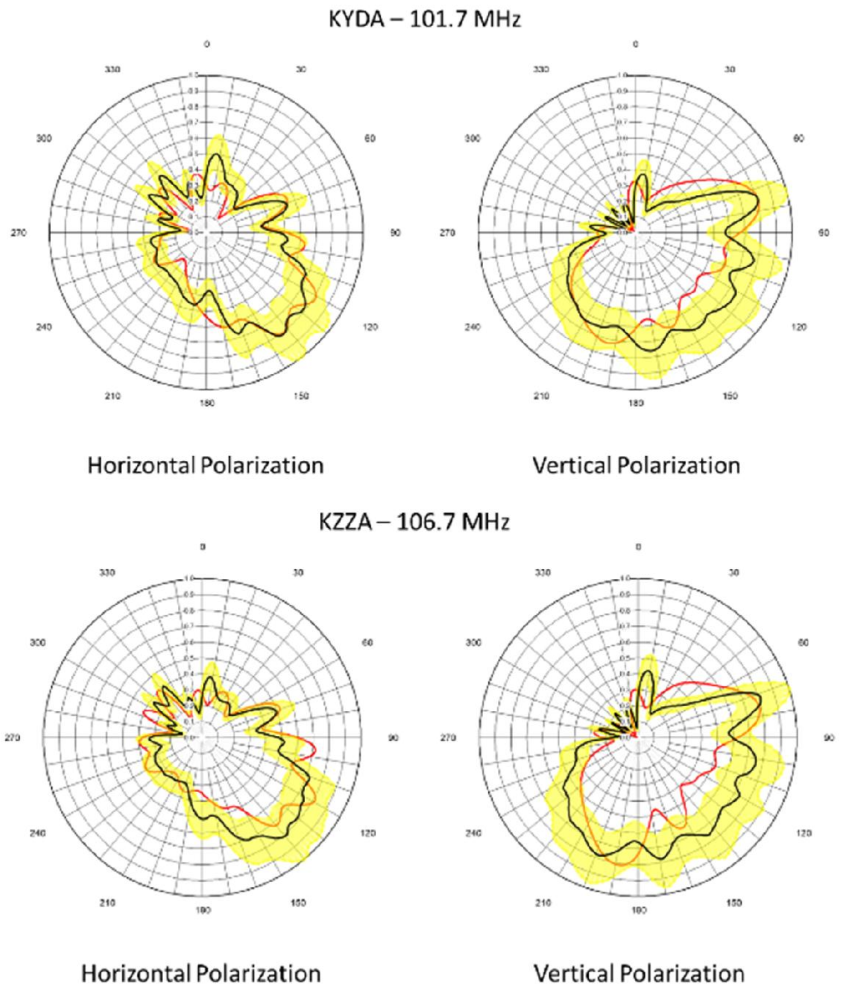


FIGURE 21: BRIDGEPORT, TEXAS, SITE WITH THE SECOND TOWER OF ON THE CANDELABRA ADDED INTO THE HFSS MODEL. BLACK – DRONE MEASUREMENT. RED – HFSS COMPUTER SIMULATION OF THE MODEL SHOWN IN FIGURE 20. YELLOW – DRONE MEASUREMENT REGION OF RELATIVE UNCERTAINTY.

The corresponding mean pattern variance between the drone measurements and the HFSS computer model simulations for each frequency are shown in Figure 22.

Frequency	HPOL $\overline{V}$	VPOL $\overline{V}$
98.3	0.059	0.041
101.7	0.024	0.04
106.7	0.022	0.059

FIGURE 22: BRIDGEPORT, TEXAS, SITE SIMILARITY SUMMARY FOR PLOTS SHOWN IN FIGURE 21. SECOND TOWER ON THE CANDELABRA ADDED INTO THE HFSS MODEL.

When comparing the results of the simulations with and without the second tower included, it is clear the simulated patterns with the second tower included are significantly closer to the drone measurements. This is reflected by the decrease in the mean pattern variances for the horizontal and vertical polarizations at all frequencies as shown in Figure 23.

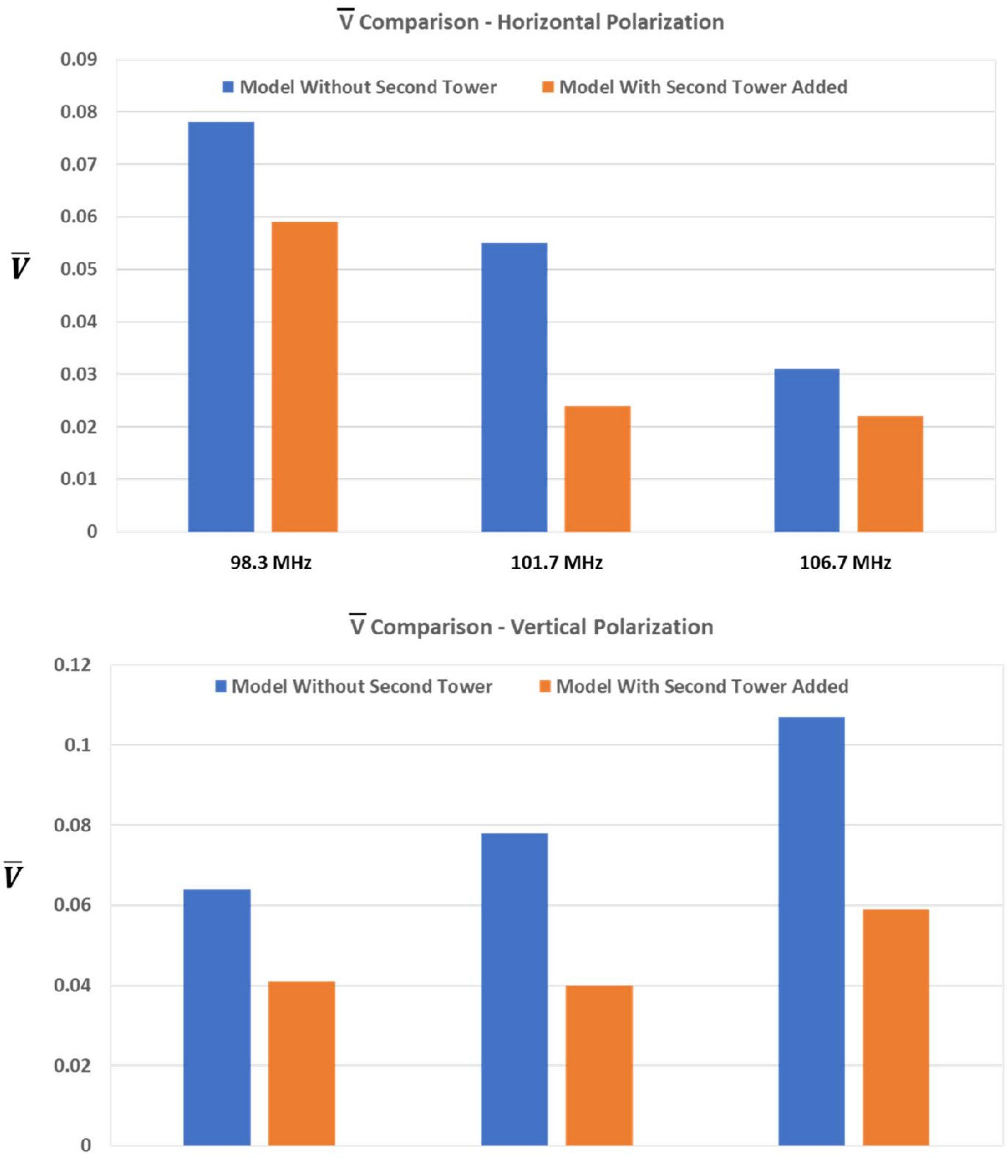


Figure 23: Bridgeport, Texas, site. Summary comparison of the mean pattern variances between the simulation models with and without the second tower for both the horizontal and vertical polarizations.

The data shows on average a 37% decrease in the mean pattern variance in the horizontal polarization and a 43% decrease in the vertical polarization.

DRONE TOWER MAPPING

The level of accuracy of the computer simulation model to the true tower geometry can have an impact on the simulated antenna's radiation pattern. The simulation is highly dependent on the accuracy of the tower drawing/modeling. In lieu of detailed and accurate tower, antenna and transmission line location drawings, drones are also able to create 3D models of the antennas and surrounding structures.
The current techniques used to create this 3D model (also known as a "digital twin") are:

- **Photogrammetry** – a 3D point cloud created by cleverly stitching photos based on common 'tie points', and
- **Lidar** – a 3D point cloud created by using pulsed light (and their reflections) to map a 3D environment.

Both techniques with the use of control points and good data capture techniques can map large objects to within 5mm accuracy.

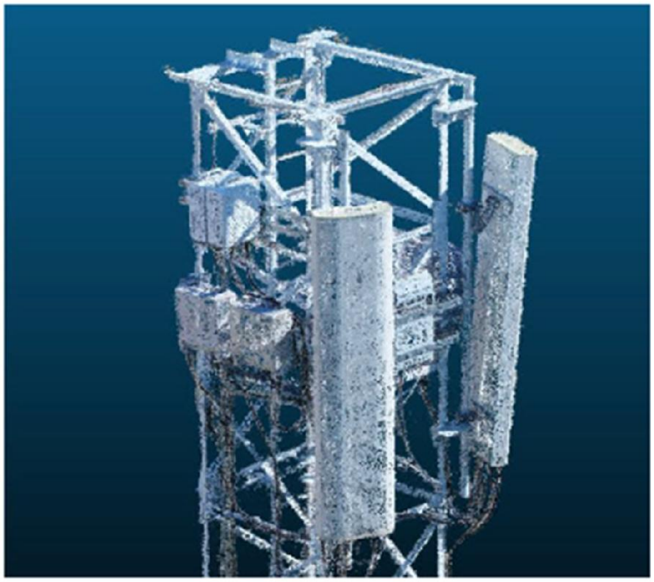


FIGURE 24: PHOTOGRAMMETRY 3D MODEL OF THE TOP OF A TOWER SECTION. IMAGE COURTESY OF PIX4D.

FIGURE 25: SIXARMS CAPTURED LIDAR DATA OF AN AM RADIO MAST.

Although capturing an accurate 3D point cloud representation of a structure is fairly well documented whether by photogrammetry or lidar, the process of converting the 3D point cloud into a useable CAD model is still complex. However, this is a quickly emerging technology that will soon be able to create accurate CAD models that can be used in computer simulations.

CONCLUSIONS

During the U.S. broadcast television Repack, extensive experience was gained in drone measurement techniques as well as computer simulation of radiating structures. It has been shown that computer simulation and drone measurements can be extended to the FM band and are an accurate and cost-effective alternative to traditional FM range measurements. Computer simulation and drone measurements can predict and measure the impact structures have on antenna radiation, which would otherwise be impractical to perform any other way. In the future, tower mapping can provide the means for more accurate and complete simulation models leading to even more accurate results. For the present, though, use of a drone pattern measurement solution can be used to understand the impacts of the supporting structure and other structures in the FM radiating pattern.

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