HD RADIO COVERAGE MEASUREMENT AND PREDICTION

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ABSTRACT

Because of its unique digital transmission, HD Radio® requires new methods and standards to measure and predict signal coverage, relative to analog FM. Because analog FM reception quality is known to decline gradually with degraded RF signal quality, analog FM service may be quantified in simple terms of signal strength. With digital audio broadcasting, reception quality remains ‘perfect’ until signal quality degrades below threshold requirements, at which point reception ends. This “cliff effect” as it is commonly known in digital television, required NPR to use new techniques to measure HD Radio reception and predict coverage.

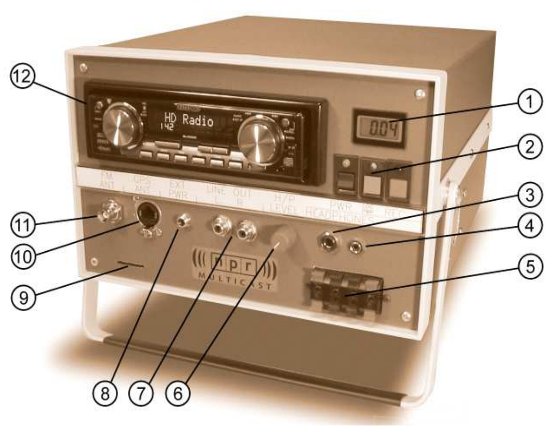
No model for measurement and prediction has been developed for this new service. Since real coverage is an oft-mentioned concern of station engineering and management, NPR Labs embarked on a year-long project to collect data from stations transmitting HD Radio and form a propagation model for this digital radio service. The following report summarizes our study, discusses current conclusions, and addresses future work that should be done to improve the coverage analysis process.

HD RADIO LOGGER DESIGN

Concurrent with the rollout of HD Radio, numerous questions have arisen about the coverage offered by the digital signal. For examples: What field strength is required to provide reliable HD Radio reception, and what does “reliable” mean? To resolve those questions, NPR Labs’ HD Radio Coverage Measurement Initiative set out to collect data from NPR member stations across the country broadcasting HD Radio. We obtained the RF signal prediction tools to estimate field strength, but we also needed data about real signal reception to calibrate our prediction model of HD Radio signal coverage. To collect these data we needed a suitable measuring device with these capabilities and features:

- Collect calibrated field strength data (from the analog host) in a log file with GPS location and time stamps;
- Easy to ship to the field, easy to set up and operate, and capable of providing best-available receiver performance;
- Log HD Radio reception information in a mobile or portable (battery operated) environment;
- Support Supplemental Program Service (“multicast”) reception;
- Provide high-quality audio outputs for HD Radio demonstration.

After examining a variety of industry solutions (none of which completely met our needs at the time) we decided to design and build our own unit for receiving, measuring and logging the HD Radio reception, as shown in Figure 1. Our ‘homemade’ approach resulted in substantial savings in capital monies for the project over the purchase of commercial units.



Key Features of the HD Radio Logger

1 Digital Volt Meter - Provides real-time RSL (Received Signal Level) and power supply conditions
2 Instrument Controls and Indicators - (from left to right) Main Power Switch (with blue LED), Logger On/Off Button (with green LED), Logger Start/Stop Button (with red LED)
3 1/4" Headphone Out
4 1/8" Headphone Out
5 Terminal Block for External Loudspeakers (4 x 20W)
6 Headphone Level Control
7 Preamp-Level Stereo Output Jacks
8 Power Input Jack
9 MMC Card Slot
10 Global Positioning System (GPS) Jack
11 FM Antenna Input Jack
12 Kenwood EZ500 Receiver Head Unit (with internal KTC-HR100MC tuner)

Figure 1 HD Radio Logger designed and built by NPR Labs.

After extensive lab testing of available receivers, we chose a Kenwood KTC-HR100MC, an FM/AM tuner for after-market car radio systems, as the HD Radio receiver. This "black box" is controlled by a Kenwood EZ500 'head unit' for tuning, display and audio amplification. NPR Labs modified the tuner to output an accurate signal level over a 70 dB dynamic range as well as provide HD Radio status measurements.

The tuner and control unit are housed in an instrumentation case with a rechargeable 12-volt battery to permit portable operation and to maintain radio memory functions when not powered externally. The unit has internal stereo loudspeakers, terminals for up to four external loudspeakers, headphone jacks and preamp-level audio output.

A suitable microcomputer-controlled data logger, providing multiple channels of analog and digital input was found. This unit, originally designed for logging race car parameters, includes the essential GPS receiver and software to log data with location and time stamps. The data is logged on a MMC memory card (similar in size to SD cards) and requires no computer to operate.

A 32" vertically polarized magnetic-mount antenna was selected for signal reception. NPR conducted field measurements with a calibrated dipole antenna at 30 feet and 7 feet above ground to characterize the reference antenna's performance on the Engineering Department's Toyota Sienna van. This provided data to convert the unit's received signal voltage readings into field strengths in microvolts/meter (or dBuV).

All functions are displayed and controlled on the front panel. Users simply lay the logger on a car floor or seat, connect the GPS unit and FM antenna (placed on the vehicle roof), tune in the desired station and press the record button.

After the logging unit had been designed and constructed, we presented it in April at the Public Radio Engineering Conference at NAB-2005. We were warmly received by engineers keen to understand their new digital coverage, and collected a long list of station engineers eager to collect data in their markets. From this list, we selected candidate stations that represented as broad of a cross-section of public radio stations as possible - we were interested in getting variety, and the final stations ended up running the gamut in terms of class, morphology, and overall market size.

Drive-Test Data Collection Requirements

To meet the demand for station measurements, and to collect a larger database of HD Radio coverage, NPR built three more HD Radio Logger units for a total of four. Over the remainder of the year the logging units were shipped to nearly 30 stations. Each station drove their broadcast area, paying attention to a few particular concerns:

- Diversity of road types – highways allowed the coverage area to be driven quickly, but often provided inflated data, as they are elevated and generally free from obstruction. We requested data be collected on a variety of roads, from city streets to small state roads.

- Driving in and out of the HD Radio reception area – the most useful information for our statistical model is gathered by crossing the boundary of a staiton's reliable HD reception, as illustrated in Figure 2. A hypothetical station's HD coverage is shown in yellow. Examples of "good" drive testing routes are displayed in green; these routes yield the most information about HD reception because they repeatedly explore the threshold of HD service, providing information about the field strengths when HD Radio reception . The route in red is not as useful to our model, as signal levels are so high that HD service is received nearly 100% of the time.

- Diversity of existing conditions – data from known problem-areas was encouraged, especially areas with adjacency concerns.

Figure 2 Drive test routes that are preferred (green) and not preferred (red) for measurement of a station's HD Radio signal coverage area (yellow).

Post-Processing Logger Data

The MMC cards containing each station's data were mailed to NPR at the conclusion of testing. Upon receipt of the memory cards, each separate data file was offloaded and concatenated into a master file for each station. Analog received signal strength (RSL) was logged as a voltage measurement (0-5V). A calibration table for each logging unit was prepared by NPR Labs and was used to convert the voltages in estimated field strength in dBµV/m. (Field strength measurements correspond to an antenna height of 2 meters, as constrasted to 9.1 meters for FCC field strength contours. This height represents the average height of the measurement antenna when affixed to a standard size car roof.)

The chart in Figure 3 shows an example of the measurement data collected on a drive-test of WAMU, Washington DC along Interstate 95 from the DC city limits through Baltimore. This sample route covers approximately 70 miles and 1½ hours of driving. The HD Radio signal (as represented by the analog FM signal measurement) declines as the distance increases from WAMU. The temporary signal drop within the Baltimore Harbor Tunnel is clearly visible.

The HD Radio reception status is logged concurrently, as displayed in red at the bottom of the chart. As the field strength drops below approximately 60 dBµ interruption of the HD Radio signal is evident. (Note that field strengths measured at a height of 2 meters differ from FCC field strengths. Also that because I-95 is a wide open roadway extending radially away from WAMU's transmitter, signal reception in this case may be better than on arterial cross streets.)

As the data arrived from stations, we gradually developed theories about how a large variety of factors were affecting the digital signal. We anticipated that the Longley-Rice propagation model would tend to overestimate signal strengths compared to measured signal levels, even when matched to a receiver antenna height of 2 meters above ground. This is because the terrain elevation data used in the predictions represent "bare earth" conditions that lack local clutter (buildings, trees, etc.) that can scatter and absorb the signal.

It is common to incorporate US Geological Survey Land Use and Land Cover (LULC) adjustment factors to minimize these prediction errors. US Geodetic Survey Land Use-Land Cover data identifies general surface characteristics, such as mixed urban, residential, rangeland, evergreen forest, water, etc., within small grid blocks. There are 21 possible categories of land cover type; these we grouped into seven primary designations for signal loss matching. Spatial resolution of the data used in NPR's study is 15 arc-seconds (approximately 500 meters). Figure 4 shows classifications in an area of the central California coast with an enlargement for the City of San Francisco.

Despite the common use of LULC with Longley-Rice predictions, we felt that fixed adjustment factors could

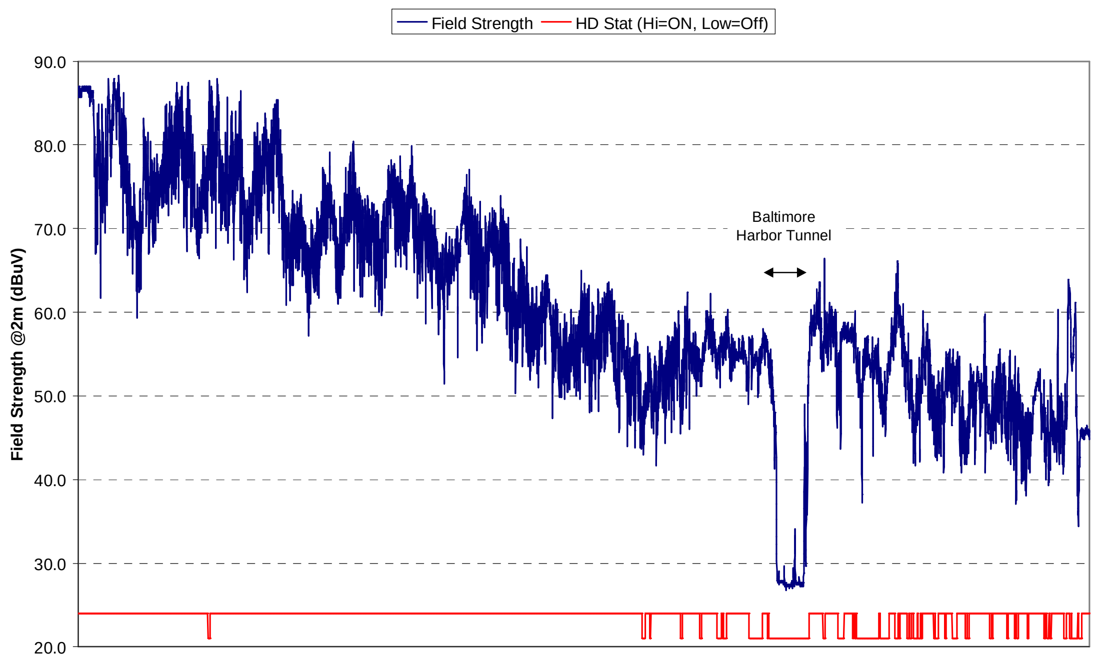


Figure 3 Timeline graph of approximately 70 minutes of raw HD Radio Logger data of WAMU(FM), on a drive from downtown Washington DC to near the Maryland-Delaware border. Field strength is blue, while corresponding HD Radio receive status is shown in the red at the bottom (high/low represents HD Radio received/not received).

increase rather than decrease errors, which required us to develop a new computational technique to generate LULC adjustments for each market drive-test.

To improve accuracy, we computed adjustments by comparing the local mean of drive-test field measurements to the underlying bare-earth predicted signal, noting the difference between measured and predicted fields. Then, the differences between measured and received signal level were averaged for each LULC type. These delta values were then used as adjustments to the Longley-Rice predictions, in a sense, a closed-loop correction at the grid-block level. This allows the signal predictions to be optimized for each market context, which substantially improved the resulting accuracy.

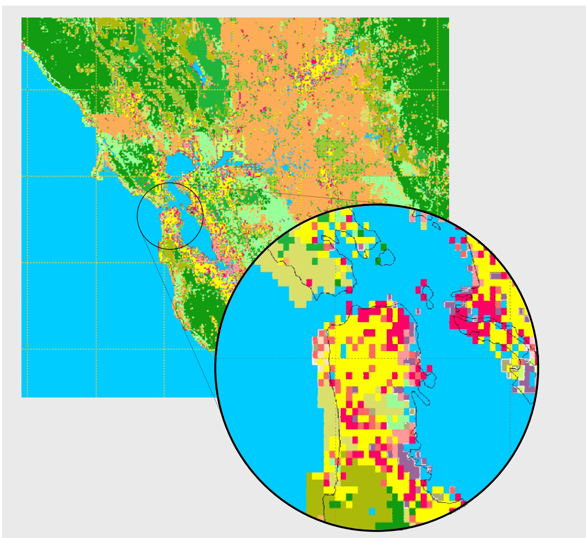


Figure 4 Illustration of Land Use-Land Cover data used in the signal propagation modeling. Enlargement in circle shows LULC bin classifications in San Francisco.

Signal Requirements for HD Radio

An important finding from the HD Radio measurement program is: How much signal is required to produce reliable reception? To answer this question, NPR studied the statistics of signal reception for the stations as a function of received signal level.

Figure 5 shows the availability of reception as a function of field strength for three stations: KXJZ, a Class C2 in Sacramento, California, WUOT, a Class C in Tampa, Florida, and KQEI a Class A in North Highlands, California. It is apparent that the reception availability falls off differently for the three stations, particularly for KQEI, even though these stations serve similar areas across Sacramento. The differences may arise from a combination of factors, including amounts of Rayleigh fading and multipath from each station, differences in environmental noise and station interference on each frequency. (KQEI shares a tight contour protection with first-adjacent channel station KVMR, a Class B1 in Nevada City, California.)

Differences in measurement techniques at each station may affect individual results. Although a standard antenna was used throughout the measurements, different vehicles were used by each station. (Minivans were recommended because of their relatively wide and level roof, providing more consistency in antenna gain.) Nevertheless, distortions of the horizontal plane pattern will occur, affecting gain at various orientations of the vehicle. Extensive driving was encouraged to help even out these directional gain variations. Vehicles may exhibit excessive RF noise from the ignition or electrical system, which could pollute the reception and degrade measured sensitivity. Also, the terrain varies from smooth and flat to hilly. Population density of the areas measured range from rural to dense urban. However, considering the measurements include 26 operating stations it can be said that the overall results represent real-world experience that may resemble the consumer's results.

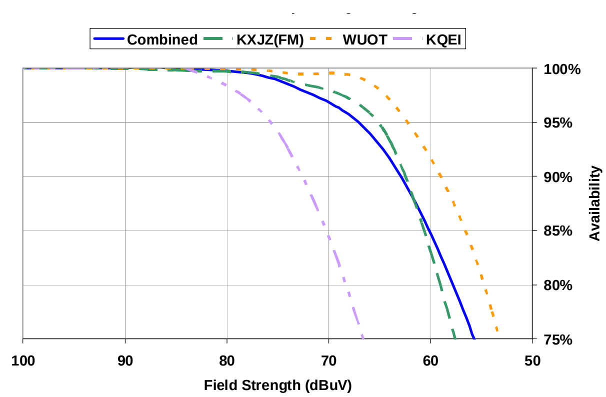


Figure 5 Availability vs. field strength for three HD Radio stations KXJZ, WUOT and KQEI (dashed lines) plus combined results for 26 stations (solid line).

Considering the variability that may result from vehicle to vehicle, it is appropriate to look at HD Radio coverage performance for all 26 stations in the current statistical database. This list contains a wide variety of transmitting facilities, from smaller Class A stations to large Class C stations. Figure 5 presents two histograms showing the numbers of stations with minimum field strengths to achieve reception availabilities of 90% and 97% (blue and gold, respectively). The stations are grouped in 5 dB ranges. As expected, the higher availability of 97% requires higher field strengths than does 90%.

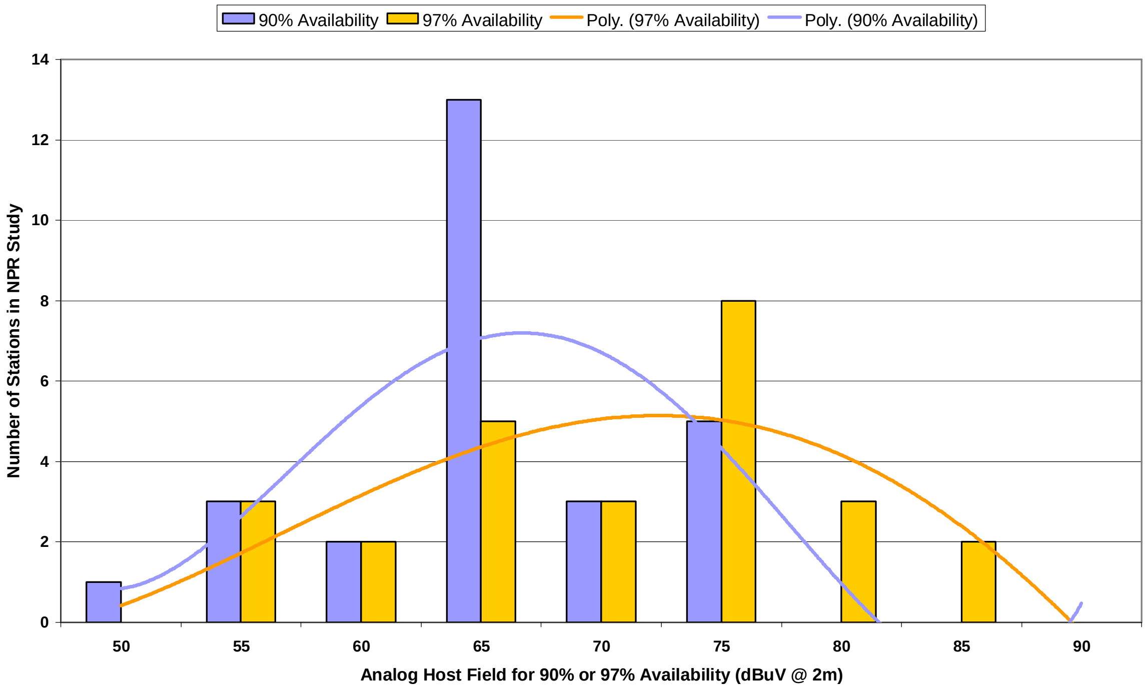


Figure 6 - Field strength requirements for 26 HD Radio stations, based on NPR Logger and measurement analysis.

The range of the field strength distribution is notable. Eight stations required at least 70 to 75 dBuV to achieve 97% availability, but two stations required between 80 and 85 dBuV and three required between 75 and 80 dBuV. On the other hand, three stations required as little as 50 to 55 dBu and two stations required 55 to 60 dBuV. The distribution for 90% is much narrower, with 13 stations requiring 60 to 65 dBuV. To help identify these trends, the chart includes 3rd-order polynomial curves in colors matching the distributions. Median field strength for the 97th percentile availability is 70 dBuV, and for the 90th percentile is 63 dBuV, referred to a receive height of 2 meters above ground.

The roof-mount whip antenna supplied with NPR's HD Radio Logger kit operates at greater heights than production antennas in automobiles and may produce higher signal levels. Also, built-in antennas are usually hidden in front, rear or side windows, or even bumpers, which may result in greater pattern distortion than the logger kit.

A study of the environment types and terrain conditions reveal some correlation with the field strength findings. There is a tendency for HD Radio to require higher signal in hilly or rough terrain and less in areas of smooth terrain. To date, the data indicate that lower class stations require the same levels of digital signal as higher class stations. However, Class A stations with minimal spacing to other first-adjacent channels may have more signal overlap than the FCC contours suggest. These may be conditions of digital interference that require further study.

Indoor Reception Projections

Indoor reception cannot be determined from these mobile measurements because signal penetration into buildings is case-specific. The FCC's early studies with television signal penetration in the lower VHF channels indicated a wide range of 5 dB to 15 dB in building penetration loss. To this variability one must add the potential inefficiency of indoor antennas, which include short wires (often provided with table model radios) having possibly 5 to 10 dB of loss relative to a dipole. These factors may combine to require greater field strength for indoor reception.

As mentioned earlier, HD Radio reception experiences a "cliff effect" when signal quality degrades below minimum requirements. For digital systems these requirements are governed primarily by the signal to noise ratio, or strictly speaking the bit energy relative to the power spectral density of the noise, expressed as Eb/No. Thus while it is convenient to predict reception by signal strength, HD Radio is effectively a noise- and interference-limited service. For mobile HD Radio, basic signal strength tends to determine system noise (unless one is in a vehicle with abnormal ignition noise or alternator hash), but in buildings, where the signal is already weakened by penetration loss sources of RF noise (computers, electric motors, etc.) may determine digital reception.

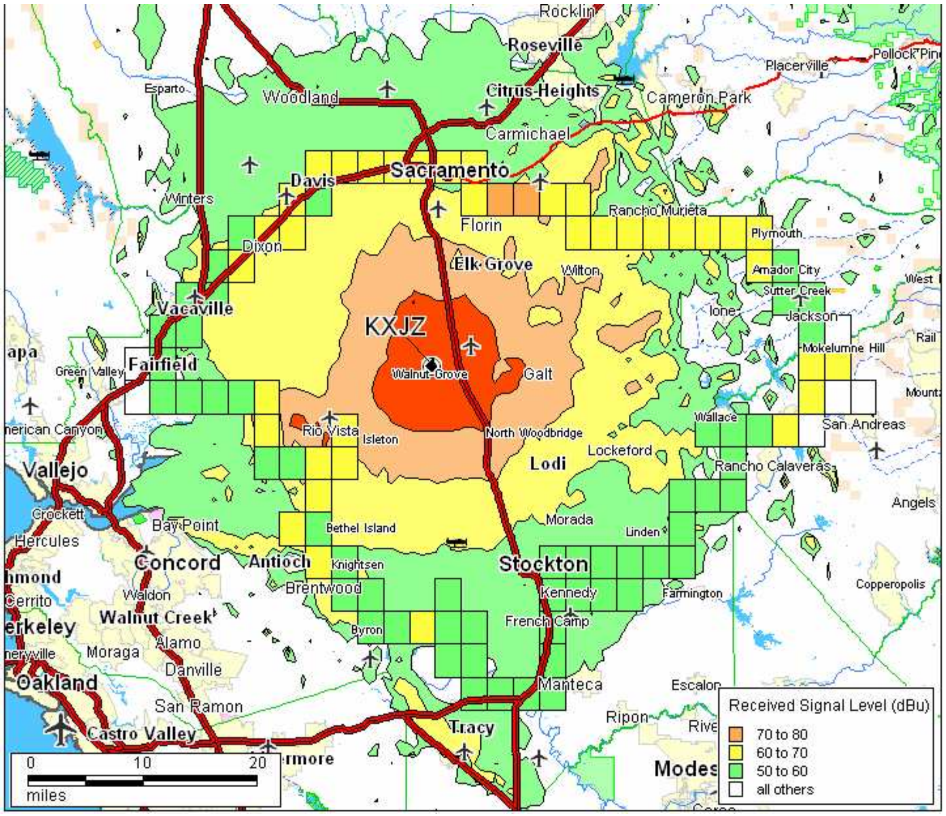


Figure 7 Drive-test map example of KXJZ, Sacramento, showing aggregated field strengths over Longley-Rice prediction.

The presence or absence of RF noise is beyond any deterministic model of HD Radio coverage. Fortunately, listeners with fixed receivers have the opportunity to adjust their radio's location and antenna position for best reception, which can contribute numerous dB to their link budget. NPR is currently engaged in a survey of early users of indoor HD Radios to gather coverage information on this important user group. These findings should provide valuable information on "best practices" for stations and radio manufacturers to achieve optimal reception of HD Radio.

Mapping Display

The optimized Longley-Rice predictions were imported into MapInfo®, a well-known Geographic Information System program used to manipulate and map multiple layers of geo-information. Using Vertical Mapper®, a suite of MapInfo tools, the Longley-Rice data were interpolated using an Inverse Distance Weighting and rendered in contour regions of 50-60dBu, 60-70dBu, 70-80dBu and 80-120dBu.

The core drive-test data were added to the maps over the optimized Longley-Rice predictions. Drive-test data was aggregated into grid blocks of typically 100-300 samples, representing the mean field strength or HD status of all drive-test samples within a specified distance of the grid block's center. This "binning" allowed large amounts of data collected by each station to be viewable on a large scale map, and offered viewers of the maps a better characterization of regional service. Figure 8 shows how the drive-test routes were converted and displayed in black, gray or white, according to reception availability. Availability refers to the percentage of time that HD Radio reception was present for the local area indicated by the grid block.

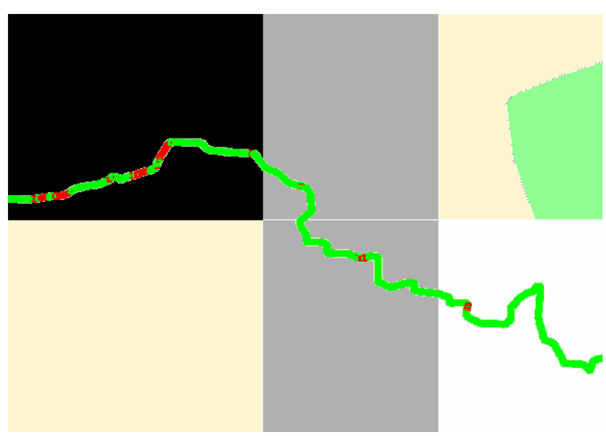


Figure 8 Highly-magnified portion of a drive-test route showing HD Receive status (green or red) overlaid on bin-aggregated results (white, gray, black).

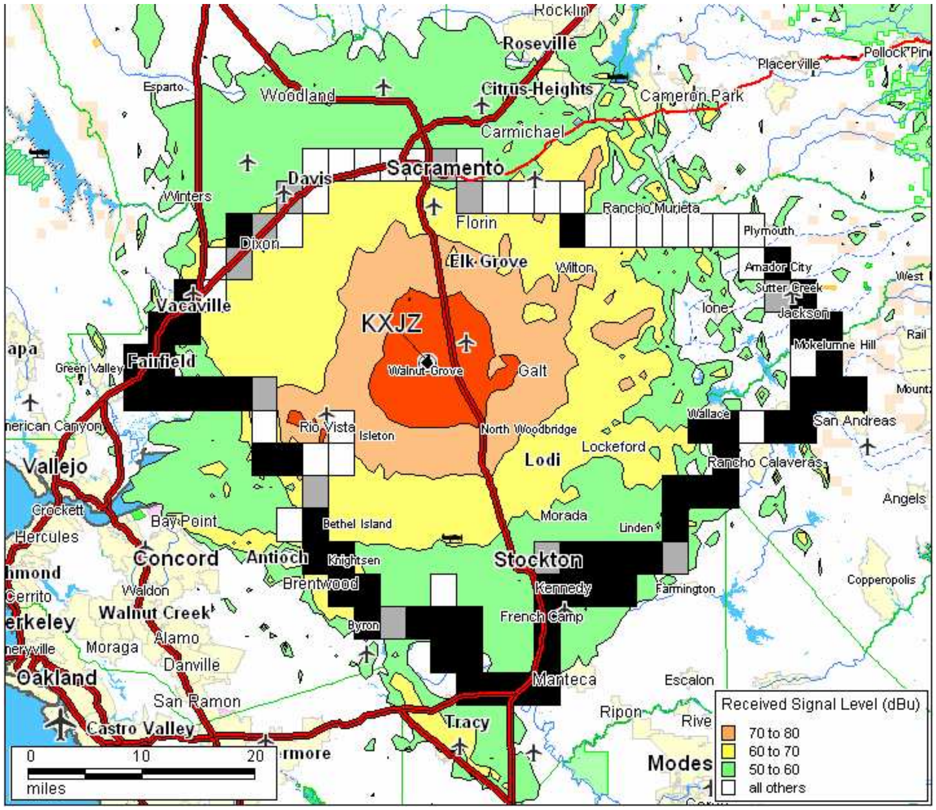


Figure 9 Example of a drive test route map for KXJZ. Aggregated data in white blocks is >97% availability of HD Radio reception; gray indicates 90%-97% availability and black indicates <90% availability.

The ranges selected for the HD Receive Status map are 0-90%, 90-97%, and 97-100%. These ranges relate to a general "annoyance factor" associated with dropout rates – the premise being that if the HD signal is not received a large amount of the time on a Supplemental Audio Channel (with no analog backup) it would quickly get annoying. Thus, a higher standard of 97% was chosen to represent availability that may be required for SAC reception. The 90% availability threshold is included more as a reference for a lower figure than to represent any specific perceived quality.

A similar method was used to aggregate received signal level for the drive-test RSL maps. Each bin was colored to correlate to the Longley-Rice contour intervals for a Received Signal Level map, and shaded to represent a percentage range of HD Reception for an HD Receive Status map

Three maps are created for each station supplying drive-test data. The first map shows a binned analog field strength along the station drive-test route over an optimized Longley Rice prediction. Figure 7 shows ans example of one station from the current group, KXJZ(FM), Channel 205B, Sacramento, California. The colors of the field strengths match so one may compare the accuracy of Longley-Rice predictions, as an underlay, to the analog field strength measurements.

The second map, Figure 9, shows aggregated and binned HD Radio Logger reception along the same route as the field strength, above. Bins that are shaded white received HD Radio at least 97% of the time, while gray bins received between 90% and 97% of the time and black bins show reception less than 90% of the time.

Evaluating the correlation between the underlying field strength and the availability of HD Radio reception is a difficult matter by eye. This problem becomes more evident if one is asked to chose what field strength represents HD service, even when it has been binned into ranges of percent availability along the route. As discussed earlier NPR Labs developed a statistical method whereby availability of reception is evaluated against measured field strength, as shown in Figure 5. From this distribution the engineer may determine the necessary field strength for specific availability targets.

Figure 10 shows the result of the KXJZ analysis, with HD Radio coverage predicted over the entire coverage

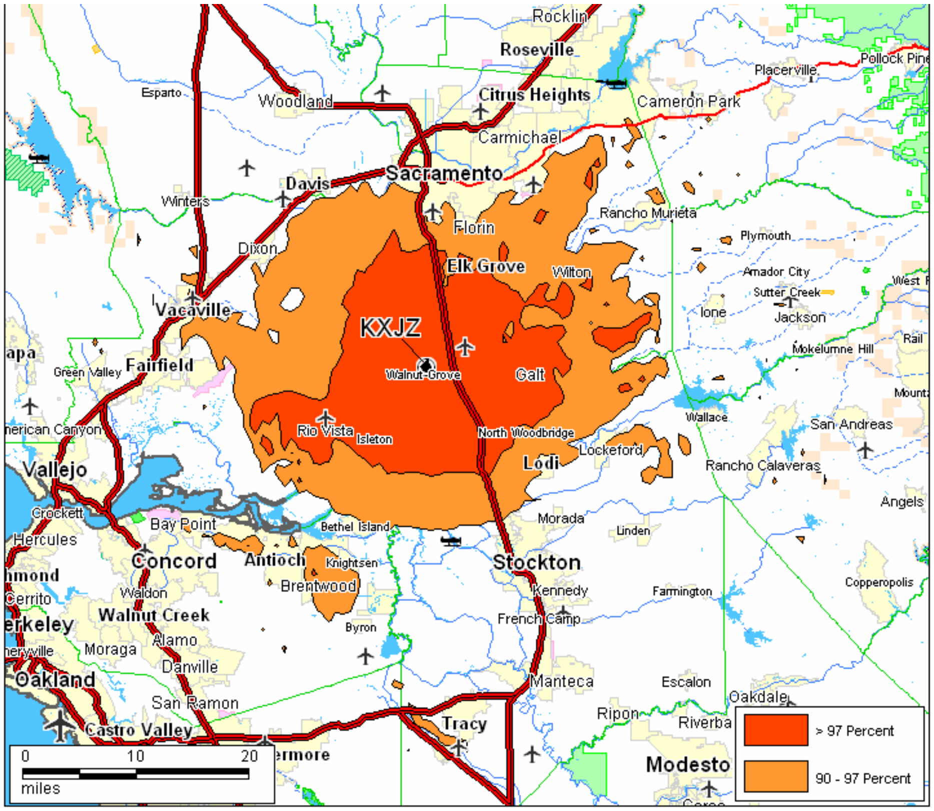


Figure 10 HD Radio availability map for KXJZ, showing geographic areas in which reception availability is expected to greater than 90% and 97%.

area to availabilities of 90% and 97%. This map results from the following steps:

- drive-test measurement collection,
- Longley-Rice signal prediction,
- optimization of the Longley-Rice predictions by using LULC corrections correlated to the measurement data,
- derivation of the statistical distribution of HD Radio availability versus measured field strength, and
- preparation of maps showing the area of predicted HD Radio service availability, as measured by the HD Radio Logger.

Methodology Issues and Future Work

As noted earlier, the predictions of HD Radio reception are based on results collected by the HD Radio Logger. Thus the results are representative of this receiving system only, and "your mileage may vary". Certainly, future work should include development of a standardized antenna system that is not influenced by the vehicle on which it is mounted. The variations from station to station should be explored and causes identified. A review of current data for adjacent channel interference is inconclusive, but futher study is needed. Rayheigh fading effects are suspected with stations having very rough terrain; the existing data can be "mined" further to investigate this effect. The statistical model was based on total service availability within discrete bins or locales, but the durations of individual outages should be considered. For example, listeners may respond differently to ten one-second outages in a minute than one ten-second outage, although the statistics register identically at present. We look forward to continued work with station engineers on these measurements and further research on the application of HD Radio.

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